Strength Verification Methods for Stabilised Soil-Cement Columns: A Laboratory Investigation of PORT and PIRT

by

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DECLARATION

I hereby declare that this thesis has not being submitted in whole or in part to any other University as part of a degree. Except were referenced, the work presented is entirely my own.

Martin J. Timoney

To my parents, Mary and Martin A.

Perhaps the missing ingredient is courage. The courage you need is the courage to start. Once launched, then each step can be evolved naturally. Each step requires careful examination. The courage to start and an unshakeable belief in one's ability to solve the new problems which will arise in the development are essential.

Peter Rice,
An Engineer Imagines
(Rice 1996)

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Upon embarking on my PhD, I joined the NUIG/GMIT Sub Aqua Club and immediately it became apparent I had a talent and flair for SCUBA diving. Although at times it may have provided more of a distraction than I would care to admit, it has created a passion and love for the underwater world, be it a shallow potter around off Coral Beach in Carraroe or a technically demanding excursion to a 20th century shipwreck in the deep and dark depths miles off the Irish coast. But most of all it has given me some truly great friends, and a special mention must go to Aimée, Dec, James and a particular heartfelt thank you to Anna for all her support and encouragement.

Finally, to my parents Mary and Martin, and my sisters Catherine and Bridget, a sincere thank you for your constant support throughout my PhD, and in particular during its final stages.

ABSTRACT

Dry soil mixing (DSM) is a form of ground improvement in which dry cementitious and/or pozzolanic binders are mixed *in situ* with a soft soil. The binders react with the soil's natural moisture to initiate hydration reactions, thus leading to improved strength and stiffness characteristics. The deep dry soil mixing method (DDSM) is one form of DSM in which stabilised soil columns are created in soft soil profiles. Although site-specific binder trials can help estimate achievable column strengths, variations in the soil profile, moisture content, organic content, curing temperature and mixing conditions may mean that *in situ* field strengths can differ from those obtained under laboratory conditions, thus requiring the need for *in situ* strength verification.

Two field methods used to estimate the strength of a stabilised soil column are the Push-In Resistance Test (PIRT), where a winged penetrometer is pushed down through the stabilised column, and the Pull-Out Resistance Test (PORT), where a winged penetrometer is pulled up through the stabilised column from beneath its base. Using a semi-empirical equation, whose origins lie with the *Iskymeter* penetrometer, the probing force is related to undrained shear strength of the stabilised column using a bearing factor, N. While N values between 10 and 15 are quoted in the literature (empirical and Scandinavian experience), few field tests and no laboratory investigations have attempted to investigate the relationship and the factors upon which N depends, thus limiting international confidence in the method.

In this thesis, the results from a unique series of one-quarter-scale laboratory tests are presented and discussed. Reduced-scale PORT and PIRT penetrometers were manufactured and stabilised column construction procedures, along with penetrometer testing methods, were developed after some preliminary trials. Stabilised columns were constructed by stabilising a soft organic silt with cement and allowed to cure for various durations before penetrometer testing. Once tested, the columns were exhumed and samples taken for unconfined compression strength (UCS) testing, with UCS values up to 800 kPa observed. Exhumed columns showed evidence of cracking caused during the penetrometer test, believed to be due to the increased brittleness of the stabilised material over the parent material, and this is an important feature when interpreting the test results.

The following considerations were also pertinent when interpreting the results:

(i) The effect of curing temperature was investigated through a comparison of separate mould samples cured at constant and ambient laboratory temperatures. In addition, thermistors within a specific column (and its test basin) were used to investigate temperature variations during curing. Temperature was found to have a significant effect and was accounted for using a framework in which the curing time was adjusted for temperature in the same manner as is applied for concrete. The framework also includes for the different binder contents and variations in the soil's moisture content.

(ii) Based on best-fit relationships, corrections were applied to the column samples strength to account for any strength gain that occurred between the column penetrometer test and the UCS testing of the column samples.

(iii) A supplementary series of column tests were carried out to establish the contribution of friction to both the PORT and PIRT column tests.

Using the probing force profile, corrected for friction, and the corrected column strength, the actual bearing factor N, was calculated. The results show N to compare reasonably well with the guideline value of 10 for both PORT and PIRT however, the strength of the stabilised soil column has an influence on the N value. In the upper portion of the column, lower PORT and PIRT N values were observed due to lack of confinement around the top of the column, allowing it to crack open ahead of the penetrometer. Where a surcharge was applied to the top of the basin, increased N values were noted. In the middle and lower sections of the column, PIRT N values are seen to show a constant value with depth, while PORT N values tend to increase with depth due to frictional forces experienced by the PORT penetrometer and its wire.

This is the first laboratory-scale study of its kind to be conducted and provides in-depth guidance on how the factors which influence the N value may be assessed in the laboratory. Furthermore, the work has international implications for increased confidence in the interpretation of the strength of dry soil mixed columns.

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LIST OF SYMBOLS

The following symbols and abbreviations are used in this thesis and when referring to a specific publication the original notation is used.

a	Non-evaporable water content
A	Penetrometer plan area
A_0	Initial sample area (UCS testing)
A_c	Sample area adjusted for deformation (UCS testing)
A_{stab}	Volume of air in a stabilised *sleech* sample per ideal cylindrical sample volume
BC	Binder content
c_{cor}	Undrained shear strength of the column corrected to the time of the column test
c_u	Undrained shear strength
c_{uss}	Undrained shear strength of the *sleech* surrounding a column
d	Depth from top of column
E_{50}	Secant stiffness at 50% of the failure stress
E_{mld}	Stabilised mould secant stiffness at 50% of the failure stress for both room-cured and 20 °C cured samples
E_{mldR}	Stabilised mould secant stiffness at 50% of the failure stress for room-cured samples only
E_{mldT}	Stabilised mould secant stiffness at 50% of the failure stress for 20 °C cured samples only
E_{col}	Stabilised column secant stiffness at 50% of the failure stress
h	Height from basin base
H	von Post degree of humification
G_s	Specific gravity
L_0	Initial sample length (UCS testing)
M	Stress level dependency power (PLAXIS)
m_b	Mass of binder
m_w	Mass of water
n	Number of samples to calculate an average
N	Column shear strength to penetrometer probing resistance relationship

N_c	Empirical cone factor for CPT
N_k	Empirical cone factor for piezocone penetration test, CPTU with pore water pressure measurement
P	Compressive force (UCS testing)
P_o	Pull-out probing force (uncorrected)
P_i	Push-in probing force (uncorrected)
P_{oa}	Average pull-out probing force over the depth occupied by a column sample
P_{oac}	Average pull-out probing force over the depth occupied by a column sample corrected for wire friction
P_{ia}	Average push-in probing force over the depth occupied by a column sample
P_{ic}	PIRT push-in force correction factor
P_{iac}	Average push-in probing force over the depth occupied by a column sample corrected for friction
P_{ref}	Reference pressure
P_{wc}	Wire friction correction
q_t	Unconfined compression strength after *t* days curing
q_{mld}	Stabilised mould UCS for both room-cured and 20 °C cured samples
q_{mldR}	Stabilised mould UCS for room-cured samples only
q_{mldT}	Stabilised mould UCS for 20 °C cured samples only
q_{col}	Stabilised column UCS (obtained from UCS testing)
q_{cor}	Corrected column UCS to the time of the column test
r	Radius out from the column centre
Ri	Rigidity index
S_r	Degree of saturation
t_{col}	Time from mixing to UCS testing for column samples
t_{mldR}	Time from mixing to UCS testing for mould-cured samples
t_{mldT}	Time from mixing to UCS testing for 20 °C cured samples
t_{Pi}	Time from mixing to the PIRT
t_{Po}	Time from mixing to the PORT
T	Average ambient laboratory temperature
TCT_{mld}	Temperature corrected time of all mould samples
TCT_{col}	Temperature corrected time of column samples

TCT_{Po}	Temperature corrected time for a pull-out test (PORT or wire)
TCT_{Pi}	Temperature corrected time for a push-in test (PIRT or cone only)
w_i	Initial soil moisture content
w_{mix}	Moisture content immediately after the addition of the binder and mixing, *i.e.,* soil-binder mixture
w_s	Stabilised soil moisture content at the test time
w_{mld}	Stabilised soil moisture content at the test time for mould samples
w_{col}	Stabilised soil moisture content at the test time for column samples
w_{ss}	Moisture content of *sleech* surrounding the column during curing
V	Voltage
v	Poisson's ratio

α	Column-penetrometer friction factor
γ	Unit weight
ΔL	Change in length of sample during UCS testing
$\Delta UCS \times WTBR$	Strength correction factor for the delay between the column test and UCS testing of samples from the column
ε	Strain (UCS testing)
ε_{50}	Strain at 50% of the failure stress, corrected for bedding error
ε_f	Strain at failure, corrected for bedding error
η	Water to binder ratio
μ_w	Frictional stress (between the pull-out wire and the stabilised column)
ϕ	Friction angle
ρ	Density
ρ_w	Density of water
ρ_f	Density of freshly compacted mould samples
ρ_s	Density of stabilised mould samples
ρ_{sleech}	Density of unstabilised *sleech*
ρ_{OPC}	Density of Ordinary Portland Cement
ρ_{col}	Stabilised column density
ρ_{mld}	Stabilised mould density for both room- cured and 20 °C cured samples
ρ_{mldR}	Stabilised mould density for room-cured samples only

ρ_{mldT}	Stabilised mould density for 20 °C cured samples only
ρ_{ss}	Density of the *sleech* surrounding cured columns
σ_1	Compressive stress (UCS testing)
σ_x	Horizontal radial stress
σ_i	Horizontal radial stress before implementation of the expansion

LIST OF ABREVIATIONS

ASTM	American Society for Testing and Materials
ALE	Arbitrary Lagrangian Eulerian
Av.	Average
BMS	Building Management System
BRN	Blade rotation number
BSI	British Standards Institute
CET	Cavity expansion theory
CPT	Cone penetration test
CPTu	Cone penetration test-piezocone
ColPT	Column penetration test
CSH	Calcium Silicate Hydrate
C-*X*	PIRT cone penetrometer experiment on column no. *X*
DAQS	Data acquisition system
DDSM	Deep dry soil mixing
DJM	Dry jet mixing; Japanese equivalent of DSM
dia.	Diameter
DPA	Deep penetrating anchor
DSM	Dry soil mixing
FACT	Fully automated cyclical triaxial
FE	Finite element
FEM	Finite element modelling
FOPS	Förinstallerad-Omvänd-Pelarsondering; pre-installed reverse column probing (penetrometer is installed before column production), alternative name for PORT
GGBS	Ground granulated blast-furnace slag
HDPE	High-density polyethylene
IBC	Intermediate bulk container
IRCSET	Irish Research Council for Science, Engineering and Technology
KPS	Kalk-Pelar-Sondering; Lime-Column Probing, alternative name for PIRT
L/D	Length-to-diameter ratio
LL	Liquid limit
LOI	Loss on ignition

LVDT	Linear variable differential transducer
MgO	Reactive magnesia cement
MS	Mass stabilisation
NI	National Instruments
NUIG	National University of Ireland, Galway
PIRT	Push-in resistance test
PI-*X*	PIRT experiment on column no. *X*
PL	Plastic limit
PORT	Pull-out resistance test
PO-*X*	PORT experiment on column no. *X*
PFA	Pulverised fly ash
PVC-U	Un-plasticised polyvinyl chloride
OCR	Over-consolidation ratio
OPC	Ordinary Portland cement
OPS	Omvänd-Pelar-Sondering; Reverse column probing, alternative name for PORT
RColPT	Reverse column penetration test
RHC	Rapid hardening cement
SC	Campbell Scientific
SD	Swedish Deep Stabilisation Research Centre
SGI	Swedish Geotechnical Institute
Sleech	A soft dark grey organic clayey silt soil local to Belfast
SM	Soil mixing
St. Dev	Standard deviation
TCT	Temperature corrected time
TS	Total sounding
UCS	Unconfined compression strength
WSM	Wet soil mixing
WTBR	Water to binder ratio
W-*X*	PORT wire pull-out experiment on column no. *X*

CHAPTER 1: INTRODUCTION

1.1 Background

Dry Soil Mixing (DSM) is a form of ground improvement in which dry binders are injected into and mixed with a parent soil, resulting in improved strength and stiffness characteristics for the soil over time. Initially developed in the 1970s, simultaneously in Scandinavia and Japan (Bredenberg 1999; Bruce *et al.* 1999), lime was the first binder used but today many other cementitious and pozzolanic binders are used, the most popular being cement and combinations of cement with lime or GGBS. Dry soil mixing is particularly applicable to soils with high moisture contents close to their liquid limit, such as clays, silts and sludges, and with an appropriate choice of binder type and content, can also be used to improve organic clays and peats. The two primary forms of DSM are Deep Dry Soil Mixing (DDSM) in which discrete stabilised columns are created, and Mass Stabilisation (MS) in which large shallow blocks are stabilised. Applications include road and railway projects, foundations for light structures, temporary works and slope stability. Furthermore, the processes may be used to confine contaminated ground by creating cut-off walls, and using specifically designed binders, even remediate contaminated ground.

A robust theoretical basis for predicting the stabilised properties of a variety of soil/binder combinations has yet to be developed. Therefore, DSM testing programmes (mainly laboratory based) have been essential in assessing the achievable stabilised properties in a variety of scenarios, and much of the published material is based upon Scandinavian (for example the work of the Swedish Deep Stabilization Research Centre) and Japanese experiences. Much of the relevant literature derives from international conferences and workshops focusing on soil stabilisation (Rathmayer & Saari 1983; Yonekura *et al*. 1996; Bredenberg *et al*. 1999; Rathmayer 2000; Rydell *et al*. 2005; Kitazume & Terashi 2009; Byle *et al*. 2012; Denies & Huybrechts 2012) and also from a number of international journals.

While laboratory stabilisation trials are helpful, inherent *in situ* variability of the soil, variations in the mixing process and curing conditions mean results from stabilisation trials may not reflect those obtained *in situ*. Therefore, a requirement exists for *in situ* strength verification. Two common methods are the Push-In Resistance Test (PIRT) and the Pull-Out-In Resistance Test (PORT), in which winged penetrometers probe the stabilised columns. The recorded probing resistance is then related to the column strength using a bearing capacity factor, N. Some guidance exists in the literature on appropriate values of N (Åhnberg & Holm 1986; Carlsten & Ekström 1996; EuroSoilStab 2002; Larsson 2006; Trafikverket 2011), mainly based on Scandinavian experience, but with limited supporting data. Given that DDSM is now gaining popularity in new markets, such as elsewhere in Europe, the USA (Burke *et al*. 2007; Filz 2009; Hussin & Garbin 2012), Australia (Liyanapathirana & Kelly 2011) and Asia (Horpibulsuk *et al*. 2012), there is a need for independent verification tests to help with the interpretation of PORT and PIRT and to improve the confidence in the method worldwide. The reduced-scale laboratory tests described and interpreted in this thesis are believed to be the first of their kind ever conducted.

1.2 Thesis Aims and Objectives

This research investigates, for the first time in the laboratory, the relationship between the probing resistance and the undrained shear strength for PORT and PIRT of reduced-scale stabilised columns, and the factors upon which the relationship depends. To this end, the following objectives were identified:

(i) Laboratory stabilisation trials will be performed with-a-view to assessing the suitability of possible soils and binders for the reduced-scale column penetrometer series.

(ii) Methods of constructing and testing reduced-scale stabilised columns will be developed based upon experiences derived from the literature and preliminary experimentation in the laboratory.

(iii) Once a soil has been chosen and the above methods established, stabilised columns with a wide range of unconfined compression strengths will be constructed and tested using bespoke reduced-scale PORT and PIRT penetrometers.

(iv) Samples taken from the exhumed tested columns will be strength tested and compared with the recorded probing resistances, thus allowing for an accurate determination of N and its governing factors.

Furthermore, additional testing performed to achieve the above objectives included:

(i) Two separate series of tests to establish the contribution of friction between the pull-out wire and the column during a PORT and the friction between the sounding bars and the column during a PIRT.

(ii) Additional PORT and PIRT were carried out in unstabilised material for reference purposes.

(iii) A study to understand the influence of curing temperature on the strength of the stabilised columns.

As mixing of a binder with a natural clay is a variable process, test data are provided throughout as a measure of quality control and a framework was developed which accounts successfully for the variability.

1.3 Thesis Layout

Chapter 2: Literature Review, is divided into two sub sections. Part A provides details on how stabilisation is carried out in the field and the methods used. A review of current field methods to estimate the strength of stabilised columns is carried out including details of *in situ* probing tests, primarily focusing on the PIRT and PORT. The origin and development of the current relationship used to estimate the column strength is given and N values from current guidance documents, field testing and Finite Element Modelling are compiled.

Part B reviews the factors which influence the stabilisation process, primarily soil characteristics, binder characteristics, mixing conditions and curing conditions, before reviewing the achievable stabilised soil properties. A short overview of laboratory stabilisation procedures is provided, including the findings of some studies relevant to the proposed laboratory work in this thesis. Finally, a review of previous laboratory stabilisation work provides guidance on how the proposed reduced-scale columns may be constructed and tested in the laboratory.

Chapter 3, Experimental Design and Testing Procedures, sets out the standard procedures used to classify and test the parent peat and silt soils used in this thesis. Arising from the review of laboratory stabilisation trials in Chapter 2b, stabilisation trial procedures for assessing strength improvements of a silt and a peat soil are described in detail. From the review of previously constructed reduced-scale columns, details of the design of the reduced-scale experiments are presented, including choice of scale and dimensions for the test series. Detailed procedures are given on how the reduced-scale columns were constructed and tested in the laboratory for PORT, PIRT, wire friction tests, PIRT cone-only penetrometer tests, and other associated tests. Details are also provided on the methods used to monitor the variations in temperature within a stabilised column during curing. Finally, in Chapter 3, there is a discussion on the variability, both inherent and some unintended, which is relevant to the subsequent chapters and a statistical (mixed model linear regression) analysis procedure is set out for the PORT and PIRT data.

Chapter 4: Preliminary Laboratory Stabilisation Trial Results, presents the results from two series of binder trials carried out on a peat and an organic clayey-silt (known as *sleech*) soil for the purpose of choosing a suitable soil and binder to use in the reduced-scale penetrometer test series. From the experience gained during the trials, the *sleech* was chosen as the most suitable soil to use for the reduced-scale column tests stabilised with Ordinary Portland Cement at binder contents of 100 kg/m^3 and 150 kg/m^3.

The results of the first series of 200 mm dia. reduced-scale probing tests using a 150 mm reduced-scale PORT penetrometer are presented in Chapter 5: Pull-Out Resistance Test (PORT) Results. The pull-out forces recorded during probing are presented, as are results from initial classification on the *sleech* used in constructing the PORT columns and the stabilised properties of the columns at the time of testing. Comparisons are drawn with some of the relationships seen in stabilised soils, presented in Chapter 2, Part b, to support the quality and repeatability of the column production and testing. A framework is presented within which moisture content, curing time and curing temperature are all accommodated, which has the effect of unifying the results. Some of the supporting evidence for this framework derives from work in Chapters 4 and 7. The chapter concludes with the results of a detailed statistical (linear mixed model regression) analysis. A very similar format is followed for Chapter 6: Push-In Resistance Test (PIRT) Results.

Chapter 7: Friction Tests, Temperature Monitored Column and Data Corrections, presents the results of a number of tests carried out to:

(i) Assess the magnitude of the friction between the PORT penetrometer pull-out wire and the stabilised column during a reduced-scale PORT.
(ii) Assess the magnitude of the friction between the PIRT penetrometer sounding bars and the stabilised column during a reduced-scale PIRT.
(iii) Assess the variations in the column curing temperature, and its associated mould samples, as a result of the exothermic hydration reactions and variations in the ambient laboratory temperature.

Based on the results of (iii), a method is defined in which the effect on strength of variations in the ambient curing temperature may be taken into account. Finally, details are provided of a correction applied to the strength results to deduct any strength gain occurring between probing of the columns and strength testing of samples taken from the tested column in the interest of deriving a time consistent N value. This correction is particularly relevant to early-age columns.

Chapter 8: Discussion, begins with a coefficient of variation assessment of the data from the four column series and a summary of the statistical (linear mixed model regression) analysis. Comparisons are then made between reduced-scale column tests and *in situ* field versions of the tests. Using the corrected strengths and the results of the friction tests, both presented in Chapter 7, the N value for each PORT and PIRT column is calculated and discussed in terms of the influencing factors and comparisons with current guidance.

Chapter 9: Conclusions, draws together the knowledge gained from these original test series and provides the findings arrived at for reduced-scale PORT and PIRT of stabilised soil-cement columns, as well as recommendations for future reduced-scale column testing.

The Appendices provide relevant published work by the author, dimensions and drawings of the reduced-scale penetrometers used, results from the preliminary stabilisation trials, summary result sheets for each individual column test, diagrams and photographs of the cracking patterns observed and some of the outputs from the SPSS statistical analysis.

1.4 Publications

During the course of this thesis, one journal paper and a number of conference papers were prepared and published. These are listed below and may be found in Appendix A:

Journal Papers:

- Timoney, M.J., McCabe, B.A. and Bell, A. 2012. Experiences of Dry Soil Mixing in Highly Organic Soils. *Ground Improvement* 165(1), pp. 3–14.
- Experiences of Dry Soil Mixing in Highly Organic Soils was awarded the Telford Premium Prize by the Institute of Civil Engineers for best paper in the ICE journal, Ground Improvement in 2012 (ICE 2014).

Conference Papers:

- Timoney, M.J., Quigley, P. and McCabe, B.A. 2011. The Stabilisation of Irish Peats. In: Nikraz, H. and Shahin, M. eds. *International Conference on Advances in Geotechnical Engineering*. Perth, pp. 633–638.
- Timoney, M.J., Quigley, P. and McCabe, B.A. 2012b. Some laboratory soil mixing trials of Irish peats. In: Denies, N. and Huybrechts, N. eds. *ISSMGE - TC 211 International Symposium & Short Courses; Recent Research, Advances & Execution Aspects of Ground Improvement Works*. Brussels, pp. 511–520.
- Timoney, M.J. 2014. Strength verification of soil-cement columns; a scale laboratory investigation of the Push-In Resistance Test. In: Arroyo, M. and Gens, A. eds. *Proceedings of the 23rd European Young Geotechnical Engineers Conference,* Barcelona 2014. Barcelona, pp. 137–140.

CHAPTER 2: LITERATURE REVIEW

Part A: Review of Field Production
& Testing Methods

Part B: Review of Soil Stabilisation
& Laboratory Stabilisation Methods

2.1 Introduction

The first section of this chapter provides an explanation of the manner in which stabilisation of weak and organic soils is carried out in the field using both column and mass stabilisation techniques, and focuses on dry soil mixing (DSM) methods. A detailed description of the most common field testing methods and the manner in which they are carried out is provided, concentrating primarily on column penetrometer testing, the subject of this thesis. The development of the current relationship used to estimate the strength of stabilised soil columns is presented and results from field observations are compiled.

2.2 *In Situ* Soil Stabilisation

Soil stabilisation, or soil mixing, is a form of ground improvement in which cementitious and/or pozzolanic binder materials are mixed *in situ* with a soft soil with the aim of improving the strength and deformation characteristics of the soil (EuroSoilStab 2002). Stabilisation may also be used as a method of confining and/or remediating contaminated soils (Al-Tabbaa *et al.* 2009). Stabilisation is achieved using either:

(i) Dry Soil Mixing (DSM) methods, where air is the medium used to carry the binder from storage to the point of mixing,

(ii) Wet Soil Mixing (WSM) methods, where water is used as the transport medium.

Dry soil mixing, the focus of this thesis, is implemented in the field using either of two methods, Deep Dry Soil Mixing (DDSM) or Mass Stabilisation. In both methods dry binders, such as lime, cement, ground granulated blast furnace slag (GGBS) or pulverised fuel ashes (PFA) from coal power stations are injected into the soil using compressed air. The natural moisture content of the soil initiates the chemical reactions of the hydration process, leading to increased strength and reduced compressibility and permeability of the stabilised soil mass.

2.2.1 Deep Dry Soil Mixing (DDSM)

Deep Dry Soil Mixing (DDSM) is a relatively new process developed in Scandinavia and first used in the 1970s (Bredenberg 1999). The method is the focus of this thesis and may also be referred to as the *Lime(-Cement) Column Method*. At the same time, a similar method, known as *Dry Jet Mixing* (DJM) was developed in Japan (Bredenberg 1999; Bruce *et al.* 1999). DDSM stabilised columns can be created in soft clays, peats and other weak soils as either single units (see Figure 2-1), in rows (see Figure 2-2) or in interlocking panels. Treatment depths are typically less than 10 m but depths of up to 30 m are achievable with current equipment in Europe (Topolnicki 2012) and treatment up to 70 m has been carried out in Japanese marine applications (Porbaha *et al.* 2001).

Figure 2-1: Grid of 600 mm DSM columns (courtesy of Keller Grundläggning AB)

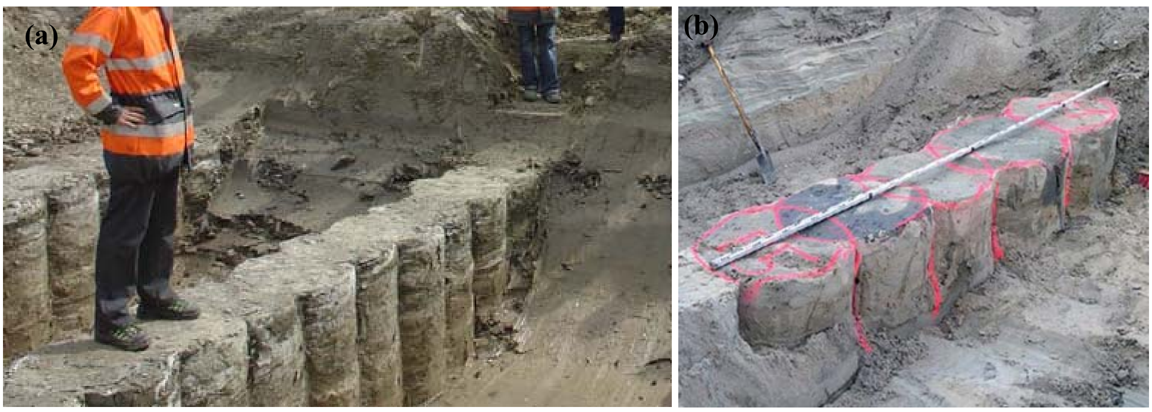

Figure 2-2: a) Over-lapping dry soil mixed columns (Rydell *et al.* 2005) & b) a secant DDSM column cut-off wall (Keller Group n.d.)

Using equipment similar to that shown in Figure 2-3, compressed air is used to carry the dry binder material from a pressure-feeder shuttle unit to the end of a rotating Kelly bar, where it is injected into and mixed with the parent soil using a mixing tool. Column diameters are typically between 0.5 m and 1.0 m in European practice, while columns of diameter up to 1.6 m have been created in Japan (Kitazume & Terashi 2013). Large multiple Kelly bar mixing rigs also exist and are typically found in Japan on both land-based and marine mixing equipment.

Figure 2-3: Keller Group's DDSM equipment: a) DDSM mixing rig, b) pressure-feeder binder shuttle unit & c) Scandinavian *Pinnborr* type mixing tool

Typical mixing tool shapes for DDSM are the *Pinnborr* mixing tool normally used for clays and silts (see Figure 2-3c) and the SGF 2:2000 semi-circular blade tool normally used for peats and clays (see Figure 2-4). The binder exits through holes in the top and bottom of the tool and is distributed to the outer edges by the injected air pressure.

DDSM columns are constructed in the following manner (Scandinavian practice) as shown in Figure 2-4:

(i) The mixing tool penetrates the soil to the column design depth, rotating while doing so to break up the soil structure. Mixing tool penetration speeds are 2 to 15 m/min and rotational speeds are 150 to 200 rpm.

(ii) As the tool is reversed out at a lesser withdrawal rate of 2 to 6 m/min, dry binder is injected using compressed air and mixed *in situ* with the soil.

(iii) A temporary surcharge, up to 1.0 m in thickness, is placed on the stabilised area to aid compaction and help remove any air entrained in the soil during mixing. This surcharge can also act as a working platform from which further columns can be produced.

(iv) After a suitable curing period, construction may begin on the DDSM column foundations.

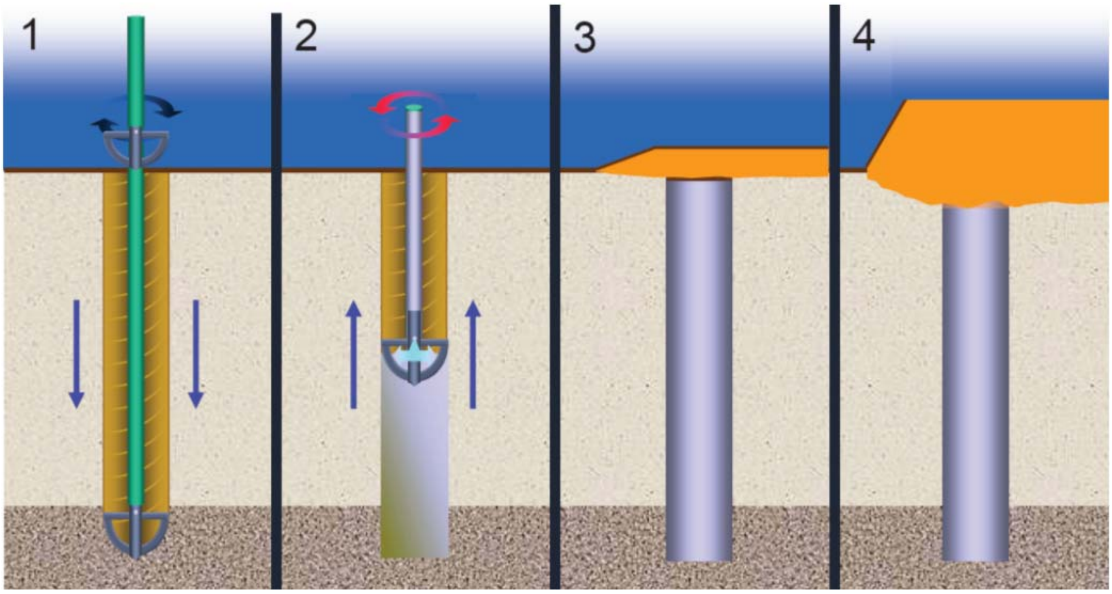

Figure 2-4: Deep dry soil mixing process procedure (courtesy of Keller Group)

Applications of DDSM include foundations for light structures such as roads, railways and residential housing, slope and embankment stability problems, confinement and remediation of contaminated soils, vibration reduction and temporary works (Dahlström 2012). In recent years DSM processes have been used not only in Europe and Japan, but worldwide with projects carried out in the USA (Burke *et al*. 2007; Filz 2009; Hussin & Garbin 2012), Australia (Liyanapathirana & Kelly 2011) and Asia (Horpibulsuk *et al*. 2012).

2.2.2 Mass Stabilisation

Mass Stabilisation (MS) is a form of DSM used to stabilise large areas of very soft shallow ground to depths of up to 5 m (EuroSoilStab 2002). Developed in Finland in the early 1990s, stabilisation is carried out in blocks using equipment similar to that shown in Figure 2-5. In the same way as DDSM, the binder is fed to the mixing tool from a pressure-feeder shuttle unit tailing the excavator and there it is mixed with the parent soil by a rotating mixing tool, mounted on the end of an excavator's arm (see Figure 2-5b). Applications of MS include stabilisation for road projects crossing peat soils, stabilisation of dredged material for land reclamation and erosion control (Allu 2007). Mass stabilisation can also be used in combination with DDSM, for example, where a soil profile is particularly soft at shallow depths requiring complete treatment (EuroSoilStab 2002).

Figure 2-5: a) Mass stabilisation for road construction (courtesy of Hayward Baker) & b) mass stabilisation mixing tool (courtesy of Allu)

2.3 Field Column Strength Verification Methods

The focus of this thesis is on the verification of DDSM column strengths and testing methods detailed in this section primarily relate to testing of DDSM columns. Low strength columns are referred to as those with shear strengths less than 150 kPa and high strength columns are those with shear strengths greater than 300 kPa (based on Carlsten & Ekström (1996)).

2.3.1 Cone Penetration Testing (CPT)

Cone Penetration Testing (CPT) is a popular form of site investigation and can be used for testing stabilised soil columns. The cone, with a 60° apex angle and plan area of 10 cm^2 (Porbaha *et al*. 2000), is advanced through the column at a rate of 20±4 mm/sec. The small size of the cone means that large reaction forces are not required and testing of columns with shear strengths up to 1 MPa is possible (Halkola 1999).

A number of issues exist with use of CPT in stabilised soil. The primary issue is that the cone tends to deviate off vertical after a few metres, particularly in strong columns (Porbaha 2002). Therefore, testing of columns is generally limited to 7 m or less in high strength columns. Column lengths up to 20 m may be tested using a combination of CPT and drilling but at a greater expense. Once the CPT cone has deviated out of the column, it is withdrawn, a 75 mm dia. hole drilled to a depth beyond the location at which the cone begun to deviate and the test restarted in the drilled hole (Halkola 1999). Furthermore, CPT only provides the strength at a point location in a column cross section and the CPT cone may tend to follow the weakest path in the column, for example in the centre of the column along the route taken by the Kelly bar during column production.

Another significant issue with CPT is the poor understanding of the correlation between CPT results and column strength (Al-Naqshabandy *et al*. 2012). The undrained shear strength of the column can be estimated using Equation 2-1:

$$c_u = \frac{q_t - \sigma_{vo}}{N_k} \text{ and } c_u = \frac{q_c - \sigma_{vo}}{N_c} \qquad 2\text{-}1$$

where c_u is the undrained shear strength (kPa), q_c is the measured tip resistance (kN/m^2), σ_{vo} is the overburden pressure (kN/m^2), N_k a force bearing capacity factor (total resistance) and N_c a bearing capacity factor (corrected resistance). Table 2-1 provides some correlations from current literature in which a wide spread of values can be seen as well as a dependence on column strength.

Table 2-1: CPT correlations for stabilised soil column testing

Correlation:	Comments:	Source:
$N_k = 15$	Norwegian experience	(Watn *et al.* 1999)
$N_c = 10\text{-}13$	-	(EuroSoilStab 2002)
$N_c = 18$ $N_k = 22\text{-}23$	UCS tests Direct shear tests	(Porbaha 2002)
$N_c = 17$	CPTu on a laboratory created stabilised peat column compared with shear vane data	(Hebib & Farrell 2003)
$N_c = 15\text{-}25$, 30	30 for high strength columns	(Larsson 2006)
$N_k = 15$	-	(Kelly & Wong 2011)
$N_c = 10\text{-}25$	-	(Kirsch & Bell 2012)
$N_k = 15\text{-}23$	Swedish practice	(Bergman *et al.* 2013)

2.3.2 Push-In Resistance Testing (PIRT)

The Push-In Resistance Test (PIRT) or the Traditional/Conventional Column Penetration Test (more commonly known as Kalk-Pelar-Sondering (KPS) in Scandinavia) (Carlsten & Ekström 1996; Axelsson 2001) involves probing of stabilised columns with a winged penetrometer, similar to that shown in Figure 2-6. The PIRT probe was developed in the late 1970s in response to the need to verify the strength of lime stabilised columns (Boman 1979; Holm *et al.* 1981), and today is one of the most common methods of testing stabilised soil columns. The PIRT wings facilitate the measurement of the strength across a cord of the column, unlike CPT which only provides the strength at a specific point. Cross-sectional strength variations can occur due to a weak core around the location through which the Kelly bar passed and also due to poor binder distribution across the column cross-section, as was seen by Kelly & Wong (2011).

Details of the penetrometer dimensions for various column sizes may be found in Carlsten & Ekström (1996) and TK Geo 11 (Trafikverket 2011), and Table 2-2 provides a summary of these guideline dimensions. The leading edge of the penetrometer has a circular bulb shape to reduce friction along the vertical plate section of the wing and the wing thickness is 5 mm less than that of the leading edge. The tip of the penetrometer is suggested to have a diameter of 50 mm and the leading edge of the two wings is located 500 mm back from the tip. Sounding rod diameters are suggested to be between 36 mm and 50 mm in diameter, with the larger diameter bars being used in high strength columns where probing resistances are high and bending of the bars may occur, *e.g.,* Carlsten & Ekström (1996) suggest the use of 44 mm Georod in pre-drilled high strength columns.

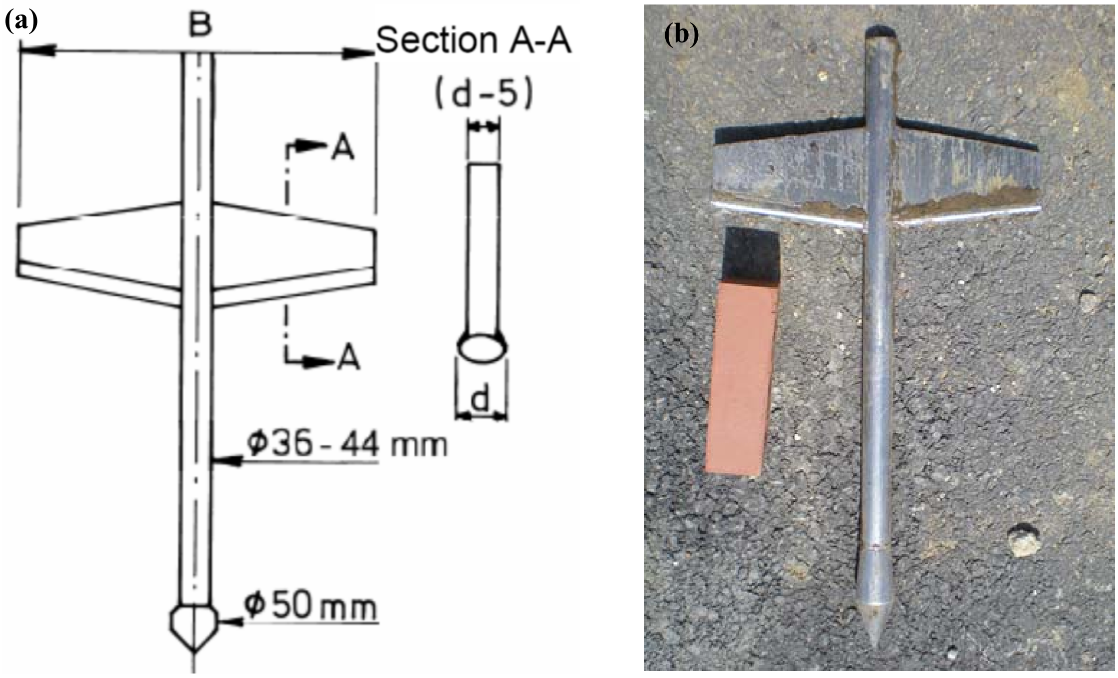

Figure 2-6: Typical PIRT penetrometer: a) guideline dimensions (Trafikverket 2011) **& b) a 400*mm* penetrometer**

Table 2-2: Suggested PIRT penetrometer dimensions (Carlsten & Ekström 1996)

Column Diameter, *D* mm	Suggested Column Length, m	Suggested Maximum Shear Strength, c_u kPa	Penetrometer Width, *B* mm	Wing Frontal Thickness, *d* mm
500	8.0	150 (300-350*)	400	20
600	8.0	150 (300-350*)	500	15
800	8.0	150 (300-350*)	600	15
Mass stabilisation	-	-	400	20

*suggested maximum shear strength for pre-drilled columns

The use of smaller penetrometers, *i.e.,* 200 mm to 400 mm in width, is suggested for testing of columns with shear strengths greater than 300 kPa. However, it should be noted that smaller penetrometers test a smaller area of column and in columns where poor binder distribution over the cross-section has occurred, this may overestimate the column strength.

Before testing, the top of the column is exposed to ensure the PIRT is carried out at the centre of the column. The penetrometer is pushed into the column at a constant rate of

20±4 mm/sec until it has reached a hard stratum or, in the case of floating columns, has passed 2 m below the column base. Testing can be carried out using a number of types of equipment such as truck mounted equipment used for CPT testing (see Figure 2-7a), excavator mounted equipment (see Figure 2-7b) or wheel-loader mounted equipment (see Hussin & Gabin (2012)). Column lengths of up to 8 m can normally be tested, but beyond this, inclinometers are recommended to monitor any deviations of the penetrometer.

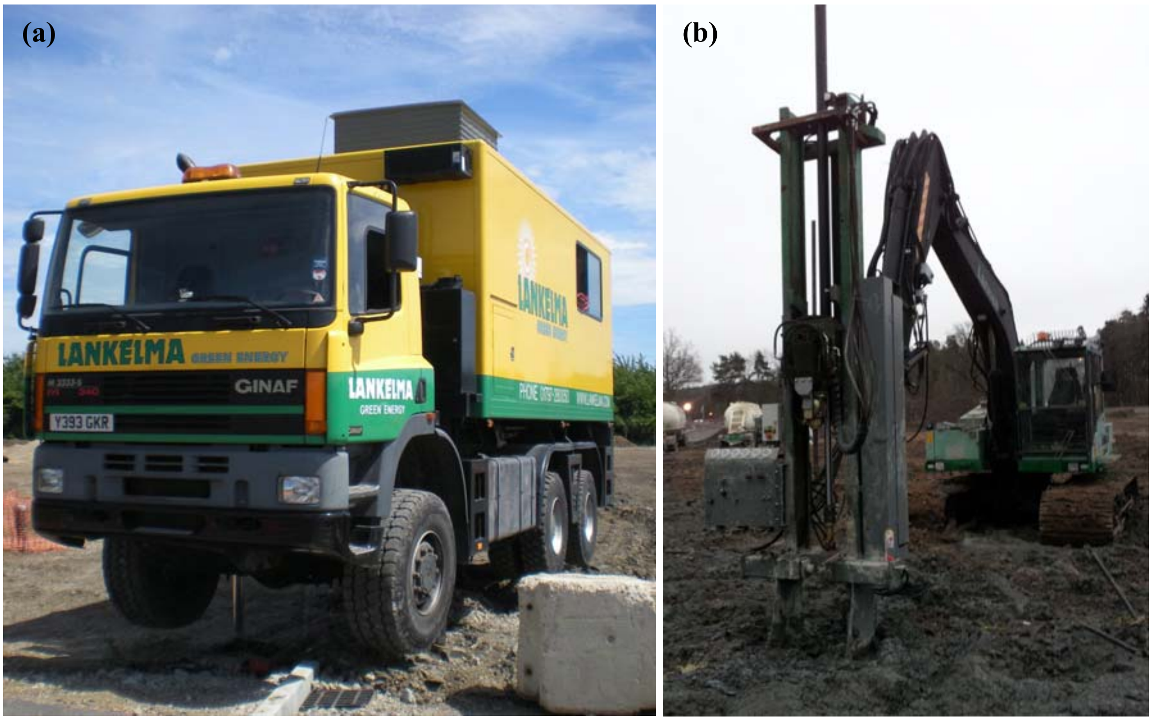

Figure 2-7: Lankelma CPT truck carrying out a PIRT & b) excavator mounted rig for performing PIRT (courtesy of Keller Grundläggning AB)

During a PIRT, the probing force required to penetrate the stabilised column is recorded and used to estimate the columns shear strength; this conversion is detailed in Section 2.4. Ideally, the force is recorded within the column at the top of the penetrometer using a pressure gauge, thus removing any contribution from friction along the sounding bars. If recorded at the surface, the portion of the force due to sounding bar friction against the column must be taken into account and this is done by continuing the test 2 m beyond the base of the column into the unstabilised material (Carlsten & Ekström 1996) or for end bearing columns by pulling the probe up 300 mm at the end of the test and pressing it back down again. Axelsson (2001) quotes frictional forces of 0.5 kN/m to 1 kN/m for 44 mm dia. sounding bar and indicates that the frictional force can be taken to be zero for pre-drilled columns.

Some typical PIRT probing force profiles with depth are shown in Figure 2-8. At the beginning of the test, a step increase in the probing force can be observed as the tip of the penetrometer is inserted into the column and once the wings reach the column, the probing force will rise due to the increased contact area. This may not be seen in pre-drilled columns as the test may commence with the PIRT tip already inside the column. Once within the column, the profile of the push-in force will be dependent on the achieved stabilised strength of the column. After the penetrometer exits the base of the column into the unstabilised material, the probing force will typically drop in the case of floating columns but can increase again if the penetrometer reaches firmer soil layers. In Figure 2-8b, pauses to insert extra sounding bars are the cause of the drops in force at depths of 2.8 m, 4.8 m and 6.8 m.

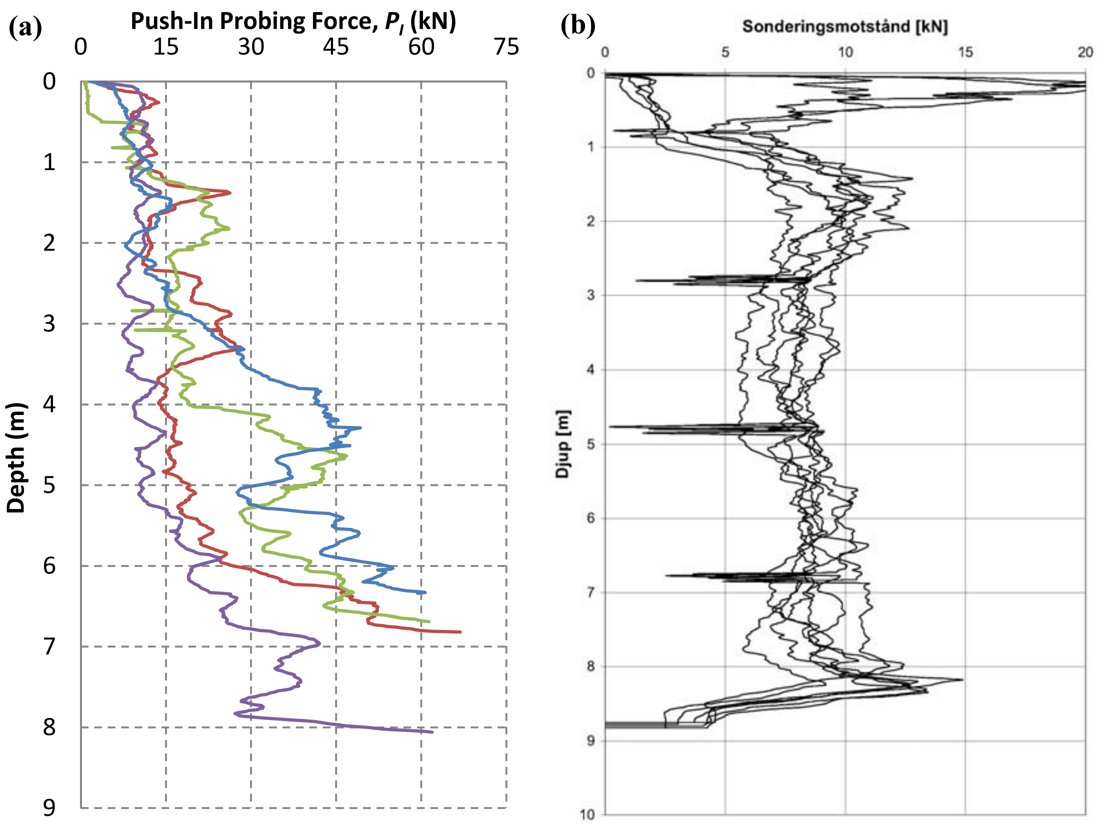

Figure 2-8: Typical PIRT force with depth profiles: a) courtesy of Keller Group & b) after Nilsson (2005)

In strong columns the penetrometer can tend to deviate off vertical and exit the column; Halkola (1999) observed this to occur after an average depth of 7 m. Once the penetrometer deviates out of column and into the unstabilised surrounding soil, a significant reduction in the probing resistance occurs. Figure 2-9a shows an example of this. In a modification to the PIRT penetrometer, aimed at preventing deviation out of the column, Holm (Hartlén 1983) presented a PIRT penetrometer with a screw tip (see Figure 2-9b) which allows the rod to rotate during probing, thus reducing the risk of the penetrometer exiting the column. However no other references to this specific penetrometer modification or its use exist in the literature.

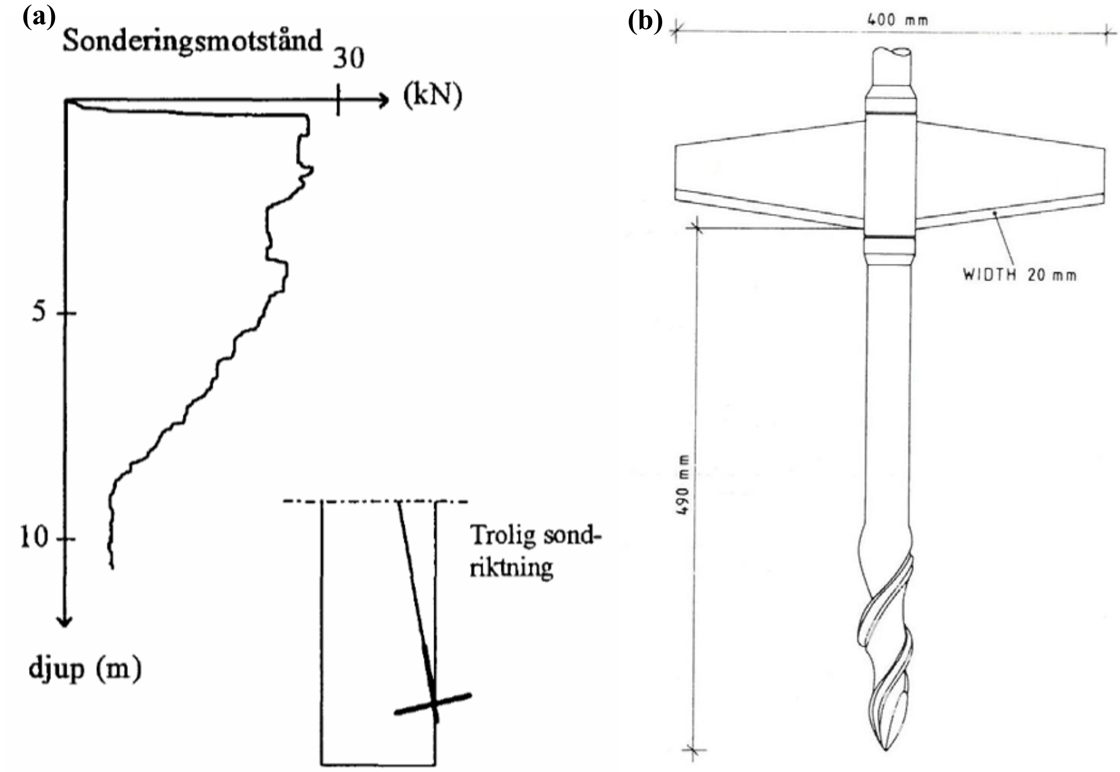

Figure 2-9: a) Probing profile where the penetrometer has exited the column after Axelsson & Larsson (1994) & b) PIRT with screw tip proposed by G. Holm, after Hartlén (1983)

Swedish guidelines suggest that columns longer than 6 m (Trafikverket 2011) or columns with shear strengths greater than 300 kPa be pre-drilled. This prevents the penetrometer deviating from the centre of the column as the hole provides a guide for the penetrometer tip to follow. Drilling is carried out using a drill bit between 50 mm and 65 mm in diameter under downward pressure and rotation only. Hammering of the drill bit or flushing with water is not permitted as it can damage the column and influence the subsequent PIRT results. Field results from pre-drilled columns have shown that the guide-hole helps to prevent the penetrometer leaving the column during probing (Axelsson & Larsson 2003). As an alternative to pre-drilling a guide-hole in the test column, the hole formed during CPT of the column has also been used to guide the PIRT penetrometer (Keller Foundations 2014) but should not be used where the CPT is thought to have deviated off vertical.

2.3.3 Pull-Out Resistance Testing (PORT)

The Pull-Out Resistance Test (PORT), also known as the Reverse Column Penetration Test (or known as Omvänt Pelarsondering (OPS) in Sweden) was developed in the 1980s by Ekström (Axelsson 2001) and can be seen as a reverse version of PIRT. To carry out a PORT on a column, the penetrometer must be installed in the column very soon after column production. Later, the development of a mixing tool (by LC Marktenik) allowed for installation of the penetrometer by the mixing rig during the penetration phase of the column production procedure. In this form the test is referred to as Förinstallerad Omvänt Pelarsondering (FOPS) in Sweden. Using a 12 mm dia. wire rope, a winged PORT penetrometer, similar to those shown in Figure 2-10, Figure 2-11 or Figure 2-12, is pulled up through the column and the pull-out force recorded. Section 2.4 details the estimation of the column strength using the recorded forces. Unlike PIRT or CPT, the penetrometer cannot deviate out of the column, although it is possible for the wire rope to snap in a particular strong section of the column. The wire rope will generally have a capacity of at least 150 kN.

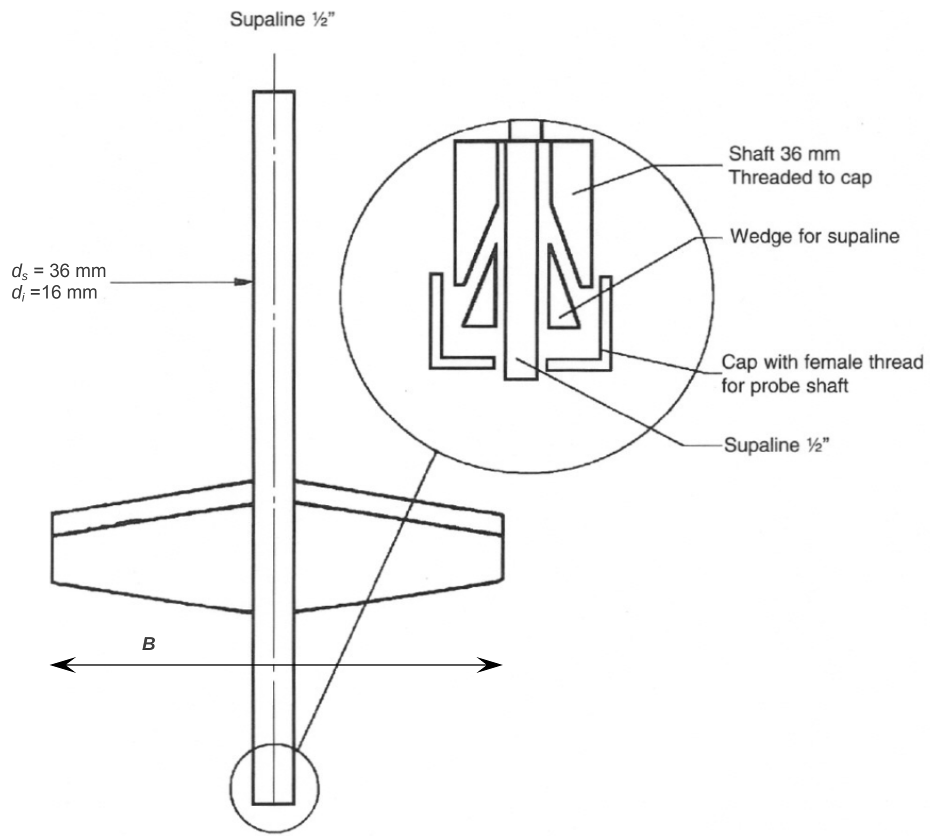

Figure 2-10: PORT penetrometer, after Carlsten & Ekström (1996)

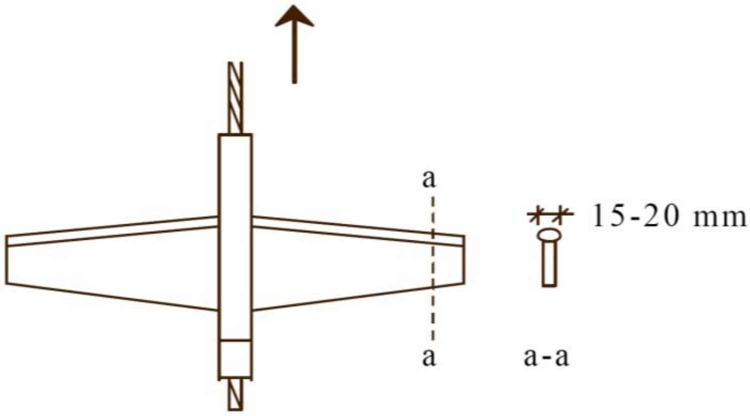

Figure 2-11: PORT penetrometer, after Axelsson & Larsson (2003)


Figure 2-12: PORT penetrometer (courtesy of Keller Group)

The PORT penetrometer has similar wings to that of the PIRT penetrometer described in Section 2.3.2 and typical dimensions relative to a number of column diameters are given in Table 2-3. Carlsten & Ekström (1996) specify the penetrometer shaft to be 1.15 m long with a diameter of 36 mm. The wings are located 500 mm from the top of the shaft, but for penetrometers installed by the mixing rig, the penetrometer is shorter with the wings located 300 mm back, as is the case with the penetrometers shown in Figure 2-11 and Figure 2-12.

Columns with shear strengths up to 600 kPa and diameters between 500 mm and 1,000 mm may be tested using PORT (Carlsten & Ekström 1996). A significant advantage of PORT, compared to PIRT, is the increased column lengths, of up to 20 m (Axelsson & Rehnman 1999), that may be tested as penetrometer deviation is not an issue and greater probing forces can be mobilised. PORT also provides a better representation of the strength at the base of the column, but can only be carried out on floating columns as the penetrometer must be installed below the column base to prevent it becoming bonded to the column. However, it is not uncommon for the PORT penetrometer to fully resist pull-out from the column, resulting in a lack of test data and loss of the penetrometer itself (Wiberg personal communication 2013).

Table 2-3: Suggested PORT penetrometer dimensions (Carlsten & Ekström 1996)

Column Diameter, *D* mm	Column Length, *l* m	Suggested Maximum Shear Strength, c_u kPa	Penetrometer Width, *B* mm	Wing Frontal Thickness, *d* mm
500	15-20	600	400	20
600	15-20	600	500	15
800	15-20	600	600	15
1000	15-20	600	600	15

The selection of the column to be tested occurs in advance of stabilisation for PORT and this may be seen as a disadvantage of the test, as it may be argued that it gives the contractor the opportunity to guarantee that a high quality column is produced, although modern in-built quality control equipment on the mixing equipment will detect any differences in the mixing process between columns. The penetrometer is installed to a depth of at least 2 m below the bottom of the column (Carlsten & Ekström 1996) and where early-age testing is to be carried out on columns with penetrometers installed post-construction, the penetrometer is rotated ninety degrees if possible (Nilsson 2005). This allows the skin friction of the wire rope to be quantified and aims to ensure the penetrometer is not pulled out along the path it took during installation.

When the penetrometer is installed prior to stabilisation by the mixing rig, *i.e.,* FOPS, the mixing tool includes an opening to allow the wire rope pass through, but this can lead to poorer mixing and issues with binder distribution over the column cross-section as binder can leak out around the wire rope. This was noted by Axelsson & Larsson (2003) in FOPS columns, where higher binder contents and strengths were noted in the core of extracted columns. The appearance of pieces of stabilised column on an extracted penetrometer rope can indicate poor binder distribution, and Carlsten & Ekström (1996) advise that care should be taken with the recorded resistances when determining the column's strength.

In a series of PORT on 800 mm diameter columns in Gamleby, Sweden, Axelsson & Larsson (2003) investigated the use of the mixing rig to install the penetrometer after production of the column. Using 350 mm and 700 mm width penetrometers, it was concluded that the installation of the penetrometer after column production resulted in uniform strengths over a column cross section. A comparison of similar columns tested using PIRT showed similar probing resistances. It is now common practice that the penetrometer is installed very soon after stabilisation of the column and this should occur within thirty minutes of column production.

To reduce the forces required to pull out the PORT penetrometer at the test time, the penetrometer may be drawn up by 100 mm to 200 mm two to three days after installation, thus breaking the bond between the column and wire rope (Carlsten & Ekström 1996). Grease may be applied to the pull-out wire before installation to reduce the bond between the rope and the column (Burke *et al*. 2007). At the required test time, the penetrometer is pulled up through the column at a rate of 20±4 mm/sec using a winch (Carlsten & Ekström 1996; Trafikverket 2011) or pull-out rig like that shown in Figure 2-13.

Figure 2-13: PORT penetrometer pull-out rig and load cell setup (photo insert), after Avery (2010)

Two typical PORT pull-out force profiles with depth are shown in Figure 2-14. As the test begins a rapid increase in force occurs primarily due to the bond between the column and the PORT wire. A portion of this force is also due to bearing on the PORT penetrometers leading edges in the unstabilised soil. The force peaks as the bond between the wire and column breaks and drops as material adhered to the wire is removed, typically during the first 1 m (Carlsten & Ekström 1996). Once the penetrometer reaches the base of the column, the force rises quickly as it cuts into the harder stabilised column and the maximum force within the column is observed. This rise does not occur immediately, as seen with the breaking of the wire bond, as the base of the column may not be as strong as higher up due to issues of mixing uniformity. After peaking, the pull-out force drops off with depth, eventually reaching zero when the penetrometer reaches the surface. In some cases, the penetrometer may break the column and pull-out the column's upper-most portion due to the imbalance between the pull-out forces and forces restraining the column, *i.e.,* column tensile strength and friction with the surrounding parent soil.

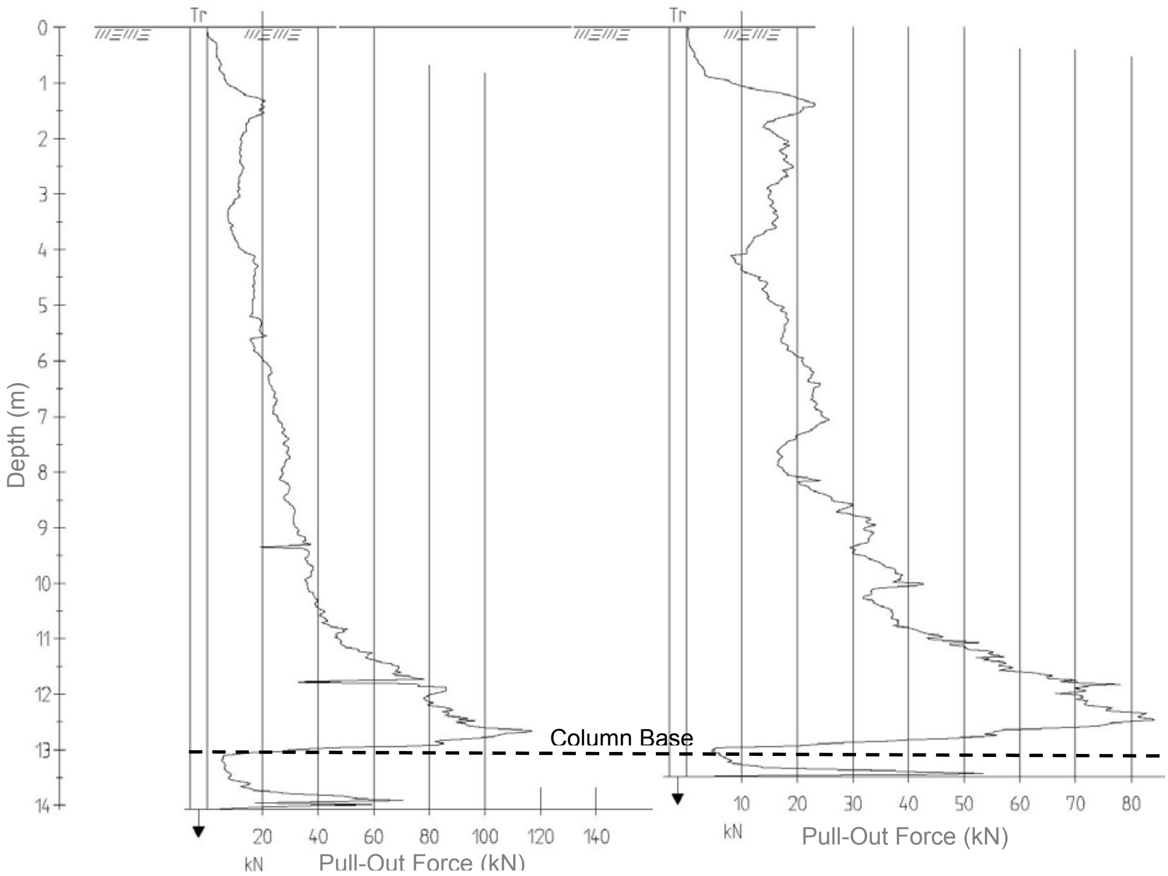

Figure 2-14: Typical PORT pull-out force with depth profile (courtesy of Keller Grundläggning AB)

Account must also be made for the skin friction along the pull-out rope, which can be significant in long columns. Although few references exist in the literature, a skin frictional resistance of 0.7 kN/m of column is quoted by Axelsson (2001) and a value of 1.3 kN/m is given by Avery (2010). The most appropriate way to determine skin friction is to carry out a wire pull-out test, where a wire is installed in a similar column to that being tested and is pulled out after the same curing time as the PORT. Figure 2-15 shows one of the few published pull-out force profiles with depth for two wire-only tests (Carlsten & Ekström 1996). A high peak in the force is observed as the bond between the wire and the column is broken at the beginning of the test. As the wire passes through the column, any adhered material is removed from the wire and once all the material is removed the force begins to reduce constantly with depth. An estimate of the skin frictional resistance can also be calculated (where the PORT penetrometer is installed below the base of the column) using the initial pull-out forces (Carlsten & Ekström 1996), but will over-estimate the frictional resistance due to bearing on the penetrometer wings.

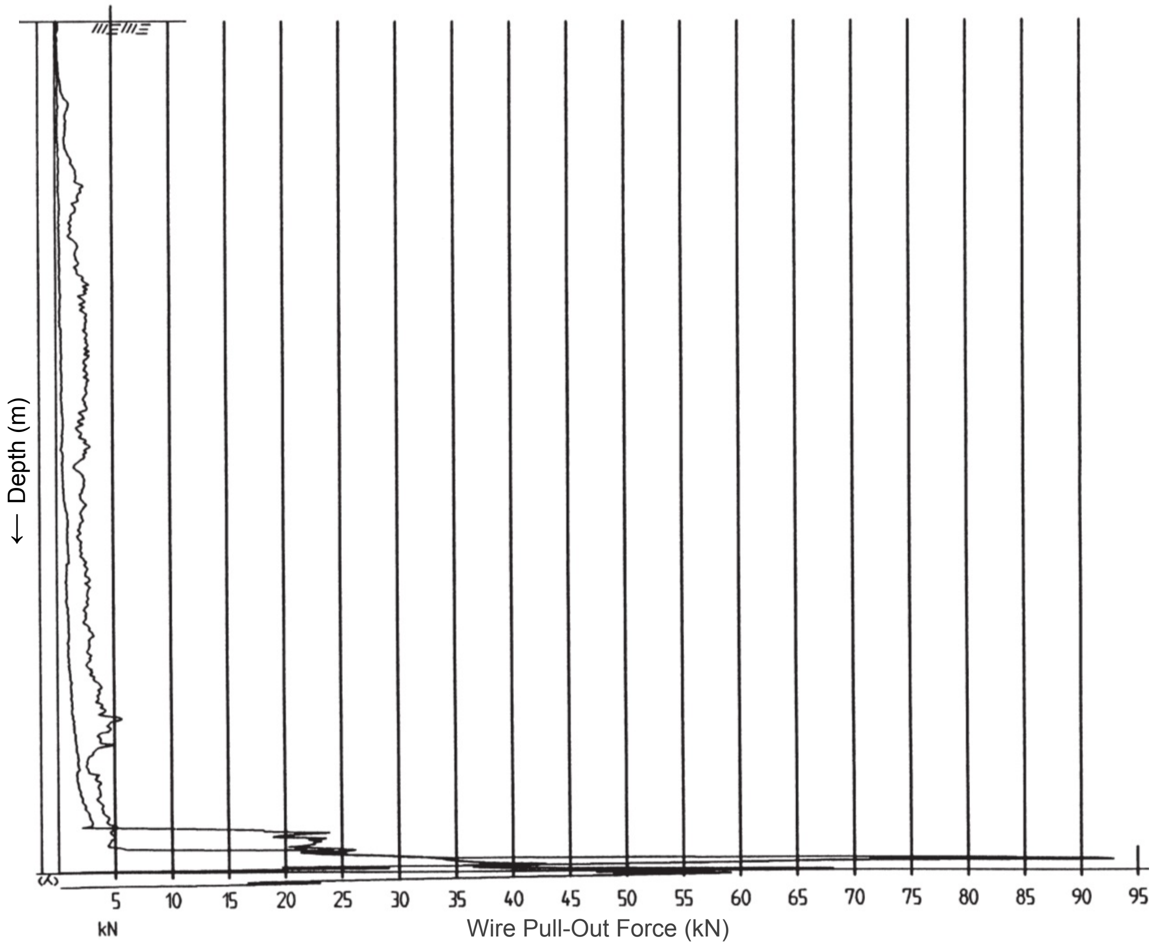

Figure 2-15: PORT wire pull-out test results, after Carlsten & Ekström (1996)

2.3.4 Other Testing Methods

Column Coring:

Coring of stabilised columns to extract samples for laboratory tests can be carried out using double and triple tube cores. Core diameters are typically 102 mm (Swedish practice) or a minimum of 150 mm for Japanese practice (Larsson 2006). A number of issues with coring are highlighted by Halkola (1983), Rogbeck (1997), Axelsson (2001) Porbaha (2002), Larsson (2005) and Kelly & Wong (2011):

- As the sample size is quite small, the strength determined is only relevant to a particular point in the column profile.
- The location of the sample in the column cross-section is often unknown due to deviations in the coring device at depth.
- In low strength columns, the coring process can result in large disturbances, which will affect the sample quality. In high strength columns, pieces of the column can break off and rotate within the coring device causing disturbances.

Rogbeck (1997) compared cored column sample strengths with samples trimmed from extracted columns, and found cored samples to give lower compressive strengths (<40 kPa) than those trimmed from an extracted column (150-210 kPa). This was thought to be due to disturbances during coring as described above.

Column Shear Vane:

The column shear vane test was developed from the conventional field vane test and is a particularly popular method in Finland. Column vanes have larger diameters than conventional vanes, of between 130 mm and 160 mm. Early vanes had a height-to-diameter ratio of 0.5 (Halkola 1983), while more modern vanes have a height-to-diameter ratio of 2 (Larsson 2006). Testing is carried out at 0.5 m to 1.0 m depth intervals and is limited to shear strengths less than 250 kPa as issues with disturbance of the stabilised column during vane insertion lead to lower strengths being observed (Axelsson 2001; Larsson 2006). The vane is pressed into the column and maximum torque required to rotate the vane is recorded. An estimate of the column strength is then obtained using Equation 2-2 (for a vane with a height to diameter ratio of 2):

$$\tau_{fu} = \frac{6M_{\max}}{7\pi D^3} = kM_{\max} \qquad 2\text{-}2$$

where τ_{fu} is the undrained shear strength (kPa), D is the wing width (m) and M_{max} is the maximum measured torque recorded (kNm) (Larsson 2006). Axelsson (2001) details a vane factor, k of 345 for a 132 mm diameter by 85 mm high vane.

<u>Total Sounding Method:</u>

To facilitate the PIRT of long and/or high strength columns, pre-drilling may be carried out to prevent penetrometer deviation and is often done using Total-Sounding (TS) methods. TS is a combination of conventional rotary pressure sounding and rock drilling where a 57 mm dia. hole is drilled under a vertical load applied to the drill bit (Bergman & Larsson 2014). The rotation speed is 25 rpm and the penetration speed is 20 mm/sec.

As a more efficient means of estimating the strength of a column, Bergman & Larsson (2014) present data in which they compare the penetration drill force recorded during TS with the probing force during PIRT. They conclude that on projects where good agreement is found between initial PIRT and TS tests, the number of PIRTs may be reduced and replaced by the more cost-effective TS test. Guidance is provided by the authors on how the relationship between PIRT and TS may be defined for an individual project, but it is stated that the method should not be used to estimate the strength of individual columns or for columns with undrained shear strengths less than 150 kPa.

Comparisons of TS with CPT in the field carried out by Fransson (2011) shows TS data can be used to estimate the undrained shear strength, but further work in relation to sleeve friction between the sounding bars and the column is needed before the method can be relied upon.

<u>Column Extraction:</u>

An alternative means of determining the strength of a stabilised column is to extract the entire column and obtain undisturbed samples for testing, but this is an expensive process and hence rarely happens outside research projects (Holm *et al.* 1999). Sampling is carried out using a 10 m long, 900 mm dia. tube sampler with a shutter door at the bottom. The sampler is driven down around the column using a vibrating hammer and the shutter door closed. A crane and vibrating hammer then extract the sampler with the column inside (see Figure 2-16) and pull-out forces of up to 200 kN are typical. Once extracted, samples may be cut from the column for strength testing and investigations of binder distribution and mixing homogeneity throughout the column cross-section and length are also possible.

Figure 2-16: 900*mm* dia. split tube column sampler, after Axelsson (2001)

KTH Penetration Test:

In the late 1990s, the KTH (Kungliga Tekniska Högskolan) probe was developed for the testing of columns using a similar penetrometer to that used in PIRT but with larger-thinner wings and no leading bulb-shaped edge (see Figure 2-17). Used in low strength columns, the penetration resistance and adhesion along the blade are taken to correspond to the column's shear strength, as the height of the blade corresponds to the length of the failure zone when the column is axially loaded. The width of the penetrometer is 80% of the column width and the wing height 1 to 1.5 times the diameter. Testing is carried out in a similar manner to PIRT, but the probe can also be pre-installed in the column and the test carried out in a similar manner to PORT.

The probing resistance is related to the column's shear strength using Equation 2-3 (Axelsson 2001):

$$c_u = \frac{P_n}{a \times A} \tag{2-3}$$

where c_u is the column undrained shear strength (kPa), P_n is the net probing force (kN), A is the probe's total area (m^2) and a is an adhesion factor relative to the shear strength mobilised against the blades. Axelsson (2001) reports that further work is required to determine appropriate adhesion factors, but quotes values of 0.25 from calibration with UCS samples and 0.18 from a comparison with PIRT strength profiles (estimated using an N value of 10, subsequently defined in Equation 2-5).

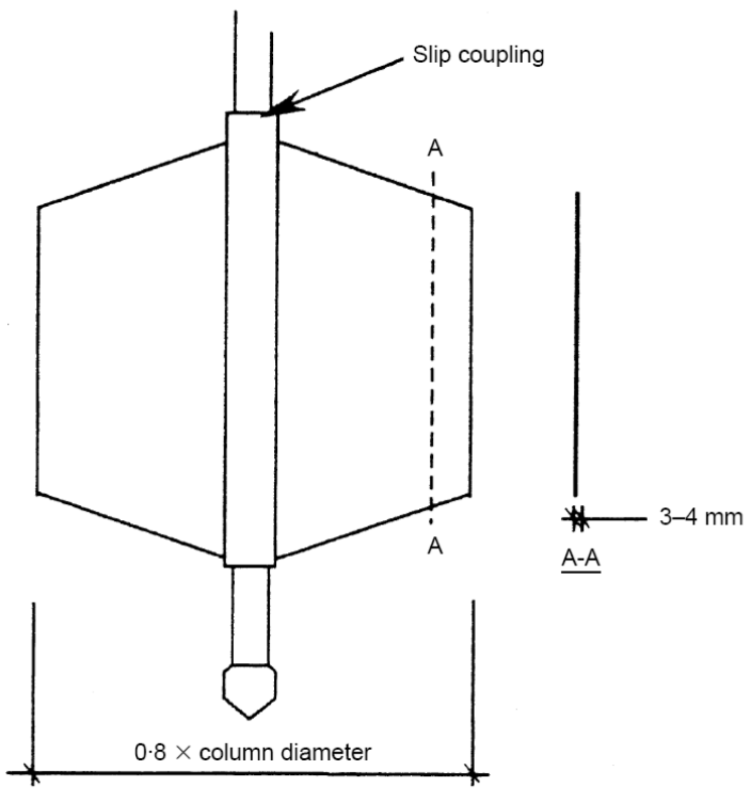

Figure 2-17: KTH Probe, after Axelsson & Rehnman (1999)

Non-Destructive Testing:

The use on non-destructive methods to estimate the strength of stabilised soil columns has been investigated and both Larsson (2005) and Massarsch (2005) provide detailed descriptions of seismic testing methods. These methods have a significant advantage over previously described methods, as they are non-destructive and can be repeated on the same column at different curing times. The seismic logging methods used to test stabilised columns are in-hole (both seismic source and receiver are in the same borehole), down-hole (source at the surface, receiver in a borehole) or cross-hole (source and receiver in separate boreholes) (Porbaha 2002). Waves may be either fast compression (P) waves or slower shear (S) waves, which provide greater accuracy and are unaffected by the water table. Using the velocity of the wave, shear strengths and shear modulus can be determined. Åhnberg & Holmén (2011) compared the UCS with shear wave velocity from bender element and resonant column free-free tests carried out by the Swedish Geotechnical Institute (SGI). They concluded that rough estimates of the UCS can be obtained from shear wave and compression wave velocities and this can be applied to stabilised soils in the field, but further work is needed to ascertain the effects of different confining stresses.

Other Test Methods:

Other less common methods used for strength verification of stabilised columns include: Dynamic Cone Penetrometer (DCP) (Huttunen *et al*. 1996), Standard Penetration Test (SPT) (Liu & Hryciw 2003), pressuremeter tests to determine compression modulus (Porbaha 2002; Larsson 2005) and loading tests (Porbaha 2002). Further details on quality assurance testing in stabilised columns may be found in Larsson (2005) and Terashi & Kitazume (2011).

2.4 Probing Force-Strength Relationships

2.4.1 Origin of the Relationship

First attempts at understanding the relationship between the column strength and the PIRT/PORT probing force were based on a semi-empirical equation for the *Iskymeter*. The *Iskymeter* (see Figure 2-18) was developed by the SGI *circa* 1939 to estimate the strength of soft clay profiles up to depths of 100 m. The *Iskymeter* is pushed into the ground using rods, during which soil stratification can be assessed, and due to its small area, minimal disturbance is caused to the soil (see Figure 2-19a). Once at the required depth, the *Iskymeter* is pulled back up by a wire rope attached to it. During the first 600 mm of pull out, two folding arms expand out into the soil, forming a T-shape (see Figure 2-19b). This T-shape remains for the complete pull-out phase but to prevent damage and/or loss of the device due to excessive forces (greater than 10 kN), pins connecting the wings to the shaft break, allowing the wings to fold downwards for the remaining pull-out thus minimising the plan contact area (see Figure 2-19c).

Figure 2-18: *Iskymeter* in the pull out position (left) and pull out winch (right), after Massarsch & Fellenius (2012)

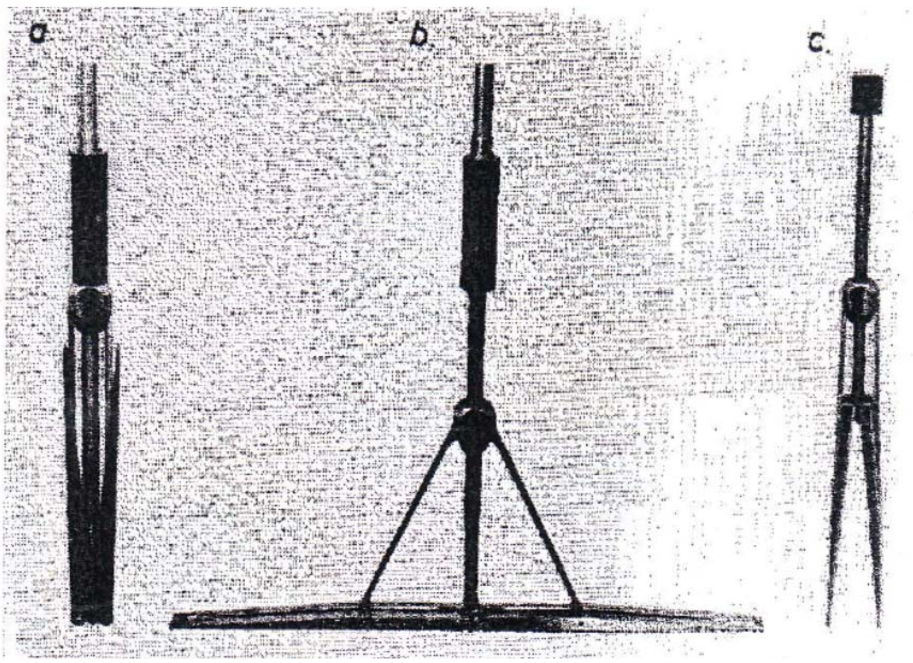

Figure 2-19: *Iskymeter* probe: a) installation shape, b) shape during pull out test, c) shape when overloaded; after Kallstenius (1961)

Calibration tests were first carried out by Kjellman between 1939 and 1941(Kallstenius 1961) on *Iskymeters* with frontal areas of 0.003 m^2, 0.01 m^2 and 0.02 m^2, using fall cone strength data, and indicated the ratio between the specific pulling force (σ_f, kg/cm^2) and shear strength (τ_f, kg/cm^2) to be approximately 10 but with considerable scatter in the data (see Figure 2-20), thought to be due to the soil's sensitivity and variations in the pull-out rate.

Tests by Jakobson and Wagner in 1955 involved varied pull-out speeds between 0.0001 m/min and 10 m/min in organic clays (Kallstenius 1961). They reported that the pull-out speed and material properties had an effect on the relationship with high N values at low speeds but that at speeds between 0.5 m/min and 2.0 m/min there was little influence (see Figure 2-21).

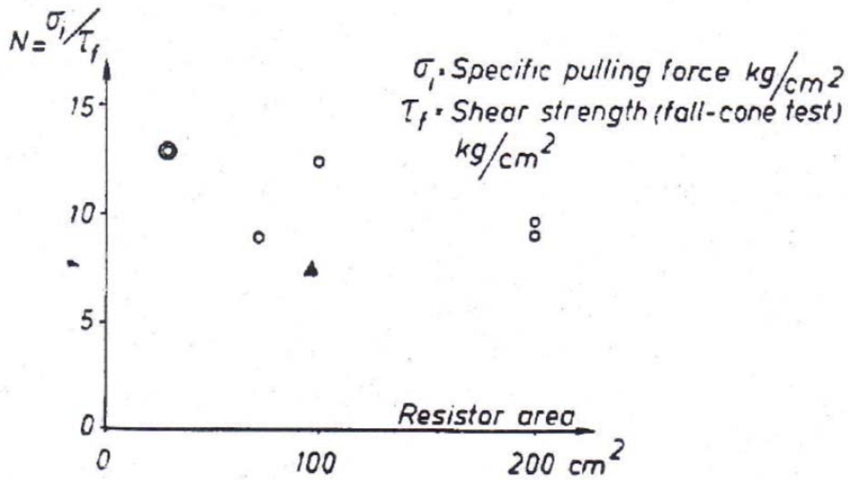

Figure 2-20: First calibration of the *Iskymeter*, after Kallstenius (1961)

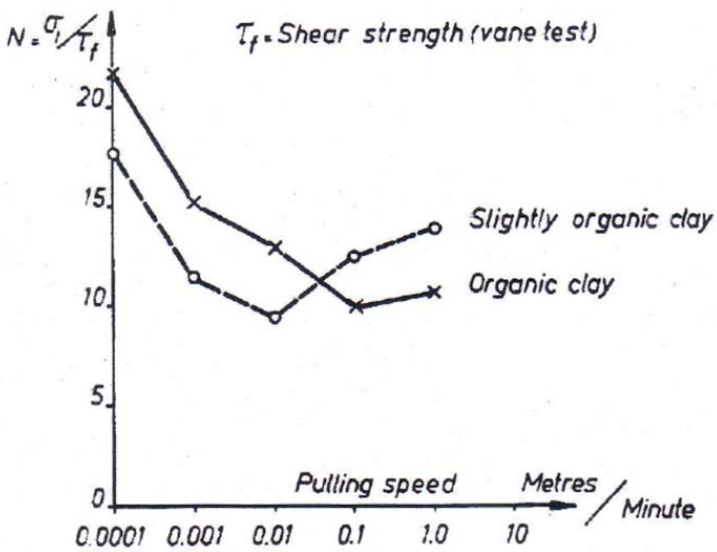

Figure 2-21: Variation in N with pull-out rate by Jakobson and Wagner, after Kallstenius (1961)

Figure 2-22 shows uncorrected *Iskymeter* results with depth where the soil strength used to calculate N was determined from field vane tests (Kallstenius 1961). Considerable scatter and a possible reduction in N with depth is notable, but may be due to fewer tests at greater depths. The scatter was thought to be due to depth and sensitivity and account is taken for their influence in Equation 2-4 which was derived by Osterman for use with a 100 cm^2 *Iskymeter* probe (Kallstenius 1961):

$$c_u = \frac{0.092 \times P}{\left(1 + \frac{2}{S_t}\right)A} + \frac{0.06 \times \gamma \times h\left(1 - \frac{1}{S_t}\right)}{1 + \frac{2}{S_t}} \qquad \text{2-4}$$

where c_u is the undrained shear strength (kg/cm^2), P is the pull-out force (kg), A is the area of the resistor body (cm^2), S_t is the soil sensitivity, γ is the soil density (Mg/m^3) and h is the depth (m).

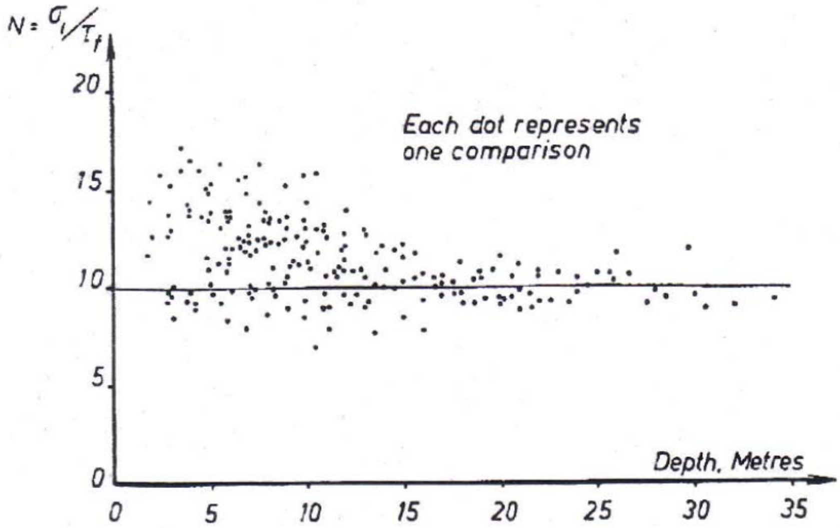

Figure 2-22: Uncorrected results from *Iskymeter* tests, after Kallstenius (1961)

Boman (1979) proposed a simplified version of Equation 2-5 by using a bearing factor (N) which he proposed to be 10 for a probe with a 100 cm^2 plan area:

$$c_u = \frac{1}{N} \times \frac{P}{A} \qquad \text{2-5}$$

where c_u is undrained shear strength (kN/m^2) of the stabilised column, P is the probing force (kN), A is the plan area of the penetrometer in contact with the column (m^2) and N

is a bearing capacity factor. To date, this equation is used to estimate the strength of stabilised columns from PIRT and PORT data, and a compilation of N values is given in Section 2.4.4.

Where columns have been pre-drilled, the plan area of the penetrometer is calculated as the width of the penetrometer minus the drilled-hole diameter multiplied by the thickness of the penetrometer wing's leading edge (Edstam *et al*. 2004; Carlsten 2012; Bergman *et al*. 2013), *i.e.,* the plan area of the penetrometer bearing on the pre-drilled column.

2.4.2 Other Similar Relationships

<u>T-Bar Relationships:</u>

Stewart & Randolph (1994) describe a 50 mm dia., 200 mm long T-bar penetrometer for use in testing soft clays using CPT equipment, as the increased area of the T-bar, compared to a CPT cone leads to higher probing forces and more accurate measurements. The relationship between undrained shear strength and T-bar resistance is dependent on the surface roughness of the T-bar with bearing factors (N_b) of between 9 and 12 suggested for smooth and rough probes, respectively. Using a bearing factor of 10.5, recorded resistances from field T-bar tests in a soft clay deposit were used to estimate the undrained shear strength. The estimated undrained shear strength profile was found to be in agreement with shear vane and triaxial test results. The similarities in plan area and bearing factor between the T-bar and the *Iskymeter* probe were also noted.

<u>Deep Penetrating Anchors:</u>

Deep Penetrating Anchors (DPA), also known as Dynamic Penetrating Anchors or Torpedo Piles, are used in the oil exploration industry to anchor floating offshore structures in waters deeper than 300 m. They consist of a cylindrical shaft with a number of flukes or fins attached to the upper end and a rounded conical nose (O'Loughlin *et al.* 2004). While obviously not used to for *in situ* testing, they bear similarities in shape to the PORT and PIRT penetrometer (see Figure 2-23). Installation is carried out by dropping the anchor, whose weight can be up to 1,000 kN, from a height above the sea bed of up to 150 m and as the anchor falls through the water, it reaches terminal velocity. The anchor embeds itself into the sea bed, generally to a depth of between 2 and 3 times its length, coming to a stop as a result of the end bearing, frictional and drag forces on the anchor.

O'Loughlin *et al.* (2004) defines the holding capacity or pull-out resistance of the anchor to be the sum of the frictional resistance along the DPA shaft and flukes (F_f), the bearing resistance on the DPA shaft and fluke ends (F_b) and the submerged anchor weight (W_s) (see Equation 2-6):

$$F = F_f + F_b + W_S \qquad \text{2-6}$$

Figure 2-23: Dynamic penetrating anchor (Deep Sea Anchors 2010)

This equation can be expanded and may be rewritten for the undrained shear strength, s_u using the terms given by O'Loughlin *et al.* (2004) as follows:

$$s_u = \frac{F - W_S}{\left[N_c A_c + \alpha A_{side}\right]_{Shaft} + \left[N_{Fluke} A_{fluke} + \alpha A_{fluke}\right]_{Fluke} + \left[\alpha \pi D z\right]_{RS}} \qquad \text{2-7}$$

where s_u is the undrained shear strength (kPa), F is the anchor holding capacity (kN), W_S is the weight of the anchor (kN), N_c is the tip bearing capacity factor, A_c is the bearing area of the tip (m^2), α is the soil friction factor, A_{Side} is the side area of the flukes (m^2), N_{Fluke} is the fluke bearing capacity factor, A_{Fluke} is the bearing area of the fluke (m^2), D is the diameter of the anchor chain/rope (m) and z is the depth of the anchor (m). Table 2-4 provides some bearing and friction factors for the anchor shaft and flukes currently used to estimate anchor holding capacities, and as will be seen in Section 2.4.4 these are similar to the values used for PORT and PIRT penetrometers.

Table 2-4: Dynamic Penetrating Anchors bearing and friction factors

Shaft Bearing Factor, N_c	Fluke Bearing Factor, N_f	Shaft Friction Factor, α	Source:
9	7.5	1	(American Petroleum Institute 2000)
9	7.5	0.8-1	(O'Loughlin *et al*. 2004)
12	7.5	0.4-1	(Richardson *et al*. 2009)

2.4.3 Finite Element Modelling

Finite element modelling (FEM) of PORT and PIRT has been carried out in Abaqus/Explicit using an Arbitrary Lagrangian Eulerian (ALE) approach by Liyanapathirana & Kelly (2010; 2011) in two separate analysis, the first using an elastic, perfectly plastic soil model and the second, using a strain-softening soil model. N values were observed to increase with rigidity index (G/c_{col}) from 9.2 to 12 as shown in Figure 2-24a for a smooth probe (blade-soil interface friction, α = 0) in an isotropic soil. Similar results were observed for both PORT and PIRT and the correlation between the N value and rigidity index found is given in Equation 2-8:

$$N = 1.6 \ln\left(G/c_{col} \right) + 1.88 \tag{2-8}$$

Using a contact algorithm in Abaqus/Explicit, the effect of various probe roughness was modelled between blade-soil interface frictions (α) of 0 for a smooth probe and 0.8 for a rough probe and Equation 2-9 was fitted to the results:

$$N = 1.6\ln\left(\frac{G}{c_{col}}\right) + 6.35\alpha + 1.88 \qquad \text{2-9}$$

The results at G/c_{col} = 150 are shown in Figure 2-24b, where N is seen to increase from a value of 10 for α = 0 to 14.3 for α = 0.8, but in reality for a cement stabilised soil, the probe will have some roughness and an α of 0.5 is quoted, giving an N value of 12.4.

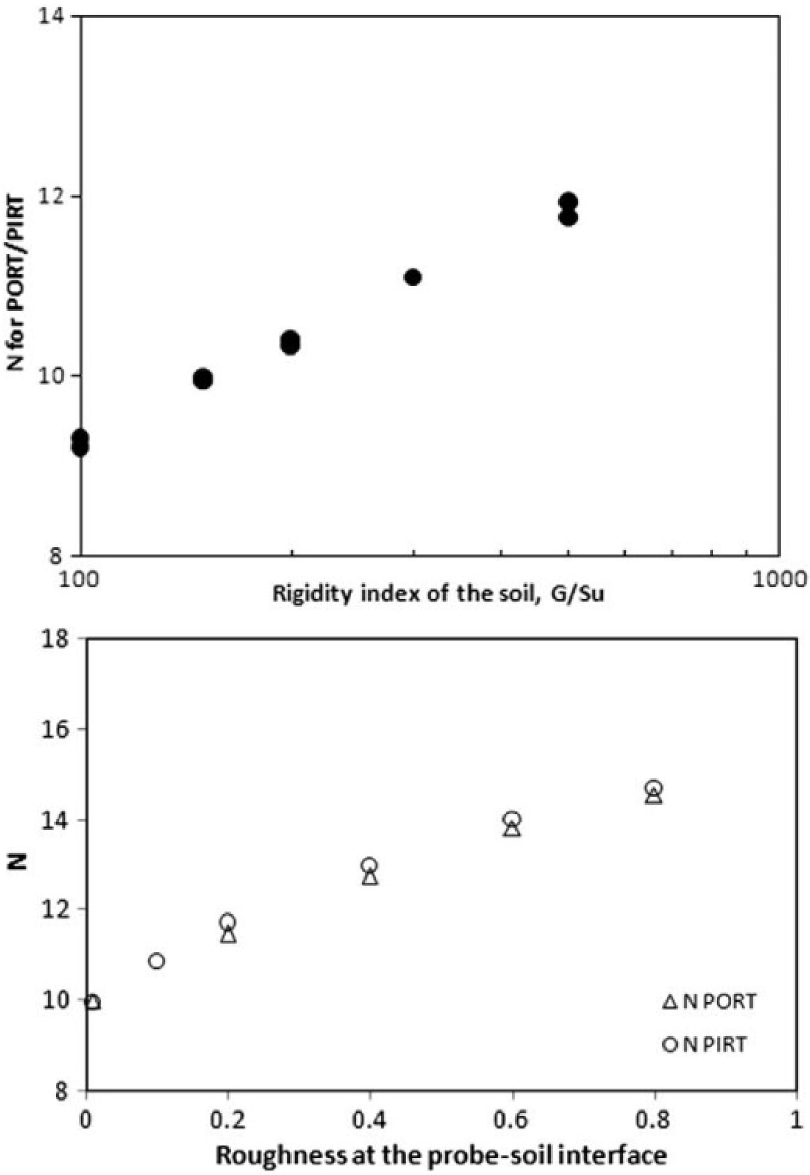

Figure 2-24: PORT and PIRT N values with a) PORT & PIRT N value with rigidity index at α = 0 & b) PORT & PIRT N value with probe roughness at G/c_{col} = 150, after Liyanapathirana & Kelly (2011)

As cement-stabilised soils often soften during remoulding, a strain softening model was used to investigate the sensitivity of the stabilised soil on the N value. Figure 2-25 shows the effect of increasing degradation parameter (δ_{rem}), *i.e.,* the ratio of the strength of the fully remoulded soil to that of the intact soil (inverse of the sensitivity of the soil), where it can be seen δ_{rem} has a significant effect on the N value. N is seen to reduce from approximately 13 to 10 as the sensitivity of the soil increased from 2 to 15 and it is stated that the use of a single N value can result in errors in the estimated field strengths when the sensitivity of the column varies. The effect of the softening parameter (ζ_{95}), *i.e.,* the value of the accumulated plastic strain at a Gauss point (ζ) at 95% of remoulding, was found not be very significant.

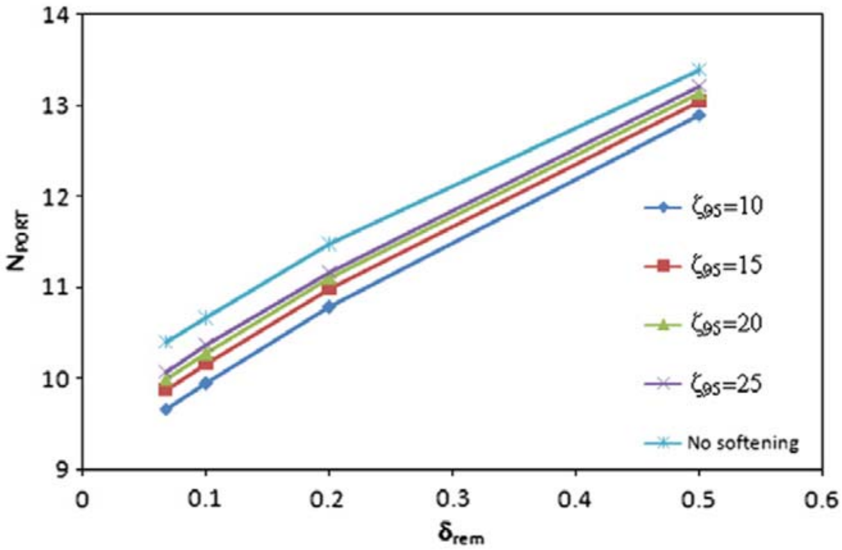

Figure 2-25: Variation in PORT N value with column sensitivity, after Liyanapathirana & Kelly (2011)

In a comparison with settlements observed in field columns, strengths were back calculated and an N value of 16.7 was interpreted from a field PORT. This value is quoted by Liyanapathirana & Kelly (2010; 2011) to be unrealistically high due to column uniformity variations and column yielding. Overall, the authors consider an N value of 10 to be optimistic and recommend values between 12 and 14 to be a more appropriate value for N.

2.4.4 N Values used in Practice

Current guidance documents such as SGI Report 4:95E (Carlsten & Ekström 1996), EuroSoilStab (2002), SGI Report 17 (Larsson 2006) and TK Geo 11 (Trafikverket 2011) recommend the use a factor of N = 10 to relate the probing force of a PIRT/PORT penetrometer (after correction for sounding bar/pull-out wire friction) to the undrained shear strength in the column. Table 2-5 provides a compilation of N values from past and current guidance documents, while Table 2-6 provides a compilation of N values back calculated from various field observations in a number of different soil types.

Holm *et al.* (1981) compared the strength of stabilised lime columns in clay, estimated from Menard pressuremeter test data and the lime column penetrometer (PIRT), and found an N value of 11 to be most suitable. In a comparison of PIRT with column shear vane results, Halkola (1983) approximated N to be between 12.5 and 16.7 from lime and lime-gypsum stabilised columns. Columns were tested with a 375 mm wide (area = 0.01 m^2) PIRT penetrometer and a 132*mm* dia. column shear vane where shear strengths up to 200 kPa were recorded. In a review of lime column data from research and field applications in the first 10 years of its existence, Åhnberg & Holm (1986) suggest the N value of 10 for a 400 × 20 mm penetrometer, but that N varies with the penetrometer's leading edge thickness (see entry in Table 2-5).

Table 2-5: Published Guidance N values for PORT and PIRT penetrometers

Test Type:	N Value:	Conditions:	Reference:
PIRT	10 8	400 × 20 mm PIRT penetrometer 400 × 15 mm PIRT penetrometer	(Åhnberg & Holm 1986)
PORT & PIRT	10	Report 4:95E, Swedish guidance document	(Carlsten & Ekström 1996)
PORT & PIRT	10	EuroSoilStab, European guidance document	(EuroSoilStab 2002)
PORT & PIRT	10	SGI Report 17, Swedish guidance document (in Swedish)	(Larsson 2006)
PORT & PIRT	10	TK Geo 11, Swedish guidance document	(Trafikverket 2011)

Axelsson & Rehnman (1999) detail the typical N value to be 10 but that the value may vary between 8 and 11, principally due to the soil stiffness. In Finland, N values used range from 10 to 15 with strengths determined from shear vane tests used to define an appropriate N value (Halkola 1999).

To investigate the variation in strength due to varied mixing speeds, withdrawal rates and mixing tool type, Rogbeck *et al.* (2000) stabilised 800 mm dia. columns with cement-GGBS and cement-lime binders. A binder content of 120 kg/m^3 was used and columns were installed to a depth of 5-6 m in a clay overlain by gyttja and peat layers. Columns were tested at 28 and 134 days after column production with a 400 × 20 mm PIRT penetrometer. Columns were not pre-drilled and the test was offset by 100 mm from the centre of the column so as not to test in weaker section created by the Kelly bar. Piston sampling of columns was carried out 28 days after production and whole columns were extracted with a 900 mm dia. sampling tube a number of days after the 134 day tests. Using an N value of 10, column shear strengths were estimated to be 80 kPa to 165 kPa at 28 days and 50 kPa to 185 kPa at 134 days. UCS tests on the piston samples showed similar shear strengths of up to 150 kPa (Rogbeck personal communication 2014), but information on the location of the samples in the columns and the actual time at which they were tested is not available.

Table 2-6: Published field observed N values for PORT and PIRT penetrometers

Test Type:	N Value:	Conditions:	Reference:
PIRT	10	Lime columns in clay, c_u < 160 kPa	(Boman 1979)
PIRT	11	Menard pressuremeter tests on lime columns compared with PIRT, $c_u \approx$ 255 kPa, (190-320 kPa)	(Holm *et al*. 1981)
PIRT	11	Reference to compiled data inc. Holm *et al.* 1981	(Broms 1991)
PIRT	12.5-16.7	Comparison with column vane (85 mm high by 132 mm dia.) results, c_u < 255 kPa	(Halkola 1983)
PIRT & PORT	10 (8-11)	Experience based value Stiffness related	(Axelsson & Rehnman 1999)
PORT & PIRT	10 10-15	Sweden Finland, defined by site specific column vane tests	(Halkola 1999)
PIRT	10	Field column tests in clay and gyttja, cement-lime and cement-GGBS binders c_u <185 kPa	(Rogbeck *et al*. 2000)
PIRT	10	PIRT in unstabilised clay (in Swedish)	(Axelsson 2001)
PORT & PIRT	10-15	PORT & PIRT of lime-cement columns in a very soft clay, c_u<600 kPa (in Swedish)	(Axelsson 2001)
PORT & PIRT	10-15	Compiled N values from literature	(Porbaha 2002)
PORT & PIRT	10 15	Columns under active loading conditions Conservative N, for use with columns in direct shear with low confinement	(Axelsson & Larsson 2003) See Axelsson (2001) for further details on the tests.
PORT & PIRT	10	Lime-cement pre-drilled columns in clay, c_u <250 kPa. (in Swedish)	(Edstam *et al*. 2004)
PIRT (& PORT)	20	N = 20 derived from field PIRT in pre-drilled mass stabilised clayey peat, $c_u \approx$100-300 kPa	(Wiggers & Perzon 2005)
PIRT	10	Field calibration tests on cement-bentonite mixture with shear vane and laboratory tests	(Burke *et al*. 2007)
PORT	10	From Report 4:95E (Carlsten & Ekström 1996)	(Kelly & Wong 2011)
PORT & PIRT	9-14 12-14	FEM using rigidity index and probe roughness. Soil-cement field column tests	(Liyanapathirana & Kelly 2011)
T-Bar	*10.5*	*Un-stabilised soft clay*	(Stewart & Randolph 1994)

Axelsson (2001) and Axelsson & Larsson (2003) created 600 mm and 800 mm dia. stabilised columns to depths of 7 m in a very soft clay at Arboga in Sweden. The columns were stabilised using lime-cement at a binder content of 50 kg/m^3 and after curing periods of four and eight weeks numerous tests including PIRT, PORT (FOPS), KTH probing, coring and column extraction were carried out. From the results of tri-axial tests on cored samples from a PIRT column, a number of weeks after coring, an N value of 10 was found to be appropriate for conditions in active loading conditions. An N value of 15 was proposed to provide a conservative estimate of the strength in direct shear zones where the confined pressure is low.

During the production of over 6,000 km of stabilised soil columns, 600 mm in diameter and to depths up to 8 m, in the Göta River Valley, Sweden, and subsequent testing, Edstam *et al.* (2004) estimated the strength of the stabilised columns using a multiplying factor derived from an N value of 10 and applied it to the probing force. The multiplying factor (β) of 12.5 was calculated for a 500 mm wide PIRT penetrometer with a 15 mm thick leading edge based on the reduction in area due to pre-drilling with a 58 mm dia. hole. In higher strength columns where a smaller penetrometer was used, a β value of 16 was used and this was based on back calculation of results from large penetrometers.

Wiggers & Perzon (2005) carried out a series of PORT and PIRT in a peat-clay soil to assess the use of DDSM and MS to improve the stability of Dutch dikes. PORT and PIRT on the same stabilised column were found to give very similar results. In pre-drilled mass stabilised blocks, an N value of 20 was found to best fit the shear strengths obtained from cored samples.

During mass stabilisation works at the Jewfish Creek, Florida, USA, Burke *et al.* (2007) used PIRT to verify the strength of the stabilised mass. Penetrometers were 26" wide with a leading edge thickness of 0.75" and a tip diameter of 2.5". To determine the appropriate bearing factor for use with Equation 2-5, a 1.8 m deep test pit was dug and filled with a cement-bentonite mixture which would obtain similar strengths to the required stabilise soil strength. PIRT, shear vane and laboratory UCS testing (samples taken from the cement-bentonite mixture after mixing) at various curing times verified that an N value of 10 was appropriate for use.

Kelly & Wong (2011) assessed the strength of OPC stabilised estuarine clay columns using PORT. Although an N value of 10 was used (based on Swedish practice), cross-sectional strength variations in the column and disturbances to cored samples meant exact calibration of the N value was not possible and it was concluded that parallel testing using other techniques is necessary.

In summary, while an N value of 10 appears to have broad acceptance, it is difficult to draw a firm conclusion from the data in Table 2-6 due to (i) variation in the stabilised materials tested, (ii) variation in penetrometer dimensions and (iii) differences in the test methods by which the column strength was measured or inferred.

Chapter 2, Part B: Review of Soil Stabilisation & Laboratory Stabilisation Methods

2.5 Factors Affecting the Stabilisation Process

In this section of the chapter, a review of the main factors affecting the dry soil mixing process is provided. The principal reasons for stabilising soft soils are to increase their strength and stiffness properties and both Babasaki *et al.* (1996) and Kitazume (2005) classify the factors affecting the increase in strength into four categories:

(i) Soil Characteristics: moisture content, organic content, pH and the physical makeup of the soil.
(ii) Binder Characteristics: the type of binder added to the soil.
(iii) Mixing Conditions: the quantity of binder added to the soil and the degree and duration of mixing.
(iv) Curing Conditions: the time, temperature and confining pressure under which the stabilised soil cures.

The effects of each of these factors are set out in the sections that follow and details are presented of the stabilised properties that can be achieved, focusing in particular on the improvement to the soil's strength and stiffness properties.

A short review is also presented of laboratory stabilisation trial procedures and how their results compare with field results. An overview of some previous laboratory-scale stabilised soil column research is given, where scale experiments were carried out to investigate the field behaviour of stabilised columns, as well as methods for better replicating field mixing processes in the laboratory and monitoring of temperature variations of the stabilised mass during curing.

2.6 Soil Characteristics

2.6.1 Soil Type - Overview

The type of soil to be stabilised will greatly influence the efficiency of the mixing process and the quality of the stabilised mass (Dahlström 2012) as addition of the dry binder will serve to reduce the plasticity of the soil. The type of binder used in a particular soil is also important, *e.g.,* stabilisation of clays using quicklime (CaO) will result in immediate reduction in moisture content as hydrated lime ($Ca(OH)_2$) is formed and the plasticity index of the soil increased. Due to the cohesive nature of clay and some silt soils, high mixing energies are required to ensure that the binder is evenly distributed throughout the soil and that unstabilised pockets of soil (known as inclusions (Denies *et al*. 2012)) do not occur. Although gyttja, sludge and peat may be more easily mixed than silts and clays, their higher moisture contents and liquid limits, and high organic content can result in low strength improvements, both of which are addressed in Sections 2.6.2 and 2.6.3.

The properties of two unique soils, in which significant improvements may be achieved using DSM methods, are now briefly set out:

Peat:

Peat is a highly organic soil type, formed from the decay of the dead remains of organic material (rich in carbohydrates) into humus, a process referred to as humification (Hobbs 1986). The von Post degree of humification is used as a method of classifying peats and ranges from *H1* (least humified) to *H10* (most humified) (von Post 1922). Peat moisture contents can range up to many hundreds and even thousands of percent, as evident in Table 1 of Timoney *et al.* (2012a) (see Appendix A), and will reduce with increasing degrees of humification. Peat densities are close to that of water, *i.e.,* 1,000kg/m^3 and may even be below that of water, *e.g.,* a fresh peat with a high fibre content coupled with high moisture content. In relation to shear strength, peat does not act like other soil types as fibres in the peat act to reinforce the soil and their horizontal orientation provides shear resistance in the vertical direction.

Peat soils comprise a significant portion of the land area of many countries, *e.g.,* 18.4% of Canada (1,2950,000 km^2), 6.7% of Russia (715,000 km^2), 29.5% of Finland (88,908 km^2), 15.6% of Sweden (65,859 km^2), 10.9% of the United Kingdom (26,519 km^2) and 16.5% of Ireland (11,392 km^2) are covered in peat (Hobbs 1986; Montanarella, *et al.* 2006). Further details on peat, its formation and stabilisation potential may be found in the papers published by the author (Timoney *et al*. 2011; Timoney *et al*. 2012a; Timoney *et al*. 2012b) some of which are provided in Appendix A.

Gyttja:

Gyttja is the Swedish term for an organic mud-like soil formed in lakes and seas from the deposition of the remains of plants and animals with high fat and protein contents, as distinguishing them from the carbohydrate-rich origin of peats (Hartlén 1996). Depending upon their origin, gyttjas can be grey, reddish-grey, or greenish-grey when formed in nutritious waters. Organic contents are typically from 6% to 20% with 50% considered as the upper limit (Hansen 1959). Moisture contents for gyttjas are lower than those seen in peats, typically lying below 300%.

2.6.2 Moisture Content

DSM methods are used to treat soft clays and silts with initial moisture contents (w_i) between 30% and 200% (Topolnicki 2012; Dahlström 2012), but gyttjas, sludges, dredged sediments and peats, having higher moisture contents of many hundreds of percent may also be treated. It is generally considered that for given conditions of curing, an increasing moisture content will result in lower stabilised strengths (Babaski *et al*. 1996; Porbaha *et al*. 2000; Jacobson 2002; Åhnberg *et al*. 2003; Kitazume 2005; Marzano *et al*. 2009; Kitazume & Terashi 2013). Marzano *et al.* (2009) varied w_i from 33% to 50% for an artificial kaolin-silica flour clay, which was then stabilised with cement. The stabilised strengths were seen to increase with reducing moisture content.

In some cases, such as low moisture content clays, addition of water to the soil can result in increased strengths as better mixing and binder distribution can be achieved (Filz 2009). Soil mixing which includes the addition of a binder slurry rather than a dry binder is known as Wet Soil Mixing (WSM) and is suitable for granular soil types.

2.6.3 Organic Content & pH

The stabilisation of organic soils is typically more challenging than that of inorganic soils as humic acids hinder the hydration processes and the related reactions required for the development of strength following stabilisation (Axelsson *et al*. 2002). During the stabilisation of organic soils, calcium hydroxide reacts with the humic acids to form insoluble products which coat the soil particles. Hebib & Farrell (2003) and Hernandez-Martinez & Al-Tabbaa (2005) inspected stabilised peat samples under an electron microscope and found that there was little or no interaction between the strengthening products created during hydration and the organic material of the stabilised peat. Finnish studies have proposed a binder threshold below which no increase in strength will occur (Axelsson *et al,* 2002). It is suggested that once this threshold is passed, enough binder is present to cause the pH to increase, neutralising the acids present.

In a series of tests on Canadian postglacial marine clay and fluvioglacial silt, both with organic contents below 1%, Tremblay *et al.* (2002) mixed various organic compounds with the soils, increasing their total organic contents to 10% before stabilising the soil with cement. Their general conclusion was that strong acids prevent the pore water from reaching a sufficiently high pH to allow strength development. High concentrations of sulphates were seen when the pH was less than 7.5, meaning little ettringite was formed and strength gain was low. On addition of the humic acid, the strength was observed to decrease and Scanning Electron Microscope (SEM) images identified the presence of an organic membrane on the particles after curing times of 28 days.

2.7 Binder Characteristics

In the early stages of Scandinavian DSM, lime was the primary binder used but cement binders soon became popular due to the greater strength gains achievable. Today, many binders including various cements, GGBS, gypsum, fly ash and even inert fillers such as silica sand, limestone and synthetic fibres, are used in soil stabilisation. The following section sets out details of some popular binders used today.

2.7.1 Cement

When dry cement is mixed with an organic soil it reacts with the water within the soil, initiating the hydration process in which calcium (C; CaO) silicate (S; SiO_2) hydrate (H; H_2O) [$C_3S_2H_4$ (CSH)] is formed during hydraulic reactions (Janz & Johansson 2002). The CSH gel binds the soil particles together, filling voids and becoming stronger and denser with time. Initially, the rate of strength gain will be controlled by the temperature; the higher the temperature the more reactions that take place leading to better strength gains. In time, the CSH gel formed will hinder the rate of strength gain as the gel slows the release of calcium ions. The ratio of Tricalcium Silicate (C_3S) to Dicalcium Silicate (C_2S) within the cement affects the rate of hydration; a high ratio results in greater CSH production and hence greater strengths. Also, the gypsum content of the cement will serve to delay the setting process.

2.7.2 Lime

Two forms of lime are used in soil stabilisation, Quick Lime (Calcium Oxide (CaO)) and Hydrated Lime (Calcium Hydroxide ($Ca(OH)_2$). When mixed with water, quick lime will react to form hydrated lime, but this will not result in any strength gain although increased plasticity will occur due to the reduced moisture content. The hydrated lime then reacts with the pozzolanic material in the soil and water to produce CSH, which contributes to strength gain. Lime provides an initial *dewatering* effect, with significant exothermic reactions occurring (see Section 2.9.2) and an increase in pH to approximately 12.5, but stabilisation of organic soils can be poor as humic acids inhibit strengthening reactions. Furthermore, stabilisation of peats with lime can be very poor due to the lack of minerals in the peat required for pozzolanic reactions (Janz & Johansson 2002).

2.7.3 Ground Granulated Blast Furnace Slag (GGBS)

Ground Granulated Blast Furnace Slag (GGBS) is a by-product of steel manufacturing processes. It contains a small amount of lime but requires activation, generally by cement or lime. This allows the latent hydraulic reactions to begin after which its own lime content provides the $Ca(OH)_2$ required for the reactions. The temperature generated during these reactions is low resulting in slow strength gains and changes in the temperature of the soil mass can affect the rate of reactions. Thus, initial strengths can be lower than material stabilised using other binders, but long-term strengths can be significant. Today, GGBS is generally used as a composite binder with cement in DSM applications and has been shown in many cases to provide better strength improvements for organic soils than cement alone (EuroSoilStab 2002; Filz 2009) in particular when stabilising peat soils (Timoney *et al*. 2012b).

2.7.4 Pulverised Fly Ash (PFA)

Pulverised Fly Ash (PFA) is obtained from flue gas in coal-fired power generation plants. Pulverised fly ash, like GGBS, requires activation due to its low calcium oxide content, achieved using either cement or lime, and is also a temperature sensitive binder. Its reactivity depends upon its fineness, vitreosity and rate of cooling following manufacture. The calcium hydroxide provided by the added cement or lime reacts with water and the pozzolanic material present in the PFA to start the strengthening process. Reaction rates are low depending upon the amount of calcium hydroxide available and CSH gel with a low C_3S content is formed, resulting in lower strengths than other binders.

2.7.5 Other Binders

Filler materials such as silica sand and limestone can be used to increase the stiffness of the soil but, unlike binders, are practically inert and do not provide any strengthening reactions. They reduce the amount of costly binders required and when used in peat soils, they augment the number of solid particles available to be bound together (Axelsson *et al*. 2002). However, checks need to be carried out to ensure that the increased density of the soil profile and the resulting higher stress states do not lead to excessive subsidence or heaving problems in neighbouring untreated soils.

Geosynthetic fibres offer an alternative binder additive to improve strength gains. In a series of laboratory tests, Kalantari and Haut (2008) used Portland cement and 12 mm long polypropylene fibres at an optimum 0.15% content in the stabilisation of a *H4-H5* peat. Stabilised sample strengths with fibres were observed to be slightly higher than those stabilised without fibres.

Recent work using sustainable reactive magnesia (MgO) cements has shown significant strength gains to be possible and when carbonated with CO_2, strengths within hours of stabilisation can reach strengths equivalent to that obtained at 28 day using OPC (Yi *et al*. 2013b).

2.8 Mixing Conditions

2.8.1 Effect of Binder Content

It is generally considered that increased binder contents result in increased achievable strengths (Babaski *et al*. 1996; Porbaha *et al*. 2000; Axelsson *et al*. 2002; Kitazume 2005; Horpibulsuk *et al*. 2011). Increased amounts of binder result in a greater number of hydration reactions taking place. Typically, binder contents range from 70 kg/m^3 to 200 kg/m^3 for clays and organics clays, and up to 300 kg/m^3 (and occasionally greater) for peat soils; Dahlström (2012) suggests suitable binder contents for various soil types. It should be noted that further increases in binder content may result in diminishing strength increases, for example as was observed by Terashi *et al.* (1977) for lime stabilised clay as uniform mixing becomes more difficult due to the reduced moisture content.

<u>Water-to-Binder Ratio:</u>

The water-to-binder ratio (*WTBR*) (η), also referred to as the water-to-cement ratio (*WTCR*) has been used by a number of authors to assess the improvements in the strength of a soil using different binder contents at particular curing times. *WTBR* or *WTCR* is defined as the mass per unit volume of water (m_w) divided by the mass per unit volume of (active) binder (m_b), and can be calculated using Equation 2-10 for DSM:

$$\eta = \frac{m_w}{m_b} = \frac{\rho_{soil}}{m_b\left(1 + \frac{1}{w_i}\right)} \qquad \text{2-10}$$

where ρ_{soil} is the bulk density of the soil (kg/m^3), m_b is the amount of binder added to 1 m^3, *i.e.,* the binder content, and w_i is the initial moisture content of the soil. The mass of water is a function of w_i for DSM as no additional water is added during mixing, but the equation may be adjusted for WSM if needed. For a particular curing period under similar curing conditions, stabilised strengths have been shown to increase with reducing *WTBR* for sands, silts and clays (Åhnberg *et al*. 1995; Jacobson *et al*. 2005; Filz 2009) and for peat soil types (Timoney *et al*. 2012a; Timoney *et al*. 2012b).

2.8.2 Degree of Mixing

Increased degrees of mixing are generally considered to result in better stabilised properties as the binder is more uniformly distributed throughout the parent soil, thereby allowing for a maximum portion of the binder to be utilised (Larsson 2003). In highly cohesive plastic soils, greater mixing energies can be required so that the mixing tool can fully break up the soil structure and prevent lumps of unstabilised material occurring (Yang *et al*. 1998). On the other hand, excessive mixing energies applied in the field can have a negative impact on the stabilised soil, as additional air is injected into the soil and stabilisation production times are longer (Dahlström 2012).

Mixing energy/efficiency in the field can be estimated by the Blade Rotation Number (BRN) (Yoshizawa *et al*. 1996; Hayashi & Nishikawa 1999):

$$BRN = \sum N \times \left({}^{R_p}\!/\!_{S_p} \times {}^{W_i}\!/\!_{W} + {}^{R_w}\!/\!_{S_w} \right) \qquad \text{2-11}$$

where N is the total number of mixing blades, R_p and R_w are the rotational speeds of the mixing tools during penetration and withdrawal (rpm), S_p and S_w are the penetration and withdrawal speeds of the mixing tool (m/min), W_i the amount of binder injected during penetration (kg/m^3) and W the total amount of binder injected. In Japanese practice, some of the binder may be injected during the penetration phase of the process, particularly with WSM to assist the mixing process (Larsson 2005). However, in Scandinavian practice the binder is only injected during the retrieval phase and BRN is calculated as the number of mixing blades divided (N) by the mixing tool retrieval rate (S_w). Rotational speeds of the mixing tool are between 150-200 rpm while penetration and retrieval rates are 2-15 m/min and 2-6 m/min, respectively for Scandinavian practice.

Laboratory mixing during stabilisation trials is generally considered to be thorough and achieve the best results possible for the soil (Babaski *et al*. 1996). Laboratory stabilisation protocols dictate that mixing is carried out for durations of between 2 and 10 minutes, typically 5 minutes (Kitazume *et al*. 2009), but mixing until a visually homogenous mixture is obtained is also recommended. For fibrous peat soils, mixing is limited to less than five minutes as over-mixing can result in excessive breakup of the fibrous structure (Pousette *et al*. 1999).

2.9 Curing Conditions

2.9.1 Curing Time

It is agreed that the strength of a stabilised soil will increase with curing time, *e.g.,* (Nagaraj *et al*. 1996; Porbaha *et al*. 2000; Jacobson 2002; Horpibulsuk *et al*. 2003; Åhnberg 2006; Filz 2009). Rates of strength gain will be dependent on the type (see Section 2.7) and amount (see Section 2.8.1) of binder used. Laboratory binder trials will typically use curing periods of 7, 28 and 91 days to assess the overall strength gain with time and additional tests may be carried out at 1, 3, 14 and 56 days to further complement the data. Further details of the effect of curing time and its use in predicting achievable strengths are reviewed in Section 2.10.3.

2.9.2 Curing Temperature

The hydration reactions that take place after the mixing of the parent soil and binder are exothermic in nature and increased temperatures accelerate the rate of stabilisation (Axelsson *et al*. 2002). The increase in temperature of a soil following stabilisation is a function of the initial temperature of the soil, its specific heat and thermal capacity, the heat generated by hydration reactions and the size of the stabilised soil mass (Kitazume & Terashi 2013).

Åhnberg *et al.* (1995) reports increases of 5 °C to 10 °C in the ground temperature for cement stabilised soils, Babaski *et al.* (1996) shows temperatures in the region of 50 °C to be maintained for several months following stabilisation with cement and Halkola (1999) reports temperatures of up to 70 °C in lime stabilised columns. Esrig (1999) quoted temperatures greater than 70 °C to be possible during wet soil mixing in soft clays using cement, and that when lime binders are used in dry form, temperatures greater than 70 °C may be obtained.

Axelsson *et al.* (2002) report that some binders are temperature-sensitive, *i.e.*, the temperature of the soil mass to be stabilised can have a significant effect on the number of reactions that take place and the rate of strength gain. This is not an issue with cement or lime binders where significant heat is created during the cementitious and pozzolanic reactions. Binders like GGBS produce less heat during the exothermic reactions, and are consequently more susceptible to temperature changes in the soil being stabilised, resulting in fewer reactions and lower initial strengths (Axelsson *et al*. 2002).

Variations in Curing Temperature:

A number of authors have addressed the variations in strength gain due to varying curing temperature using a parameter known as maturity (M) (Kitazume & Terashi 2013) and is similar to that used in concrete technology. Maturity combines curing time and curing temperature into a single parameter, and is based on the theory that the samples from the same stabilised mixture, cured for different periods and at different curing temperatures, but having the same maturity, will have the same strength (Marzano *et al*. 2008). Equations 2-12 and 2-13 define two methods of calculating M:

$$M_T = \left[20 + K\left(T_c - 20\right)\right]^2 \sqrt{t_c} \qquad \text{2-12}$$

$$M = \int_0^{Tc} 2\exp\left(\frac{t+10}{10}\right) dT_c \qquad \text{2-13}$$

where M_T is the maturity defined by Åhnberg & Holm (1984), K is a factor which depends on the soil type, binder and curing temperature (above curing temperatures of 20 °C, a K value of 0.5 was obtained from a compilation of cement stabilised clay data by Åhnberg & Holm (1984), while below 20 °C values of 0 to 0.5 were seen), M is the maturity defined by Babasaki *et al.* (1996), t is the curing temperature (°C) and T_c is the curing period (*days*).

Investigating the use of accelerated aging techniques on an artificial (stabilised) clay using increased temperatures, Marzano *et al.* (2008) proposes a mathematical shift factor which is applied to the actual curing time (t) and determines the equivalent curing time (t_e) using the temperature at which the samples actually cured (T) (see Equation 2-14):

$$t_e = t \times \exp\left[-{}^{E_a}\!/_{R}\left({}^{1}\!/_{T} - {}^{1}\!/_{T_0}\right)\right] \qquad \text{2-14}$$

where E_a is the apparent activation energy (J/mol), R is the universal gas constant (8.3144 J/K mol) and T_0 is the reference curing temperature (°C). Similarly, Eurocode 2 (BSI 2008) defines Equation 2-15 as a method to account for curing temperature variations between 0 °C and 80 °C. The correction factor accounts for differences in temperature by adjusting the curing time of the sample in question. For temperatures above 20 °C the equation serves to shorten the curing time, while temperatures below 20 °C will have an extended curing time.

$$t_T = \sum_{i=1}^{n} \exp\left[-\left(\frac{4000}{273 + T(\Delta t_i)} - 13.65\right)\right] \times \Delta t_i \qquad \text{2-15}$$

where t_T is the temperature adjusted age of the concrete (days), $T(\Delta t_i)$ is the temperature during the curing period (°C) and Δt_i is the number of days for which $T(\Delta t_i)$ prevails, *i.e.,* the curing time (days).

2.9.3 Confining Pressure

In the field a layer of fill, up to 1 m deep, is typically placed over the stabilised area to aid compaction and remove air entrained in the soil during mixing. Åhnberg *et al.* (2001) investigated the effect of prestress loading on a peat stabilised with cement-lime and cement-slag at 100 kg/m^3. Samples were loaded with 0 kPa, 9 kPa and 18 kPa immediately after preparation and at delays of 45 minutes, 4 hours and 24 hours after preparation. Samples where an 18 kPa prestress was applied were found to have strengths three to four times those of their non-loaded counterparts. It was also observed that samples with a delayed loading had reduced strengths in the region of 25% after 45 minutes and 75% after 24 hours when compared to the samples that were loaded immediately. One possible reason proposed for this is that when the loading is delayed bonds between the soil particles are formed and the effect of the prestress in compressing the void is reduced. Voids will still remain within the stabilised mass, although some will be filled with products from the afore mentioned reactions.

Åhnberg (2007) investigated the effect of three different curing stress conditions for a clay, stabilised with 70 kg/m^3 of lime-cement binder. Samples were cured in triaxial cells under effective confining stresses of 20 kPa and 60 kPa, vertical effective stresses of 40 kPa and 120 kPa respectively and a pore pressure of 20 kPa, while a third set of reference samples cured without external stresses. The samples were cured at 20 °C for 28 days before undrained triaxial testing was carried out. It was found that the increased stresses during curing resulted in increased strengths, caused by the soil and binder particles being closer together as a result of the stresses that were applied very soon after sample preparation.

2.10 Achievable Stabilised Soil Properties

2.10.1 Stabilised Moisture Content

After the addition of the dry binder to the parent soil, the moisture content will reduce as a result of the increased amount of solid particles present and the binding of water to reaction products during hydration. A small amount of moisture may also be lost due to evaporation during laboratory mixing (Åhnberg 2006). Åhnberg (2003) defined Equation 2-16 as a method to calculate the stabilised moisture content and found it to agree well with the measured stabilised moisture contents for two stabilised clays and a gyttja.

$$w_s = \frac{\rho_{soil}\left(\frac{w_i}{w_i + 1}\right) - ax}{\rho_{soil}\left(\frac{1}{w_i + 1}\right) + (1 + a)x} \qquad 2\text{-}16$$

where w_s is the stabilised soil moisture content, ρ_{soil} the raw soil density (kg/m^3), w_i is the raw soil moisture content, x is the binder content (kg/m^3) and a is the non-evaporable water content of the binder. Typical values of the non-evaporable water content are 0.20 to 0.23 for hydrated cements, 0.20 for slags and 0.30 for lime (Taylor 1997; Åhnberg *et al*. 2003).

2.10.2 Stabilised Density

The density of a stabilised soil is a function of the initial soil density, its moisture content and the type and amount of binder added. In the case of laboratory compacted samples, the type and amount of compaction applied also affects the achieved density (see Section 2.11.2). Achievable stabilised densities may be estimated using the specific gravities of the unstabilised soil and the binders used but, from laboratory stabilisation trials, Åhnberg (2006) highlights that the density for dry mixed binders may be smaller than predicted.

After addition of the binder and mixing, the moisture content of the soil will reduce and a certain amount of air will become entrained. The addition of the binder and reduction in moisture content implies compacted densities should be higher than those of the original soil, but air voids entrained during mixing (and compaction for laboratory samples) can mean densities are similar to that of the original soil (Åhnberg *et al*. 2003). Degrees of saturation for 50 mm dia. laboratory stabilised clay samples were noted by Åhnberg (2004) to lie between 93% and 98%.

Marzano *et al.* (2009) showed density to be related to the type of compaction used in the preparation of laboratory samples and the initial moisture content of the soil. Density was shown to be unaffected by curing time and curing temperature. Samples with poorer compaction had lower densities and achieved lower strengths compared to better-compacted samples, further details on these tests are discussed in Section 2.11.1. The increase in density is more evident in stabilised peat soils due to the parent peats low density close to that of water, *e.g.,* Åhnberg *et al.* (2001) and Axelsson *et al.* (2002), and the application of surcharges during curing further serves to increase the density.

2.10.3 Stabilised Strength & Strength Prediction Models

It is generally considered that the addition of dry binders to a soil will improve the strength characteristics of the soil and increased strengths will occur with increasing binder contents, curing time, curing temperature and degree of mixing, and reducing moisture and organic contents of the parent soil (Filz 2009).

Although some literature may quote the undrained shear strength (c_u) of stabilised soils, the Unconfined Compression Strength (UCS, q) is generally used when quoting stabilised-soil strengths as UCS tests are quick and cost effective to carry out in the laboratory (Kitazume 2005). Yang *et al.* (1998) shows the unconfined compression strength to be close to twice that of the undrained shear strength for an organic soil stabilised using cement and dry jet mixing methods, when the unconfined compression strength is less than 1 MPa. At higher UCS values the ratio was noted to increase. A value of 2 has been used by a number of authors (Åhnberg *et al*. 2003; Axelsson & Larsson 2003) and in Eurocode 7 (BSI 2007).

Although it is inappropriate to quote achievable strengths for various soil types without consideration of the factors set out in Section 2.5, Topolnicki (2012) quotes achievable field UCS ranges for cement stabilised sludge, peat and clay after 28 days to lie between 0.1-0.4 MPa (250-400 kg/m^3), 0.2-1.2 MPa (150-350 kg/m^3) and 0.5-1.7 MPa (150-300 kg/m^3), respectively. Further compiled data on peat stabilisation may be found in Appendix A.

As detailed in Section 2.9.1, following stabilisation the strength of the soil will increase with time if an appropriate binder type and content are used. A number of authors have fitted strength prediction curves to data from their laboratory studies in the form of Equation 2-17:

$$\frac{q_t}{q_T} = A \ln t + B \tag{2-17}$$

where q_t is the estimated strength after t days curing, q_T the known strength after a curing time of T days and A and B are constants from statistical analysis. Table 2-7 lists the coefficients of some strength prediction models for clays stabilised with cement and are based on strengths normalised by the strength achieved after a particular curing period (T), typically 28 days, although Nagaraj (1996) uses a T of 14 days. The models detailed in Table 2-7 are presented in Figure 2-26 and show good general agreement with each other. The Filz (2009) model indicates an initial higher rate of strength gain than the others, although it should be noted this model is fitted to a number of stabilisation trials including both DSM and WSM data.

Table 2-7: Strength prediction models for cement stabilised soils

Soil Type:	Comparison Curing Time, T	A	B	R^2	Source:
Clay	14 days	0.458	-0.20	-	(Nagaraj *et al*. 1996)
Clay	28 days	0.345	-0.151	-	Nagaraj *et al.* (1996) altered to T = 28 days
Clay	28 days	0.281	0.038	95.6%	(Horpibulsuk *et al*. 2003)
Clay	28 days	0.283	0.039	90.8%	(Horpibulsuk *et al*. 2011)
Clay	28 days	0.293	0.026	91.1%	(Horpibulsuk *et al*. 2012)
Clay & Gyttja	28 days	0.305	-0.04	94%	(Åhnberg 2006)
Compiled data on clays	28 days	0.187	0.375	-	(Filz 2009)

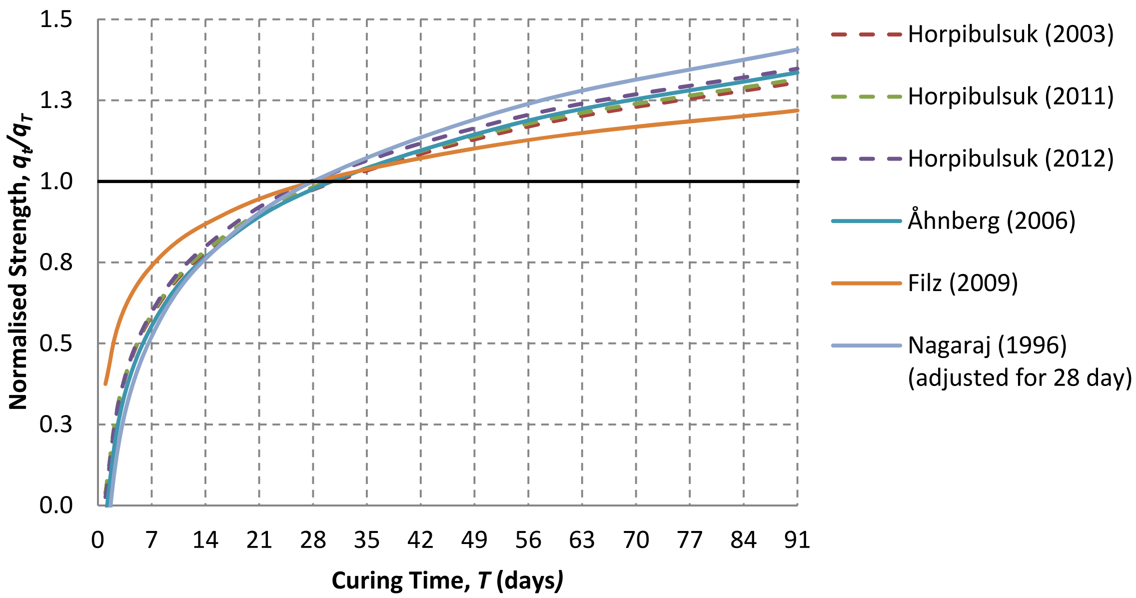

Figure 2-26: Compiled normalised (28 day) strength prediction models with time for cement stabilised clays

Recent work by Shrestha & Al-Tabbaa (2012) investigated the development of models to predict achievable strengths in cement stabilised soils. Variables of moisture content, particle size distribution, organic content, binder content, curing time and curing temperature were investigated using Artificial Neural Network (ANN) models. These models provided good predictions using additional data not used to develop the models.

The Coefficient of Variation (CoV), defined as the standard deviation (σ) divided by the average (μ), of stabilised strengths has previously been used to assess strength variations of both laboratory and field DSM samples (Hosoya *et al*. 1996; Larsson 2003; Larsson 2005; Srivastava & Babu 2011; Kitazume & Terashi 2013). CoVs for stabilised field strengths are typically found to lie in the range 20% to 40% but may range up to 76% as shown in an extensive compilation of field strength CoVs worldwide by Larsson (2005) (see Figure 2-27). The variations are shown to be the result of variations in the soil profile, different sampling techniques and different laboratory testing procedures.

More recently, CoVs between 21% and 59% from strengths estimated by PORT were obtained Kelly & Wong (2011) and accumulated Japanese data show field CoVs between 50% and 68% for Japanese land-based DJM (Kitazume & Terashi 2013), the high values reported to be due to different layers in the soil profile stabilised.

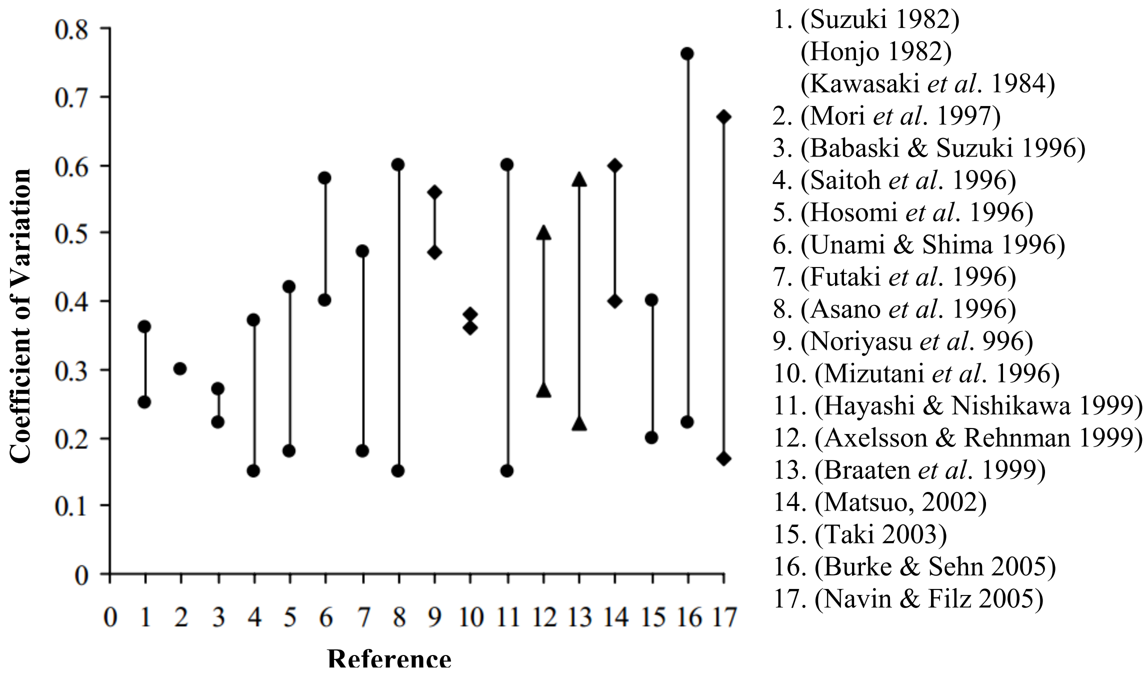

Figure 2-27: Compiled strength coefficients of variation for *in situ* DSM samples, after Larsson (2005)

For laboratory stabilisation trial data, lower CoVs may be expected due to the greater controls in place in terms of the mixing uniformity and curing conditions. Jacobson (2002) observed CoV of less than 5% for two very soft clays with moisture contents up to 80% and 200%, respectively stabilised with lime-cement binders. Åhnberg & Holm (2009) report CoVs of 5% and 7% for stabilised gyttja prepared using tamping and rodding compaction procedures; it should be noted that the gyttja had a liquid consistency (LL = 170%, w_i = 200%) and as such was easier to compact than a stabilised mixture with a lower moisture content.

2.10.4 Stabilised Stiffness & Failure Strain

The stabilisation of a soil will result in increases in the stiffness of the soil and reductions in the soil's ductility (Baker 2000), the magnitudes of which are also dependent on the factors set out in Section 2.5. The behaviour of stabilised soil will be similar to that of an over-consolidated stiff clay. In soil stabilisation, stiffness is typically quoted as the secant modulus of elasticity or Young's modulus (E). Using unconfined compression strength stress-strain data, E_{50} is calculated as the slope of the stress-strain curve, corrected for any bedding error, at half the failure stress (EuroSoilStab 2002). Table 2-8 illustrates a number of relationships between E_{50} and either q or c_u for both laboratory and field samples, where E_{50} is typically seen to lie between 50 to 250 times the UCS. No information is available in the literature on E_{50} CoV measurements.

Table 2-8: Secant stiffness-strength relationships for cement stabilised soils

Lab/Field:	Soil Type:	Binder Type:	Relationship:	Source:
Laboratory	Clay	Lime-cement	E_{50} = [50-150]c_u	(Ekström 1994)
Field	Clay	Lime-cement	E_{50} = [250-350]c_u	(Ekström 1994)
Laboratory	Cohesive & organic soil	Cement, Lime & GGBS	E_{50} = [50-200]q	(Yang *et al*. 1998)
-	Japanese DMM	Cement	E_{50} = [350-1000]q	(Porbaha *et al*. 2000)
-	Boston blue clays	Cement	E_{50} = [50-150]q	(Porbaha *et al*. 2000)
Laboratory & Field	Organic clay	Lime-cement	E_{50} = [70-140]q	(Baker 2000)
Field	Soft clay	Lime-cement	E_{50} = 188q	(Axelsson 2001)
-	Various	Various	E_{50} = [100-200]q	(EuroSoilStab 2002)
Laboratory	Organic clays	Cement & lime-cement	E_{50} = 75q	(Jacobson 2002)
Laboratory	Dredged organic clay	Cement & Cement-GGBS	E_{50} = 115q	(Van Impe *et al*. 2004)
Laboratory & Field	Clay	Lime-cement	E_{50} = 160q	(Massarsch 2005)
Laboratory	Dredged organic clay	Cement & Cement-GGBS	E_{50} = 110q	(Van Impe & Verástegui Flores 2006)
Laboratory	Laboratory prepared kaolin	Cement	E_{50} = [60-125]q	(Marzano *et al*. 2009)
Laboratory	Organic clay & peats	Cement	E_{50} = [50-110]q	(Hernandez-Martinez & Al-Tabbaa 2009)
Laboratory & Field	Clay; dry mixed	Cement	E_{50} = [50-250]q	(Filz 2009)
Field	Estuarine clay	Cement	E_{75} = 120q	(Liyanapathirana & Kelly 2011)*
-	Dry mixed soils	Cement	q <300 kPa: E_{50} = [25-50]q q = 0.3-2 MPa: E_{50} = [50-250]q	(Topolnicki 2012)
Laboratory	Peat	Cement	E_{u50} = 116c_u	(Hebib & Farrell 2003) †
Laboratory	Peat	Cement	E_{50} = 180c_u (best fit) (Range [110-240])	(Quigley & O'Brien 2010)

*Secant stiffness at 75% of the failure strain not 50% as with all other compiled data

† E_{u50} = Undrained secant stiffness modulus at 50% strength

The failure strain (ε_f) observed in UCS testing is typically found to reduce with increasing strength. For cement treated soils, ε_f values between 0.8% and 5% have been observed by a number of authors at strengths up to 2 MPa (Åhnberg 2006; Van Impe & Verástegui Flores 2006; Kitazume & Terashi 2013), while larger failure strains were noted with stabilised peats compared to stabilised clays due to the reinforcing effect of the fibres (Åhnberg 2006).

2.11 Laboratory Stabilisation Practices

2.11.1 Laboratory Stabilisation Trials

Laboratory stabilisation trials or binder trials provide a cost-effective method of ensuring, in the first instance, that a particular soil can be stabilised and help in defining an appropriate binder type and content for *in situ* stabilisation. Numerous laboratory stabilisation procedures and protocols exist across the world and a detailed compilation of the procedures used in Japan, Scandinavia, the UK and the USA can be found in Kitazume *et al.* (2009). The procedure for carrying out a binder trial can be defined under the following headings:

Parent Soil Sampling:

In situ samples from the parent soil profile to be stabilised may be obtained using tube and piston samples (EuroSoilStab 2002). Samples should be taken from each individual layer in the profile and in thicker layers from multiple depths as properties may vary with depth. When sampling peats, care should be taken to ensure that sampling is carried out with minimal disturbance to the peat so as to ensure moisture is not squeezed from the sample (Landva *et al*. 1983). Samples of peat water from the location may also be taken to reproduce the *in situ* moisture content in the laboratory. Classification of the sampled soil is carried out in accordance with current practices (BSI 1996a; ASTM 2011) and as a minimum, moisture content, organic content, Atterberg limits and pH are determined, as well as density and strength tests on undisturbed samples.

Homogenisation:

The sampled soil is first homogenised by mixing so as to ensure the initial properties of the batch are the same throughout and any foreign or over-sized material is removed. Homogenisation is carried out for between 3 and 5 minutes but for peat soils may be less so as to ensure the fibre structure is not excessively broken up (Pousette *et al*. 1999;

EuroSoilStab 2002). Samples are taken at this stage to determine the initial moisture content of the unstabilised soil.

<u>Stabilisation:</u>

Following homogenisation, the batch of soil is stabilised using a particular binder type(s) and content(s). Based on the size of the batch, a mass of binder is weighed out in the correct proportions and mixed with the soil for a time of between 3 and 10 minutes, typically 5 minutes. Again, samples are taken to determine the moisture content of the soil-binder mixture. A number of stabilised batches will be created over a range of binder contents for each individual binder type being investigated.

<u>Mould Preparation:</u>

The soil-binder mixture is then compacted into cylindrical plastic or tin moulds in which they will cure. Moulds are typically 50 mm in diameter but larger diameter moulds (*e.g.,* 65 mm or 70 mm dia.) are used for peat soils or soils containing larger particles, and mould lengths are a minimum of twice the mould diameter. Moulds, of sufficient length to allow for two samples may also be used, as was carried out by Pousette *et al.* (1999) and Hebib & Farrell (2003) where 65 mm dia., 320 mm long moulds were used.

The compaction method varies depending on the type of soil and the protocols being adhered to, but preparation of all samples must occur within 30 minutes of stabilisation (Kitazume *et al*. 2009). The moulds are compacted in 20 mm to 30 mm layers using a tamping rod. For stabilised clays and silts, a static stress of 100 kPa may also be applied to further compact the sample. Before compaction of the subsequent layer, the compacted surface is scarified to ensure the layers bind with each other. Stabilised mixes with high workability or that are liquid in nature may be prepared by pouring the mixture into the mould, followed by tamping and rodding to remove any air bubbles.

<u>Curing:</u>

As previously mentioned, the most common curing times are 7, 28 and 91 days but other times of 1, 3, 14 and 56 days are also popular. Once prepared the samples are cured at a constant 20 °C in temperature-controlled storage units, or, if sealed with plastic wrap, in temperature-controlled water baths. Some Scandinavian protocols indicate the samples should be cured at 7 °C (Carlsten & Ekström 1996) or at 20 °C for the first seven days and at 7 °C thereafter (Larsson 2006). Stabilised peat samples are typically cured under water with an 18*kPa* loading applied (Pousette *et al*. 1999; Åhnberg *et al*. 2001; EuroSoilStab 2002). This approximately corresponds to the vertical stress imposed by 1 m of fill that is placed on stabilised peats in the field following mixing and the loading helps remove air entrained in the peat during mixing, resulting in improved strengths (Åhnberg *et al*. 2001).

Strength Testing:

Once the required curing period has elapsed, the stabilised samples are removed from their moulds, their densities determined, and are prepared for testing. UCS testing is the most common form of strength testing used in soil stabilisation due to its speed and cost effectiveness, and triaxial tests may also be carried out but are more time consuming. Testing is carried out at strain rates of between 0.5 %/min and 2 %/min (BSI 1994; Kitazume *et al*. 2009) and from the results, the sample UCS, stiffness and failure strain values may be determined. Finally, a portion of the sample is taken from the tested specimen to determine its stabilised moisture content.

A detailed procedure for performing a series of binder trials, compiled from current protocols, is presented in Section 3.3.

2.11.2 Research using Laboratory Stabilisation Trials

For research purposes, laboratory stabilisation trials have been carried out by many authors to investigate the effect on the stabilised properties of numerous variables including soil type (*e.g.,* Åhnberg, 2006; Hernandez-Martinez & Al-Tabbaa, 2009), binder content and binder type (*e.g.,* Jacobson, 2002; Axelsson *et al*. 2002), curing temperature (*e.g.,* Van Impe & Verástegui Flores, 2006; Marzano *et al*. 2008; Marzano *et al*. 2009), prestress loading (*e.g.,* Åhnberg *et al*. 2001; Åhnberg, 2007), laboratory preparation procedures (*e.g.,* Marzano *et al*. 2009; Åhnberg & Holm, 2009) and individual soil characteristics such as moisture content (*e.g.,* Marzano *et al*. 2009) and organic content (*e.g.,* Tremblay *et al*. 2002). Further details from compiled Japanese data may be found in Kitazume & Terashi (2013).

One particularly relevant piece of work for those carrying out stabilisation trials in clays is that of Marzano *et al.* (2009), where variations in density, strength and secant stiffness as a result of different compaction procedures, curing temperatures and sample preparation delays were investigated. Artificial kaolin-silica flour clay with moisture contents of 33%, 40% and 50% was stabilised with OPC. Samples were prepared using no compaction, static compaction and rodding (using an 8 mm dia. bar) compaction methods, curing temperatures were 10 °C, 20 °C and 40 °C and delays of between 0 and 60 minutes were applied before addition of the binder and mould preparation. The findings are as follows:

- The application of increasing compactive efforts improved the achieved stabilised properties with rodding techniques providing best results. For all compaction methods, samples at the highest moisture content were found to give similar results, while the influence of the compactive efforts became more prevalent with reducing w_i as greater densities were achieved.
- Similar trends were observed in the achieved strengths with strength increasing with both improved compaction and a reducing moisture content.
- Samples cured at various temperatures were all compacted using rodding methods and no effect of curing time or curing temperature was noted on the density. However, increased strengths were obtained at higher curing temperatures.
- Delays in the addition of the binder slurry to the soil and the preparation of the mixed soil into moulds were found not to affect the achieved stabilised properties. All samples were compacted using rodding techniques and cured at 20 °C.

Similar work was also carried out by Åhnberg & Holm (2009), where it was concluded for a gyttja that the delay between mixing and moulding should be a minimum so as to reduce the possibility of strength differences between the first and last moulds prepared. Tamping compaction methods were found to give less scatter in the results but it should be noted that the gyttja had a liquid limit and moisture content of 170% and 196%, respectively. Testing of peat samples cured at temperatures of 10 °C, 20 °C and 40 °C showed increased temperatures resulted in an increased rate of strength gain.

2.11.3 Laboratory to Field Strength Comparison

Due to a number of factors such as mixing homogeneity, variations in the soil profile, different organic contents, variations in the *in situ* water content at the time of mixing and differences in curing temperatures, the strengths achieved in the field may not reflect those achieved in laboratory binder trials. Even for a specific soil, different laboratories may return different strength results due to different interpretation of the various laboratory protocols, as has been shown by a number of authors (Edstam & Carlsten 1999; Edstam *et al.* 2004; Jacobson *et al.* 2005). Larsson (2003) provides a compilation of the ratio of field to laboratory strengths from published data (see Figure 2-28) where it can be seen the majority of laboratory trials overestimate the field strength, *i.e.,* the ratios of field to laboratory strengths, are generally less than unity, but a divide between Nordic and Japanese data can be seen. Hayashi and Nishikawa (1999) and Porbaha *et al.* (2000) (see Figure 2-29) both discuss a factor of between 0.5 and 0.2 (with an average of 0.33) as the ratio observed between field strengths and laboratory strengths in Japanese projects, although sample disturbance is believed to have caused an increase in this ratio for some of the data.

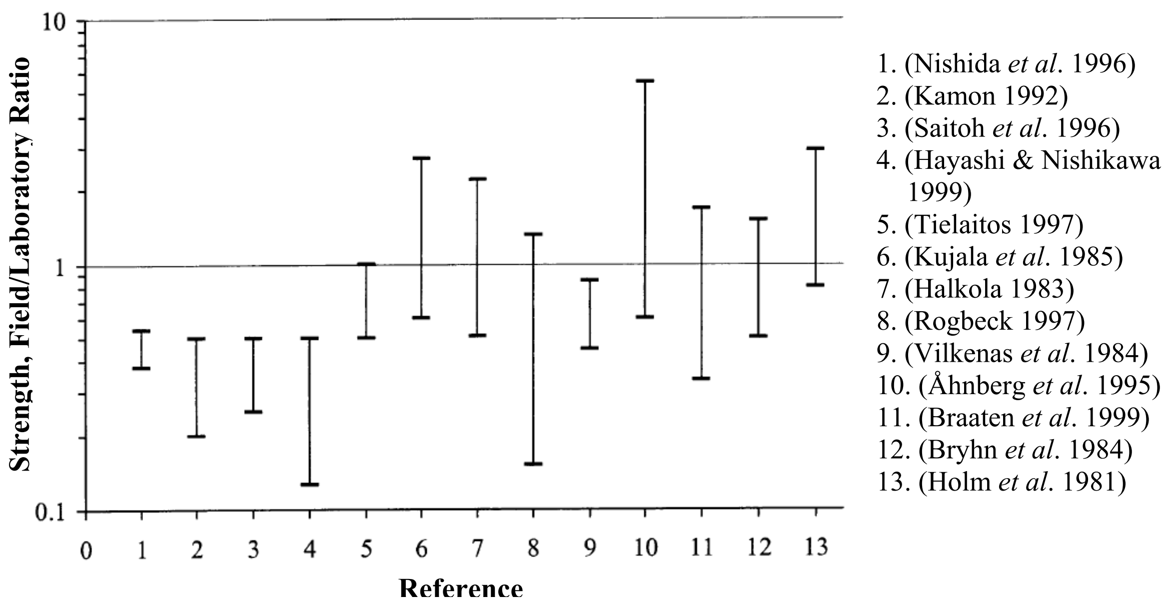

Figure 2-28: Compiled field to laboratory strength ratio, after Larsson (2003)

It is the belief of a number of authors (Babaski *et al.* 1996; Terashi 1997; Bruce *et al.* 1998) that current laboratory stabilisation procedures do not effectively replicate the mixing or curing conditions that occur in the field, and that laboratory trials can only be used to define an appropriate binder and estimate a suitable binder content for field stabilisation to be achieved. In the Section 2.12 some experiences in replicating *in situ* mixing in the laboratory are provided.

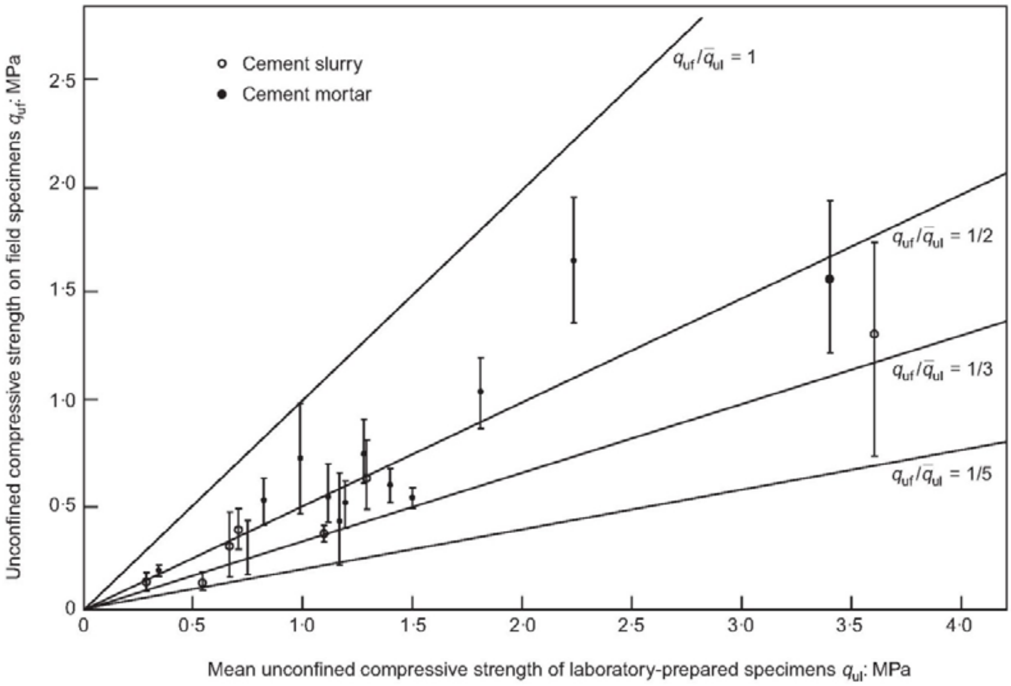

Figure 2-29: Compiled laboratory-field strength comparison, after Porbaha *et al.* (2000)

2.12 Laboratory Scale Column Production & Experiments

To the author's knowledge reduced-scale PORT and PIRT probing of laboratory stabilised soil-cement columns have never been attempted. However, a number of authors have constructed reduced-scale columns to investigate the variations in column construction using various mixing blade types, the effects on the surrounding soil due to the installed columns, the behaviour of laterally loaded columns and methods to better replicate field mixing conditions in the laboratory. This section provides a short description of the construction methods used to create the columns, the tests that were carried out and highlights some issues that occurred during the processes, which has helped define the procedures outlined in Chapter 3.

<u>Irish Laboratory Stabilised Columns:</u>

As part of a series of peat stabilisation experiments by Hebib & Farrell (2003), laboratory tests were carried out to better understand the behaviour of stabilised peats in the field. The large-scale tests were carried out in a 1.68 m dia. by 2.3 m high concrete chamber in which large undisturbed blocks of peat were placed to a height of 1.5 m. A 0.6 m dia., 1.5 m high void was created in the centre of the chamber by pressing a 0.6 m dia. pipe into the peat and while doing so, excavating out the peat from within the pipe. Peat stabilised using OPC at a binder content of 250 kg/m^3 *w*as used to create the column and a 0.5 m thick layer of stabilised peat, stabilised with OPC at a binder content of 200 kg/m^3, was used to fill the basin to a height of 2.0 m. A system of air bags was used to apply loading to the peat and pore pressure, settlement and *in situ* stresses were recorded. Following curing, CPTu, shear vane and UCS tests of recovered samples were carried out for back analysis of the data recorded during loading in a PLAXIS 2D finite element (FE) model.

<u>Swedish Reduced-Scale Stabilised Columns:</u>

In investigating the horizontal failure surface of stabilised columns, Larsson (1999) created 50 mm dia., 500 mm long dry soil mixed lime-cement (30%-70%) columns in consolidated kaolin in a 500 mm dia. by 600 mm high test chamber (see Figure 2-30). Two 12 mm dia. columns of dry cement were formed in the kaolin at the location of each column. A copper tube was used to displace the kaolin and as the tube was removed, the binder was compacted into the void created. Using a 50 mm dia. mixing tool with three pairs of inclined paddles, rotating at 320 rpm and retrieved at a rate of 2 m/min, the dry binder was mixed *in situ* with the kaolin.

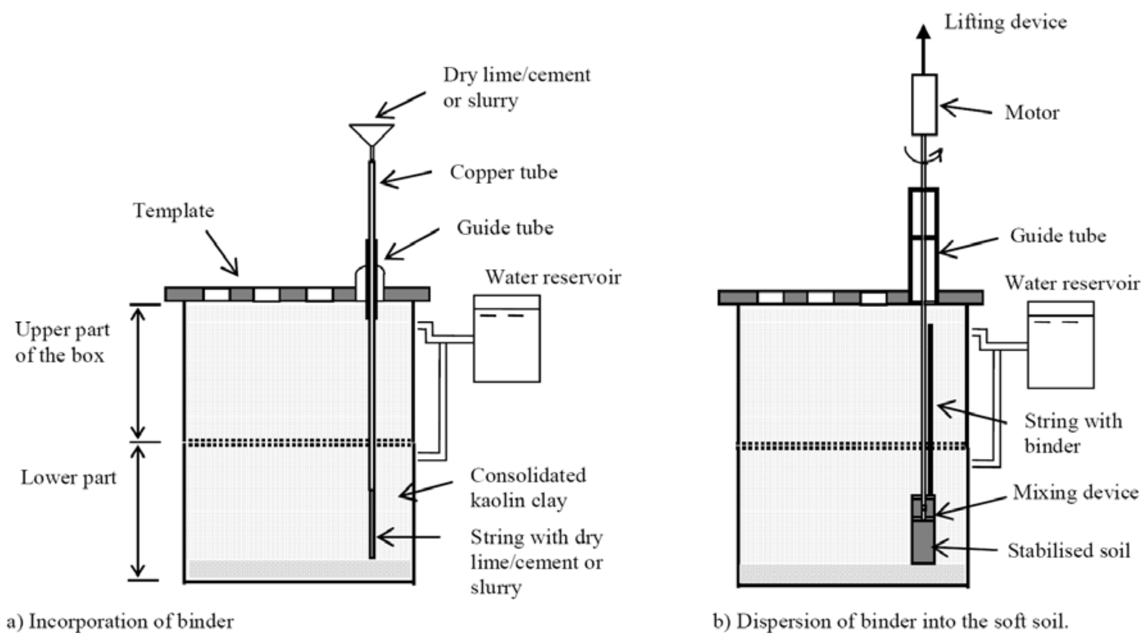

Figure 2-30: Setup devised and used by Larsson (1999) and later authors (Honkanen & Olofsson 2001; Kosche 2004) to created 50 mm dia. stabilised columns using a scale mixing tool

Following horizontal shearing, the chamber was dismantled and shear strength of the columns determined using a shear vane. Larsson (1999) concludes that it was possible to simulate the column installation procedure in the laboratory but due to oscillations of the mixing tool, the column diameter increased by 10% over the column's length. The lack of confining pressure at the top of the basin is thought to have hindered mixing and have impeded binder distribution in the column cross section. Finally, strength variations in the column are said to be due to differences in the moisture content of the kaolin and casting is suggested as a means to improve column uniformity. In a continuation of the work by Larsson (1999), similar methods were used by Honkanen & Olofsson (2001) to create over-lapping rows of reduced-scale stabilised kaolin columns for shear box testing.

Later work by Kosche (2004), investigating the transition zone and boundary layers around lime-cement columns used the above method, as well as two further methods of column construction, wet mixing and casting. Wet mixing was carried out in a similar manner to the dry mixing procedure. A single 20 mm dia. hole was created in the kaolin with a brass tube at the centre of the proposed column. The hole was filled with a lime-cement slurry and mixed with the previously-described mixing tool. To cast the columns, a 50 mm dia. tube was pressed into the kaolin and its contents removed. The lime/cement slurry was poured into the void and mixed with a small paddle mixer to prevent any air pockets. After curing periods of 7, 14, 30 and 90 days, transitional zones up to 30 mm into the unstabilised surrounding kaolin were noted. Within these zones, the strength was higher than that of the unstabilised material and this is reported to be due to migration of calcium ions from the stabilised kaolin. Moisture contents in the transitional zone surrounding columns after stabilisation were found to be unchanged from those of the moisture content of the surrounding kaolin.

<u>UK Reduced-Scale Stabilised Columns:</u>

Evans & Al-Tabbaa (1999) investigated the use of laboratory scale-column mixing as a method to better assess achievable wet soil mixed column properties in the field. One-tenth scale 60 mm and 90 mm dia. augers (see Figure 2-31a) were used to mix a contaminated scale soil model profile. In initial tests, poor mixing of the actual field samples was observed due the presence of large particles. Attempts to scale the soil's particle size resulted in a cohesive soil which adhered to the augers, thus only the granular fraction of the soil was scaled. Issues with delivery of the binder to the extremities of the mixing auger meant the grout used had to have a high flow consistency to prevent clogging of the delivery pipe. Scale columns (see Figure 2-31b) were found to be well mixed and gave similar consistency and uniformity to their equivalent field trials.

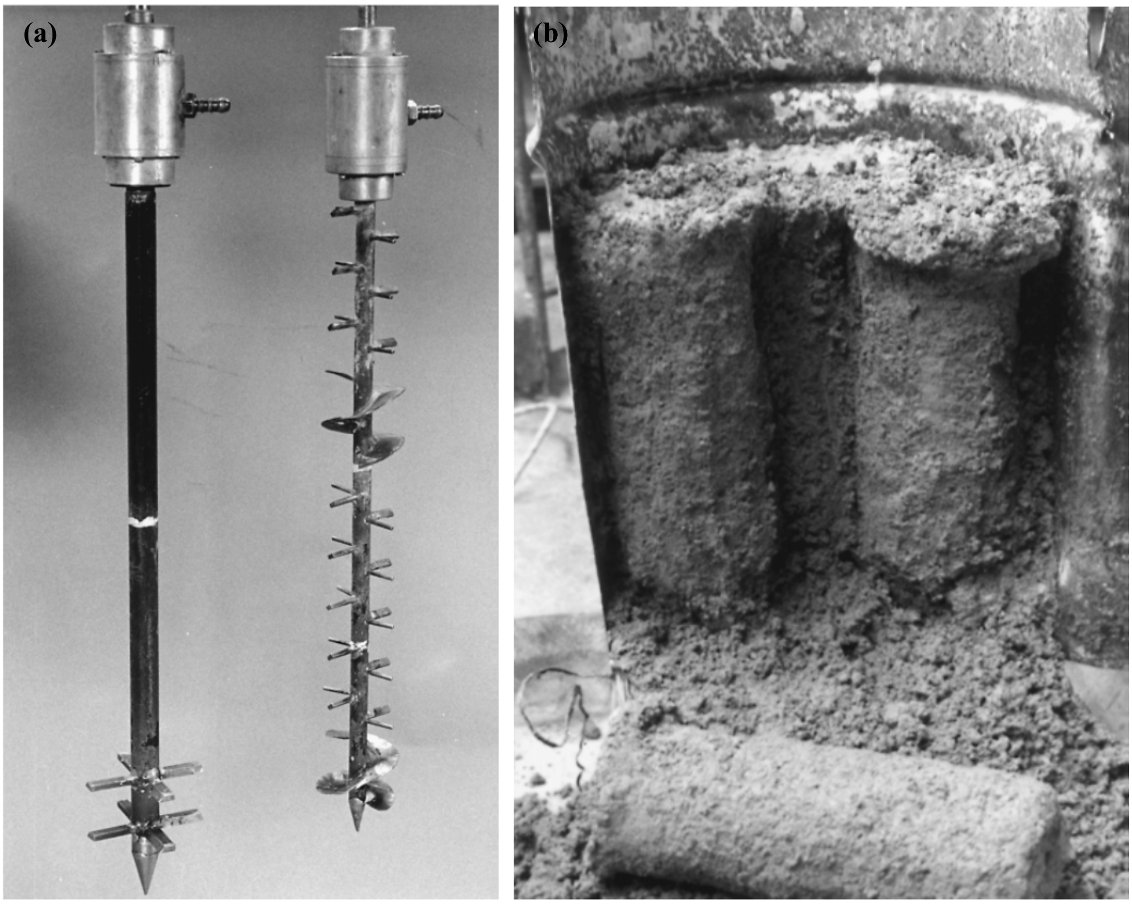

Figure 2-31: Laboratory column production using reduced-scale mixing methods: a) 90 mm and 60 mm dia. mixing augers & b) exposed grout columns, after Al-Tabbaa & Evans (1999)

Investigating the performance and microstructure of soil-MgO columns, Yi *et al.* (2013a) created carbonated soil-MgO columns in the laboratory using WSM methods and in a sand profile. MgO grout was delivered to the mixing auger, which consisted of four layers of mixing blades of a 100 mm dia. on a 20 mm dia. Kelly bar rotating at a speed of 50 rpm and auger penetration and withdrawal rates were 5.2 mm/sec. Following column production, a hole was noted in the centre of the column occurring as a result of the poorer mixing in the column centre.

Asian Reduced-Scale Stabilised Columns:

Investigating the achievable strengths using different mixing tool shapes, tool rotation speeds and penetration/withdrawal rates, Dong *et al.* (1996) constructed a laboratory-scale mixing apparatus (see Figure 2-32) to replicate *in situ* mixing conditions. The apparatus was capable of creating 400 mm dia., 1 m high columns and was used to stabilise a clay-sand soil using rapid hardening cement injected in slurry form through the mixing tool. The stabilised strength was found to increase with the blade rotation number *i.e.,* the number of blade rotations per metre.

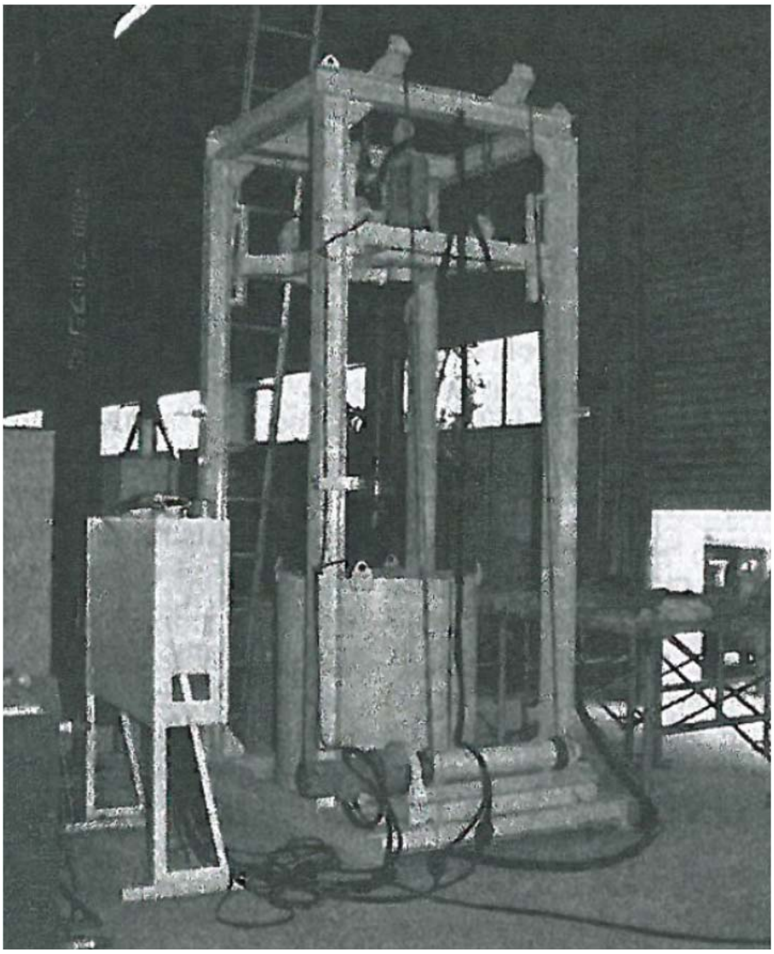

Figure 2-32: Laboratory mixing apparatus constructed by Dong *et al.* (1996)

Kitazume *et al.* (2000) describes centrifuge model tests on clay-cement columns, investigating failure patterns under vertical and horizontal loadings, where the columns were formed in 20 mm dia., 250 mm long pipes. After curing the columns were placed in rows in a consolidated kaolin profile and a kaolin slurry was injected around the columns to fill any voids. Shen *et al.* (2003) details the use of a laboratory-scale mixing device to produce 250*mm* long columns with diameters of 50 mm, 100 mm and 150 mm and later work by Horpibulsuk *et al.* (2004) used the same mixing device to produce 100 mm dia., 600 mm long columns. Mixing speed, penetration rate and binder injection pressure were fully controlled and in both cases the cement binder was injected as a cement slurry.

Dynamic Penetrating Anchors:

Although not carried out on stabilised columns, investigations of the embedment depth and holding capacity of dynamic penetrating anchors (DPAs) have been carried out using reduced-scale dynamic penetrating anchors. These experiments were carried out in centrifuges, so that *in situ* stresses could be replicated (O'Loughlin *et al*. 2004; Richardson *et al*. 2009) and the shape of the DPA bear similarities to the shape of the PIRT and PORT penetrometer (see Section 2.4.2). The reduced-scale anchors were installed into a consolidated kaolin bed at 200 g in a centrifuge and the holding capacity determined by pull-out of the anchors at a rate of 0.3 mm/sec. The strength of the kaolin was determined using a 5 mm dia., 20 mm wide T-Bar penetrometer and the results were used to gain a better understanding of the prediction of the embedment depth and holding capacity of DPAs.

The actual reduced-scale anchors, 75 mm long and 24 mm wide, were manufactured from brass and aluminium (see Figure 2-33) with a 0.45 mm dia. nylon coated stainless steel rope to represent the mooring chain and provide guidance on tolerances that may be achieved in manufacturing reduced-scale penetrometers and suitable materials.

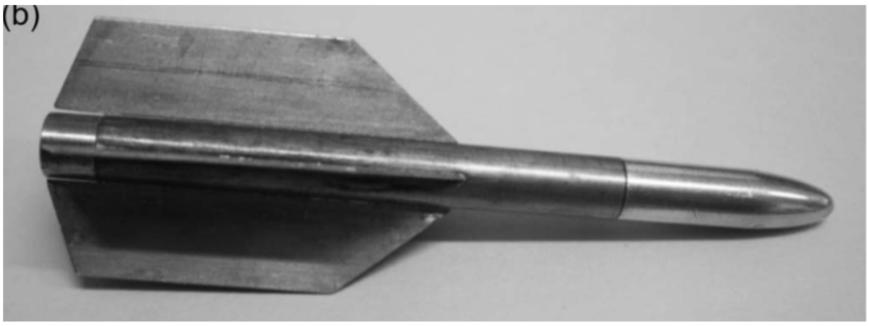

Figure 2-33: 1:200 reduced-scale dynamic penetrating anchor, after Richardson *et al.* (2009)

Laboratory Curing Temperature Monitoring:

Van Impe & Verástegui Flores (2006) describe an experiment to monitor the temperature in a stabilised mass during curing. A dredged sediment with a moisture content of 115% and an organic content of 6% was stabilised with blast furnace cement at a binder content of 275 kg/m^3. Prior to stabilisation the soil was stored at 10 °C. The mixed material was poured into a 0.8 m high, 0.6 m dia. basin and cured at a constant temperature of 10 °C and temperature in the stabilised mass was continuously monitored by eight temperature transducers. The results show a sudden increase in temperature after mixing, reaching a maximum of 25 °C after 3 days and then decreasing to 11.7 °C at 56 days. Samples taken from the stabilised mass were found to be twice as strong as samples cured as per laboratory procedures and is reported to be due to the greater temperatures maintained in the stabilised mass due to its large size compared to the smaller 115 mm high, 57 mm dia. laboratory samples. In an experiment to ascertain the effects of curing temperature on stabilised samples, samples cured at 20 °C were found to have strengths 1.7 to 2.0 times that of their 10 °C cured counterparts.

2.13 Literature Review - Concluding Remarks

DSM is a popular form of *in situ* ground improvement, originally developed in Nordic countries and Japan and now practiced worldwide, in which dry cementitious and pozzolanic binders are used to improve the strength and deformation characteristics of soft soils. Stabilised columns may be formed using DDSM techniques or large shallow areas, may be stabilised using mass stabilisation techniques.

Although site-specific laboratory binder trials can help estimate achievable stabilised strengths, laboratory strengths are typically higher than field strengths. This, along with inherent *in situ* variability of the soil characteristics, curing temperature and mixing differences, mean estimates of field strength must be verified to ensure that the minimum design strength has been achieved.

Two methods of determining the *in situ* strength of stabilised columns in the field are the Push-In Resistance Test (PIRT), and to a lesser extent, the Pull-Out Resistance Test (PORT). In both of these methods, the stabilised column is probed with a winged penetrometer and the force required to do so is related to column strength using a bearing capacity factor, N; the use of winged penetrometers allows for testing of a chord in the column cross-section, thus including for any strength variations over the column cross-section. Current guidance documents suggest the use of an N value of 10 but from the compiled values in Table 2-5 it is clear that N values can range from 8 up to 20. Overall, it is difficult learn from former experience as column strengths were inferred in different ways (*e.g.,* pressuremeter, shear vane and UCS testing of cored samples), different soil characteristics and different binders were used. Thus laboratory investigations, in which the significant characteristics and variables of soil stabilisation can be controlled, are required.

In this thesis, it is proposed to carry out, for the first time, a series of laboratory-scale tests, investigating the relationship between the probing force and the strength of a reduced-scale stabilised column for both PORT and PIRT methods. By varying the binder content and the curing time, a range of strengths may be achieved, thus allowing for an investigation of the influence of column strength on the relationship. Laboratory stabilisation trials will be used to assess the suitability of both a peat and soft clay/silt soil for the test series, and from the results of the trials a suitable binder type and content will be chosen.

The research experiences reviewed in Section 2.12 show the significant efforts required in developing the equipment needed to replicate *in situ* mixing in the laboratory. Although reduced-scale column mixing can reproduce *in situ* mixing conditions, clogging issues require injection of the binder in slurry form (therefore the process being WSM rather than DSM), and issues with mixing uniformity over the column cross-section and with depth, imply better control may be applied to columns formed using casting techniques. The methods used to construct reduced-scale DSM columns in this thesis are set out in Chapter 3.

CHAPTER 3: EXPERIMENTAL DESIGN AND TESTING PROCEDURES

3.1 Introduction

In this chapter the standard methods and procedures used to classify and test the parent, mixed and stabilised soils are detailed. Generic methods for the carrying out of laboratory stabilisation trials using dry mix methods are set out for both clay/silt and peat soil types and will be used in subsequent chapters. The design of a series of reduced-scale PORT and PIRT experiments is presented, including the choice of the experiment scale, the soil type and the binder to be used. A PLAXIS 2D FE model is used to define the dimensions of the test basin appropriate to the chosen reduced-scale column size. Detailed procedures are defined for the construction and testing of reduced-scale stabilised soil-cement columns in the laboratory for the following purposes:

(i) To determine the relationship between column strength and probing force, *i.e.,* the N value, during pull-out of a PORT penetrometer.

(ii) To assess the contribution of friction between the PORT pull-out wire and the column on the PORT penetrometer pull-out force.

(iii) To determine the relationship between column strength and probing force, *i.e.,* the N value, during push-in of a PIRT penetrometer

(iv) To assess the contribution of friction between the sounding bars and the column on the PIRT penetrometer push-in force.

Finally, methods to monitor the temperature of the stabilised mould samples and columns during curing are presented, as is a context for addressing variability in the overall data.

3.2 Parent & Stabilised Soil Classification

3.2.1 *Sleech* Sampling & Classification

Classification of the organic clayey-silt, hereafter referred to as *sleech* (Crooks & Graham 1976), used in the stabilisation trials and the reduced-scale stabilised columns was carried out in accordance with Eurocode 7 (2007) and British Standard procedures.

<u>Onsite Soil Sampling (Kinnegar *Sleech*):</u>

The *sleech* used in the testing programme was sourced from a site adjacent to the Kinnegar Waste Water Treatment Plant, 8*km* north-east of Belfast City near the shoreline of Belfast Lough in Co. Down. This location was chosen as the site had previously been extensively classified by a number of authors (Crooks & Graham 1976; Bell 1977; McCabe 2002; Lehane *et al*. 2003) and classification results of the sampled *sleech* are given in Section 4.3. The overburden layer of fill was removed to expose the *sleech*. Approximately 5 m^3 of s*leech* was excavated from depths of 3 m to 4.5 m, placed in 1 m^3 intermediate bulk containers (IBC) and sealed for transport to NUI Galway. Onsite samples were taken and sealed in plastic bags for moisture and organic content determination. From undisturbed blocks of excavated *sleech*, samples were cut with a knife and sealed in air tight containers for density and strength tests. On completion of the sampling, the site was reinstated to its original condition.

Moisture Content:

All moisture content tests were carried out in accordance with BS 1377-2: 1990, Methods for soils for civil engineering purposes - part 2: classification tests (BSI 1996a). Two samples, a minimum of 20 g each, were taken to verify the moisture content of the soil and were dried in an oven at 105 °C for a minimum of 12 hours after which their masses were recorded. The samples were returned to the oven for 4 more hours and re-weighed to ensure all the moisture had been dried off. This method was used for the determination of raw, mixed (soil-binder mixture immediately after mixing) and stabilised moisture contents.

Organic Content:

All organic content classification tests were carried out in accordance with BS 1377-3: 1990, Methods for soils for civil engineering purposes - part 3: chemical and electro-chemical tests (BSI 1996b) using the loss on ignition (LOI) method by burning the samples in a ceramic crucible at 440 °C in a muffled furnace. Samples used to determine the organic content for the *sleech* to be used for the stabilised mixes of the PIRT column, cone penetrometer and wire friction tests had been used beforehand to determine its moisture content. As such, the samples were dried at 105 °C instead of the prescribed 50 °C before crushing and burning. However, tests on separate *sleech* samples dried at both 50 °C and 105 °C before LOI indicated the use of moisture content samples for organic content tests with the *sleech* had no effect on the result.

Density:

All density classification tests were carried out in accordance with BS 1377-2: 1990, Methods for soils for civil engineering purposes - part 2: classification tests (BSI 1996a) using the linear measurement methods. *In situ sleech* densities were determined from 65 mm dia. cores taken from large excavated blocks of undisturbed *sleech* at the time of sampling in Belfast. The density of the raw *sleech* surrounding the column during curing and testing was determined using 50 mm dia. cores, taken at three locations across a single depth.

Stabilised mould densities were determined by trimming the ends of the sample with a sharp knife to be flat and perpendicular to its sides, and recording its dimensions and mass. Stabilised column sample densities were determined by trimming samples to a diameter of 50 mm in a Wykeham Farrance soil trimmer with a sharp knife and recording its dimensions and mass.

Liquid Limit and Plastic Limit:

All Liquid Limit (LL) tests (using the fall-cone penetrometer method) and all Plastic Limit (PL) tests were carried out in accordance with BS 1377-2: 1990, Methods for soils for civil engineering purposes - part 2: classification tests (BSI 1996a).

Specific Gravity:

All specific gravity tests were carried out in accordance with BS 1377-2: 1990, Methods for soils for civil engineering purposes - part 2: classification tests (BSI 1996a) using the gas jar method.

Strength (Unstabilised):

Undisturbed *sleech* strengths were estimated using a Geonor Swedish fall cone, and the procedures set out by the manufacturer, on undisturbed samples cut from excavated blocks of *sleech* on site. To determine the remoulded strength, the sample was remoulded by hand, pressed into a stainless steel cup and the fall cone test repeated. The strength of the *sleech* surrounding the columns during testing was determined using a Pilcon Engineering shear vane using a 49.5 mm long, 33 mm wide vane and the procedures set out by the manufacturer for its use. The vane was inserted 50 mm to 60 mm into the soil and rotated at a constant speed of 2 revolutions per minute. Methods for determining the

Unconfined Compression Strength (UCS) testing of stabilised mould and column samples are described in Section 3.4. The shear vane was deemed unacceptable for the strength testing of stabilised soil as the insertion of the vane caused cracking of the stabilised soil.

pH:

All pH tests were carried out in accordance with BS 1377-3: 1990, Methods for soils for civil engineering purposes - part 3: chemical and electro chemical tests (BSI 1996b).

3.2.2 Peat Sampling & Classification

Peat classification tests were carried out in accordance with a series of peat specific classification tests defined by the ASTM (ASTM 2007c). The specific guidance of Landva (1983) and Hobbs (1986) on the sampling and determination of the index properties of peat was also used in light of the highly variable nature of this soil type.

Onsite Soil Sampling (Ballynahown Peat):

The Ballynahown peat was sampled from an open cut at Ballynahown near Athlone in Co. Westmeath. The exposed face of the peat was trimmed back and the peat was cut from the freshly exposed face before being placed in plastic bags for transport to NUI Galway. Individual samples to determine *in situ* density were cut with a sharp blade and stored in plastic containers.

Moisture Content:

Peat moisture content tests were carried out in accordance with ASTM D2974-07a, Standard test method for moisture, ash and organic matter of peat and other organic soils (ASTM 2007b). On the basis of the work by O'Kelly (2005), on the determination of peat moisture contents, raw, mixed and stabilised peat samples were dried at a lower temperature of 80 °C to reduce oxidation and charring of the organic matter present.

Organic Content:

Peat organic contents were determined in accordance with Method C of ASTM D2974-07a, Standard test method for moisture, ash and organic matter of peat and other organic soils (ASTM 2007b) using loss on ignition methods at a temperature of 440 °C.

Density:

Peat densities were determined in accordance with ASTM D4531-86, Standard test methods for bulk density of peat and peat products (ASTM 2008) using linear measurement methods.

Degree of Humification:

The degree of humification of the peat was estimated primarily using the guidance provided by Hobbs (1986), as well as ASTM D5715-00, Standard method for estimating the degree of humification of peat and other organic soils (ASTM 2006).

Specific Gravity:

All specific gravity tests were carried out in accordance with BS 1377-2: 1990, Methods for soils for civil engineering purposes - part 2: classification tests (BSI 1996a) using the gas jar method.

pH:

All pH tests were carried out in accordance with ASTM D2976-71, Standard test method for pH of peat materials (ASTM 2004).

3.3 Laboratory Stabilisation Methods

Two soils were initially proposed for the reduced-scale columns, a peat from Ballynahown in Co. Westmeath and a clayey-silt (*sleech*) from Kinnegar in Co. Down. To assess their suitability and determine an appropriate binder type and content to produce reduced-scale columns (with strengths up to 600 kPa), a series of binder trials were undertaken. Laboratory stabilisation was carried using procedures derived from EuroSoilStab (2002) and Carlsten & Ekström (1996). Mould samples were created from the stabilised soil and allowed to cure for set curing periods (see subsequent results chapters for actual curing times used) before UCS testing to determine the strength achieved. The terms *column stabilisation* and *mass stabilisation,* given in EuroSoilStab (2002), are used to refer to the procedures for the stabilisation of an organic clay and a peat, respectively. Further guidance from other current literature (Pousette *et al*. 1999; Jacobson 2002; Jacobson *et al*. 2003; Åhnberg 2006; Marzano *et al*. 2009; Åhnberg & Holm 2009) was also considered.

3.3.1 *Column Stabilisation* Method (Organic Clay Stabilisation)

The *column stabilisation* method refers to the preparation of laboratory samples where the parent material is typically a soft cohesive clay or silt soil, and is primarily associated with deep dry soil mixing or column stabilisation applications.

Raw Soil Homogenisation:

1) A quantity of raw soil, large enough to fill the number of mould samples required, was placed in a large pan mixer (see Figure 3-1). Any stones, shells or foreign material were removed from the soil and the mass of raw soil was determined.
2) The soil was mixed for approximately 2 minutes until a visually homogeneous mass was obtained.
3) During mixing, any material that stuck to the side wall of the mixer was returned to the centre of the mixer so as to ensure uniform mixing.
4) Two samples were taken to determine the moisture content of the raw soil.

Binder Addition and Mixing:

1) Using Equation 3-1, the *in situ* bulk density of the soil and the desired binder content, the mass of binder to be added to the homogenised soil was determined and weighed out.

$$\text{Binder Required (kg)} = \frac{\text{Mass of Raw Soil (kg) x Binder Content (kg/m}^3\text{)}}{\text{In Situ Raw Soil Bulk Density (kg/m}^3\text{)}} \qquad 3\text{-}1$$

2) Where two or more binders were to be used, the binders were weighed out in accordance with the chosen proportions and mixed together by hand.
3) The binder was added to the raw soil in two parts and mixed to ensure uniform distribution throughout. During mixing, any material that stuck to the sides or the corners of the mixer was returned to the centre of the mixer.
4) The soil and binder was mixed until a visually homogeneous mixture was obtained (typically mixing was 3-5 minutes) and the mixing duration noted.
5) Two samples were taken to determine the moisture content of the mixed soil.

Figure 3-1: NUIG 27 l soil pan mixer

<u>Sample Compaction:</u>

1) All samples were compacted into the moulds in which they cured within thirty minutes of mixing.
2) The moulds, 65 mm dia. by 320 mm long, having a slit running lengthways to reduce disturbance when removing the samples at the test time, were bound closed by adhesive tape (see Figure 3-2).
3) 30*mm* of mixed soil was placed in the bottom of the mould and prodded and pressed with the bar to remove any large air pockets from the mixture.
4) The soil was compacted into the mould by applying thirty tamps per layer using a 62 mm dia. tamping bar and a pressure of 100 kPa for six seconds, applied by placing 30 kg on a 62 mm dia. area (see Figure 3-3).
5) The top of the compacted layer was scarified to allow it to bind with the next layer and prevent layering in the final compacted sample.
6) An additional 30 mm of soil was added to the mould and the compaction and filling process repeated until the mix just exceeded the top of the mould rim.

7) The mass of the sample was recorded and the sample sealed with industrial plastic wrap to prevent moisture entering or exiting the sample during curing.

Figure 3-2: 65 mm dia. by 320 mm long moulds used for *sleech* and peat stabilisation trials

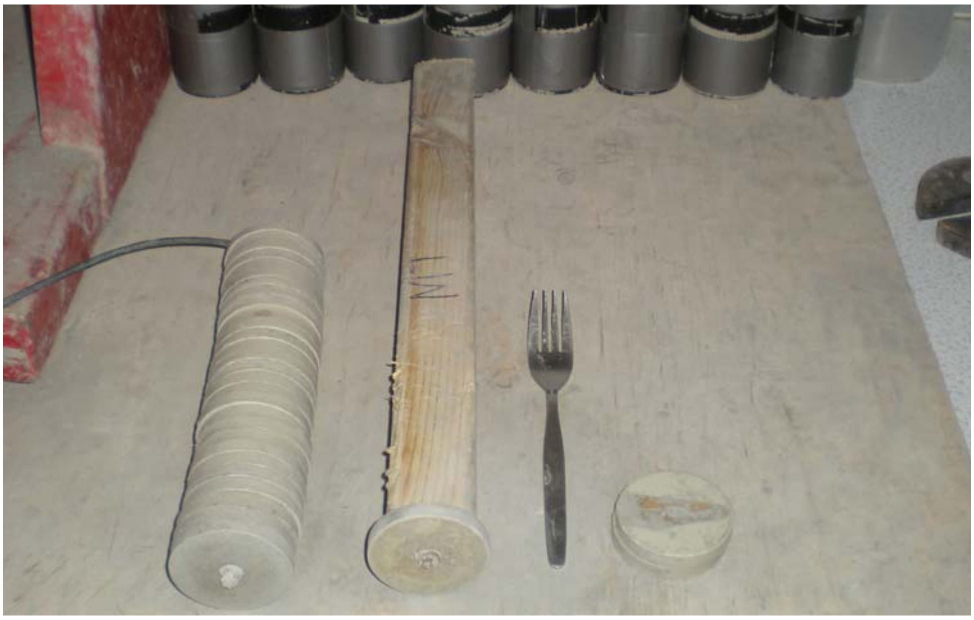

Figure 3-3: Tools used during mould compaction

<u>Sample Storage:</u>

All samples were stored at a constant curing temperature of 20 °C in a water bath. A circulation pump ensured that all samples cured at a uniform temperature.

Sample Preparation for Strength Testing:

1) At the designated test time (see results chapters for individual times), the sample was removed from its plastic wrap and using the end of the mould as a guide, any extruding material was trimmed off, giving a flat surface perpendicular to the sample sides.
2) The adhesive tape bindings were cut and the sample removed from the mould with minimal disturbance.
3) Using a fine-blade hacksaw and sharp knife the sample was cut to the required length and the ends were ensured to be flat and perpendicular. Any small voids or holes in the ends were filled with cut material so as to ensure a flat surface, as per standard practice.
4) The mass of the sample and the sample height (average of three measurements) were recorded so that the bulk density of the sample could be determined.

Sample Strength Testing:

The procedures for strength testing of the stabilised soil samples are detailed separately in Section 3.4.

3.3.2 *Mass Stabilisation* Method (Peat Stabilisation)

The *mass stabilisation* (MS) method refers to the preparation of laboratory samples where typically the parent material is a peat soil or sludge, and is principally used for stabilisation of large shallow areas of peat. The primary difference between MS and column stabilisation laboratory methods is the application of an 18 kPa pre-stress during curing in MS to compress the freshly stabilised mass and remove air entrained during mixing.

Raw Peat Homogenisation:

1) A quantity of raw peat, large enough to fill the number of mould samples required, was placed in a large mixer (see Figure 3-1). Any large roots, coarse fibres or foreign materials were removed from the peat and the mass of raw peat recorded.
2) The peat sample was mixed until visually homogeneous. The mixing of fibrous peats was limited to less than 5 minutes to prevent excessive breakup of the fibre structure (Pousette *et al*. 1999).

3) During mixing, any material that stuck to the side wall of the mixer was returned to the centre of the mixer.
4) Two samples of the raw peat were taken to determine its raw moisture content.

Binder Addition and Mixing:

1) Using the *in situ* bulk density of the peat, the desired binder content and Equation 3-2, the mass of binder to be added to the homogenised soil was determined and weighed out.

$$\text{Binder Required (kg)} = \frac{\text{Mass of Raw Peat (kg) x Binder Content (kg/m}^3)}{\text{In Situ Raw Peat Bulk Density (kg/m}^3)} \qquad \text{3-2}$$

2) Where two or more binders were to be used, the binders were weighed out in accordance with the chosen proportions and mixed together by hand.
3) The binder was added to the raw peat in two parts and mixed to ensure uniform distribution throughout. During mixing, any material that stuck to the side or the corners of the mixer was returned to the centre of the mixing bowl.
4) The soil and binder were mixed until a visually homogeneous mix was obtained (typically mixing was 3-5 minutes) and the mixing time noted.
5) Two samples of the mixed peat were taken to determine its moisture content.

Sample Compaction:

1) All samples were compacted into the moulds in which they cured within thirty minutes of mixing.
2) The moulds, 65 mm dia. and 320 mm long, having a vertical slit running lengthways to reduce disturbance when removing the samples at the test time, were bound closed by adhesive tape.
3) 30 mm of mixed peat was placed in the bottom of the mould and prodded with a bar to ensure that no voids occurred in the compacted mixture.
4) Using a 62 mm dia. tamping bar the mix was further compacted into the mould by applying thirty tamps to the layer.
5) The top of the compacted layer was scarified to allow it bind with the next layer and prevent layering in the final compacted sample.

6) An additional 30 mm of stabilised peat was added into the mould and the compaction and filling process repeated until the mix just exceeded the top of the mould.
7) Any material exceeding the top of the mould was trimmed back with a sharp knife.
8) The mass of the sample was recorded to determine the compacted fresh density of the mixture for compaction quality assessment.

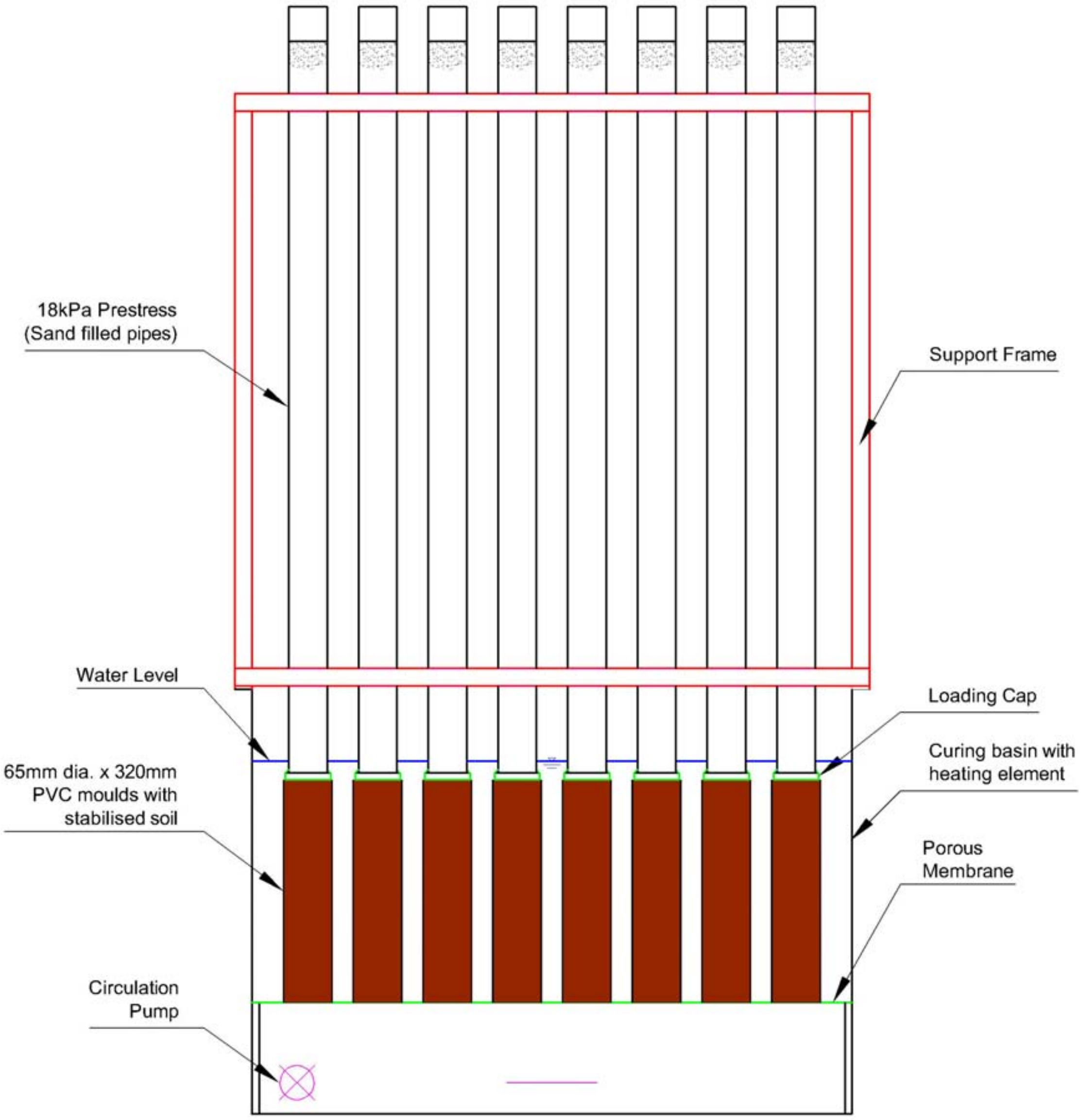

Figure 3-4: Mass stabilisation (peat) sample curing basin cross-section

Sample Storage:

1) The sample was placed vertically on the porous membrane in the curing basin (see Figure 3-4 and Figure 3-5).

2) An 18 kPa pre-stress was applied to the sample using a 5.7 *kg*, 1.2 m long plastic sand-filled pipe with a 62 mm dia. plastic loading cap immediately following compaction of each individual sample.
3) The samples were cured at 20 °C with access to water at both ends of the sample.
4) A circulation pump ensured all samples cured at a uniform temperature and the water level was maintained at 50 mm above the top of the samples during curing.

Figure 3-5: Mass stabilisation (peat) sample curing basin

Sample Preparation for Strength Testing:

1) At the designated test time (see results chapters for individual times), the sample was removed from the curing basin and the compression and mass of the sample were recorded for quality purposes.
2) The sample was removed from the mould with minimal disturbance by cutting the adhesive tape and opening the mould.
3) Using a fine-blade hacksaw the sample was cut to the required length and the ends trimmed with a sharp knife to ensure they were flat and perpendicular to the sides.
5) Any voids or holes on the ends were filled with finely cut material to ensure a flat surface, as per standard practice.

4) The sample height was recorded, taking the average at three locations, as was the mass of the sample to determine the bulk density of the stabilised sample.

3.4 Unconfined Compression Strength Testing

Unconfined compression strength (UCS) tests were carried out at a rate of 1 mm/min and at a sample length-to-diameter ratio (L/D) of 2:1, in accordance with BS 1377-5: 1990, Methods of test for soils for civil engineering purposes – part 7: shear strength tests (total stress) (1994).

3.4.1 Wykeham Farrance Tristar

Unconfined compression strength tests for the Ballynahown peat and Kinnegar *sleech* binder trials were carried out using a Wykeham Farrance Tristar 5,000 kg stepless compression testing machine (see Figure 3-6) using either a 5 kN (No. 13160) proving ring or a larger 50 kN (No. 11868) proving ring (used where high strengths were anticipated) and running at a rate of 1 mm/min. The tests were performed as follows:

1) The prepared sample's mass and average length was recorded along with details of the sample on a recording sheet similar to that of Form 7f of BS 1377-7.
2) The sample was placed in the compression machine and the platens lowered until they made contact with the specimen.
3) The initial reading on the proving rings dial gauge was recorded.
4) The machine was started, raising the lower platen at a rate of 1 mm/min and simultaneously a stop watch was started.
5) Proving ring dial gauge readings were recorded every 15 seconds.
6) The sample was compressed until the maximum force had been reached and the force had reduced to approximately two thirds of its maximum. If failure occurred between reading intervals the time at failure and gauge reading were noted.
7) If a clear failure of the specimen did not occur, the test was run for a maximum of 15 minutes.
8) The sample was removed from the machine and a sample was taken from the centre of the strength specimen to determine its stabilised moisture content.

Figure 3-6: Wykeham Farrance Tristar compression machine with a 65 mm dia. stabilised *sleech* sample

3.4.2 IPC Global Fully Automated Cyclic Triaxial (FACT)

All strength tests carried out for the PORT, PIRT, PORT wire and PIRT cone only penetrometer experiments were carried with an IPC Global Fully Automated Cyclic Triaxial (FACT) machine using its stress-strain function. All samples were tested at a rate of 1 mm/min and the data were digitally recorded at a rate of seventeen samples per second. The tests were carried out in the following manner:

1) Details of the sample were input to the FACT UCS template and included test type, mixing and testing dates, sample reference, average sample height (n = 3), sample diameter, sample mass, binder type and binder content.
2) The prepared sample was placed in the FACT on clean platens.
3) The platens were lowered until they just made contact with the specimen and the load cell was zeroed.

4) The sample was compressed at a rate of 1 mm/min until the maximum force was reached and the force had reduced to approximately two thirds of its maximum. If a clear failure of the specimen did not occur, the test was run for a maximum of fifteen minutes.
5) The sample was removed from the machine and a sample taken from the centre of the strength specimen to determine its stabilised moisture content.

Figure 3-7: Fully Automated Cyclic Triaxial machine with a 65 mm dia. stabilised *sleech* sample during UCS testing

3.4.3 Unconfined Compression Strength and Stiffness Calculation:

Using the running time, platen displacement and compressive force, the unconfined compression strength (q) was determined in accordance with BS 1377-5: 1990, Methods of test for soils for civil engineering purposes – part 7: shear strength tests (total stress) (BSI 1994) in the following manner:

1) The strain (ε) was calculated at each recorded interval using Equation 3-3 and the platen displacement, where ΔL and L_0 are the change in length and original length respectively. Note: for tests using a proofing ring, the compression of the proofing ring must also be taken into account to calculate the compression of the sample at each interval.

$$\varepsilon = \frac{\Delta L}{L_0} \tag{3-3}$$

2) The area of the sample adjusted for deformation (A_c) was calculated using Equation 3-4:

$$A_C = \frac{A_0}{1-\varepsilon} \tag{3-4}$$

3) Where UCS tests were carried out in the Wykeham Farrance Tristar machine using a proving ring, the recorded readings for the compression of the proving ring were converted to forces using its calibration curve. For tests carried out in the FACT, force readings were provided in the data sheet generated for each test.
4) The stress (σ_1) at each recorded interval was determined from the recorded compression force (P), A_c and Equation 3-5:

$$\sigma_1 = P/A_C \tag{3-5}$$

5) The unconfined compression strength (q) was taken to be the maximum stress experienced by the sample during compression.
6) The secant stiffness (E_{50}) was calculated as the slope of the stress-strain data at 50% of the UCS after accounting for any bedding errors as per EuroSoilStab (2002) procedures.

Note, as samples obtained from the reduced-scale columns were prepared by hand trimming with a knife, the sample L/D ratio may not have been 2:1. The effect of different L/D sample ratios in concrete and soil-cement strength tests has been addressed by a number of guidance documents and authors:

- ASTM C39 (2012) recommends that the L/D ratio be between 1.9 and 2.1 for concrete cylindrical samples and that strengths achieved from samples with an L/D below 1.75 require adjustment. Factors are suggested appropriate to samples with strengths between 14 MPa and 42 MPa and it is stated that larger corrections may be required for samples with strengths greater than 42 MPa.
- ASTM D1633 (2007a) provides details on the compressive strength testing of moulded soil-cement cylinders and to convert strengths from L/D ratios of 2.0 to L/D ratios of 1.15, a multiplication factor of 1.1 is applied.

- Wilson (2013) investigated the effect of varying L/D ratios on soil-cement cylinders in a series of strength tests on 71 mm dia. soil-cement cylinders with L/D ratios varying from 1.0 to 2.0 in 0.25 intervals. Tests were carried out on two soils at cement contents of 5%, 6% and 7%, achieving UCS values up to 4 MPa after seven day curing periods. Application of the ASTM C39 correction factors to the varied L/D samples was found to underestimate the strength of the L/D = 2 samples and it was concluded that no adjustment was required to be made to the strength of samples with an L/D less than 2.0.

It was concluded that at the low strengths expected in the forthcoming column series (*i.e.,* less than 700 kPa), there was no need to correct the effects of different L/D ratios but an assessment would be carried out, the results of which are presented later in Section 7.6.3.

3.5 PORT and PIRT Experimental Design

In this section, details of the design of the reduced-scale PORT and PIRT experiments are presented, and include:

- The choice of soil type and binder to be used for the reduced-scale columns, along with the duration of curing allowed before testing.
- A method to construct the columns, based on the previously reviewed literature on laboratory constructed columns (see Section 2.12).
- The choice of scale based on a number of factors such as time requirements and quality control during construction.
- Design and fabrication of the reduced-scale penetrometer is discussed.
- Details are presented of a PLAXIS 2D FE model used to define an appropriate size of basin in which the stabilised columns are constructed, cured and tested.

3.5.1 Test Programme

The aforementioned Kinnegar *sleech* and a peat from Ballynahown, Co. Westmeath, were considered as potential parent soils for the tests with stabilisation trials carried out on both to ascertain achievable stabilisation results. During the stabilisation trials and the subsequent *sleech* column test series, a number of issues were envisaged regarding column probing tests in peat, in particular the time requirements for construction and testing, the difficulty in replicating *in situ* conditions for peat, the effect of fibres in a reduced-scale penetrometer test and the lack of resistance provided by the raw surrounding peat during a PORT. Therefore, the PORT and PIRT column series were based on the use of *sleech* only.

Of the binders used in stabilisation trials in current literature (see Section 2.7), Ordinary Portland Cement, Rapid Hardening Cement, GGBS, and lime are readily available from Irish suppliers. The achievable strengths with these binders, as both single and composite binders, were investigated in a series of stabilisation trials, whose aim were to choose a suitable binder for use in the column tests. The results of these stabilisation trials are presented in Section 4.3.

Initially, PORT and PIRT reduced-scale column penetration tests were to be carried out after 1, 3, 7 and 28-day curing periods but due to higher than expected strengths in initial columns, compared to the strengths seen in the binder trials, the curing times were altered to 1, 2, 4, 6 and 12 days while still encompassing a range of strengths up to 800 kPa. This had the benefit of allowing quicker testing turn-around periods.

3.5.2 Reduced-Scale Column Construction Method

Some methods used to construct reduced-scale columns in the laboratory in previous studies have been summarised in Section 2.12. In particular, methods detailed by Larsson (1999) and Kosche (2004) to form reduced-scale DSM columns using either a mixing tool or a form-pipe to cast the columns were considered. The use of a scale mixing auger would provide a stabilised column constructed in a single operation and in a short time frame, but a number of issues were envisaged for laboratory implementation:

- A column mixing device and a method of maintaining the penetration and withdrawal rates would be required. This would be costly in terms of time and programme.
- From experience with the *sleech* for use in the tests, it was thought that its highly cohesive nature would inhibit uniform mixing, leading to un-mixed inclusions.

- Injection of the binder may require the use of a binder slurry to ensure uniform mixing over the column cross-section as seen by Al-Tabbaa & Evans (1999).
- The mixing tool Kelly bar would create a void in the column, as seen by Al-Tabbaa & Evans (1999).
- The lack of confinement at the top of the basin would result in a poorly mixed column with high voids, as noted by Larsson (1999).
- Oscillations of the mixing tool from the centre line of the column would result in a variation of the column diameter with depth as seen by Larsson (1999) with a 50 mm dia., 500 mm long columns.
- Installation of the PORT penetrometer post-column construction would split the column and possibly lead to a weak plane in the column, while installing the penetrometer during column production would require the mixing device to accommodate the PORT penetrometer and its wire.
- This *in situ* method precluded the production of mould samples as a reference to samples from the laboratory-scale column.

Casting of the column in a void created by a form pipe in the raw *sleech* was considered but suction and cementitious bonds between the raw *sleech*, the constructed column and the form pipe would lead to difficulties in extracting the pipe and could possibly damage the column. Pre-casting of the whole column as one unit was considered in order to reduce the time between mixes but difficulties in compaction of the column in a long form-pipe would lead to uniformity issues and a greater risk of damage to the column during placement of the surrounding raw *sleech*.

It was decided to construct the column by casting the column in lifts before surrounding it with *sleech* to 50 mm below the level of the lift. This would allow for the inclusion of the PORT penetrometer during construction without affecting the column's uniformity. The time frame required would be significant and layering between mixes could occur but uniform compaction could be ensured and the *sleech* could be compacted by hand against the column face. Details of the exact methods used to construct the stabilised columns for PORT and PIRT are set out in Sections 3.7.2 and 3.8.2, respectively.

3.5.3 Reduced-Scale Column Tests

The choice of scale and dimensions for the reduced-scale columns tests was deemed to be primarily dependent on the size of column that could be constructed uniformly in a reasonable time frame, as well as the time required to test and profile the stabilised column. The following factors were relevant to the final decision:

- Table 3-1 provides a compilation of times required to construct, test and profile the stabilised columns. Minimising the delay between carrying out the column test and the strength test was considered to be a high priority.
- Each stabilised mixture was required to create enough height of column so as to ensure good quality samples could be obtained from the tested column. Due to mixing uniformity limitations of the soil mixer, stabilised *sleech* batches would be a maximum of 12 kg. It was assumed that samples bridging two mixtures would be problematic due to the possible formation of a weak plane between mixes and should be avoided.

Table 3-1: Estimate of construction, PORT/PIRT probing and UCS testing times

Task:	Time Requirement:
Stabilisation of a single mix and creation of 2 no. 65 mm dia. by 130 mm high mould samples	1 hour
Compaction of a mix into the column form pipe and surrounding of column with *sleech*	1 hour
Setup and carrying out of the reduced-scale PORT/PIRT	1 hour
Column extraction and sampling of surrounding *sleech*	2-3 hours
Trimming of column to 50 mm dia. by 100 mm high samples (12-15 samples)	2-3 hours
UCS testing of column and mould samples 20-24 samples	7 minutes per sample Overall 3 hours

- An initial column height of 2 m was proposed for the test series but on consideration on the construction times (based upon experience gained during the *sleech* stabilisation trials), this was reduced to 1 m. Furthermore, at a density of between 1,600 kg/m^3 and 1,700 kg/m^3 the mass of the constructed column test would be significant and be difficult to move.
- For strength testing of the stabilised soil columns, 50 mm dia. by 100 mm long samples were deemed most suitable. Sampling of 38 mm dia. by 76 mm long

samples was considered but imperfections in trimming would lead to greater inaccuracies in the recorded parameters, in particular sample density.

- Consideration was also given to the size of the reduced-scale penetrometers that could be fabricated to accurately replicate the full-scale penetrometers.

Construction of a uniform 200 mm dia. column was deemed to be possible within 12 hours, *i.e.,* one working day, and each (12 kg) stabilised mixture would allow for a height of column of approximately 200 mm to be built. In ideal conditions, 8 no. 50 mm dia. by 100 mm long cylindrical samples could be obtained from each mixture in the column for UCS testing. Considering all these factors, a 1:4 scale applied to an 800 mm column was deemed appropriate, and thus the width of the reduced-scale penetrometers was defined to be 150 mm, in keeping with the proportions set out in Table 2-2 and Table 2-3 for full-scale PIRT and PORT penetrometers, respectively. In practice column construction took approximately 8 hours, and a complete column test (PORT/PIRT, column exhumation, sample preparation and UCS testing) took 9 to 18 hours, depending on the number of column samples obtained.

3.5.4 Penetrometer Fabrication

The reduced-scale PORT and PIRT penetrometers (see Figure 3-8 a & b) were designed to withstand the maximum anticipated force of 5 kN, calculated using Equation 2-5, an N value of 10 (obtained from Table 2-5) and a maximum UCS of 1,000 kPa. Measurements taken from actual penetrometers and guidance documents, primarily Carlsten & Ekström (1996), were used to dimension the reduced-scale penetrometers. As the penetrometers would be exposed to moisture and cementitious materials, grade 304 stainless steel was chosen over mild steel.

The wings of both the PORT and PIRT penetrometer were manufactured from 6 mm dia. bar and 4 mm sheet steel (see Figure 3-8c) and are 1 mm greater than the actual scaled dimensions due to issues of the steel warping during welding. Stainless steel bar, 10 mm in dia., was used for the central shaft of the penetrometer and for the PIRT sounding bars, which were between 0.25 m to 1 m in length with male and female threaded ends to allow coupling. The scaled diameter of the PORT wire rope was increased from 3 mm to 4 mm to carry the 5 kN design load.

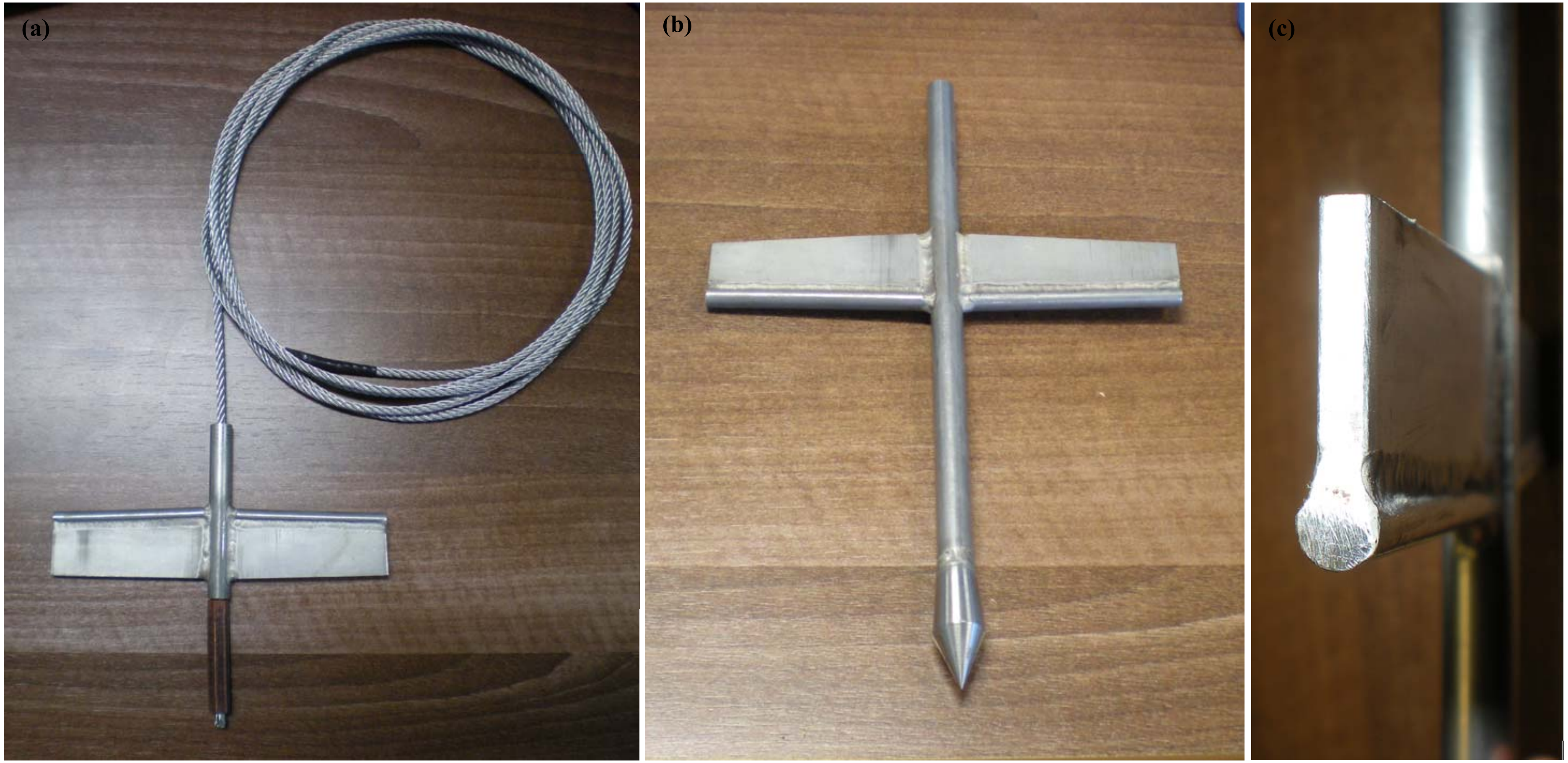

Figure 3-8: a) 150 mm (one-quarter scale) PORT penetrometer, b) 150 mm (one-quarter scale) PIRT penetrometer & c) penetrometer wing profile

In total, two PORT and two PIRT penetrometers were manufactured, along with a PIRT cone-only penetrometer (see Figure 3-9a) and a wing-only penetrometer (see Figure 3-9b), 6 m of 10 mm dia. PIRT sounding bar and four 3 m lengths of 4 mm dia. PORT pull-out wire to be used to determine frictional contributions of each respective test. All penetrometers were manufactured by Marine Technology Ltd, Galway, and the actual dimensions of the penetrometers may be found in Appendix C.

Figure 3-9: a) 14 mm dia. cone-only PIRT penetrometer & b) 80 mm wide wing-only penetrometer

3.5.5 PORT and PIRT Column Curing Basin Sizing

A PLAXIS 2D (axisymmetric) FE model was used to determine the minimum diameter of curing basin required to ensure the basin walls did not influence the penetrometer tests on the 200 mm dia. columns. In the model it was assumed that the penetrometer split the column in half and created a 6 mm gap (the width of the penetrometer wing's leading edge) between the two semi-circular column sections, *i.e.,* each semi-circular section was displaced 3 mm horizontally into the surrounding *sleech*.

A 1 m by 30 m FE model was created and meshed with 9,000 six-noded triangular elements (see Figure 3-10). To model the test, a prescribed horizontal displacement of 3*mm* was applied at the column face. The properties used for the *sleech* (modelled using the HS model) were based on McCabe (2002) and McCabe *et al.* (2013) and are set out in Table 3-2. Although a Young's modulus of 6.5 MPa has previously being observed for *in situ sleech* (McCabe 2002), a value of 1 MPa was used in the model as the *sleech* surrounding the column was not in an undisturbed condition. This lower value of 1 MPa was based on stiffness values observed during testing of stabilised samples (see Section 4.3) with shear strengths similar to the remoulded *sleech* strength and provides a better representation of the remoulded stiffness of the *sleech* surrounding the column than the *in situ* value of 6.5 MPa.

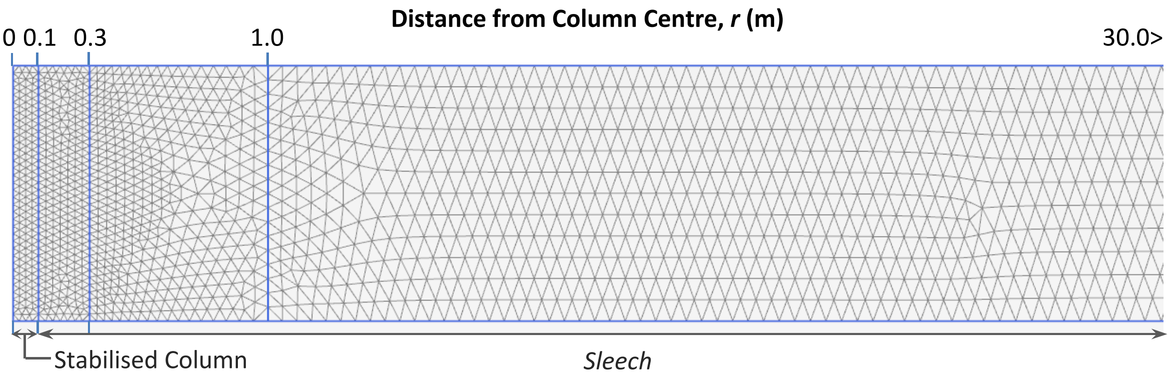

Figure 3-10: Finite element model and mesh

Table 3-2: Properties used for the *sleech* in the FE model

Poisson's Ratio, v	Friction Angle, ϕ	Unit Weight, γ	OCR	*Sleech* Stiffness, E	Reference Pressure P_{ref}	Stress Level Dependency Power, M
0.5	33°	16.5 kN/m^3	1.0	1.0 MPa	30 kPa	1.0

From the model the horizontal radial stress (σ_x) was calculated at depths of 0.5 m and 0.99 m. and Figure 3-11 shows the variation of σ_x normalised by the horizontal radial stress before implementing the expansion (σ_i) with r. It was concluded that a 750 mm dia. basin would be suitable as σ_x beyond an r of 375 mm were less than 5% of those of the initial σ_x before testing. The curing basins were constructed by JFC Ltd of Tuam, Co. Galway, from 750 mm (internal) dia. HDPE Weholite piping with a 6 mm thick HDPE plate welded in place to seal the end of the pipe.

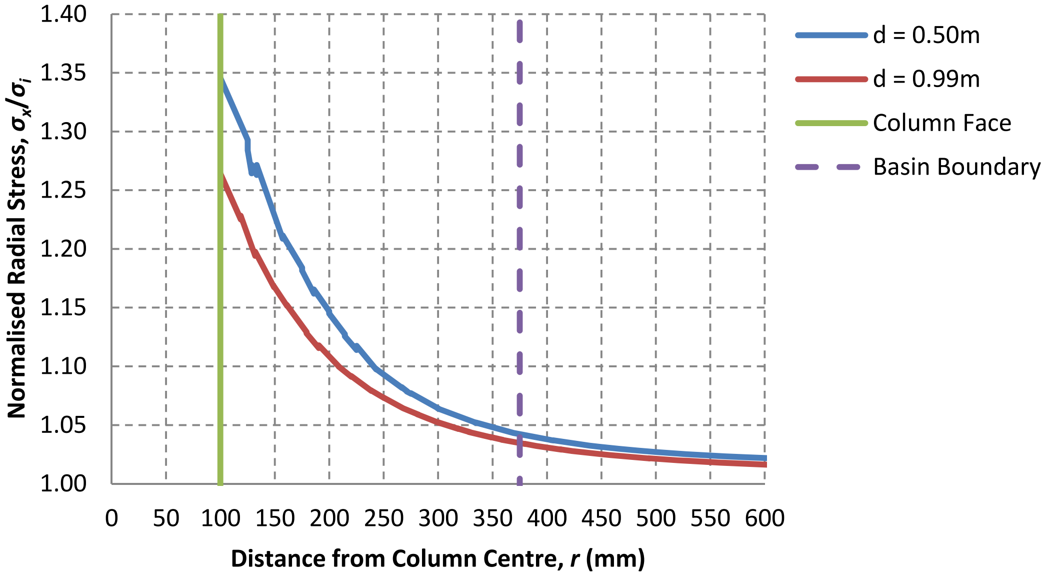

Figure 3-11: Normalised horizontal radial stress with distance from column centre

3.6 Data Acquisition System (DAQS)

During the reduced-scale PORT, PIRT, PORT wire and PIRT cone-only experiments on the stabilised soil-cement columns, penetrometer displacement, push-in/pull-out forces and other displacements were monitored by a data acquisition system (DAQS).

The push-in and pull-out forces in all column penetrometer tests were recorded using a Richmond Industries 5 kN 700-series S-beam load cell (S/N: 26599) with a 10 m cable (see Figure 3-12 and Figure 3-13), connected to a National Instrument (NI) 9237 simultaneous-bridge module. Penetrometer displacements were monitored by an Applied Measurement Posiwire WS10 potentiometer (or draw-wire gauge) (see Figure 3-14), connected to a NI 9205 analogue-input module. A Thurlby Thandar PL330 power supply unit provided the required 10 V excitation voltage (see Figure 3-15). Vertical displacement of the CPT reaction frame during PIRT was monitored using a 25 mm MDE linear-variable differential-transducer (LVDT) (see Figure 3-16), connected to a NI 9237 simultaneous-bridge module. All NI modules were slotted into a NI cDAQ-9178 8-slot USB chassis (see Figure 3-17), from which National Instruments LabVIEW software on a PC laptop recorded the data. Data samples were recorded at a rate of 10 per second.

Figure 3-12: PIRT load cell setup with sounding bar sleeve

Figure 3-13: PORT load cell setup

Figure 3-14: Posiwire WS10 draw wire gauge (potentiometer)

Figure 3-15: Thurlby Thandar 10 V power supply unit

Figure 3-16: 25 mm LVDT

Figure 3-17: NI module USB chassis

3.7 Pull-Out Resistance Test (PORT)

During a reduced-scale PORT, the winged penetrometer shown in Figure 3-8a, already installed in the stabilised column during its construction, was pulled up through the column using a wire rope in a similar way to that described in Section 2.3.3 and the pull-out force is used to estimate the strength of the column. The following section details the procedure, refined after a number of preliminary tests, to construct reduced-scale stabilised soil columns for PORT and subsequently perform PORT probing on the cured column. Procedures are also presented for construction and testing of the PORT wire friction experiments.

3.7.1 Preliminary PORT Column Trials

The pull-out of the PORT penetrometer from the column was carried out using the 5,000 kg gantry crane of the NUI Galway Heavy Structures Laboratory. A crane was used as it could extract the penetrometer in a single lift rather than the CPT rig whose stroke limit would necessitate two or more lifts. Performing the test in two lifts would introduce sources of error in monitoring the penetrometer's location and the pull-out force. Furthermore, where the wire was looped to attach it to the load cell, a kink would have formed in the wire. This could affect the verticality of the wire when reused in later columns.

A number of preliminary column trials were carried out to define the methods for construction and testing of the columns, *i.e.,* PORT columns 1 to 4, designated PO-1, PO-2, PO-3 & PO-4. In PO-1 and PO-2 a single piece of pipe, and a single piece of pipe with four 150 mm vertical slits, respectively, were used to form the column. This method was found to create layers and horizontal cracks in the column as the form-pipe was raised. PO-3 and PO-4 used two semi-circular sections of pipe bound together by adhesive tape which allowed the pipe to be peeled from the column once a section of column was compacted and formed the basis of the method described in detail in the subsequent section.

The first attempts at a PORT were carried out on PO-2 and PO-3. During the tests the columns were pulled from the basin with loadings of 50 kg and 160 kg, respectively, on the columns. PO-4 incorporated a layer of compacted sand and raw *sleech* beneath the column. The purpose of the sand being to hold the penetrometer in place during column construction and the raw *sleech* to allow the bond to be broken between the wire and column before the penetrometer entered the column. PO-4, loaded with 170 *kg*, was the first successful PORT carried, but issues with column cracking meant few samples were recovered.

3.7.2 PORT Column Construction

PORT columns were constructed in the following manner (see Figure 3-18):

1) A 160 mm long, 225 mm dia. piece of PVC-U pipe was placed in the centre of the 750 mm dia. HDPE basin and surrounded with raw *sleech*, as shown in Figure 3-18, step i.
2) A 90 mm layer of sand was compacted into the pipe with a 70 mm layer of raw *sleech* above it, thus filling the pipe. The sand layer, into which the penetrometer was installed, ensures that the penetrometer remains vertical during construction of the column, while the layer of raw *sleech* replicates the field practice of the penetrometer being installed below the column base and allows the penetrometer to gain momentum before it begins to cut into the column during the test.
3) A 6*mm* wide by 150 mm long vertical cut was made in the centre of the *sleech* and sand layers using a knife and the PORT penetrometer was pushed into this cut.
4) The location of the penetrometer's leading edge was noted and it was covered with raw *sleech* (see Figure 3-18, step i). The level of the top of the raw *sleech* was noted.
5) Two 600 mm long semi-circular pieces of PVC-U pipe were taped together with a strong adhesive tape, making a 200 mm dia. column form-pipe which was then centred above the PORT penetrometer.
6) As described in Section 3.3.1, the first stabilised mix (Mix 1) was produced using raw *sleech* and the designated binder content. Two mould samples were created for curing under laboratory conditions, one cured at the ambient temperature at which column cured at, *i.e.*, room temperature, and one in a water bath at 20 °C in accordance with EuroSoilStab (2002). 65 mm dia. by 130 mm long moulds were used instead of 65 mm dia., 320 mm long moulds so as to maximise the amount of stabilised soil available for column construction (see Figure 3-19).

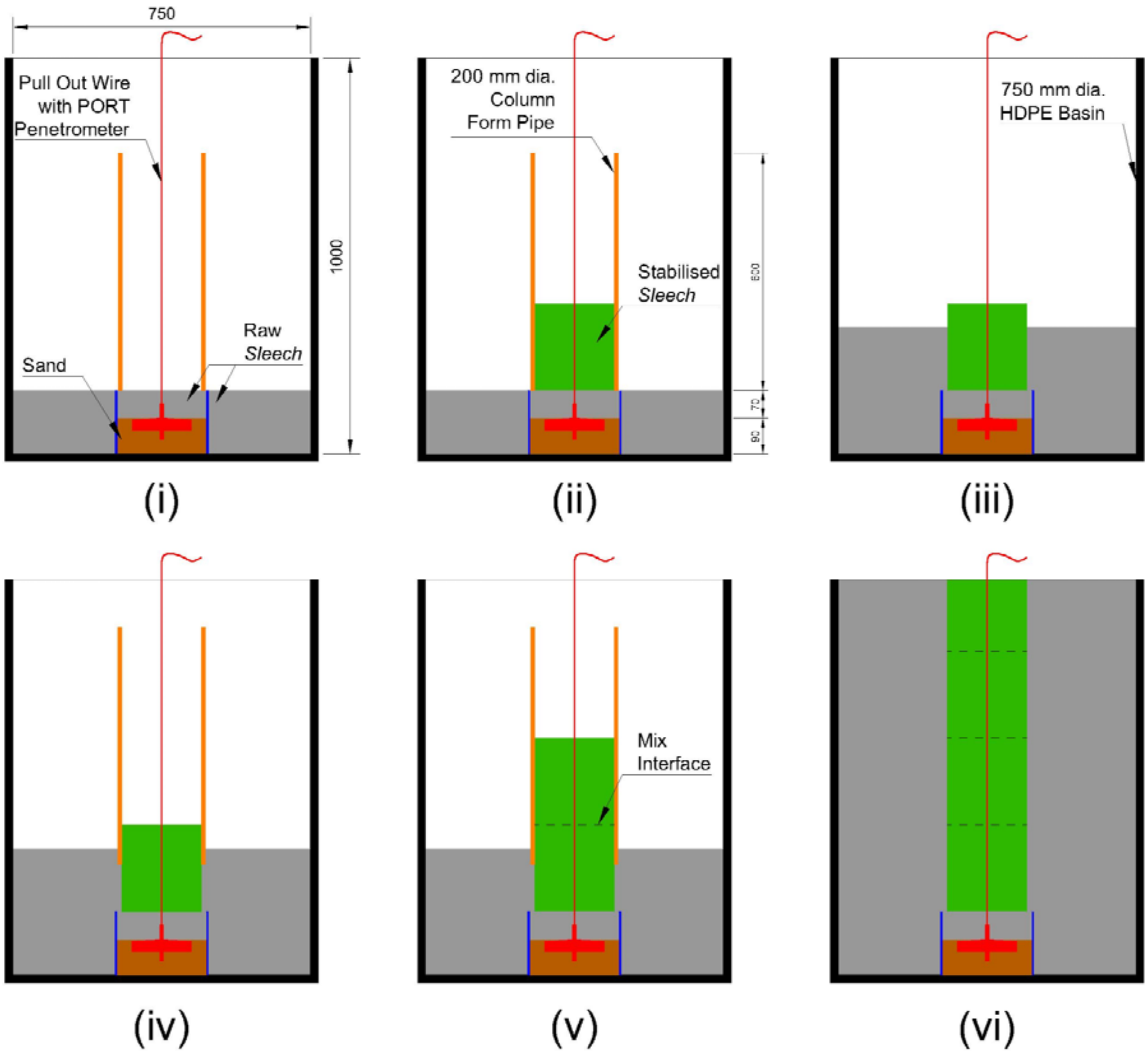

Figure 3-18: PORT column construction method (dimensions in mm)

Figure 3-19: 65 mm dia. by 130 mm long moulds at various stages during filling

7) The form-pipe was filled in 40 mm to 50 mm layers of stabilised *sleech*, with each layer compacted initially by a 62 mm tamping bar to remove any large air pockets, followed by 30 tamps using a 180 mm dia. tamping bar. A hole in the 180 mm

tamping bar allowed the wire rope to remain vertical during compaction. The alignment of the PORT penetrometer's wire rope was checked and adjusted, if needed, following compaction (see Figure 3-18, step ii).

8) The top surface of the layer was scarified with a fork, before the next layer was added and the filling and compaction procedure repeated.
9) Once all the mixed *sleech* was used, the adhesive tape binding the semi-circular pipes was cut and the form-pipe carefully removed.
10) Any voids in the column face were patched with material from the top of the column and the level of the top of the stabilised mixture was recorded.
11) Raw *sleech* was placed and compacted around the column to a level roughly 50*mm* below its current top (see Figure 3-18, step iii).
12) The semi-circular form-pipe was placed around the top 50 mm to 60 mm of the column and bound together with adhesive tape (see Figure 3-18, step iv).
13) Subsequent stabilised soil mixes (Mix 2 to Mix *n*), were made and the above process was repeated until the desired height of column was achieved (see Figure 3-18, steps v and vi).
14) Once complete, the column and surrounding soil were loaded with a light surcharge of 9 kPa and 3 kPa, respectively to remove any possible remaining voids.
15) The basin was covered with plastic to prevent moisture loss and allowed to cure until the required test time.

3.7.3 PORT Column Test Method

The PORT penetrometer was pulled out of the column by the gantry crane at a rate of 16.5 mm/sec to 17.5 mm/sec. A draw-wire gauge mounted on a nearby independent structure monitored the penetrometer displacement, while a 5 kN S-beam load cell recorded the pull-out force. Pull-out of the entire column was prevented by placing a ballast on the column during the PORT. PORT columns were tested in the following manner:

1) The basin was positioned alongside the independent structure and the gantry crane positioned above the centre of the column.

2) To prevent pull out of the column from the raw *sleech* a load, typically 150 kg, was placed on the column.
3) The load cell was suspended from the crane and attached to a loop formed in the wire rope using two 6 mm D-shackles.
4) The crane block was raised until the wire rope was lightly taut and the level of the load cell was noted (see Figure 3-20a).
5) The penetrometer was pulled through the column in a single lift while time, pull-out force and displacement were recorded using a data acquisition system (DAQS) (see Section 3.6).
6) To prevent damage to the testing setup if the penetrometer were to make contact with the ballast on the column, the test was stopped when the penetrometer was roughly 50 mm below the top of the column.
7) The level of the load cell was recorded to compare with the draw-wire gauge recordings and the test setup was dismantled.

Figure 3-20: a) Typical PORT setup & b) exposed column and PORT penetrometer

8) A soil sampling probe was used to take a vertical profile in the *sleech* surrounding the column. This was carried out at three locations at a radius r from the column centre: (i) at the basin wall (r = 375 mm) (ii) midway between the wall and column (r = 240 mm), and (iii) at the column face (r = 100 mm). From each profile, samples were taken at 200 mm intervals to determine the *sleech's* moisture content.
9) During extraction of the column, the strength of the raw *sleech* was determined using a pocket shear vane and cores pushed into the *sleech* were taken to determine its density and degree of saturation. The final location of the PORT penetrometer was noted, as was the location and direction of any cracks (see Figure 3-20b).
10) *Sleech* in contact with the face of the column was discarded and the remaining raw *sleech* was kept for reuse in later columns.
11) Samples were taken from the extracted column and trimmed into cylinders for unconfined compression strength tests (see Figure 3-21 and Figure 3-22) where samples are shown at various stages during trimming. Best efforts were made to produce 50 mm dia. by 100 mm high cylindrical specimens but cracking in the column lead to smaller sample lengths in some instances, as well as poor sample distribution in some columns. The mass and length of each sample was recorded.

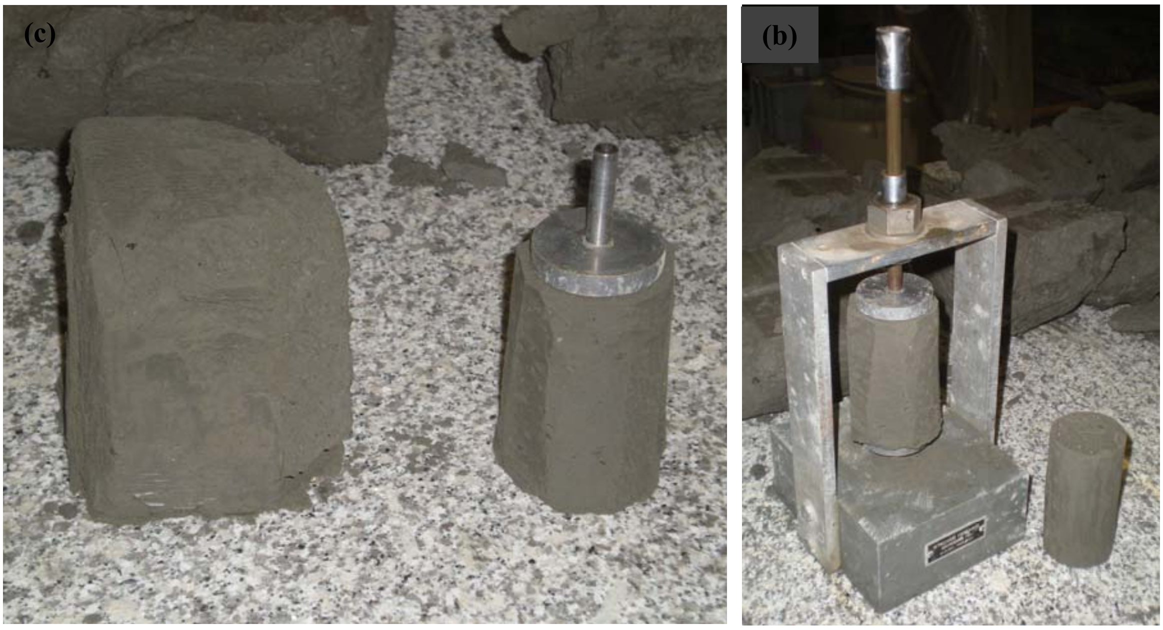

Figure 3-21: Column samples at various stages during trimming

Figure 3-22: Prepared 50 mm dia. column strength samples before UCS testing

12) Following UCS testing as per Section 3.4, a minimum of 20 g of stabilised soil was taken from the centre of each UCS specimen to determine the stabilised soil's moisture content.
13) Mould samples created at the time of mixing were tested at this time. They were removed from their moulds, their ends squared, and their mass and dimensions recorded. Any small stones extruding from the ends were removed and the void filled with trimmed material.

3.7.4 PORT Wire Friction Test

To investigate the portion of the PORT penetrometer pull-out force due to friction along the wire length, a series of wire friction tests were carried out using 104 mm dia. stabilised columns. The column was constructed around a similar 4 mm wire to that used in the reduced-scale PORT penetrometer. After the required curing period, the wire was pulled from the column in a similar setup to that of a reduced-scale PORT.

<u>PORT Friction Column Construction Process:</u>

Columns for PORT wire friction tests were constructed as follows:

1) An 800 mm long, 104 mm dia. PVC-U pipe with a joining collar at one end and a slit running along its length, was bound closed with adhesive tape along the length of the slit and at three locations around the pipe.

2) A stopper with a 6 mm hole was placed in the joining collar of the pipe to close off the end (see Figure 3-23a). To ensure 50 mm dia. samples could be obtained the hole was located off-centre of the stopper.
3) The 4 mm PORT wire was threaded through the stopper and a D-shackle put in place so as the wire could be kept taut during column construction (see Figure 3-23a). The wire was allowed to extend 40 mm to 50 mm beyond the end of the column.
4) As per Section 3.3.1, a stabilised mix was created at the required binder content and two mould samples were produced for curing at room temperature and in a water bath at 20 °C.
5) The stabilised mixture was compacted into the PVC-U pipe (see Figure 3-23b) initially using a 25 mm square tamping bar and then an 86 mm circular tamping bar in 30 mm to 40 mm layers. To ensure that the wire followed a straight path, it was kept taut during compaction.
6) Each layer was scarified after each compaction effort to reduce layering effects.
7) The pipe was filled with stabilised *sleech* and the top of the column was sealed with plastic to prevent drying out.

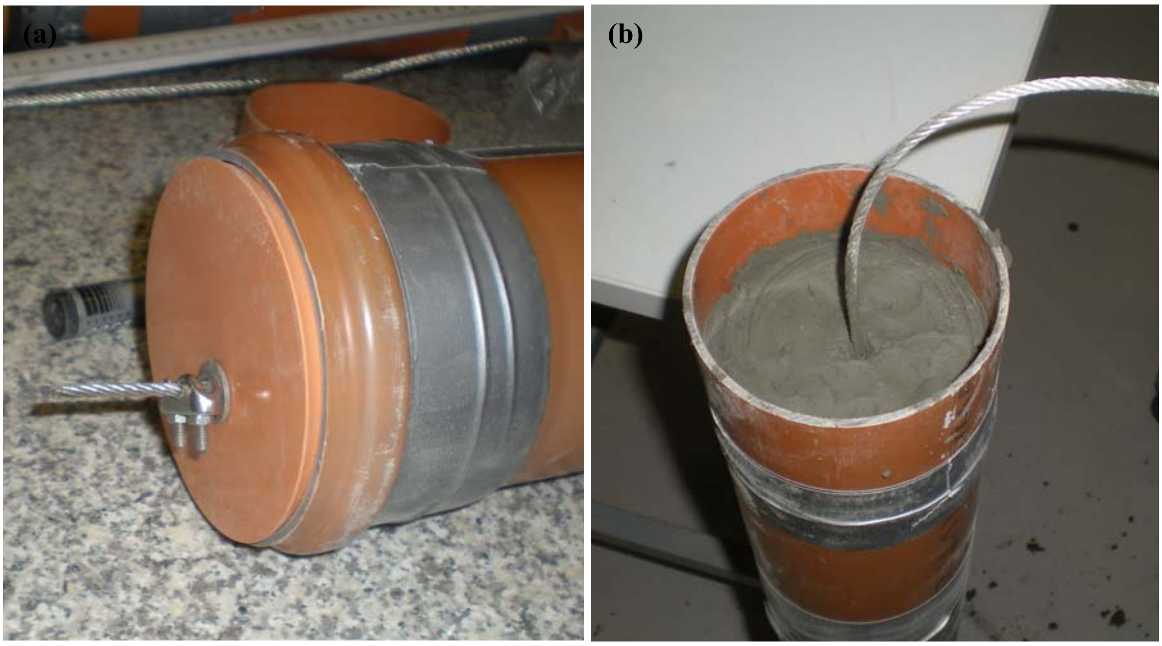

Figure 3-23: a) Shackle to hold wire during compaction & b) column during compaction

<u>PORT Friction Test Process:</u>

The PORT wire pull-out tests were carried out as follows:

1) At the required test time the D-shackle was removed from the wire and the column was placed in the test frame. To resist any vertical movement, the column was secured in place by a plate bearing on the top surface of the column (see Figure 3-24).
2) The DAQS was set up to record the displacement of the wire, the pull-out force and to monitor any vertical movement of the bearing plate.
3) The wire was pulled from the column in a single lift at an average rate of 16.5 mm/sec to 17.5 mm/sec by the gantry crane.
4) On completion of the test, the setup was dismantled and the condition of the wire was noted.

Figure 3-24: PORT wire friction test

5) The column was removed from the PVC-U pipe, any defects or cracking were noted before it was cut into 105 mm lengths, which were then cut in half along a vertical axis.
6) The alignment of the wire pull-out path was noted and photographed.
7) The column sections were sampled to obtain specimens for UCS testing. As the diameter of the column will not provide for two 50 mm dia. by 100 mm long samples at one level, a 38 mm dia. by 76 mm sample was taken from the smaller section of column.
8) Mould samples made at the time of mixing were also tested at this time.

3.7.5 PORT Penetrometer in Raw *Sleech*

The magnitude of the pull-out force in raw *sleech* under the stabilised column was measured in a reference PORT experiment with the penetrometer passing through raw *sleech* only. A loading of 40 kg on the *sleech* simulated the weight of the stabilised column.

1) In a 500 mm long, 225 mm dia. PVC-U pipe an 85 mm layer of sand was placed and compacted.
2) Raw *sleech* was placed on top of the sand and compacted to a level of 160 mm.
3) As described in Section 3.7.2, a 6 mm wide by 150 mm long vertical slit was made in the centre of both soil layers using a knife and the PORT penetrometer was pushed in.
4) The level of the leading edge of the PORT penetrometer was recorded.
5) Raw *sleech* was placed and compacted into the pipe, taking care to ensure the PORT penetrometer wire remained vertical.
6) Once filled, the top of the pipe was sealed with plastic and a 40 kg loading was applied using a circular loading plate to replicate the mass of a column bearing on the *sleech*.

After a period of one day, the PORT penetrometer was pulled to the top of the pipe using a similar method to that used to test the reduced-scale soil-cement columns.

1) The pipe was centred underneath the crane and the load cell attached to the wire rope.

2) The draw-wire gauge was set up to record the displacement of the penetrometer.
3) Using the crane, the penetrometer was pulled to the top of the pipe.
4) During dismantling of the pipe, a strength profile was determined using a shear vane and cores taken to determine the density and moisture content of the raw *sleech*.

3.7.6 Column-Raw *Sleech* (pull-out) Friction Test

To determine the friction between the stabilised column and surrounding raw *sleech* a 65 mm dia. 225 mm long mini-column was built and surrounded with raw *sleech* in a 225 mm dia. basin. Using a 62 mm dia. circular plate and a wire rope running from the column base up through the column, the column was pulled out of the basin at a rate of 15 mm/min. The pull-out load and column displacement were monitored by a DAQS to determine the friction.

3.8 Push-In Resistance Test (PIRT)

During a reduced-scale PIRT, the winged penetrometer, shown in Figure 3-8b, was pushed into the centre of the cured column using 10 mm dia. sounding bars in a similar way to that described in Section 2.3.2 and the push-in force is used to estimate the strength of the column. The following section details the procedure derived from a number of preliminary tests to successfully construct reduced-scale stabilised-soil columns for the purpose of PIRT and the subsequent performance of the test. Procedures are also presented for construction and testing of the PIRT cone penetrometer friction experiments using the penetrometer shown in Figure 3-9.

3.8.1 Preliminary PIRT Column Trials

To define the appropriate setup for PIRT, early preliminary tests were carried out on 200 mm dia. columns, up to 500 mm in height cured in 225 mm dia. pipes. Significant deviations of the PIRT penetrometer were noted in these early tests, with the penetrometer typically exiting the column at a depth of approximately 400 mm (see Figure 3-25), suggesting that successful PIRT probing of longer columns would be difficult to achieve. Tests using cone-only and wing-only penetrometers also showed significant deviations during testing.

After discussions with a DSM practitioner (Wiberg personal communication 2013), it was decided to attempt to replicate pre-drilled columns for PIRT, a procedure that is carried out on field columns to prevent penetrometer deviation (Axelsson & Larsson 2003; Larsson 2006; Trafikverket 2011). Two methods were investigated:

(i) Drilling a hole in a formed column prior to PIRT probing of the column.

(ii) Forming a hole in the column using a hole-form bar put in place during column construction and removed prior to PIRT probing.

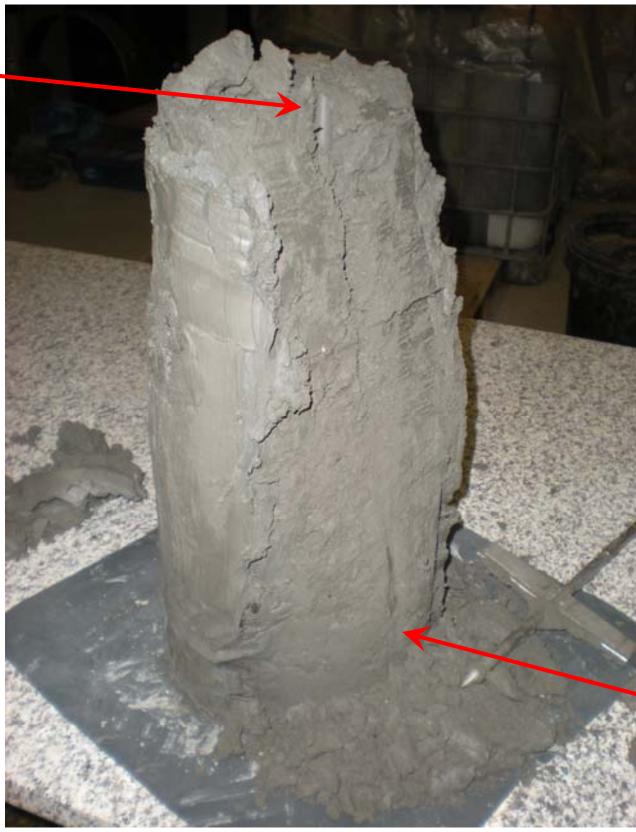

Figure 3-25: Early trial PIRT column showing significant deviation of the PIRT penetrometer

Columns, 200 mm in diameter, were constructed in 225 mm dia. basins and allowed to cure for 2 days. To achieve early high strengths a cement binder content of 200 kg/m^3 was used. Pre-drilling of the column was carried out with a 16 mm dia. timber auger bit but maintaining verticality of the drill bit and removal of spoil were noted to be difficult. PIRT of the column was successful without the deviations seen in non-pre-drilled columns, although the larger diameter of the drilled hole compared to the penetrometer tip diameter (14 mm dia.) did result in some minor unwanted out of plane movement of the penetrometer. The load cell was fitted with a tight sleeve into which the sounding bar end would slot and this was found to give an easier and quicker method of inserting additional sounding bars.

Pre-forming a hole in the column was achieved through the inclusion of a 13 mm dia. metal bar in the column during construction. To reduce lateral movement of the penetrometer during probing, the diameter of the bar was chosen to be 1 mm less than the diameter of the PIRT cone tip. During curing, the bar was rotated a number of times to prevent a bond building up within the column and at the test time the bar was removed. PIRT probing was again successfully carried out with reduced lateral movements noted compared to the 16 mm pre-drilled trial test.

Larger trial column tests were then carried out in 750 mm dia. basins, *i.e.,* PI-1, PI-2 & PI-3. Construction of the columns was carried out using the experience gained during the reduced-scale PORT experiments and the installation of the hole-form bar after placement of Mix 1 was found to be effective. To investigate whether the proposed method would work, PI-1 and PI-2 were carried out on low and high strength columns respectively using a pre-formed hole during which the CPT rig was secured to the basin using the basin mass as a reaction. As these tests were successful, an independent reaction frame specific to the tests was specified and the set up tested in PI-3. During PI-3, a high strength column, significant bending of the sounding bars was observed in the first 150 mm and the test was stopped. The column was retested with a hard plastic guide at the base of the CPT rig put in place to prevent buckling of the sounding bars. This set up was deemed suitable and a description of the construction and testing methods for reduced-scale PIRT columns follows in Section 3.8.2.

3.8.2 PIRT Column Construction

PIRT columns were constructed in the following manner (see Figure 3-26):

1) A 200 mm long, 225 mm dia. piece of pipe was placed in the centre of the 750 mm dia. HDPE basin and surrounded with raw *sleech*.
2) Raw *sleech* was compacted into the pipe, filling it to the top and the level was recorded.

3) Two 600 mm long semi-circular pieces of PVC-U pipe were taped together with a strong adhesive tape, making a 200 mm dia. form-pipe, which was centred above the 225 mm dia. pipe (see Figure 3-26, step i and Figure 3-27a).
4) As described in Section 3.3.1, the first stabilised mix (Mix 1) was produced using raw *sleech* and the designated binder content. Two mould samples were produced from the mix, one cured at room temperature and the other in a water bath at 20 °C.

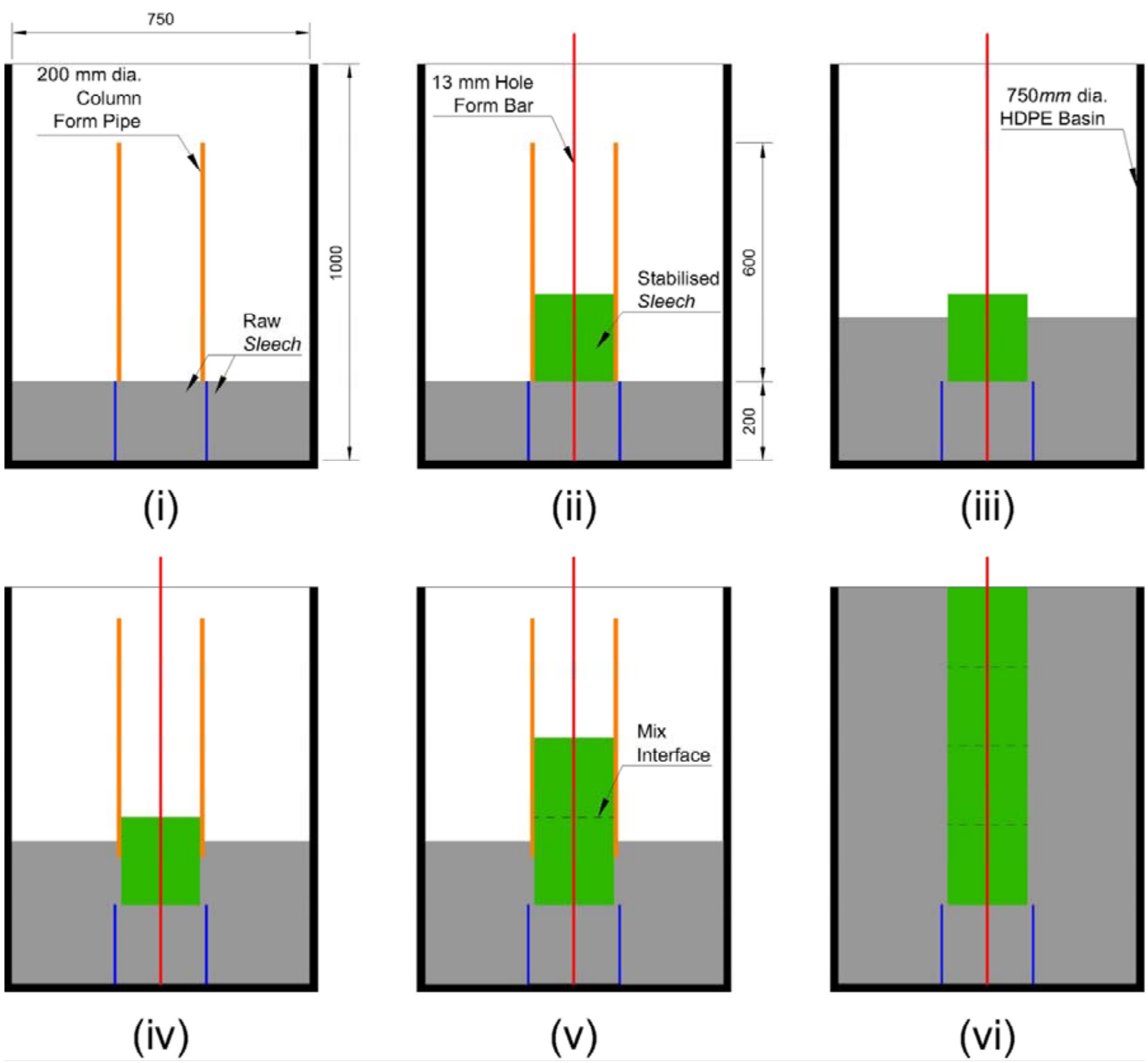

Figure 3-26: PIRT column construction method (dimensions in mm)

5) The form-pipe was filled in 40 mm to 50 mm layers, with each layer compacted initially by a 62 mm tamping bar to remove any large air pockets and then applying 30 tamps using the 180 mm dia. tamping bar shown in Figure 3-27b.
6) The top surface of each layer was scarified before the next layer was added.

7) Following compaction of the first stabilised soil mix, a 13 mm dia. hole-form bar was pushed down through the centre of the column to the base of the basin (see Figure 3-26, step ii).
8) The tape binding the semi-circular form-pipe was cut and the form-pipe carefully removed. The level of the top of the compacted mixture was recorded.
9) Raw *sleech* was compacted into the basin to a level roughly 50 mm below the top of the constructed column, the semi-circular pipes were placed around the top 50 mm to 60 mm of the column and bound together with adhesive tape (see Figure 3-26, steps iii to iv).

Figure 3-27: a) 200 mm dia. column form-pipe bound closed with adhesive tape & b) 180 mm dia. tamping bar

10) Subsequent stabilised soil mixes (Mix 2 to Mix *n*) were created and the above process was repeated until the desired height of column was achieved (see Figure 3-26, steps v and vi), with care taken to ensure the bar remained vertical and the column remained centred around the bar. A hole in the 180 mm dia. tamping bar allowed for compaction around the 13 mm dia. bar (see Figure 3-27b).

11) Once complete, the column and surrounding soil were loaded with a light surcharge of 9 kPa and 3 kPa, respectively, to remove any possible remaining voids.
12) During construction and at least once every two days during curing, the 13 mm dia. bar was rotated by hand to prevent it binding with the column.
13) The basin was covered with plastic to prevent moisture loss and allowed to cure until the required test time.

Figure 3-28: PIRT column during construction: a) column after removal of form pipe-from mix 2 & b) column before placing for final layer surrounding raw *sleech*

3.8.3 PIRT Column Test Method

To push the PIRT penetrometer through the stabilised soil column, the NUIG Gouda CPT rig was used. The rig was mounted on an independent reaction frame above the basin, with total weight of the frame and CPT rig designed to exceed 5 kN, *i.e.,* the maximum push-in force envisaged during the test series. If movement of the frame was detected, additional ballasting could be added to the frame along the base runners to increase the weight of the setup in subsequent tests, but this was not required as the maximum vertical movement did not exceed 0.5 mm. A draw-wire gauge monitored the

CPT rig ram's movement, while an LVDT monitored any vertical movement of the CPT rig and frame during the test. The test was conducted as follows:

1) At the desired curing time, the 13 mm dia. hole-form bar was removed from the column and the loading was removed from the basin.
2) The basin was placed under the frame and centred beneath the CPT rig (see Figure 3-29a).
3) The penetrometer was positioned in the column with a length of sounding bar attached to it and the load cell and sleeve were lowered over the sounding bar (see Figure 3-29b). The sleeve ensured the bar remains centred on the load cell.
4) The penetrometer was pushed into the column at a target rate of 20±4 mm/s, while the load cell recorded the force required to do so.
5) Once the stroke limit of the rig was reached, the ram was raised and another length of sounding bar inserted. This was repeated until the column was fully penetrated, *i.e.,* the penetrometer's wings having entered the raw *sleech* at the base of the column. The penetrometer was left in place so as its final position could be verified and was removed when the column had been fully extracted.
6) A soil sampling probe was used to take a vertical profile in the raw *sleech* surrounding the column. This was carried out at three locations at a radius *r* from the column centre: (i) at the basin wall (r = 365 mm) (ii) midway between the wall and column (r = 240 mm), and (iii) at the column face (r = 100 mm). From each profile, samples were taken at 200 mm intervals to determine the *sleech's* moisture content.
7) The basin was dismantled in a top-down manner, *sleech* in contact with face of the column was discarded and the remaining raw *sleech* was kept for reuse.
8) During extraction of the column (see Figure 3-29c), cracks in the column and the path taken by the penetrometer were noted.
9) The strength of the surrounding *sleech* was determined using a pocket vane penetrometer and cores were taken to determine the *sleech*'s *in situ* density and the degree of saturation.

Figure 3-29: a) Overall testing PIRT frame setup, b) load cell and draw wire gauge setup for PIRT & c) PIRT column during extraction

3.8.4 PIRT Cone-Only Penetrometer & Sounding Bar Friction Test

To quantify the portion of the push-in force due to bearing on the PIRT cone tip and friction along sounding bars with the stabilised column, cone-only penetrometer tests were carried out on 104 mm dia. stabilised columns. As the test would not split the column, as seen in PIRT, columns were not surrounded with raw *sleech* during curing and testing. *Sleech* at the base of the column was used to replicate the *sleech* under the reduced-scale PIRT columns tested and in the same manner as a PIRT column, a hole was pre-formed with a 13 mm dia. hole-form bar.

<u>PIRT Cone Penetrometer Column Construction Process:</u>

Columns for PIRT cone penetrometer tests were constructed as follows:

1) A 900 mm long, 104 mm dia. PVC-U pipe with a single full length split was bound closed with adhesive tape along the length of its split and at three locations around the pipe (see Figure 3-30a). A metal collar, used to hold the pipe during the cone test, was placed over the pipe before taping.
2) Raw *sleech* was compacted into the bottom of the pipe to a height of 150 mm to 170 mm.
3) As per Section 3.3.1, a stabilised mix was created at the required binder content and two mould samples were created for curing at room temperature and in a water bath at 20°C.
4) The stabilised mixture was compacted into the PVC-U pipe in 30 mm to 40 mm layers, initially using a 25 mm square tamping bar and then applying thirty tamps using an 86 mm dia. circular tamping bar, with a central 17 mm dia. hole. Each layer was scarified after each compaction effort.
5) Once the pipe had been filled to at least 350 mm, the 13 mm dia. hole-form bar was pushed into the stabilised column and raw sleech. To ensure 50 mm dia. samples could be obtained the hole was located off centre of the pipe.
6) The pipe was filled with stabilised *sleech* and the hole-form bar was rotated at regular intervals to prevent it binding with the column.
7) The top of the column was sealed with plastic and left to cure until the required test time.
8)

PIRT Friction Test Process:

The PIRT cone penetrometer tests were carried out as follows:

1) At the required test time, the hole-form bar was carefully removed from the column.
2) The curing pipe was secured to the support frame, to hold it during testing, with the metal collar, and centred beneath the CPT rig (see Figure 3-30b).
3) The DAQS was set up to record vertical displacement of the cone and the probing force on the cone.
4) The cone was pushed into the column at a target rate of 20±4 mm/sec. Once the stroke limit of the rig was reached the ram was retracted and additional sounding bars added. Care was taken to ensure the cone penetrometer was not retracted as the ram was raised.

Figure 3-30: a) PIRT sounding bar friction test curing pipe during construction & b) PIRT sounding bar friction test setup before testing

5) The second push was carried out with the cone entering the *sleech* to the desired depth.
6) The setup was dismantled and the location of cone was verified by measuring the distance from the top of the column to the top of the cone penetrometer.
7) The column was removed from the PVC-U pipe and any defects or cracking were noted, as was the exact final location of the cone in the *sleech*.
8) The column was cut into 105 mm long sections, which were then cut in half along a vertical axis, thus displaying the path of pre-formed hole. The locations of any stones or defects along the hole were noted and the column was photographed.
9) The cut column sections were sampled to obtain specimens for UCS testing. As the diameter of the column only provided for one 50 mm dia. sample at one level, a 38 mm dia. by 76 mm sample was taken from the smaller section of column.

3.9 **PIRT Penetrometer Probing in *Sleech***

As a reference for PIRT in a stabilised column, PIRT was carried out in the unstabilised *sleech* surrounding the columns. The following method details the manner in which this was achieved:

1) Following the PIRT on the stabilised column, the basin was taken out from under the test frame.
2) As the column was tested with a pre-formed hole the 13 mm dia. bar was inserted into the raw *sleech* midway between the column and basin wall.
3) The bar was rotated and then removed from the *sleech*.
4) The basin was replaced under the testing frame with the hole centred under the CPT rig.
5) Using the method defined for carrying out a PIRT (see Section 3.8.3), a second PIRT penetrometer was pushed into the raw *sleech* with the push-in force and displacement recorded by the DAQS system.
6) During exhumation of the tested stabilised column, the strength of the raw *sleech* was determined at either side of the penetrometer's path of travel with a pocket shear vane.
7) The final level of the penetrometer was recorded to compare with the recorded displacement readings.

This method was also used where the cone-only penetrometer was pushed into the raw *sleech*, providing the resistance and friction between the raw *sleech* and PIRT cone and sounding bars.

3.10 Surcharged Column Tests

During the testing programme it was noticed that N values near the top of the column were lower than those at greater depths. The reduced confinement at the top of the column was thought to be a contributor to this as the surrounding soil provides a lesser resistance allowing the column to crack open, leading to reduced push-in forces. Therefore, a surcharge was used to increase the confinement stresses in the basin, particularly at the top of the column. Four surcharged columns, two for PORT and two for PIRT, were constructed as follows:

1) The stabilised columns for PORT and PIRT were constructed in accordance with the procedures in Section 3.7.2 and Section 3.8.2, respectively.
2) On completion of the column construction process a circular piece of geotextile was placed over the top of the basin.
3) The geotextile was covered with a layer of air-dried sand and its thickness was recorded at various locations.
4) Six samples of the sand were taken across the top of the basin to determine the sand's initial moisture content.
5) The top of the basin was sealed with a sheet of plastic to prevent moisture loss and a 722 mm dia. loading plate was put in place.
    a) In the case of a PORT column, the pull-out wire was run through a hole in the centre of the geotextile, the plastic and the loading plate to allow the penetrometer be pulled to the top of the column.
    b) For a PIRT column, a slot was cut in the geotextile and loading plate to allow the PIRT penetrometer to enter the column. This slot was filled with raw *sleech* to prevent sand particles being pushed into the column by the PIRT penetrometer.
6) The surcharge was placed on the loading plate in a uniform manner and the total mass added was noted.

7) Dial gauges were put in place to monitor settlement of the surcharge loading during the curing period.

Testing of the PORT or PIRT columns was carried out in the same manner as detailed in Section 3.7.3 and Section 3.8.3, respectively, with the surcharge remaining in place until the test was complete. On completion of the test, the moisture content and compressed depth of the sand layer was recorded before dismantling the setup and sampling for testing. Figure 3-31 a & b show the PORT and PIRT column testing setups for the respective surcharged columns.

Figure 3-31: a) Surcharged PORT column test setup & b) surcharged PIRT column during curing

3.11 Stabilised Mould and Column Temperature Monitoring

The hydration reactions that occur during stabilisation are exothermic and effects of this heating and the temperature of the laboratory on the tests were investigated in a series of temperature monitored experiments. Thermistors were placed in the centre of mould samples after their creation to monitor the samples core temperature during curing, with additional thermistors monitoring the ambient temperature at which the samples cured.

Temperatures within a stabilised soil-cement column and the raw *sleech* surrounding it were monitored with similar thermistors placed at various locations in a column constructed solely for temperature monitoring, *i.e.,* no PORT/PIRT was performed on the column due to the presence of thermistors which would interfere with the test. The ATC Semitec IP68 thermistors (see Figure 3-32a) were 5 mm in dia. and 20 mm long with a temperature range of -50 °C to +110 °C. Data from the thermistors were collected by a Campbell Scientific (CS) AM16/32 relay multiplexer and CS CR1000 data logger all housed in an electric meter box (see Figure 3-32b). A compact flash card in a NL115 Ethernet/Compact Flash Module stored the data.

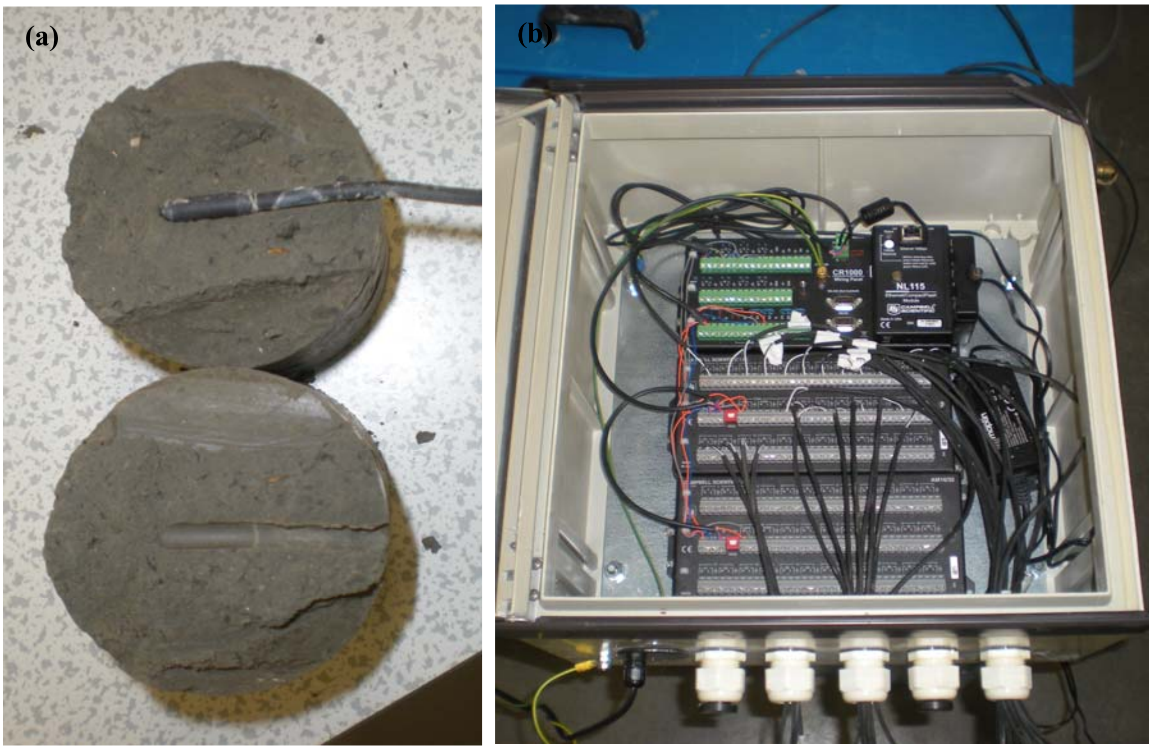

Figure 3-32: a) ATC Semitec IP68 thermistor in a mould sample after curing & b) Campbell Scientific thermistor data logger

3.11.1 Mould Temperature Monitoring:

Temperature monitored mould samples were created in the following manner:

1) All the required thermistors were connected to a Campbell Scientific data logger as shown in Figure 3-32b.
2) Thermistors were set up to monitor the ambient temperature of the room and of the water bath, *i.e.*, the temperatures at which the samples would cure.

3) A sample of raw *sleech* was taken from storage and two thermistors were placed in the 2 kg sub-sample to measure its initial temperature. The time at which this occurred was noted.
4) The main sample of *sleech* was stabilised as per the procedures set out in Section 3.7.2.
5) Once mixing of the raw *sleech* and binder was complete, the two thermistors were removed from the raw *sleech*, cleaned and each placed in a 2 kg sample of mixed *sleech.* The time at which this occurred was noted.
6) Mould samples were created and immediately after the creation of each individual sample, the thermistor was removed from the mixed *sleech* and inserted into the mould sample. The time at which this occurred was noted.
7) The area around the hole in the mould was surrounded with stabilised *sleech* and sealed with tape to prevent ingress of water around the thermistor.
8) Each sample was placed in its ambient location to cure, *i.e.,* at 20 °C in a water bath or at room temperature.
9) Two further mould samples were created for strength testing and were left alongside their respective monitored samples to cure.

Following curing the samples were removed from the moulds but were not strength tested due to the presence of the thermistor in the samples. The samples were split open and the location of the thermistors noted (see Figure 3-32b) as was the presence of any moisture around the thermistor. The separate moulds created for UCS testing were tested at this time.

3.11.2 Column Temperature Monitoring:

Temperature monitored columns were constructed in the following manner:

1) A column was constructed in the same manner as a PIRT column, as set out in Section 3.8.2 but without the inclusion of the hole-forming bar.
2) As set out in the previous section, the temperatures of the raw and stabilised *sleech* were monitored during the stabilisation process, and immediately after forming of the mould samples they were instrumented with thermistors.

3) On completion of the compaction of each mix to form the column, 5 mm dia. holes were drilled in the side wall of the curing basin and the thermistors, connected to the data logger, were passed into the basin.
4) Thermistors were placed at the following locations within a single mix:
   - At the column centre, *i.e.,* 100 mm into the column
   - 50 mm into the column
   - On the face of the column
   - In the middle of the raw *sleech* surrounding the column
   - On the internal face of the curing basin wall
5) Where a thermistor was inserted into the column, a 5 mm guide hole was drilled to ensure it reached its desired location. To prevent water ingress to the thermistor, stabilised soil was pinched around the wire at the column face (see Figure 3-33).
6) The location and level of each thermistor and its recording channel was noted, as was the time at which it is placed at the desired location.
7) The thermistor wires were surrounded with raw *sleech* and care taken to ensure compaction of *sleech* above them did not disturb their location.
8) As per Section 3.8.2, additional mixes were created until the desired height was achieved, with further thermistors added where necessary.

Figure 3-33: Two thermistors wires entering the stabilised column and a third on the column face

Cured Temperature Column Assessment:

1) After the desired curing period, the thermistors were disconnected from the data logger and the *sleech* surrounding the column was carefully removed.
2) The column was extracted from the basin in one piece, photographed and the depth of the thermistors noted.
3) The stabilised column was then cut into sections and the thermistors exposed and photographed.
4) The diameter of the column at various depths was noted so as to provide an assessment of the cross-sectional profile with depth.
5) From the cut sections, samples were recovered to assess the variation in strength across a column cross-section and the variation in strength at different height-to-diameter ratios.

3.12 Variability

It is important at this stage to highlight the variability in the processes described earlier in this chapter. Soft natural clays and peats used in this thesis are inherently more variable than stiff clays, for instance. The process of mixing in a binder and subsequent sample preparation adds further layers of variability. The results presented from Chapter 4 onwards should be considered in this context and of the discussion that follows.

3.12.1 Variation of the *In Situ Sleech*

McCabe (2002) presents moisture content (w_i) profiles of the Kinnegar *sleech* which vary widely from 48% to 70% between 3.0 m and 7.0 m, with corresponding in situ bulk densities ranging from 1,610kg/m^3 to 1,680kg/m^3. The average organic content was reported to be 11%. Older classifications by Crooks & Graham (1976) show the variation in w_i to be between 55% and 80% with bulk densities of 1,550 kg/m^3 to 1,750 kg/m^3 and an organic content of 4%, while Bell (1977) observed average moisture contents of 60% and found the organic content to range from 3.0% to 5.1%.

Results from *sleech* classification test on samples taken on site by this author show w_i values of 60% to 67% (average 63%, n = 8) while a greater range of between 48% and 71% was observed from the preliminary stabilisation trials (see Section 4.3). Bulk density cores obtained from excavated blocks of sleech on site gave values of 1,618 kg/m^3 and

1,622 kg/m^3. Organic tests by LOI on samples during classification tests produced an average LOI of 5.2% (n = 4).

3.12.2 Effects of Storage and Construction Procedures

During the PORT column series, it became apparent that losses of moisture occurred due to the column construction procedures used. Overall, PORT w_i values ranged from 46% to 69% (predominately 46% to 60%). *Sleech* with a w_i below 46% was not considered for column construction. Losses in moisture from the *sleech* occurred over the testing period due to the following factors:

(i) Moisture losses occurring during the repeated re-handling and remoulding of the *sleech* to surround the columns.

(ii) Moisture losses occurring from the *sleech* towards the top of the storage basin during storage between tests.

Variations in w_i within a single column were as a result of sampling the required *sleech* from different depths in the storage basin during the column construction period rather than at the very beginning from a single location. This resulted in a trend of increasing w_i with column height in some columns as *sleech* at the top of the storage basin had a lower w_i than *sleech* deeper down due to the two factors above. It was also noted that the ambient temperature of the laboratory in which the columns cured was varying seasonally due to the outside air temperature, with average ambient temperatures of 14 °C to 21 °C.

As a means of redressing the w_i variations in the PIRT column series by sampling all *sleech* for a single column from one location in a given basin and setting it aside on the morning of column construction, thereby removing the effect of variations with depth in the storage basin. Overall, lower variability was observed for the PIRT series and w_i ranged from 42% to 56% (predominately 46% to 53%). Furthermore, for the two friction column series the *sleech* used was set aside two months prior to the tests and this resulted in a narrower range of w_i (45% to 52%) but as the *sleech* had previously been used to surround columns during curing, its w_i values are at the lower range seen in this thesis.

During the PIRT and friction column series, organic content tests were carried out for each mixture used and show values of 2.2% to 4.6%, notably lower than the 5.6% observed in the classification tests. Tests carried out in February 2014 on *sleech* held in sealed containers since initial sampling show similar organic contents to those obtained in the classification tests. Although initial organic content data specific to each storage basin is limited, it is thought that a reduction in organics may have occurred over the storage and testing period. Strick van Linschoten (2004) reported lower than expected Atterberg limits in Kinnegar *sleech,* which had its organic content removed by LOI, to be the result of diminishing organics due to a considerable time between sampling and testing.

Wardwell *et al.* (1983) highlights the rate of degradation of the organic matter to increase with increased temperatures and under aerobic conditions. Thus, breakdown of the organics present in the *sleech* may have been occurred due to increased temperatures at which the *sleech* was stored (12 °C to 20 °C), compared to *in situ* (approximately 9 °C), and the aerobic conditions experienced during sampling of the *sleech* and its repeated remoulding during the testing programme.

3.12.3 Effects of Trimming Stabilised Samples

Unlike the mould samples, all column samples were trimmed by hand with a sharp knife into 50 mm dia. by 100 mm high (target length) cylinders, so some variation in the calculated density of the samples can occur due to minor over trimming of the cylindrical samples vertical face and associated errors in the assumed geometry. This results in a minor underestimation of the sample density in some but not all samples, the exact amount of which cannot be easily quantified. For instance, a 1 mm reduction in the diameter of a 50 mm dia. by 100 mm high sample at its centre will result in lower actual sample volume and for a typical sample mass of 350 g the error in calculating the sample volume will lead to a difference of 36 kg/m^3 in the calculated bulk density. Therefore the spread in density, over and above that due to moisture content differences, should not always be interpreted as a real spread.

3.12.4 Assessment of Variability

A number of measures have been taken to confirm that the quality of the test data is high, in spite of the inherent variability. Where relevant, guideline CoVs quoted by Phoon & Kulhawy (1999), albeit for *in situ* clay and silt samples, are referred to. The authors quote CoVs of 8% to 30% for natural moisture content and values less than 10% for bulk density variability. The review of variability in stabilised strengths in both laboratory and field samples in Section 2.10.3 is also called upon.

A framework for presenting the results, in which the effects of moisture content, binder content and curing temperature are superimposed on the strength-curing time relationship, is also implemented successfully. Some statistical mixed model regression analyses are also presented to show the unintended variations, particularly w_i, may be accounted for when determining stabilised strengths.

3.13 Statistical Analysis

3.13.1 Introduction

To provide further insight into the variables affecting the strength, a series of separate mixed model regression analyses was carried out on the mould and column sample data from both the PORT and PIRT series using the IBM package, SPSS Statistics. SPSS has the capability of managing data which are not independent of each other within an overall database, *e.g.,* stabilised samples from the same column having the same binder content and cured for the same time can have similar strengths.

3.13.1 SPSS Statistical Analysis Methods

Bivariate Correlation:

In a first attempt to assess the correlation between the *dependant variable* (or the output, in this case the UCS) and the *covariates* (or the inputs), a *bivariate correlation* analysis using Pearson Correlation was performed to indicate *covariates* that have a possible effect on the *dependant variable* and their significances. A *significance* value of less than 0.01 is considered highly significant and a *significance* of up to 0.05 is considered significant.

Linear Mixed Model:

Within SPSS, the mixed model linear analysis was used. For the mould data, the *subject* of the analysis was set to be a number corresponding to the column reference number. The *subject* allows the model to expect and account for similarities in the results of samples from the same column test, *i.e.,* samples from a particular column test which have the same binder content and curing time but whose other properties vary can produce similar results. For example, in the PORT analysis, the *subject* for PO-6 was 6 and, in the PIRT analysis, PI-10 was 10.

For column data analyses, a further designation was added to the *subject* to allow SPSS to take into account similarities in samples obtained from similar depths in a given column. To this end, the columns were divided into 100 mm sections and labelled based on the sample depth, *e.g.,* a sample from PORT column 6 obtained between depths of 200 mm and 300 mm was given the *subject* 6.3.

The UCS of the samples (at the time of the UCS test, q_{mld} or q_{col}) was the *dependant variable* and the *covariates* and *fixed effects* considered were time (t_{mld} or t_{col}), binder content, initial moisture content (w_i), ambient laboratory curing temperature (T), stabilised density (ρ_{mld} or ρ_{col}), depth (d) and organic content depending on the analysis being carried out. The model produced *descriptive statistics* and *estimates of the fixed effects* as well as producing the *predicted values* and *residuals* from the analysis. The significance of each *covariate* in the model was checked, with values less than 0.05 being significant.

Finally, three graphs were produced to visually analyse the results:

(i) Residual values *versus* predicted q values, to check for independence and similar variance, *i.e.,* residuals should behave like white noise.
(ii) Histogram of the residuals to show violation of normality of the underlying random response at each combination of the covariates.
(iii) Actual q versus predicted q with a linear trend-line fitted, to compare the predicted data.

Models should not be judged blindly on their R^2 values but should be used along with the above graphs to assess the quality of the model. During the analyses of the initial models, an increase in the spread of the residuals about the zero residual with increasing predicted value, referred to as flaring, was noted. This is particularly evident in the PIRT column models (see Section 6.7 and Appendix G.3). To remove this effect on the model, the natural log of both the time and strength was calculated and the models repeated. Initial models investigated the effects of time and binder content only and the remaining *covariates* were progressively added to subsequent models. As there is a known geotechnical relationship between the moisture content and density (see Equation 5-1), an *interaction* between these two *covariates* was included in some of the later models.

CHAPTER 4: PRELIMINARY LABORATORY STABILISATION TRIAL RESULTS

4.1 Introduction

In this chapter, the results of the classification tests and stabilisation trials carried out on a peat from Ballynahown in Co. Offaly and an organic clayey-silt from Kinnegar in Co. Down (known as *sleech*) are presented. Ordinary Portland Cement (OPC), rapid hardening cement (RHC), ground granulated blast-furnace slag (GGBS) and lime binders were mixed with the parent soils at various binder contents up to 300 kg/m^3, and allowed to cure for up to 91 days before UCS testing in accordance with the methods set out in Chapter 3. The purpose of these trials, were:

(i) To gain experience of laboratory soil stabilisation methods and procedures prior to the PORT/PIRT series.

(ii) To choose a suitable soil type for the PORT/PIRT series.

(iii) To define an appropriate binder type and content for the PORT/PIRT series.

Furthermore, the data obtained will contribute to the limited database currently available on the stabilisation of Irish soils.

4.2 Ballynahown Peat

4.2.1 Ballynahown Peat Properties

Table 4-1 provides a classification of the Ballynahown peat carried out in accordance with the methods set out in Section 3.2.2. The peat was sampled in an open cut at a depth of 1.0 m from a raised peat bog in Ballynahown near Athlone in Co. Westmeath. For density and strength testing, best efforts were made to cut undisturbed samples from the freshly exposed peat using a sharp knife and these were then stored in sealed boxes. Following sampling, all samples for the stabilisation trials were stored in sealed plastic bags.

An average initial moisture content of 800% was recorded during classification tests on the peat, and later during the binder trials, initial moisture contents of the raw peat (w_i) used (in each stabilised batch) were found to range from 684% to 864% (average 770%, n = 24). The average peat density was found to be 950 kg/m^3 (n = 2) and a pH of 4.8 (n = 4) shows the peat to be acidic. Loss on ignition by burning the samples at 440 °C during the classification and stabilisation trials indicated the organic content to lie between 94% and 98% (average 96.5% *n* = 20). The peat was determined to be in an early stage of decomposition with roots clearly identifiable and when squeezed the peat released a cloudy water with no particles present. Using current classification guidance (Landva *et al*. 1983; Hobbs 1986; ASTM 2006) the peat was classified to be at a *H3* stage of degradation. Attempts were made to estimate the strength of the undisturbed samples using a small shear vane but were unsuccessful due to its natural horizontal fibre structure which hindered insertion of the vane.

Using the extended von Post classification proposed by Hobbs (1986), the Ballynahown peat is classified as follows:

$$H_3\, B_3\, N_5\, P_0\, pH_L$$

Table 4-1: Average Ballynahown peat properties (classification)

Parameter:	Value:
Sampling Depth:	1.0 m
Moisture Content:	800%
Organic Content:	96.5%
Peat Bulk Density:	950 kg/m^3
Degree of Humification:	*H3*
pH:	4.8

4.2.2 Testing Programme

The peat stabilisation trials were carried out as specified in Section 3.3.2 and the binders used were OPC, RHC and combinations of each with GGBS. Binder contents used were 150 kg/m^3, 200 kg/m^3, 250 kg/m^3 and 300 kg/m^3 and OPC-GGBS (OPC+G) and RHC-GGBS (RHC+G) composite binders were trialled at 25:75 and 75:25 proportions. Table 4-2 provides details of the binder content and proportions used. The peat-binder mixture was compacted into 65 mm dia. by 320 mm long plastic moulds. Moulds were cured under water at a constant temperature of 20 °C with an 18 kPa surcharge applied immediately after mould preparation (see Figure 3-4 and Figure 3-5). Samples were cured for 7, 28 and 91 day curing periods, after which two 130 mm high samples were typically taken from each mould for strength testing (see Figure 4-1). Summary sheets with details of the results achieved during the stabilisation trials may be found in Appendix B.1.

Table 4-2: Details of the binders used during the Ballynahown peat stabilisation trials

Binder Type:	Binder Label:	Binder Content: kg/m^3	Proportions:	Curing Time: days
Ordinary Portland Cement	OPC	150, 200, 250, 300	1	7, 28, 91
Ordinary Portland Cement & GGBS	OPC+G-25:75 OPC+G -75:25	150, 200, 250, 300	25:75 75:25	7, 28, 91
Rapid Hardening Cement	RHC	150, 200, 250, 300	1	7, 28, 91
Rapid Hardening Cement & GGBS	RHC+G-25:75 RHC+G-75:25	200, 250, 300	25:75 75:25	7, 28, 91
GGBS	GGBS	250, 300	1	7, 28, 91

Figure 4-1: 65 mm dia. by 130 mm high stabilised peat sample before UCS testing

4.2.3 Moisture Content, Density & Compression Properties

Moisture Content:

As samples were stored with access to water, an assessment of the change in moisture content with time was carried out. Figure 4-2 shows the variations in moisture content of the raw peat (w_i), the peat-binder mixture (w_m) and the 7, 28 and 91 day stabilised peat (w_s). w_{mix} for the GGBS binder and mixes involving RHC were not recorded. The greatest reduction in moisture content is seen to occur upon mixing the dry binder with the raw peat (*i.e.,* w_i - w_{mix}), and the reductions are clearly reflected in the amount of binder added. A further small reduction in moisture occurs in the time between mixing and the 7 day w_s due to binding of water during the hydration reactions that take place and consolidation due to the application of the prestress. No further noticeable reduction in w_s was seen after 7 days.

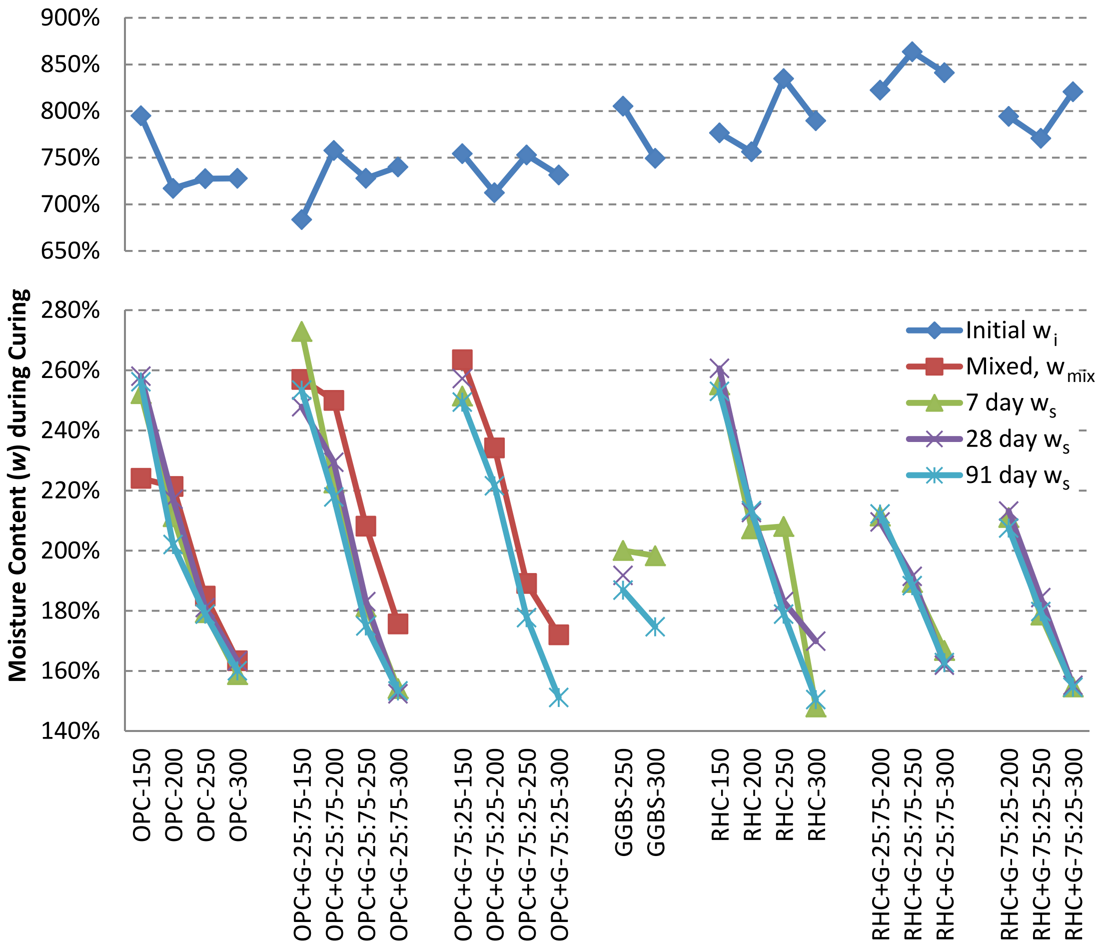

Figure 4-2: Change in moisture content during stabilisation and curing

Stabilised Density:

Freshly compacted densities (ρ_f), *i.e.,* the density of the mixed peat after compaction into the mould, are shown in Figure 4-3 for peat stabilised with OPC binders. ρ_f for other binders were not recorded. The stabilised densities (ρ_s), *i.e.,* the density of the stabilised peat sample at the time of UCS testing, are shown in Figure 4-4 for all binders. Both ρ_f and ρ_s are observed to increase with increasing binder content in most cases and ρ_s values are higher due to the surcharge loading applied during curing. The stabilised densities for each individual binder content show little variation over each of the three curing periods.

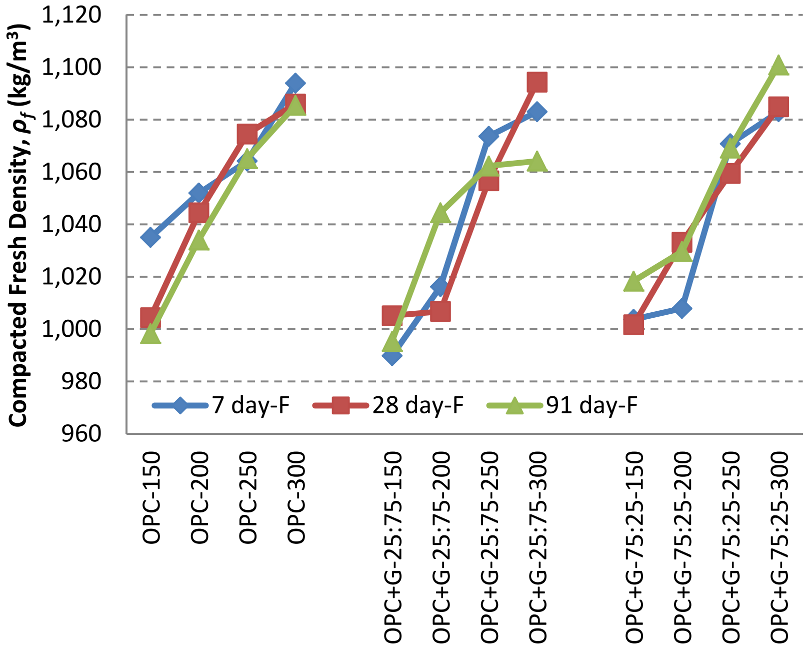

Figure 4-3: Compacted fresh density for 7, 28 & 91 day samples

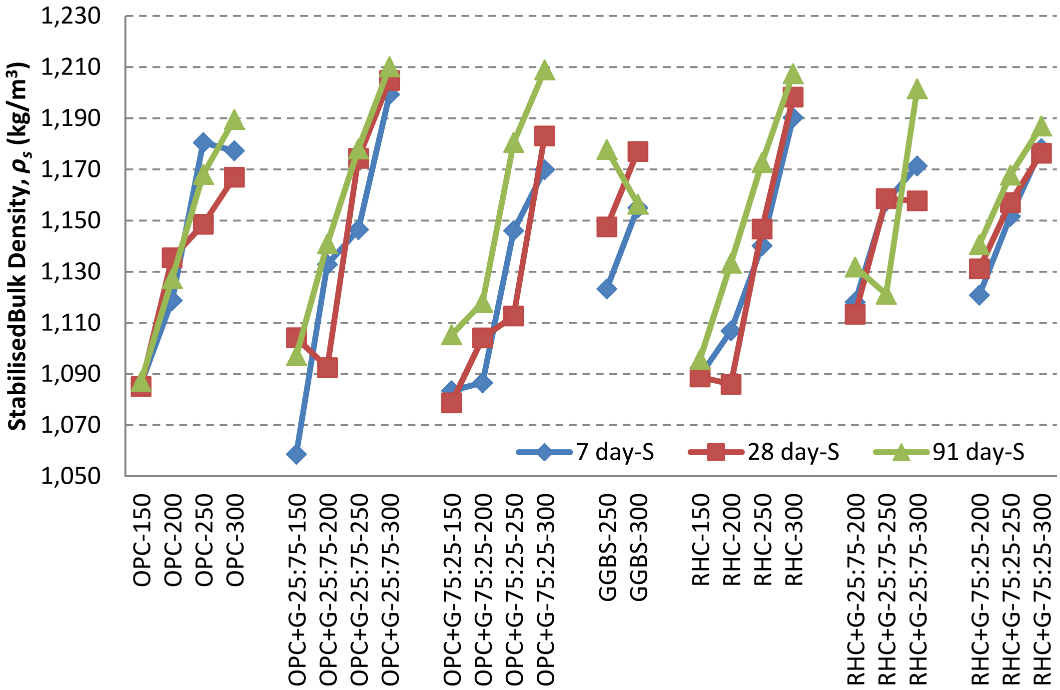

Figure 4-4: Average sample stabilised density after 7, 28 & 91 day curing periods

A small number of anomalies exist in the stabilised densities but are thought to be due to compaction issues or voids in the samples rather than measurement errors, *e.g.*, the 91 day

RHC+G-25:75-250 sample shows a lower stabilised density than other binder contents at the same curing period and is thought to be due to poor compaction or a void in the sample rather than a measurement error as later, in Figure 4-6, a similar type of anomaly is seen in its strength. No data on the ρ_f is available for this sample.

Sample Compression:

Figure 4-5 shows a comparison of the recorded compression in each individual 320 *mm* mould (due to the 18 kPa surcharge) at each of their respective curing times, *i.e.,* 7, 28 and 91 days. As expected, samples with a low binder content (and which attained poor strength results, see Section 4.2.4) are seen to have the highest compressions. Overall, a comparison of the mould sample compression with time shows the majority of compression to have occurred within the first 7 days of curing, although it is acknowledged that data at each curing period is for different mould samples. The compression results are lower than those seen by Åhnberg *et al.* (2001) for a cement-lime (80:20) stabilised peat (w_i = 1,600%), where compression values of approximately 30% were observed for hand prepared samples with no compaction, cured under an 18 kPa surcharge loading, where all compression was noted to have ended after one day.

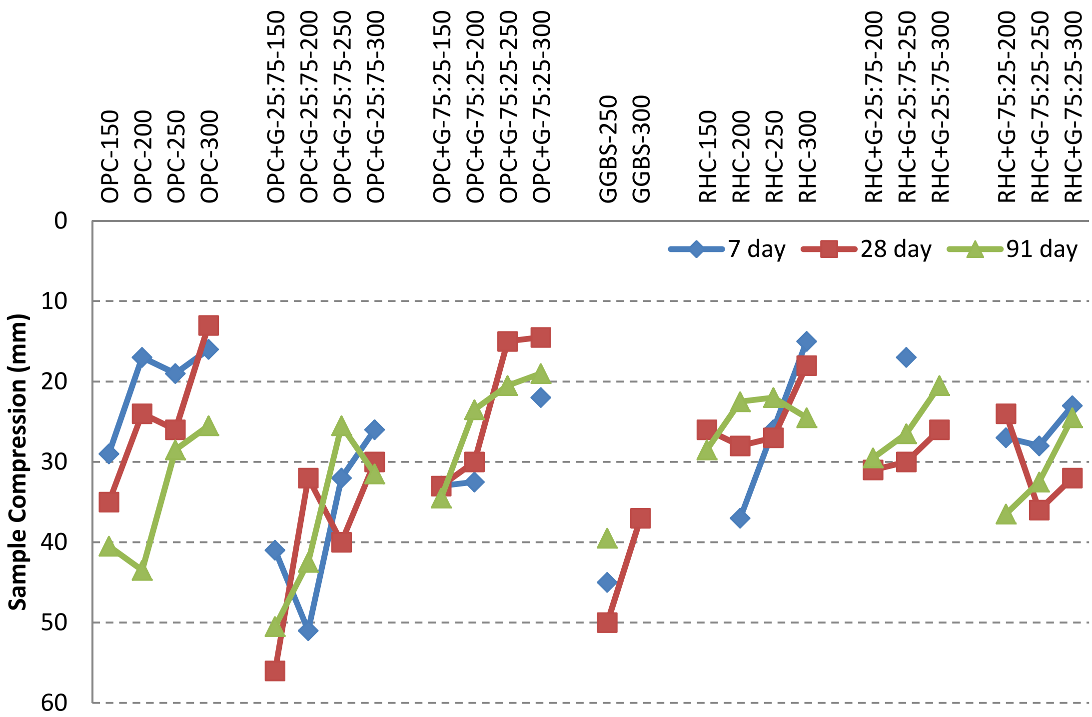

Figure 4-5: Sample compression after 7, 28 & 91 day curing periods

4.2.4 Unconfined Compression Strength

All stabilised samples show an increase in strength with both curing time and binder content, although some binders provided significantly better strength improvement characteristics. Figure 4-6 shows the increase in average unconfined compression strength (q_t) (n = 2) at each curing time for each of the binders trialled, and it can be seen that:

- OPC alone provided good overall strength improvements at all binder contents, with strength increasing with both binder content and curing time.
- In the composite OPC+G binders, the cement reactions provided the $Ca(OH)_2$ required to activate the GGBS portion of the binder. Where the proportion and amount of cement was low, poor initial reactions due to the presence of humic acids in the peat resulted in a lack of $Ca(OH)_2$ production. This can be seen at 150 kg/m^3 and 200 kg/m^3 in the OPC+G-25:75 results where poor strength improvements (lower than OPC alone) were achieved.
- At the higher OPC+G-25:75 binder contents of 250 kg/m^3 and 300 kg/m^3 very notable improvements in strength can be seen, as well as the long-term strength improvement properties of GGBS binders.
- For the OPC+G-75:25 binder, at 150 kg/m^3 and 200 kg/m^3, similar strengths were observed at all curing times and were typically below those of OPC alone. Again, the long-term strength improvements associated with GGBS were observed at 250 kg/m^3 and 300 kg/m^3 binder contents.
- GGBS alone was seen to give very poor strength gains at 7 and 28 days but, although strengths still remain less than 50 kPa, a noticeable strength improvement was seen by 91 days.
- RHC provided higher strengths than those seen using OPC with noticeably greater strengths at the highest binder content of 300 kg/m^3.
- The use of RHC+G resulted in excellent strength improvements, higher than those obtained using OPC+G binders and the long-term strength gains were evident. Good strength improvements were noted using the RHC+G-25:75-200 binder, compared to the very poor strength improvement that occurred with OPC+G:25:75-200.

In some samples, strengths did not follow the trend of increasing strength with binder content and reduced strengths were observed, see 300 kg/m^3 and 250 kg/m^3 RHC+G-

27:75 samples at 28 days and 91 days, respectively. These can be ascribed to the same anomalies that caused the density differences seen in Figure 4-4.

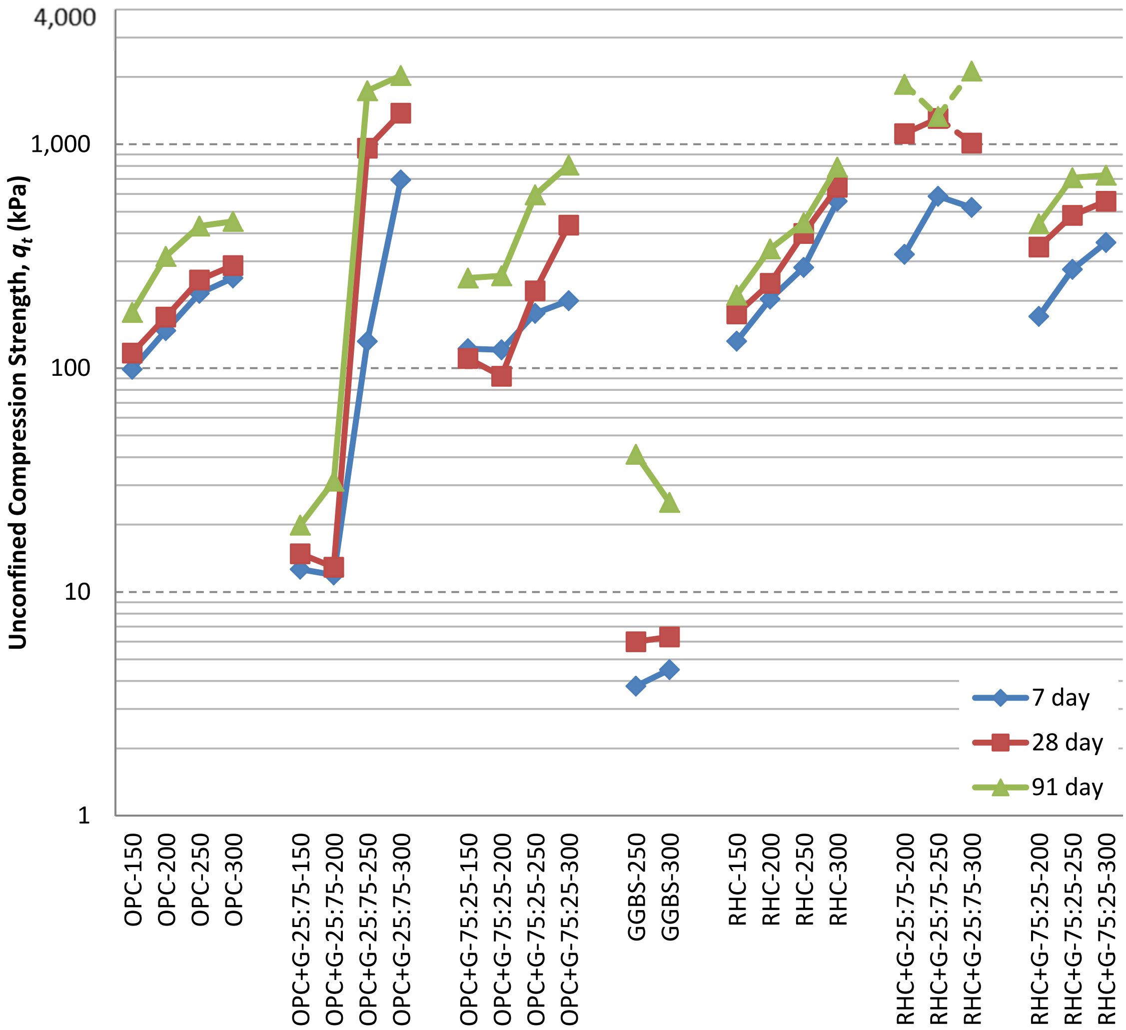

Figure 4-6: Average UCS after 7, 28 & 91 day curing periods

The moisture content of the raw peat used in each stabilised batch varies due to the inherent variability of the peat (see Figure 4-2). The *WTBR* term conveniently captures the effect of different moisture and binder contents in a single parameter and as seen in Section 2.8.1, *WTBR* (η) is defined as:

$$\eta = \frac{\rho_{soil}}{m_b\left(1 + \frac{1}{w_i}\right)} \qquad \text{4-1}$$

where ρ_{soil} is the *in situ* density of the soil (kg/m^3), m_b the binder content (kg/m^3) and w_i is the soil's initial moisture content.

In Figure 4-7, the strength is seen to increase with reducing *WTBR* for all binders at each of the curing times. The relationship between log q_t and *WTBR* is approximately linear for OPC, RHC and RHC+G-75:25 binders, showing uniform trends of increasing strength with a reducing *WTBR* across all binder contents. The significant strength increases of both OPC and RHC with high proportions of GGBS at low *WTBRs* are clear, as is the near lack of improvement in strength seen at high *WTBRs* (*i.e.*, η>4) for OPC+G-25:75.

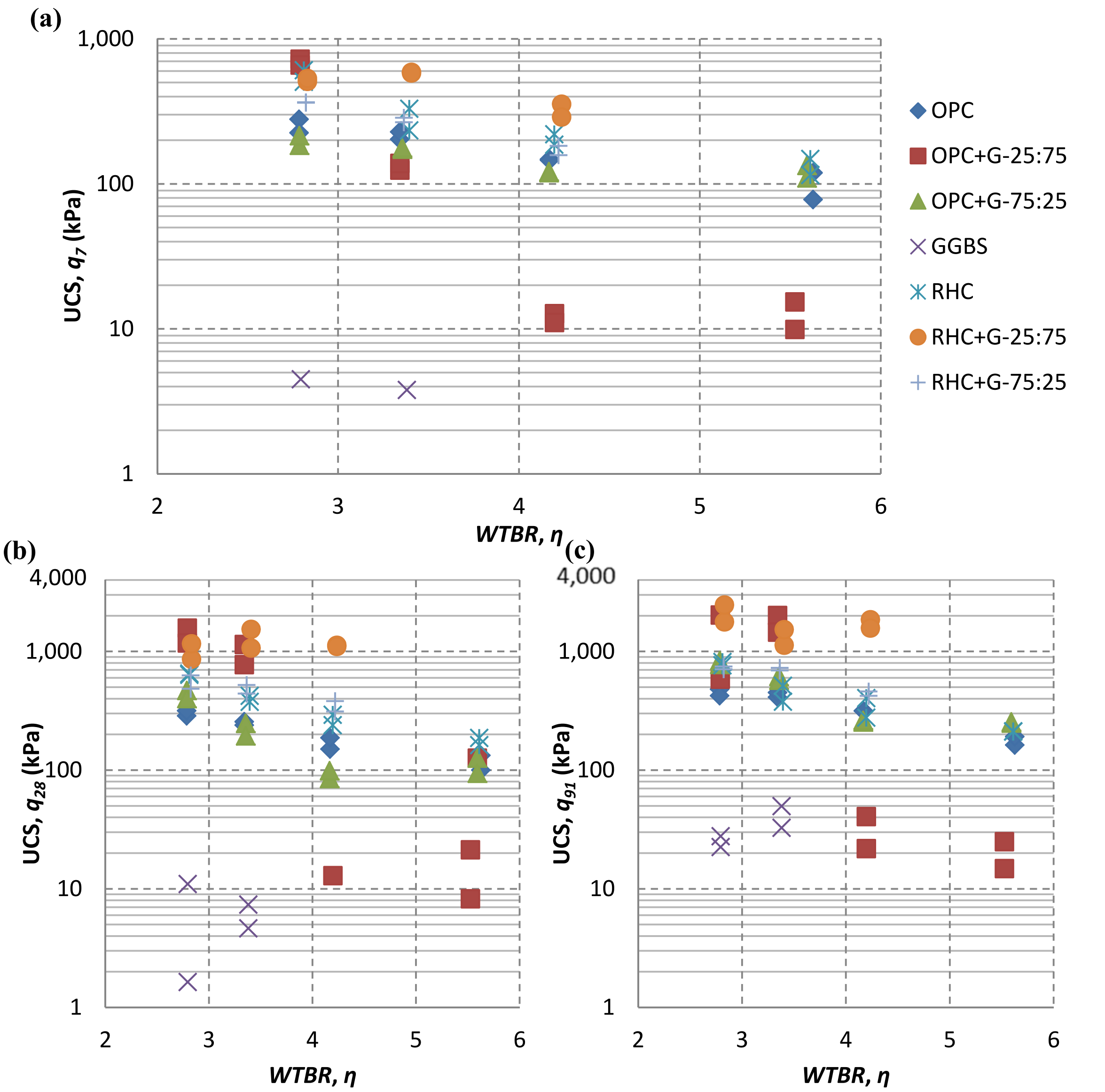

Figure 4-7: UCS with WTBR after curing periods of a) 7 days, b) 28 days & c) 91 days

4.2.5 Stabilised Stiffness & Failure Strain

Figure 4-8 shows the average secant stiffness at 50% of the failure stress (E_{50}) for each binder trialled. E_{50} is seen to increase with both curing time and binder content as expected and similar trends are observed to those seen for q_t as previously shown in Figure 4-6.

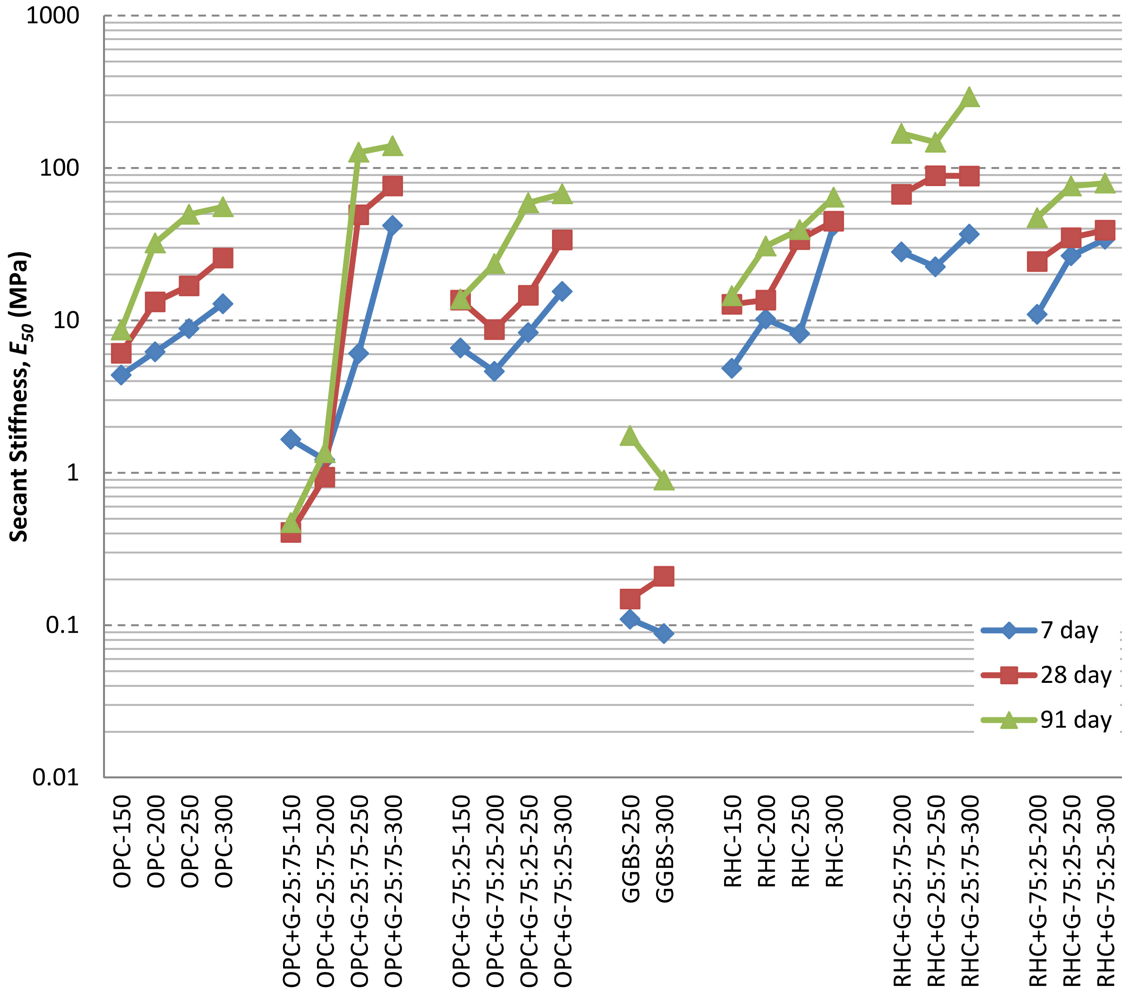

Figure 4-8: Secant stiffness (E_{50}) after 7, 28 and 91 day curing periods

Figure 4-9 shows the relationship between the c_u and E_{50} for all stabilised peat samples tested. E_{50} is found to lie in the range 75 to 250 times c_u and compares well with the approximate factors of 116 (Hebib & Farrell 2003) and 180 (range 110 to 240) (Quigley & O'Brien 2010) detailed in current literature for cement stabilised Irish peats (see Section 2.10.4). The reason for the spread in E_{50}/c_u values is illustrated in Figure 4-10, which shows the strong dependence on the failure strain ($\mathcal{E}_f$) for all samples tested. A number of points can be seen to lie outside the range for E_{50}/c_u previously stated. This is as a result of testing difficulties, where very low strengths occur (q_t < 25 kPa), *e.g.,* the 7 day OPC+G-25:75 samples and all GGBS samples, and where very high strength samples create difficulties in monitoring the rapidly increasing stress as a proving ring and dial gauge was used. Also superimposed on the graph, is the minimum E_{50}/c_u with $\mathcal{E}_f$

relationship (derived on the basis that $\mathcal{E}_f \geq 2\times\mathcal{E}_{50}$) and all data points are found to satisfy this relationship.

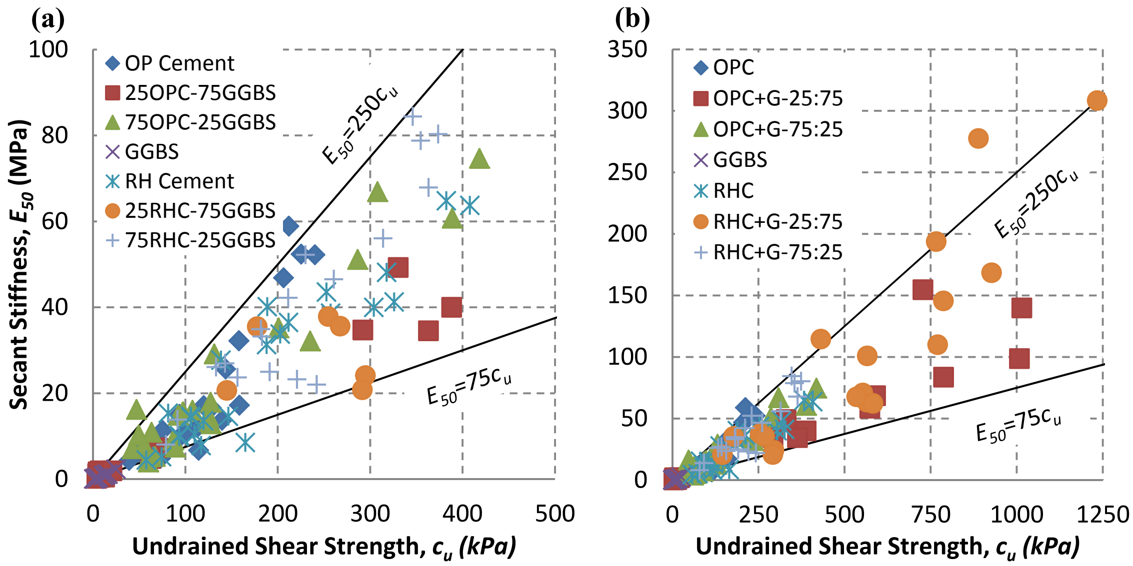

Figure 4-9: Secant stiffness (E_{50}) with undrained shear strength, a) data up to 500 kPa & b) all data

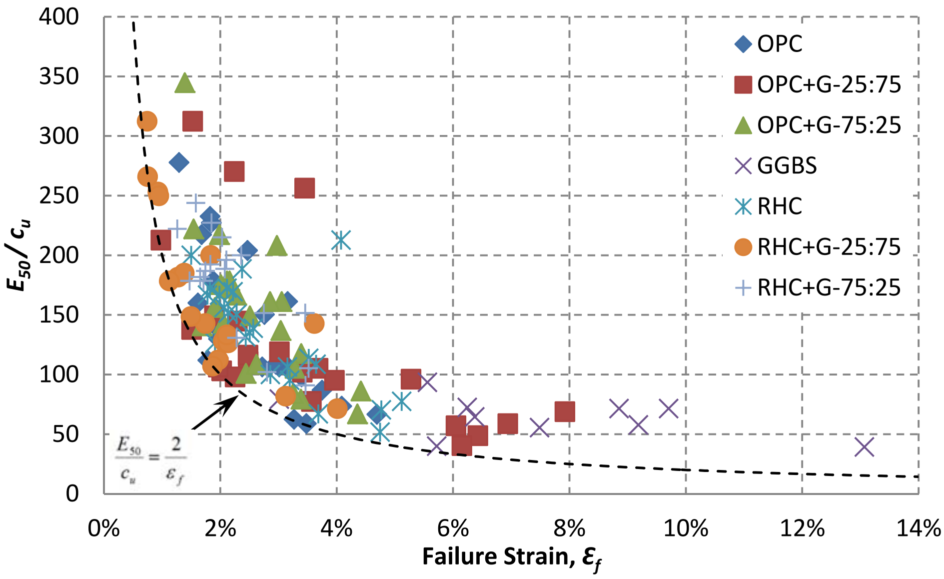

Figure 4-10: E_{50}/c_u with failure strain for all stabilised peat samples

4.2.6 Peat Stabilisation Compilation

A compilation of data on peat stabilisation from European and Japanese laboratory experiences may be found in Timoney *et al.* (2012a) in Appendix A. Furthermore, comparisons of the results achieved for the Ballynahown peat with other Irish peat stabilisation results may be found in Timoney *et al.* (2011; 2012b) (see Appendix A).

4.3 Kinnegar *Sleech*

4.3.1 *Sleech* Properties

A soft dark grey organic clayey-silt, known locally in the area as *sleech* (Crooks & Graham 1976), was sampled from Kinnegar, Hollywood in Co. Down in March 2011. The *sleech* was formed as a result of the deposition of clastic materials by the Lagan, Connswater and Blackstaff Rivers in the period following elevated sea levels due to retreating glacial ice over 9,000 years ago and an isostatic uplift of the land which followed (Crooks & Graham 1976). The *sleech* lies at depths between 2.2m and 9 m on a medium dense sand overlain by a layer of fill material and a sandy-silt. Extensive classification of the site has previously been carried out to investigate the geotechnical properties of Belfast clays (Crooks & Graham 1976; Bell 1977) and the behaviour of loaded pile groups (McCabe 2002).

Table 4-3 provides a summary of the properties of the *sleech,* sampled from a depth of between 3.0 m and 4.5 m, determined in accordance with BS1377-2:1990 (BSI 1996a). Moisture contents recorded during classification tests of the *sleech* were between 60% and 67% (average 63%, n = 8) and later during (the first series) of binder trials, w_i values were found to range from 48% to 71% from samples taken from the homogenised *sleech* used for each stabilised batch (see Figure 4-12). These values compare well to those found by Crooks & Graham (1976), Bell (1977) and McCabe & Lehane (2006), where further details of the *in situ* properties and their variability with depth may be found.

Table 4-3: Kinnegar *Sleech* properties (classification)

Parameter:	Value:
Sampling Depth:	3.0-4.5 m
Moisture Content Range:	60-67%
Organic Content Range:	4.5-5.6%
Average *In Situ* Bulk Density:	1,620 kg/m^3
Specific Gravity:	2.73
Liquid Limit:	75%
Plastic Limit:	27.5%
Average pH:	8.0

The average density of the *sleech* was found to be 1,620 kg/m^3 (n = 2) (having an average w_i of 65%) and had a specific gravity of 2.73 (n = 4) determined using the gas jar method. The liquid limit of 75% and plastic limit of 27.5% indicate a very high plasticity soil, while an average pH value of 8.0 (n = 4) indicates the soil to be slightly alkaline. Swedish fall cone tests carried out on undisturbed samples cut from excavated blocks of *sleech* indicated an undrained shear strength of 15 kPa using 100 g and 400 g fall cones and a remoulded strength of 4.5 kPa using a 100 g fall cone.

The organic content of the *sleech* from the classification tests was found to range from 4.5% to 5.6% (average 5.2%, n = 4) using the loss on ignition method by burning samples at 440°*C*. These values are lower than the 11% found by McCabe & Lehane (2006) in their classification tests but are similar to the value of 4% obtained by Crooks and Graham (1976) and the 3.0% to 5.1% range obtained by Bell (1977), both of whom carried out loss on ignition tests at 850 °C. During the reduced-scale column testing series, the results of which are presented in subsequent chapters, thin brown peat lenses, small layers of broken and intact shell, along with full oyster shells were found in the sampled *sleech* suggesting the origin of the organic content.

Table 4-4: Details of the binders used during the Kinnegar *sleech* stabilisation trials

Binder Type:	Label:	Binder Content: kg/m^3	Proportions:	Curing Time: days
OP Cement	OPC	25, 50, 100, 150	1	7, 28, 91
OP Cement & GGBS	OPC-G	50, 100, 150	50:50	7, 28, 91
GGBS	GGBS	50, 100, 150	1	7, 28, 91
OP Cement & Lime	OPC-L	50, 100, 150	50:50	7, 28, 91
Lime	L	50, 100, 150	1	7, 28, 91

4.3.2 Testing Programme

The *sleech* stabilisation trials were performed, as set out in Section 3.3.1, in two phases, the first comprising the use of OPC and GGBS in March 2011 and the second using OPC-Lime and Lime in October 2011. Overall, binder contents used were 25 kg/m^3, 50 kg/m^3, 100 kg/m^3 and 150 kg/m^3 and OPC-GGBS and OPC-Lime composite binders were created by mixing equal portions of each binder by hand. Further details of the binders used are given in Table 4-4. The *sleech*-binder mixture was compacted into 65 mm dia. by 320 mm long plastic moulds and sealed with plastic wrap, before being cured underwater at a temperature of 20 °C. Samples were cured for 7, 28 and 91 day curing periods, after which two 130 mm long samples were taken from each mould for UCS testing (see Figure 4-11). Summary sheets with details of the results obtained during the trials may be found in Appendix B.2.

Figure 4-11: 130 mm high, 65 mm dia. stabilised *sleech* sample

4.3.3 Moisture Content & Stabilised Density Properties

<u>Moisture Content:</u>

Figure 4-12 shows the variation in moisture content of the raw *sleech* (w_i), mixed *sleech* (w_m) and stabilised *sleech* at each curing time (w_s) for each binder tested. The variation in moisture content is particularly apparent during the OPC-GGBS binder trials and is due to the inherent variability of the *sleech* as highlighted in Section 3.12. Lower moisture contents were noted during the OPC-Lime and Lime trials as some moisture was lost due to drying out of the *sleech* also described in Section 3.12. Although data for initial moisture contents is limited, the greatest reductions in moisture content are seen after addition of the binder and only minor variations are seen thereafter. As each prepared mould was sealed in plastic wrap, no moisture is thought to have entered the samples during curing in the water bath.

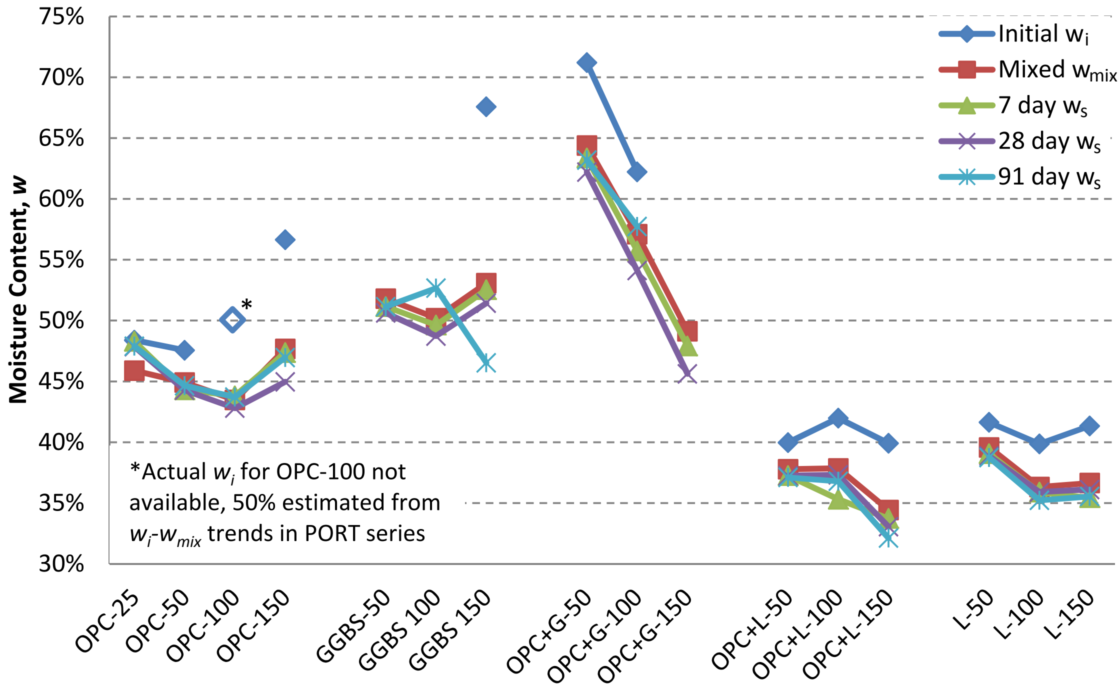

Figure 4-12: Moisture content at various stages during stabilisation and curing

Equation 2-16 was proposed by Åhnberg (2006) for estimating the stabilised moisture content of a soil using its initial moisture content, binder content and a non-evaporable water content for the binder used. Table 4-5 lists the non-evaporable water contents for the binders used in this series and where more than one binder was used, the non-evaporable water content is calculated using the proportions of each binder. Figure 4-13 shows a comparison of the estimated stabilised moisture content (w_{se}) and the measured value from the stabilised sample (w_s). Despite some scatter, good agreement is seen between w_s and w_{se}, although w_{se} for the GGBS binder appears to be overestimated.

Table 4-5: Non-evaporable water contents

Binder:	Non-Evaporable Water:	Source:
Cement	0.23	(Taylor 1997; Åhnberg 2006)
Lime	0.30	
GGBS	0.20	
Cement + GGBS	0.22	Estimated from Åhnberg (2006) using binder proportions
Cement + Lime	0.27	

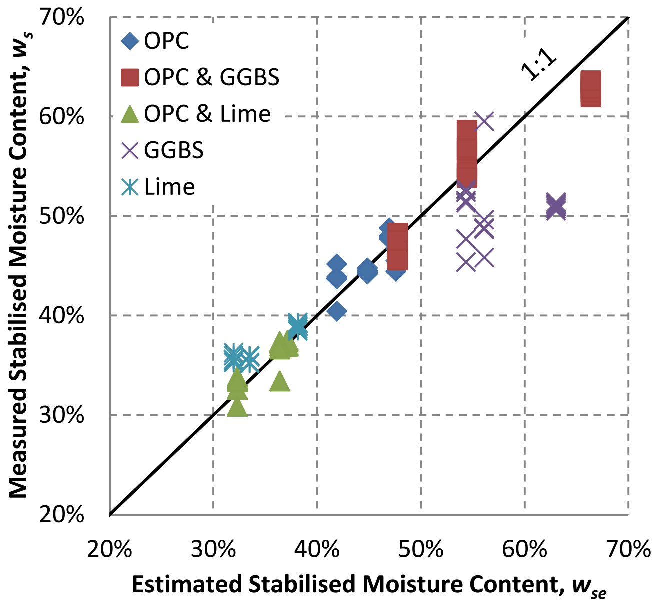

Figure 4-13: Measured versus estimate stabilised moisture content

Stabilised Density:

Figure 4-14 shows a comparison of the average stabilised density (ρ_s) at each curing time for each binder tested. Overall, no clear time effect can be seen in the stabilised densities and as data for the freshly prepared density (ρ_f) were not recorded, any changes in the individual sample densities of each mould during curing cannot be assessed.

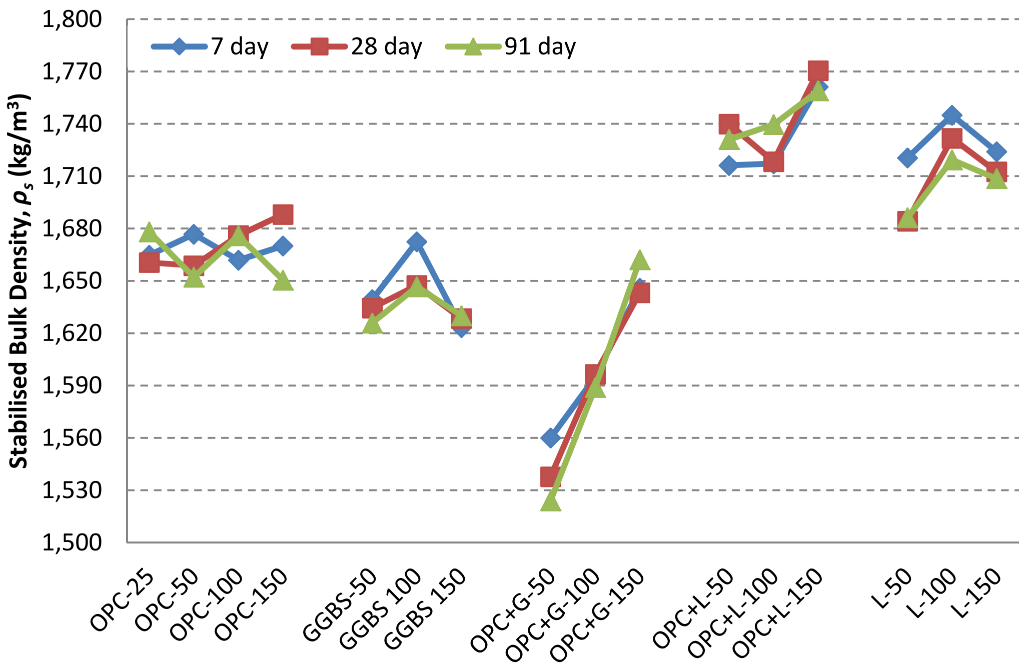

Figure 4-14: Stabilised density after 7, 28 & 91 day curing periods

Across the series a notable variation in ρ_s is evident, particularly with the OPC-GGBS results, but consideration must be given to the variation in w_i seen in Figure 4-11 which affects achieved densities. Figure 4-15 a, b & c shows ρ_s with w_{mix} at binder contents of 50 kg/m^3, 100 kg/m^3 and 150 kg/m^3, respectively as well as the effect of variations in w_m on the achieved densities. A reducing ρ_s with increasing w_{mix} is evident for all binder contents. Superimposed on the graph is an estimation of the compacted densities, calculated using Equations 4-2 and 4-3:

$$\rho_{Sleech} = \frac{G_s + w_i G_s}{1 + w_i G_s} \rho_w \qquad 4\text{-}2$$

$$\rho_{stab} = \frac{MS + BC}{MS/\rho_{Sleech} + BC/\rho_{OPC}} (1 - A_{stab}) \qquad 4\text{-}3$$

where ρ_{sleech} is the estimated fully saturated *sleech* density (kg/m^3) at a moisture content w_i, G_s is the specific gravity of the unstabilised *sleech*, ρ_w is the density of water (kg/m^3), ρ_{stab} is the estimated density of the stabilised sample (kg/m^3), MS is the mass (kg) of *sleech* in 1 m^3, BC is the mass (kg) of binder added to 1 m^3 of soil, ρ_{OPC} is the density of OPC (taken to be 3,150 kg/m^3 (Taylor 1997)) and A_{stab} is the volume of air in the stabilised *sleech* sample for an ideal cylindrical sample.

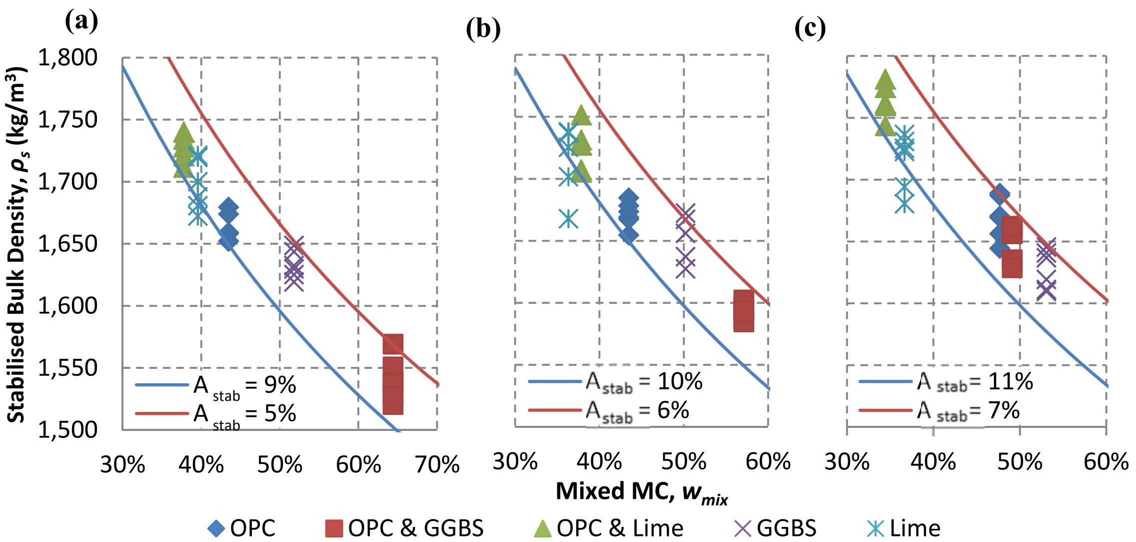

Figure 4-15: Stabilised density with mixed moisture content for a) 50 kg/m^3, b) 100 kg/m^3 & c) 150 kg/m^3 samples

A_{stab} values of 5% to 11% were found to fit all data best and increase with binder content, as well as showing a dependence on the moisture content. The presence of air in the laboratory stabilised samples has previously been noted by Åhnberg (2004) where degrees of saturation of 93% to 98% were seen in 50 mm dia. laboratory stabilised clay samples.

4.3.4 Unconfined Compression Strength

All stabilised samples show an increase in strength with both curing time and binder content, although some binders provided significantly better strength improvement characteristics. Figure 4-16 shows the average UCS (q_t) (n = 2) achieved for each binder after curing periods (t) of 7, 28 and 91 days, where it can be seen:

- At the lowest OPC binder content of 25 kg/m^3, little to no strength improvement occurs with a q_t less than 30 kPa and strengths similar to those measured in undisturbed blocks of raw *sleech* using a fall cone.
- At OPC binder contents of 50 kg/m^3 to 150 kg/m^3 notable strength improvements can be seen with a continued significant strength improvement occurring after 7 days with the 100 kg/m^3 and 150 kg/m^3 binder contents.
- GGBS alone gave poor stabilisation results in general but the long-term improvement properties can be seen at binder contents of 100 kg/m^3 and 150 kg/m^3 respectively where the q_t achieved at 91 days were 128 kPa and 466 kPa compared to 23 kPa and 27 kPa at 28 days. The delayed strength improvements are due to the slow formation of the reaction products associated with GGBS.
- When combined with OPC, GGBS at 100 kg/m^3 and 150 kg/m^3 gave higher strengths than their respective 7 day OPC samples and continue to gain strength in the long term producing the maximum observed strengths (up to 2.1 MPa) in this stabilisation trial.
- Lime alone resulted in poor strength gains with q_t between 30 kPa and 100 kPa in all cases. When combined with OPC, improved strength gains were observed but at all curing times strengths remained less than those at 28 days for OPC alone.
- The occurrence of a binder threshold, below which stabilisation results are very poor and little to no improvement with time occurred, may be seen with the OPC-25 and GGBS-50 binders.

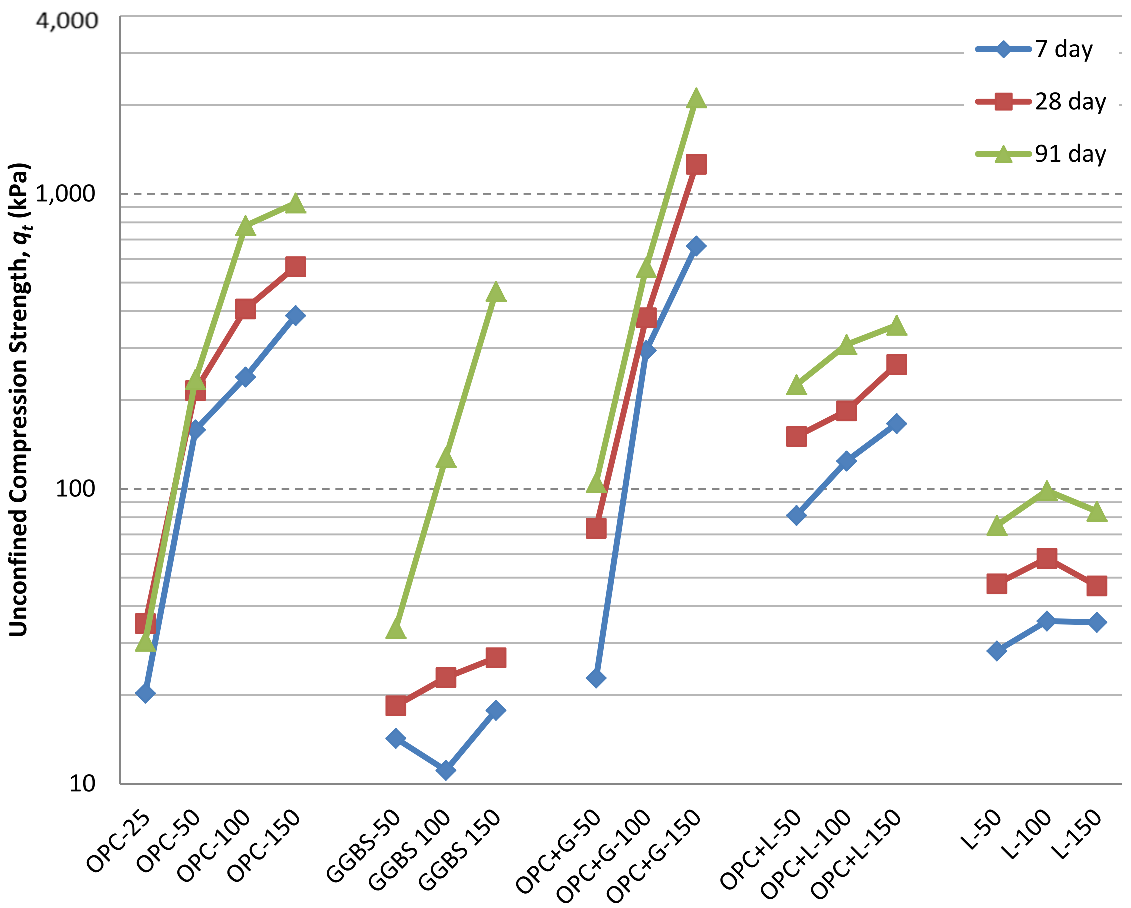

Figure 4-16: Average stabilised UCS after 7, 28 & 91 day curing periods

In order to account for the variations in the *sleech*'s w_i on the stabilised strength, Figure 4-17 shows q_t against *WTBR* (calculated using Equation 4-1) at each of the respective curing times. Once again, the *WTBR* captures the variations in w_i and binder content, with strength seen to increase with reducing *WTBR* in all cases. OPC and OPC-Lime binders show uniform trends of increasing strength with a reducing *WTBR* across all binder contents. The significant strength increases of OPC-GGBS at low *WTBRs* are clear, as is the very poor stabilisation seen with GGBS alone and again with the OPC-25 binder. For OPC binders, it can be seen that q_t varies linearly with inverse *WTBR* as shown in Figure 4-18, with high R^2, and this is exploited to help interpret strength data later in Chapters 5, 6 and 7.

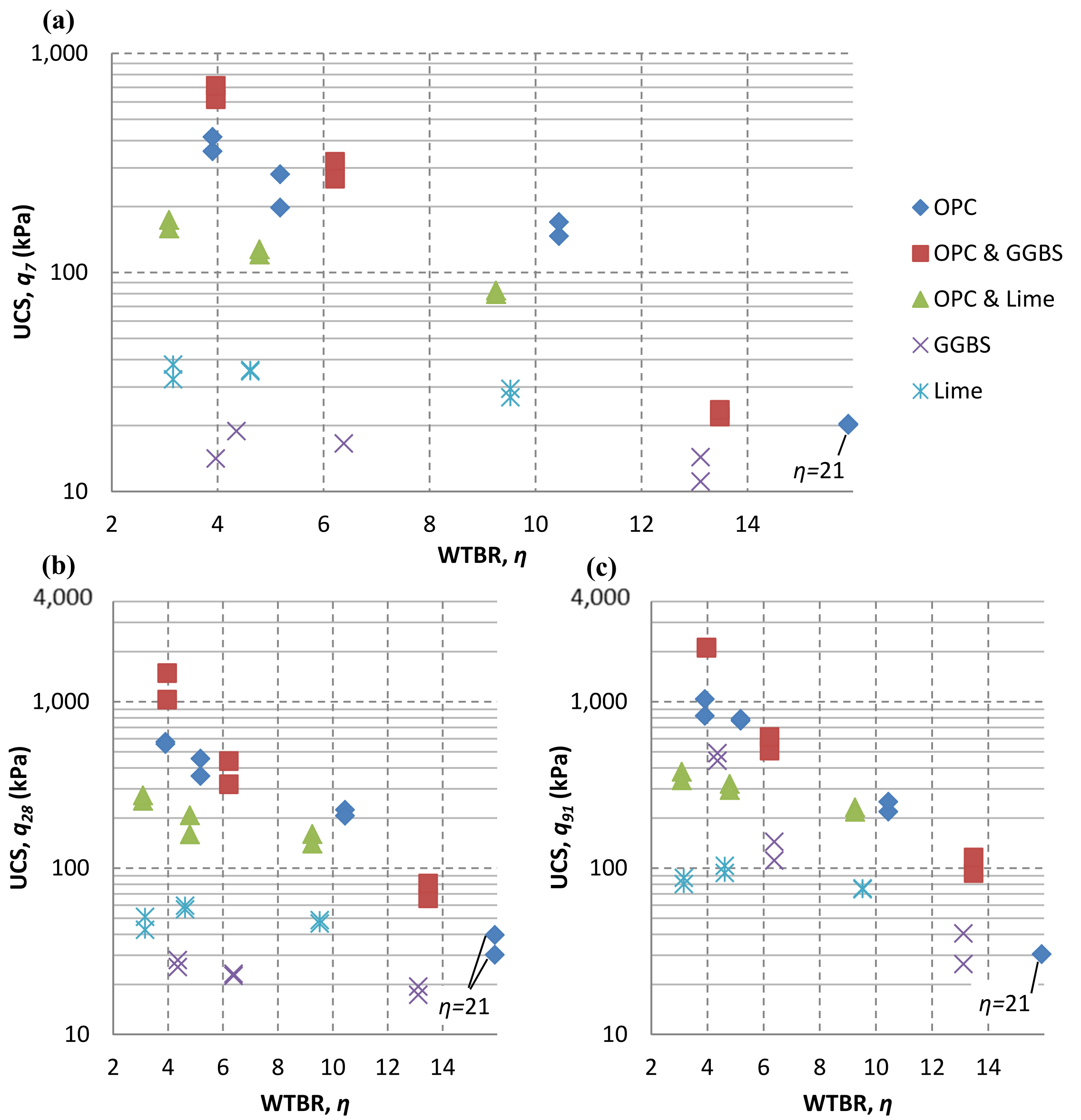

Figure 4-17: Average UCS vs WTBR after a) 7 days, b) 28 days & c) 91 days

4.3.5 Stabilised Stiffness & Failure Strain

Figure 4-19 shows the average stiffness at 50% of the failure strain (E_{50}) achieved for each binder after 7, 28 and 91 day curing periods. Similar trends of increasing stiffness with binder content and curing time were observed to those seen with q_t. Figure 4-20 shows the relationship between c_u and E_{50} for all stabilised samples tested. Overall E_{50} values are seen to lie in the range of 100 to 275 times c_u (E_{50} = [50-138]q_t) but at lower strengths the data fits within a narrower range of E_{50} = [100-200]c_u. These relationships are compatible to those compiled in Section 2.10.4 for other stabilised clays and silts.

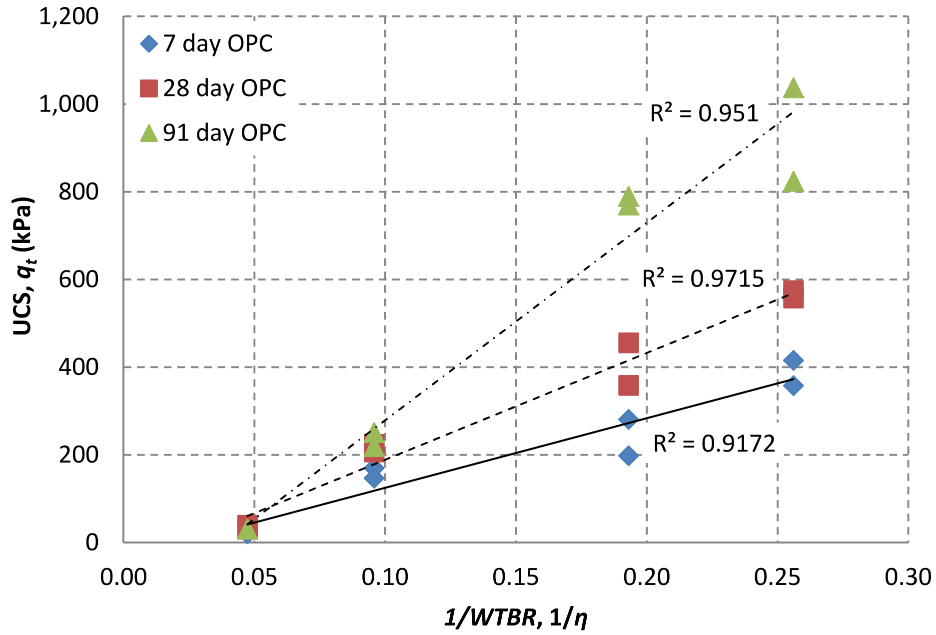

Figure 4-18: Unconfined compression strength with 1/*WTBR* at each curing period for OPC binders

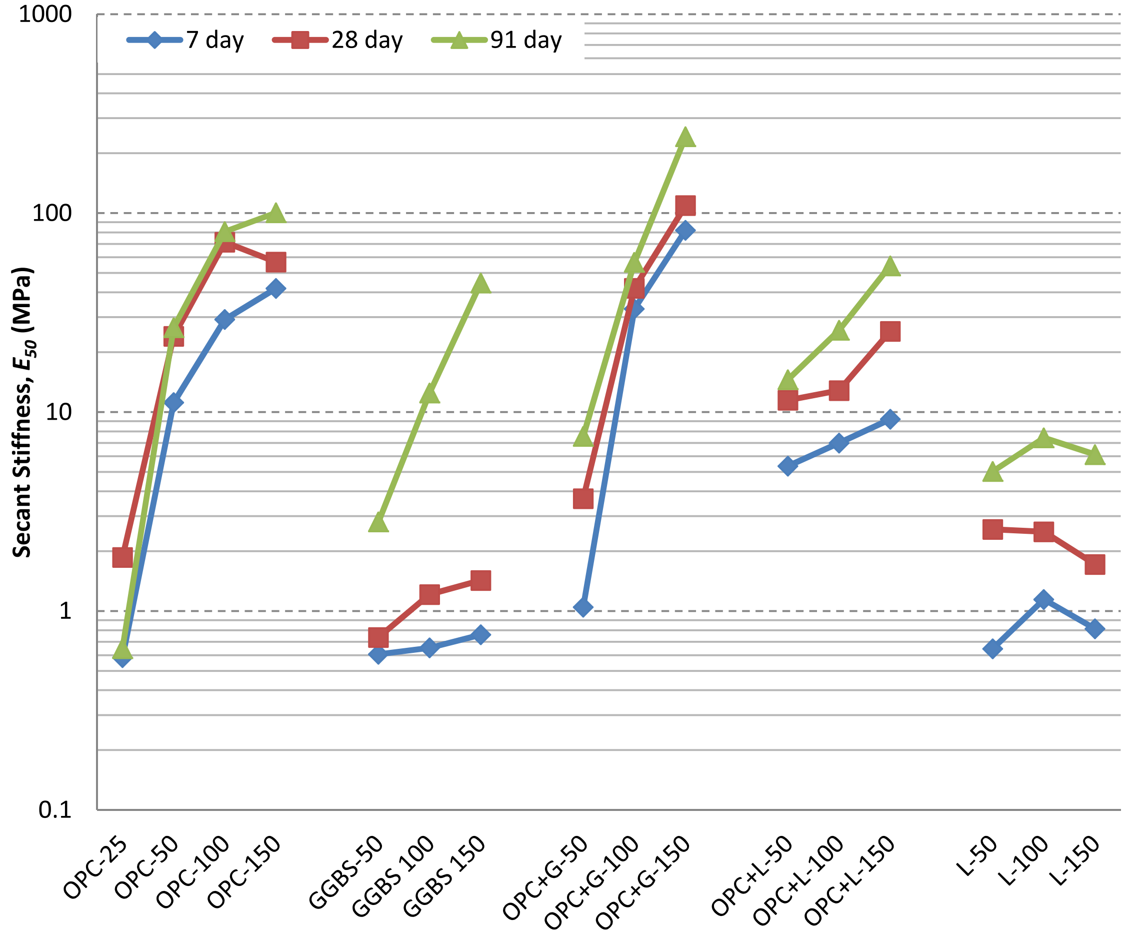

Figure 4-19: Secant stiffness (E_{50}) after 7, 28 & 91 day curing periods

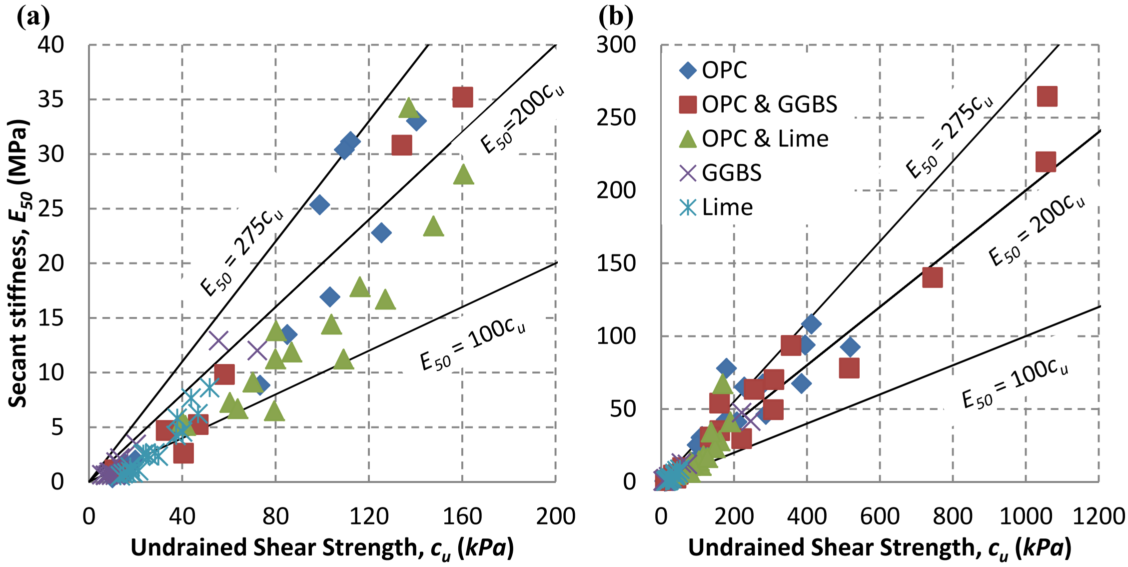

Figure 4-20: Secant stiffness with undrained shear strength: a) data up to 200 kPa & b) all data

Figure 4-21 shows the E_{50}/c_u relationship with failure strain ($\mathcal{E}_f$) for all samples tested, where E_{50}/c_u is seen to increase with reducing $\mathcal{E}_f$. A number of points can be seen to lie outside the range for E_{50}/c_u previously stated and are as a result of similar issues to those described in Section 4.2.5, but again all data satisfies the minimum E_{50}/c_u with $\mathcal{E}_f$ relationship.

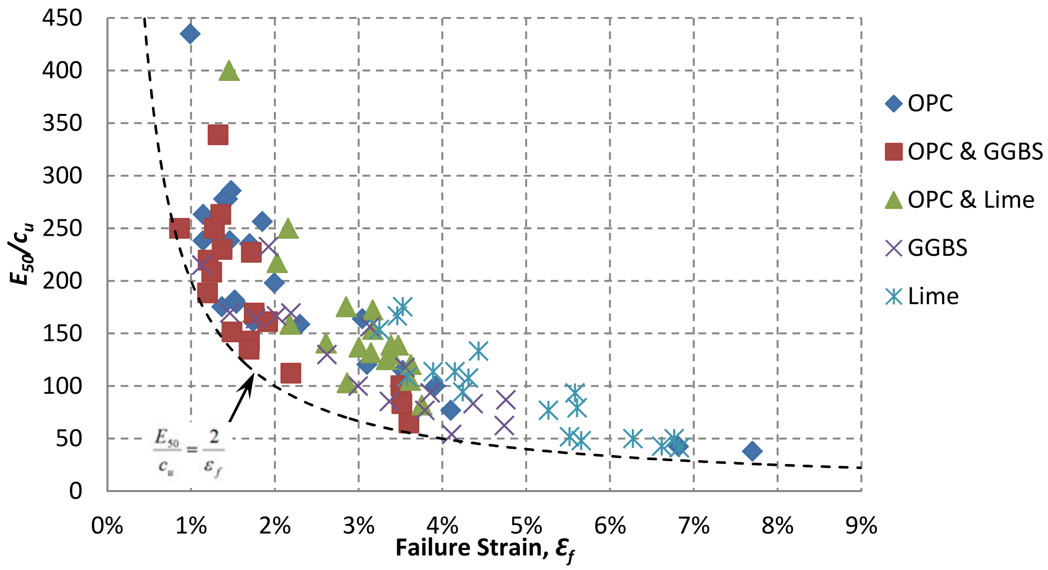

Figure 4-21: E_{50}/c_u relationship with failure strain

4.4 Laboratory Stabilisation Concluding Remarks

4.4.1 Achieved Stabilisation Results

Two organic Irish soils, a H3 peat and a clayey silt (*sleech*), were successfully stabilised, achieving strengths up to 1.5 MPa at 28 days using binder contents up to 300 kg/m^3 and 150 kg/m^3, respectively. Cement binders were found to give good strength improvements, while cement-GGBS binders were found to give the best results in both soils. Strength was seen to increase with both curing time and binder content, in agreement with that seen in Chapter 2 and, due to the higher organic content of the peat soil and its low mineral content, higher binder contents were required to stabilise the peat compared to the *sleech*.

4.4.2 Subsequent Reduced-Scale Column Testing

The experience gained and the results obtained during both series of stabilisation trials led to a number of decisions regarding the proposed reduced-scale column tests. Initially, the tests were proposed to be carried out in either a soft clay/silt or a peat, and although samples of peat for the test series would be easily accessible, a number of issues were envisaged regarding the use of peat:

- Due to the overall time required to complete the test series, the initial properties of the peat could change. The moisture content is envisaged to be the most difficult to control as during storage, of the large volume required to complete the proposed penetrometer test series, moisture may pool at the base of the storage basins and the upper layers may dry out. The increased temperature experienced during storage, compared to that *in situ*, may also result in an increased rate of humification of the peat.
- Issues regarding replication of *in situ* field conditions of the peat surrounding the column during curing and reuse of the peat in multiple tests were envisaged. Previous tests by Hebib & Farrell (2003) used large undisturbed blocks of peat (1 m cubes) which were then cut to the required size and lowered into the testing basin specifically to ensure similar conditions were obtained to that in the field.

- With regard to PORT of a stabilised column, the surrounding peat would provide little to no friction resistance to the pull-out of the column by the PORT penetrometer, even at low stabilised strengths.

From the experience and results gained, it was concluded that the organic clayey-silt (or *sleech*) would be the most suitable soil type for carrying out of the reduced-scale column series. OPC was chosen as the most suitable binder type due to it being readily available from local builder's merchants. Binder contents of 100 kg/m^3 and 150 kg/m^3 were chosen due to the suitable strengths (of up to 600 kPa) that they provided at curing periods up to 28 days.

CHAPTER 5: PULL-OUT RESISTANCE TEST (PORT) RESULTS

5.1 Introduction

In this chapter, the results from a series of reduced-scale PORTs on 200 mm dia. stabilised soil-cement columns are presented. Four preliminary columns (PO-1 to PO-4) were constructed to define suitable construction and testing procedures, but the results are not considered in this thesis.

The results of 13 no. PORT (PO-5 to PO-17*) carried out between July 2012 and July 2013 are considered and are summarised in Table 5-1. Each PORT column experiment is given a full designation *PO-X-Y-Z,* where:

(i) *X* refers to the column test reference number and *PO-X* is used as an abbreviated reference to the test.

(ii) *Y* represents the curing time, to the nearest day, from column construction to PORT and ranges from 1 to 13 days to achieve certain target strengths.

(iii) *Z* represents the binder content (kg/m^3) used to stabilise the *sleech* and was either 100 kg/m^3 or 150 kg/m^3 of OPC.

The "*" designation for PO-17-12-150* (or PO-17*) is used to highlight that while most of the column was constructed using a binder content of 150 kg/m^3, one of the four mixes was stabilised with 100 kg/m^3, with the aim of ascertaining the effect of a significant strength difference within the column. The "S" designation (PO-13S and PO-14S) indicates columns where a surcharge was applied during curing and testing of the column, the purpose being to increase confinement in the curing basin, particularly around the top of the column during testing.

The relevant properties recorded during construction, curing and testing of each column (and their associated mould samples) are presented in this chapter. Section 5.2 presents the recorded PORT pull-out force profiles for each column, along with the results of a PORT in unstabilised *sleech* and a stabilised column-*sleech* friction experiment. Section 5.3 details the moisture content of the *sleech* used in each individual mix, while Section 5.4 presents details of the test conditions such as ambient laboratory curing temperature, curing stress conditions and the properties of the surrounding *sleech* in which each column cured. In Section 5.5, the stabilised moisture content and the stabilised density at the time of UCS testing are presented. Section 5.6 presents the stabilised strength and stiffness properties of the respective mould and column samples tested in the PORT column test series. Finally, in Section 5.7 the results of a statistical analysis carried out on the mould and column strength sample data are presented.

While it is inevitable that there will be scatter in data that involves DSM of a natural clay (which is inherently variable to begin with) as discussed in Section 3.12, a framework is presented within which the variability can be accounted for and the quality confirmed.

5.2 Pull-Out Resistance Test Experiments

5.2.1 Introduction

This section sets out the pull-out forces recorded during each of the PORT column experiments, as well as a reference PORT penetrometer pull-out experiment in unstabilised *sleech* and an experiment to determine the friction between the stabilised column and the surrounding *sleech*.

5.2.2 PORT Experiments on Stabilised Columns

Pull-out of the PORT penetrometer was carried out in a single pull without pause and average pull-out rates recorded were typically between 16 mm/sec and 17 mm/sec. Table 5-1 shows each column's average pull-out rate. Loading on each column to prevent extraction of the whole column during the test was typically 150 kg, but PO-5, the first successful test, was loaded with 100 kg while a greater loading of 200 kg was placed on PO-12 due to the higher strengths envisaged at the 13 day curing time.

Figure 5-1 shows the uncorrected pull-out force (P_o) with the height from the basin base (h) for each of the 13 no. PORT columns under consideration, grouped by curing times. Due to slight variations in constructed column lengths, the basin base is used as a datum to present the probing force profiles.

Table 5-1: PORT column details

PORT No.	PORT Time, t_{Po} days	UCS Time, t_{col} days	Binder Content kg/m^3	No. of Mixes	Column Height, *h*, mm	*Sleech* Moisture Range, w_i, %	No. Column Samples	Average Column UCS, kPa (*Uncorrected*)	Column UCS St. Dev, kPa	Average Column UCS, kPa (*Corrected*)	Average Ambient Temp. *T*, °C	Column Loading kg	Pull-Out Rate mm/sec
PO-5	4.95	5.10	100	2	550	56-58	3	232.6	58.3	229.5	18.0	100	14.8
PO-6	5.88	6.07	150	4	965	54-59	18	586.6	114.4	581.3	19.2	150	15.3
PO-7	5.96	6.14	100	5	1,040	54-60	8	348.2	80.0	345.0	20.5	150	16.9
PO-8	1.95	2.22	150	4	1,000	48-54	11	411.6	47.0	389.6	20.1	150	16.5
PO-9	3.95	4.15	150	3	860	48-49	11	470.7	71.1	461.9	19.6	150	16.5
PO-10	11.97	12.25	150	4	970	(55) 65-69	16	442.5	47.4	439.1	14.6	150	16.8
PO-11	5.89	6.28	150	4	960	61-65	13	439.6	67.8	429.8	14.1	150	16.8
PO-12	12.95	13.36	150	4	1,000	55-58	17	677.8	76.4	672.9	15.5	200	16.6
PO-13S†	5.96	6.24	150	5	975	49-54	7	470.3	42.6	462.3	14.9	567†	16.5
PO-14S‡	11.98	12.28	150	5	985	50-52	18	633.0	102.9	628.8	13.5	570‡	16.5
PO-15	0.95	1.23	100	5	995	47-40	12	147.4	21.1	117.2	14.1	150	16.7
PO-16	11.92	12.23	100	4	950	46-50	9	502.5	78.0	499.5	14.6	150	17.3
PO-17*	11.81	12.05	150*	4	1,040	52-56	17	493.0	75.2	489.7	18.0	150	16.2

†13.6 *kPa* surcharge on the basin during curing and testing via a 722 mm dia. loading plate

‡13.7 *kPa* surcharge on the basin during curing and testing via a 722 mm dia. loading plate

* Mix 2 (height from basin base 380 mm to 595 mm) was stabilised with 100 kg/m^3 rather than the 150 kg/m^3 used in all other mixes in PO-17*

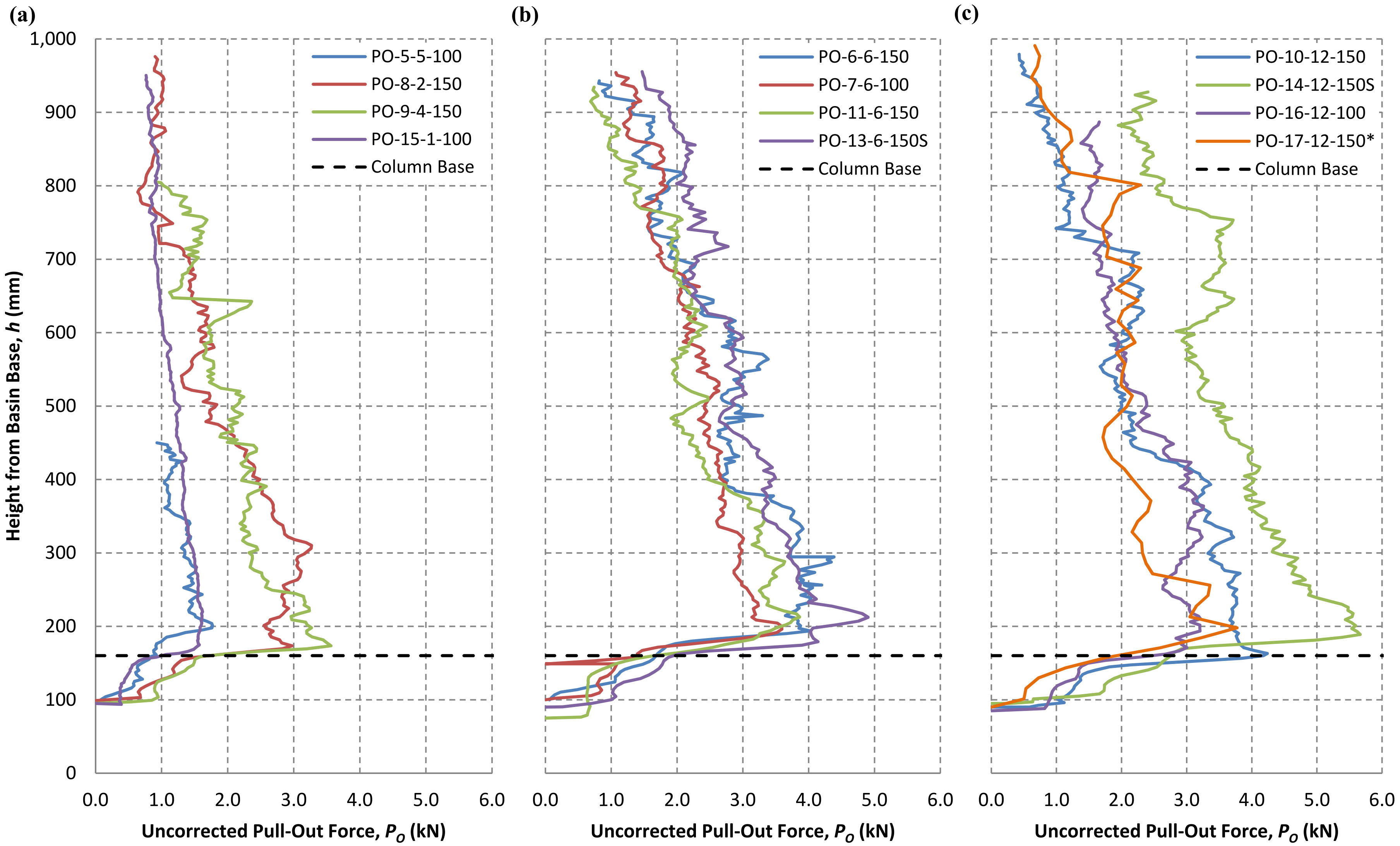

Figure 5-1: Recorded PORT probing force with height from basin base: a) 1-4 day columns, b) 6 day columns and c) long duration (12 & 13 day) columns

At the beginning of the test, P_o increased to a magnitude of between 0.5 kN and 1.0 kN as the penetrometer exited the sand layer and cut through the unstabilised *sleech* under the column. This force also incorporates that due to the breaking of the bond between the pull-out wire and the stabilised column. As the penetrometer approached the base of the column the force rose sharply again and reached its peak a short distance into the column. From the peak, the force reduced with increasing h as the penetrometer cut through the column but does not reach zero force as the test was stopped roughly 50 mm below the top of the column so as not to damage the penetrometer or the test setup.

Overall, P_o shows a general increase with curing time and binder content but at this stage it is inappropriate to compare P_o solely based on these two factors as other factors, such as moisture content and curing temperature, influence the strengths achieved. These factors are considered later in this chapter.

In PO-7, the PORT penetrometer was pulled up by 47 mm, 4 days after construction so as to reduce the bond between the wire and stabilised column at the time of PORT, a procedure which is also carried out in field tests. P_o was seen to rise instantly to 0.82 kN as the bond with the column broke and then on to 1.09 kN as the penetrometer cut through the unstabilised *sleech* layer approaching the base of the column where the test was stopped. When PORT of the column was carried out two days later, the P_o profile appears to be unaffected by the pause between the two pull-out phases. As trends similar to those seen in field PORT of a high initial peak P_o (see Figure 2-15) were not observed, breaking the bond between the wire and the column before the full test was deemed unnecessary in these reduced-scale tests. It is thought that repeated straightening of the wire during PORT column construction disturbed the bond that had formed and although some bond did reform, it was not to the extent of that if the wire had not been disturbed. This was further supported in the results of the wire friction tests described in Section 7.2 and is revisited in Section 8.5.2.

Comparisons of the surcharged columns with non-surcharged columns, *i.e.,* PO-6 and PO-11 with PO-13S, and PO-12 with PO-14S, show the presence of the surcharge resulted in an increased P_o at the top of the column. As column strengths at this location at the time of the test were found to be similar, approximately 434 kPa to 445 kPa (PO-6, PO-11 and PO-13S) and 618 kPa and 654 kPa (PO-12 and PO-14S), the increased P_o is deemed to be the result of increased confining stresses around the top of the column which prevented it from cracking open. In the varied binder content column (PO-17*), P_o shows notably lower forces than that of other similar columns with a near constant force of approximately 2 kN in the middle and upper section of the column (from h = 300 mm to 800 mm).

Upon exhumation of the columns, similar cracking patterns were noted throughout the tested columns, running from the centre of the column diagonally upwards and out to the face of the column and in places significant cracking was noted over the column's cross-section. It is likely that this cracking is the explanation for the jaggedness in some P_o profiles. The PORT column crack patterns are shown in the column cracking diagrams in Appendix F.2 and are discussed in Section 8.3.3, along with the effect of cracks in the column on the probing force.

5.2.3 PORT in Unstabilised *Sleech*

A PORT penetrometer experiment was carried out in unstabilised *sleech* to investigate both the N value in an unstabilised soil and the pull-out forces underneath a column without the contribution of friction between the pull-out wire and the column. To replicate the mass of the PORT column on the *sleech* underneath it in this test, the 225 mm dia., 500 mm high basin was loaded with 40 kg after construction and during testing which was carried out in two pulls at average pull-out rates of 16.6 mm/sec and 16.4 mm/sec.

Figure 5-2a shows the pull-out force (P_o) recorded during the test, where it can be seen that P_o rises instantly to a peak as the penetrometer is pulled out of the sand layer. Once in the *sleech,* a trend with depth consistent to that shown in Figure 5-2b for the *sleech* c_u can be seen. Pull-out forces (< 0.2 kN) are seen to be a small proportion of those observed under the stabilised columns during PORT (typically < 1.2 kN), the difference in magnitude being due to material adhered to the pull-out wire being removed at the beginning of the test and friction between the column and pull-out wire.

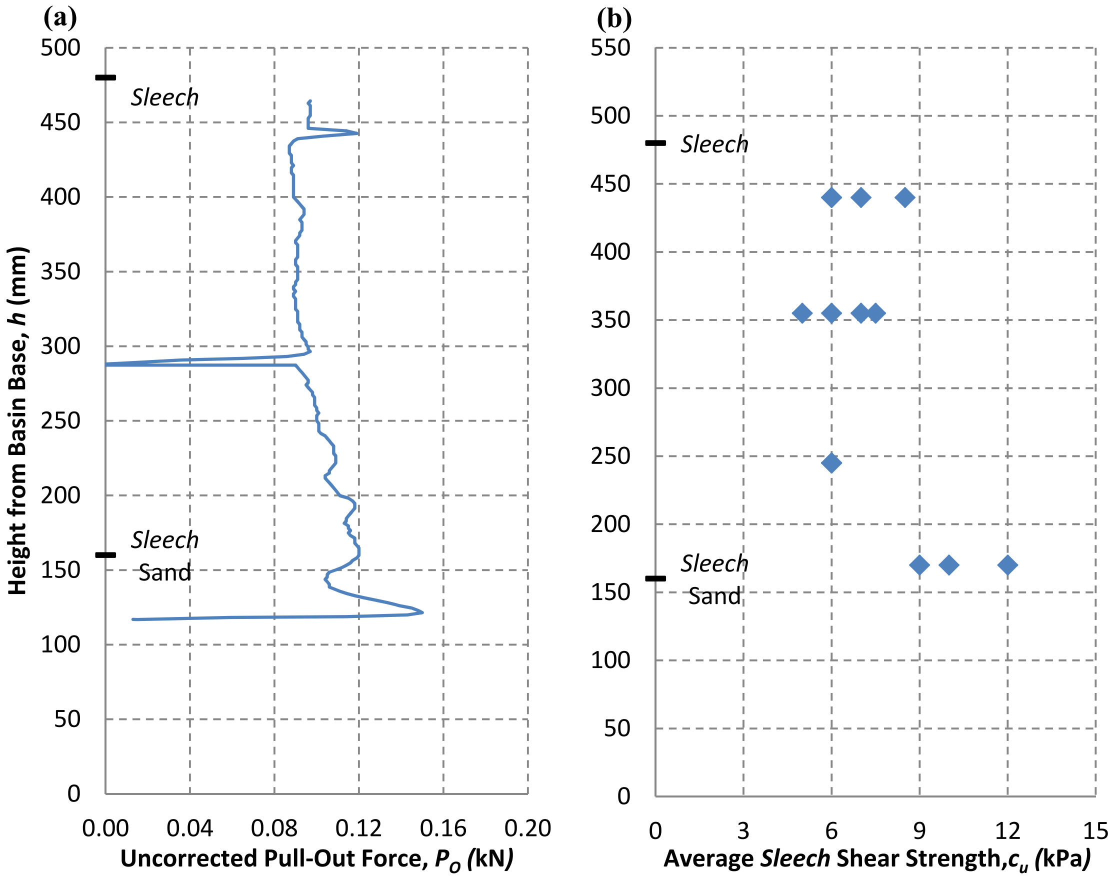

Figure 5-2: a) PORT in unstabilised *sleech* & b) average *sleech* undrained shear strength

5.2.4 Stabilised Column-*Sleech* Friction Experiment

To estimate the friction between the column and the unstabilised *sleech* around it, a mini stabilised column, 320 mm long and 65 mm in diameter was created with a 4 mm dia. wire rope running through its centre and a fixed plate at the column base (see Section 3.7.6). After a curing time of 7 days, the column was pulled out of the surrounding *sleech* and the pull-out force is shown in Figure 5-3. From the recorded data, the maximum force was seen to be 0.25 kN after a displacement of 12 mm and the peak friction between the column and surrounding *sleech* was determined to be approximately 4 kN/m^2. This test was performed following pull-out of the entire column during PO-3 and was used as an aid in defining the magnitude of the loading required to prevent pull-out of the column from the surrounding *sleech*.

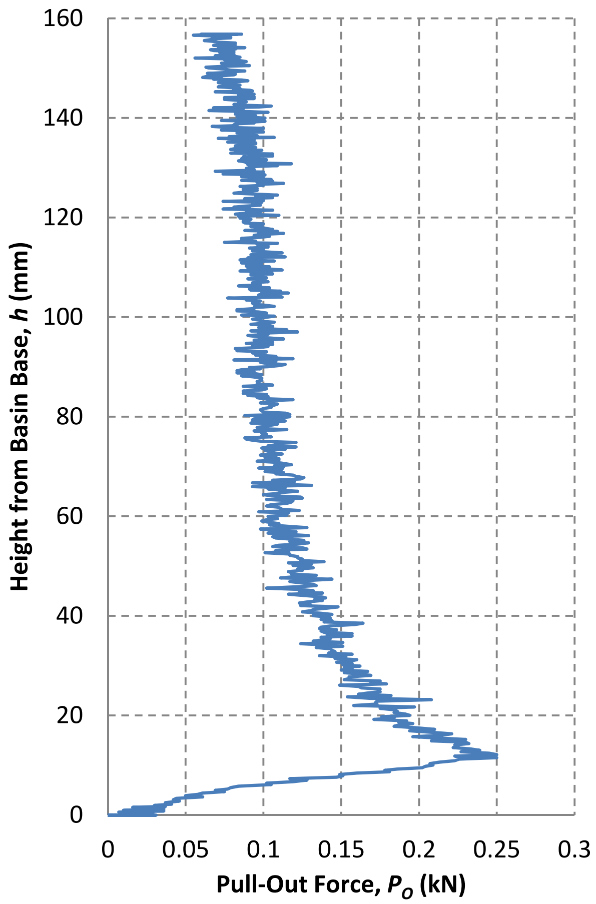

Figure 5-3: Column pull-out friction experiment

5.3 PORT Column Moisture Content

Figure 5-4 shows the initial moisture content of the *sleech* (w_i) at mid-depth for all mixes within each column, while the number of mixes in each column, typically either four or five mixes, is given in Table 5-1. The value of w_i, determined from samples taken from the homogenised *sleech* before addition of the binder, was found to range between 46% and 69%, but predominantly lie in the range 46% to 60%. The factors influencing the variability of w_i in the *sleech* over the test series and within a particular column have previously been set out in Section 3.12.

Coefficients of Variation (CoV) for w_i within a single column (see Table 5-1, no. mixes for n) were found to range up to 5.1% with the exception of PO-10 where a CoV of 10.2% was seen, as the w_i of Mix 3 was 12% lower than the average w_i of the other three mixes. These values are typically below those quoted by Phoon & Kulhawy (1999) for the inherent natural variability of clays and silts. CoVs for w_i for each column may be found in Appendix E.3.

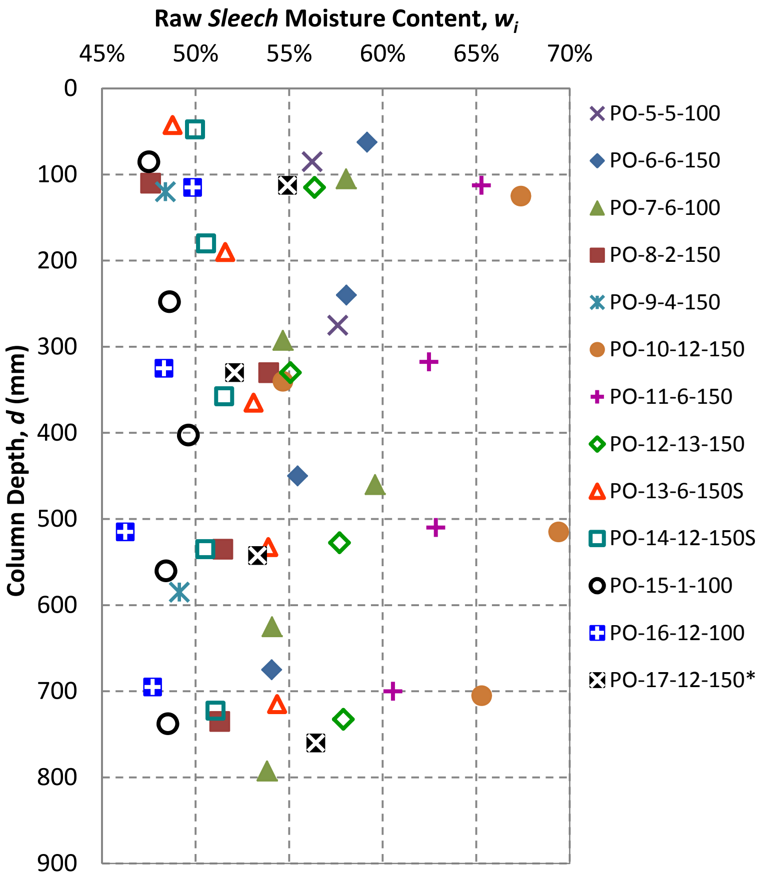

Figure 5-4: PORT column unstabilised *sleech* moisture content

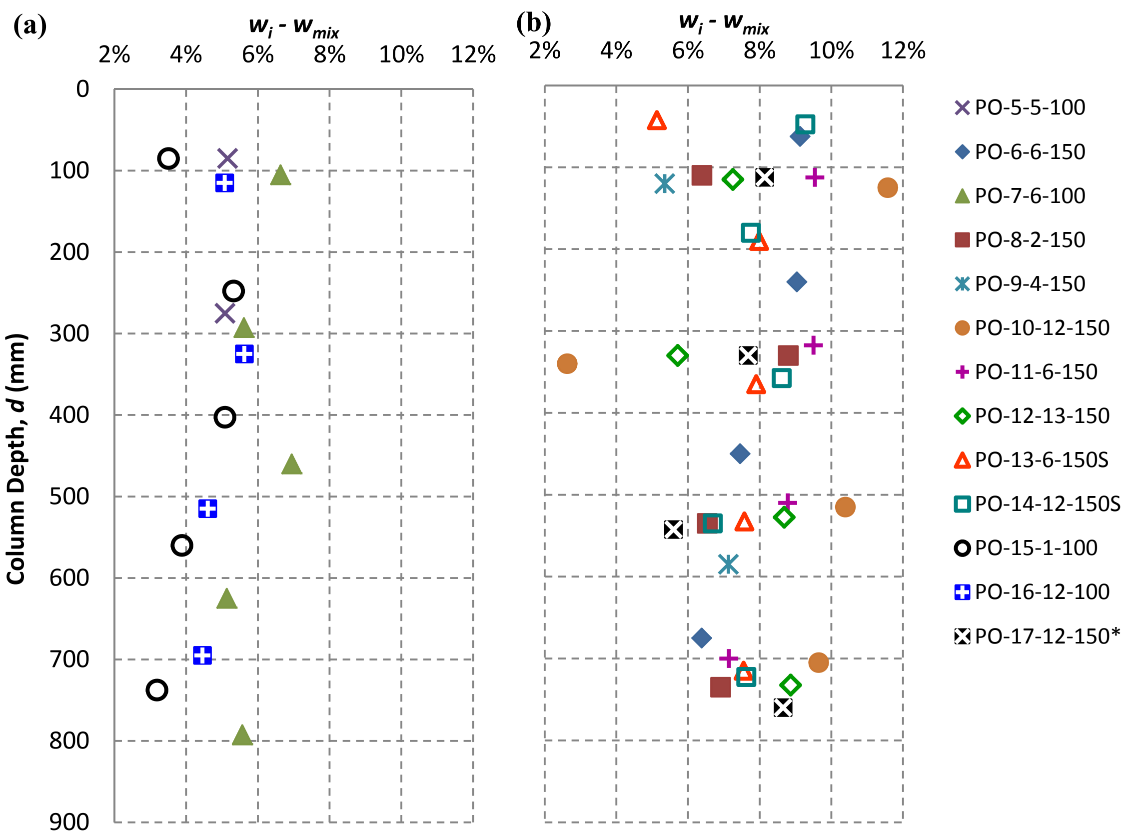

Figure 5-5: Reductions in moisture content after addition of the binder and mixing: a) 100 kg/m^3 binder content & b) 150 kg/m^3 binder content

The addition of binder to the unstabilised *sleech* resulted in a reduction in the moisture content (see Figure 5-5) where the difference between w_i and the mixed *sleech* moisture content (w_{mix}) is presented for both binder contents. A binder content of 100 kg/m^3 resulted in reductions of 4% to 7% while higher reductions of 5% to 10% were noted for the 150 kg/m^3 binder content. The moisture content of the stabilised *sleech* (w_s) at the time of UCS testing is discussed in Section 5.5.2 for mould and column samples.

5.4 PORT Column Curing Conditions

5.4.1 Introduction

This section sets out the curing conditions which influence the behaviour of both the laboratory-cured mould samples and the PORT columns at the time of testing. These conditions include:

(i) The historical ambient temperature profile of the laboratory in which the columns cured.

(ii) The stress conditions to which the columns were subjected during curing and testing.

(iii) The properties of the surrounding *sleech* in which the columns cured.

A consideration of all these factors is relevant to the quality and interpretation of the PORT results.

5.4.2 Laboratory Temperature

The PORT column basins and one mould sample from each mix were cured at ambient laboratory room temperature. Figure 5-6 presents the ambient laboratory temperature data, recorded at an hourly rate by the Building Management System (BMS) (IRUSE 2014) during the PORT column series, with mixing and testing dates superimposed for each column. The average ambient temperature (T) over the curing period of each column was calculated and found to vary between 13.5 °C and 20.5 °C (see Table 5-1). Where temperature data were not recorded by the BMS due to archiving issues, *i.e.,* during PO-5, a best estimate was made using the trends seen in the outside air temperature and the laboratory temperature either side of the missing data. These data provide the basis for the temperature corrections presented in Section 7.5.

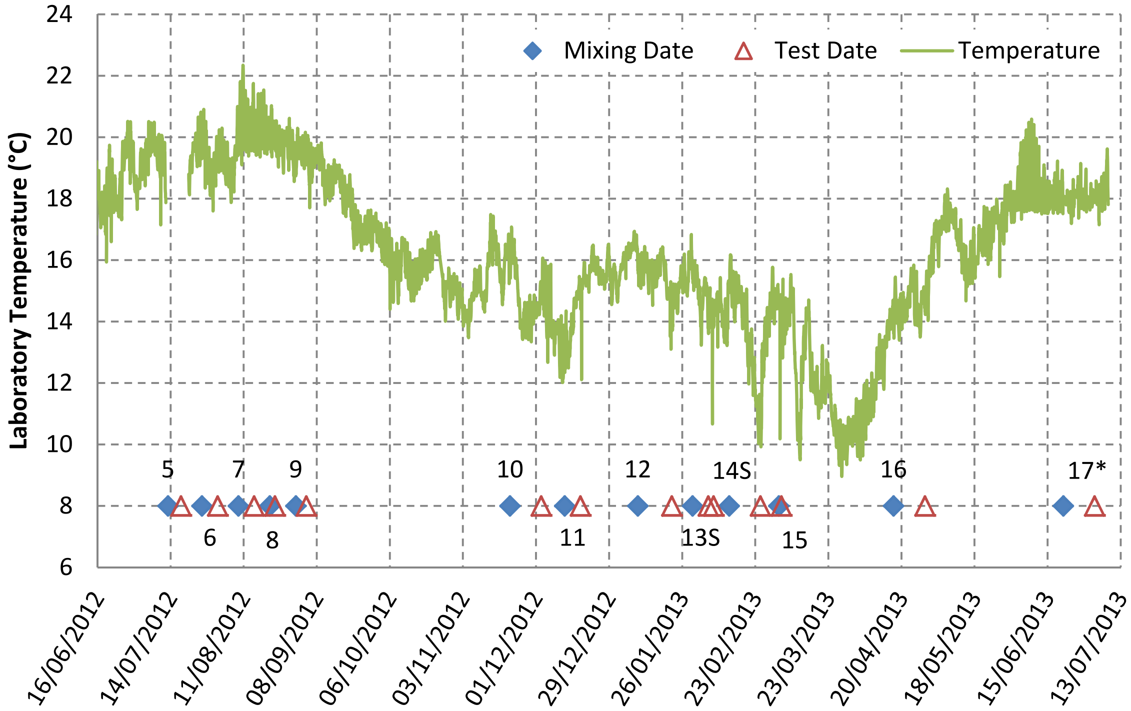

Figure 5-6: PORT column ambient curing temperature

The second mould sample, created for each stabilised mix from PO-11 onwards, was prepared and sealed in plastic wrap in the same manner as the room-cured samples, but was cured in a water bath at a constant temperature of 20 °C in accordance with EuroSoilStab (2002) procedures.

5.4.3 Surcharged PORT Columns

To increase confining stresses throughout the basin, particularly around the top of the column, PO-13S and PO-14S were surcharged with 13.6 kPa and 13.7 kPa, respectively, over the entire top of the basin, *i.e.,* over the column and surrounding *sleech*. The surcharges were applied immediately after construction of the columns and remained in place during the PORT. Mould samples from the surcharge tests were cured in the same manner as all other tests and were not stressed in any way.

Figure 5-7 shows a number of relevant stress distribution profiles in a column during testing. These are:

(i) The Boussinesq vertical stress distribution due to the influence of a 150 kg loading on the column only (required to prevent column pull-out).

(ii) The Boussinesq vertical stress distribution due to the influence of the surcharge, distributed using a 722 mm dia. circular loading plate over the column and surrounding *sleech*.

(iii) Although never tested, the stress distribution in a non-loaded column is shown for comparison.

Both the column and the surcharge loadings are shown to increase the stress conditions over and above those due to the self-weight of the column. The column loading is shown to cause a significant increase in the stresses in the top of the column compared to those in the surcharged column and the non-loaded column. The influence of the loading reduces quickly with depth and within 225 mm has reduced below that seen in surcharged columns. The inclusion of a surcharge on the basins is seen to increase the stresses throughout the basin, particularly around the top of the column where the increased confinement was sought. Due to the surcharge, the increased stresses were found to be comparable to those at a depth of 0.70 m in a 150 kg loaded column situation.

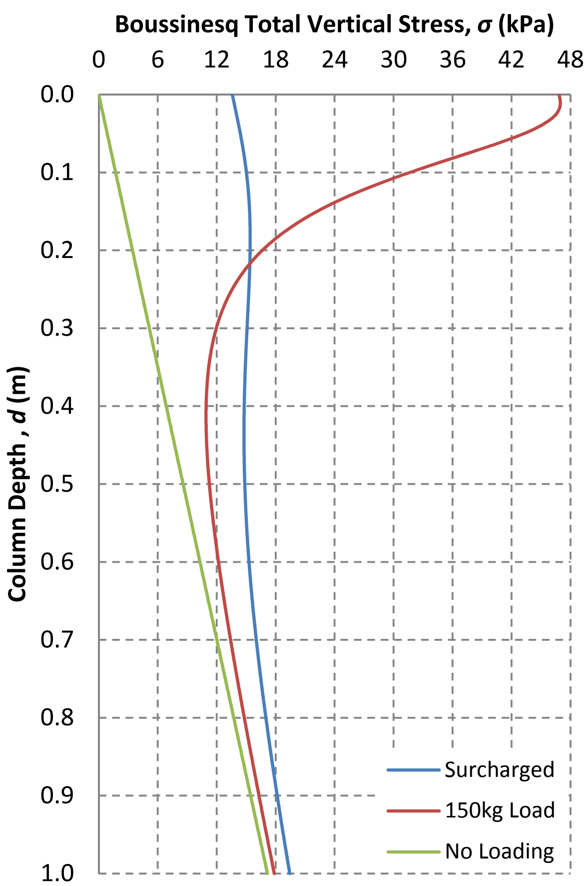

Figure 5-7: Boussinesq vertical stress distribution

5.4.4 PORT Column Surrounding *Sleech* Properties

Figure 5-8 a & b show the average (n = 3) moisture content (w_{ss}) and bulk density (ρ_{ss}) of the *sleech* surrounding columns PO-10 to PO-17* during curing and were determined using 50 mm dia., 50.5 mm high cylindrical stainless steel cores at depth intervals of approximately 200 mm. As column built heights varied between 860 mm and 1,040 mm the basin base is used as a datum. Organic contents were not determined for the *sleech* surrounding the PORT columns.

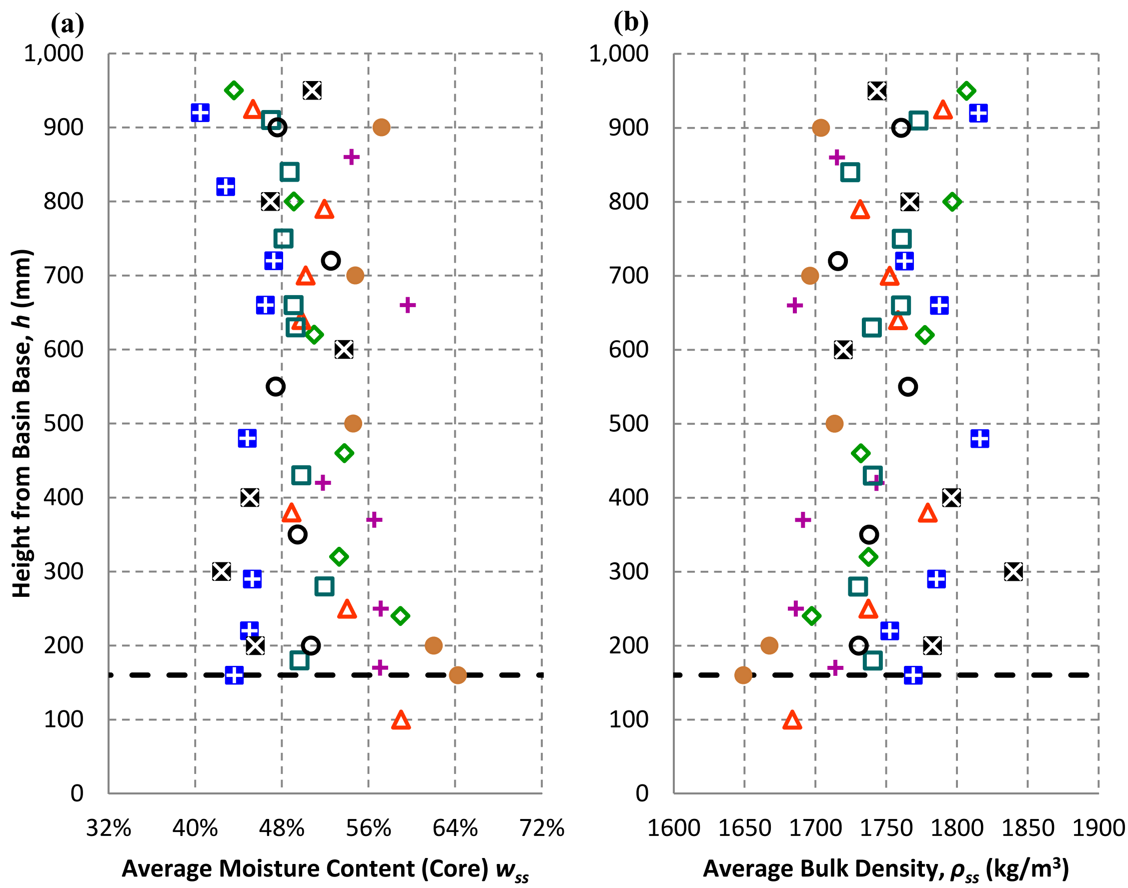

Figure 5-8: Average unstabilised surrounding *sleech* properties: a) moisture content & b) bulk density

Surrounding *sleech* moisture contents typically lie in the range 42% to 58% and vary as a result of the construction procedures used (see Section 3.12). *Sleech* with a moisture content below 42% was discarded from use in further tests as it was no longer easily workable. Average densities lie in the range 1,650 kg/m^3 to 1,840 kg/m^3, compared to the 1,620 kg/m^3 obtained from undisturbed *in situ* samples (w_i = 63%) (see Section 4.3). *In situ sleech* densities can range from 1,550 kg/m^3 to 1,750 kg/m^3 at moisture contents between 48% and 80%, as was seen in Section 3.12 where the factors influencing the density ranges observed are addressed. In Figure 5-9, ρ_{ss} is compared with w_{ss} and it can be clearly seen that the variations in ρ_{ss} are largely due to the different w_{ss} values with density increasing with reducing moisture content. Variations in ρ_{ss} at a particular w_{ss} are perhaps the result of small stones, shell fragments and small air pockets in the sampled cores.

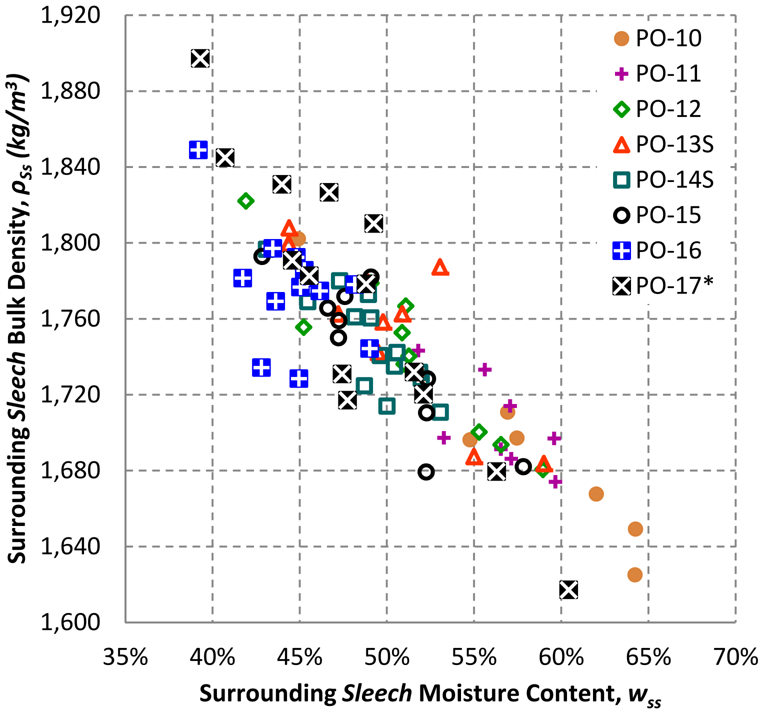

Figure 5-9: Surrounding *sleech* compacted density with moisture content

The average undrained shear strength of the surrounding *sleech* (c_{uss}) (n = 3-4), determined with a pocket shear vane, was typically found to lie between 7 kPa and 12 kPa (see Figure 5-10) and is within the undrained shear strength limits of 4.5 kPa and 15 kPa obtained during initial fall cone classification tests for remoulded and undisturbed *sleech*, respectively. Strengths show a constant trend with depth and near the base of the column show increased values as *sleech* at this location remained in place for all tests. Figure 5-11 shows the average undrained shear strength with the w_{ss} within each column, where a loose relationship between strength and moisture content is evident.

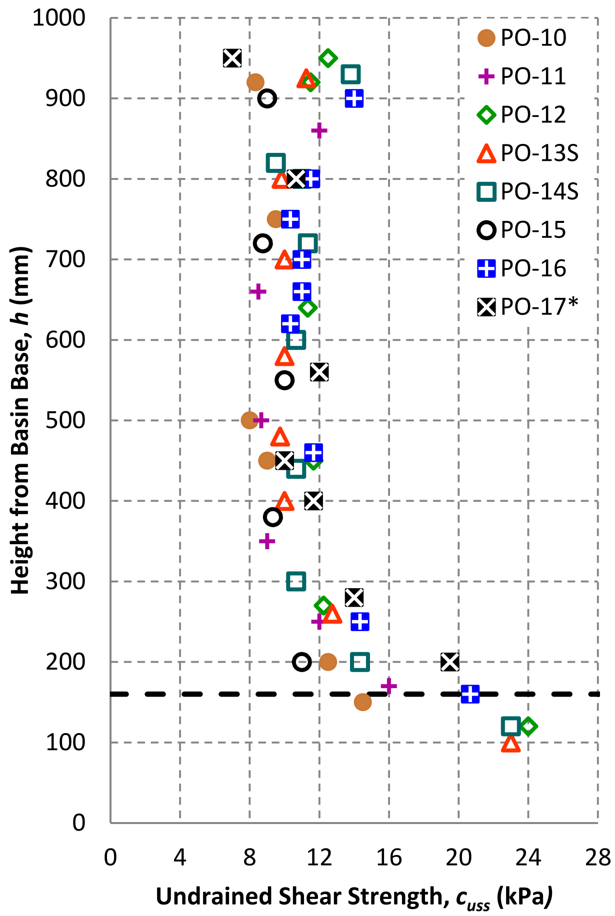

Figure 5-10: Average undrained shear strength of surrounding *sleech*

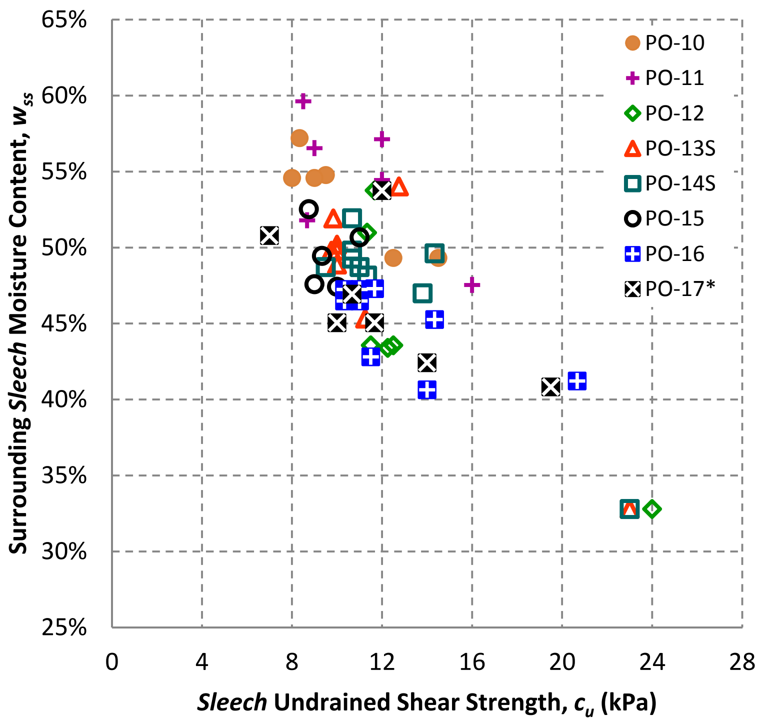

Figure 5-11: Surrounding *sleech* undrained shear strength with moisture content

To investigate the possibility of lateral migration of moisture in the surrounding *sleech* after curing and PORT, moisture content samples were taken with a soil profile sampler at the basin wall (r = 375 mm, where r = radius from column centre), mid-way between the wall and the column (r = 240 mm) and at the column face (r = 100 mm) from PO-7 onwards. No systematic trend could be seen in terms of a radial movement of moisture within the surrounding *sleech*. This is in agreement with previous laboratory work on 50 mm dia. stabilised kaolin-cement columns by Kosche (2004), where it was found that the moisture content does not vary with distance from the column face.

As columns were moulded in place rather than mixed *in situ*, 30 mm transition zones and boundary layers like those seen in field and cement-lime laboratory-scale columns (Kosche 2004) were not noted. Increased plasticity of the unstabilised *sleech* at the column face was noted during column extraction but exact recordings were not made of the thickness of this zone, its plasticity or any strength variations with distance from the column face. However, the thickness of this plastic zone is estimated visually to have been up to 10 mm and is possibly the result of the migration of calcium ions from the stabilised column to the *sleech* similar to that described by Kosche (2004). As a result, this *sleech* was discarded from future tests. Similar conditions were observed around the PIRT columns presented in Chapter 6.

5.5 PORT Column Stabilised Moisture Content and Density

5.5.1 Introduction

In this section the stabilised moisture content and stabilised density of the 65 mm dia. laboratory prepared mould and 50 mm dia. column samples are presented. In view of repeatability of column production, comparisons are drawn between column samples and their respective room-cured mould samples, as well as samples cured at 20 °C in accordance with EuroSoilStab (2002) requirements.

5.5.2 PORT Mould and Column Stabilised Moisture Content

For each individual mix, the stabilised mould moisture contents (w_{mld}) for the room-cured and 20 °C cured samples were similar. No systematic trend in w_{mix} - w_{mld} with curing time was observed. The actual stabilised moisture contents may be found on

Figure D-1 and on the PORT summary sheets in Appendix E.2. Minor variations in the mixed *sleech,* small losses of moisture due to evaporation during mould preparation and column construction, and the small numerical differences between w_{mix} and w_{mld} or w_{col} mean that again it is difficult to identify any exact moisture content dependence upon curing time within the data. Figure 5-12 shows the difference between w_{mix} and the stabilised column moisture content (w_{col}), *i.e.,* the change in moisture content during curing.

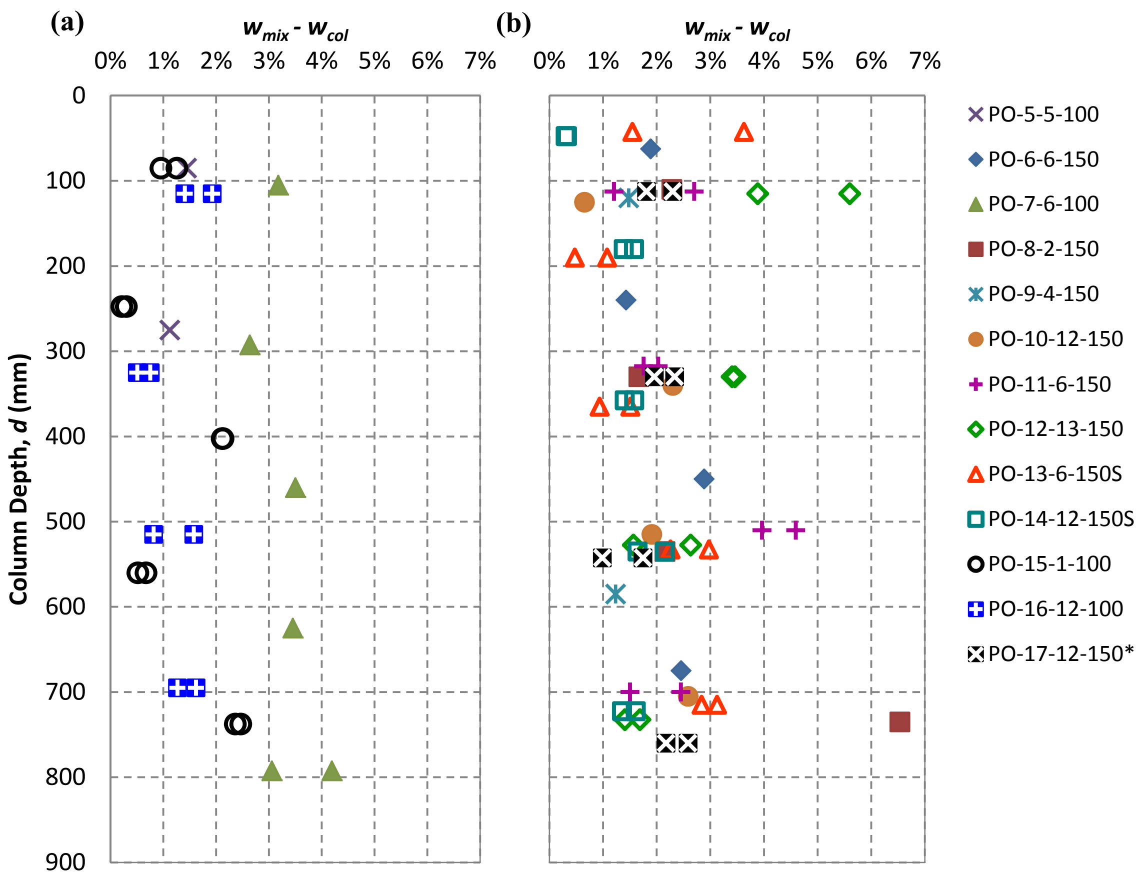

Figure 5-12: Reductions in column moisture content during curing: a) 100 kg/m^3 binder content & b) 150 kg/m^3 binder content

Using Equation 2-15, proposed by Åhnberg (2006), Figure 5-13 a & b show a comparison of the measured stabilised moisture content (w_s) and the estimated stabilised moisture content (w_{se}) for mould and column samples, respectively. Using least sum of squares calculation, a non-evaporable water content of 0.18 was used and found to fit the data best. This is at the lower limits of values suggested by Taylor (1997), is below the value of 0.23 used by Åhnberg (2006) for 28 day cement stabilised clay samples.

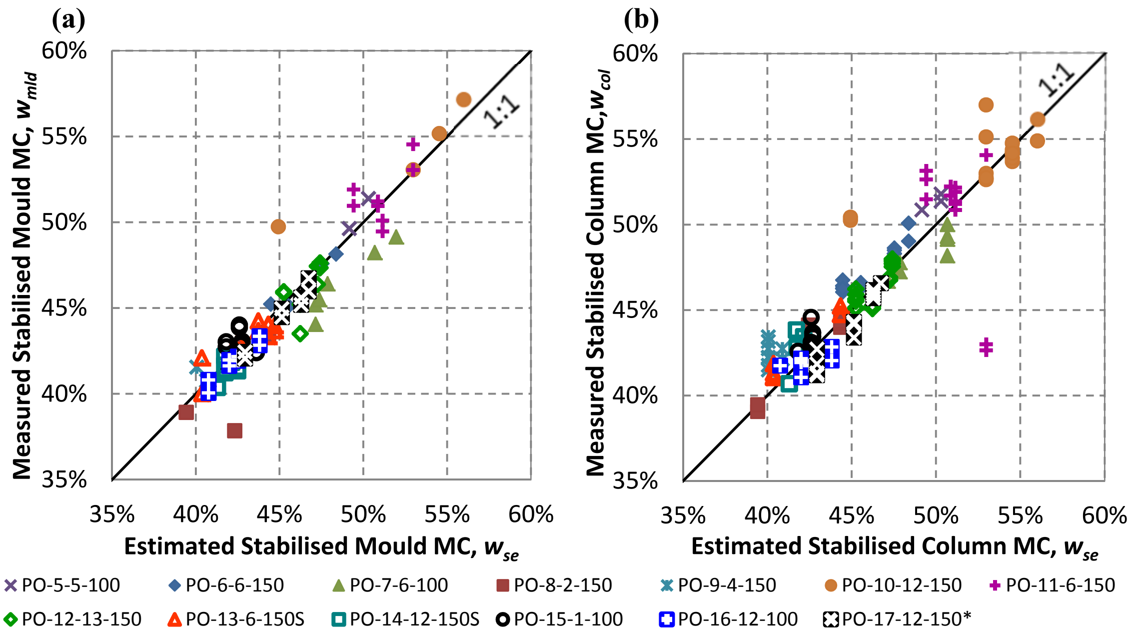

Figure 5-13: Estimated and measured stabilised moisture content: a) mould sample & b) column sample

5.5.3 PORT Mould and Column Stabilised Density

The stabilised bulk density of all mould samples (ρ_{mld}) was found to vary from 1,575 kg/m^3 to 1,750 kg/m^3, as seen in Figure 5-14, where a comparison of the room-cured density (ρ_{mldR}) and the 20 °C cured density (ρ_{mldT}) is given. Curing temperatures for the room-cured samples are all below 20 °C (see Table 5-1), but it can be implied that variations in curing temperature do not to have an appreciable effect on the stabilised density, in keeping with the findings detailed in Section 2.11.2, *e.g.,* Marzano *et al.* (2009). Minor variations in the mould density are a result of small voids on the sample's face and as will be seen later, the overall range of densities occurs as a result of the different w_{mix} values. The CoV for both sets of mould densities within a given column all lay below 2.5%.

Figure 5-15 shows the average density of the 50 mm dia. samples recovered from each column (ρ_{col}) for UCS testing with depth; in this plot samples whose centre's depths were within 25 mm of each other in any one column were averaged and all individual column sample densities can be found on the summary sheets in Appendix E.2. Differences in column density at a given depth are primarily a result of sampling and trimming effects set out in Section 3.12, while different w_i values for the mixes also contributes to the differences in density as will be seen later in this section. Of the 13 no. PORT columns considered, the calculated CoVs for each column were found to be a maximum of 3.9%.

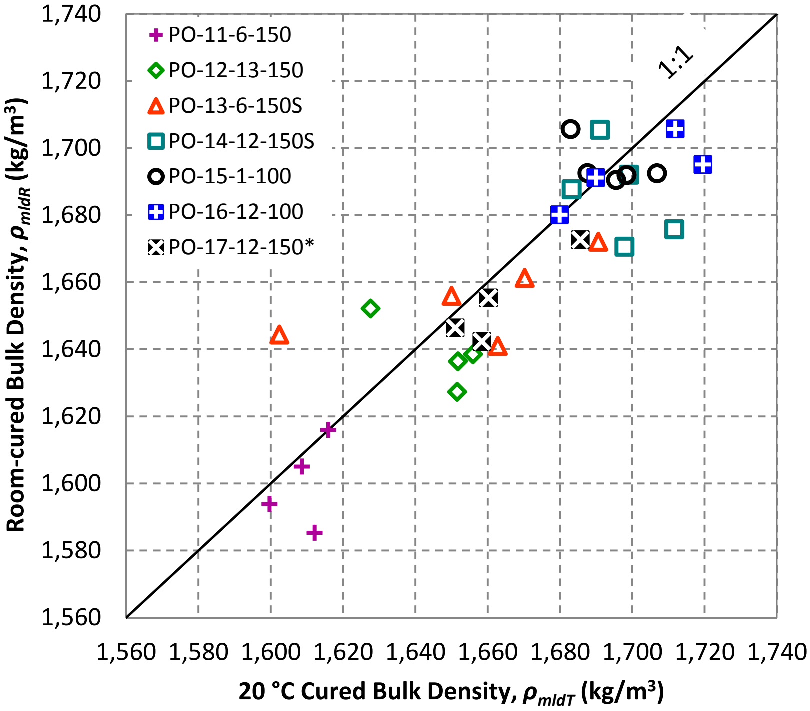

Figure 5-14: Room and 20 °C cured mould sample density

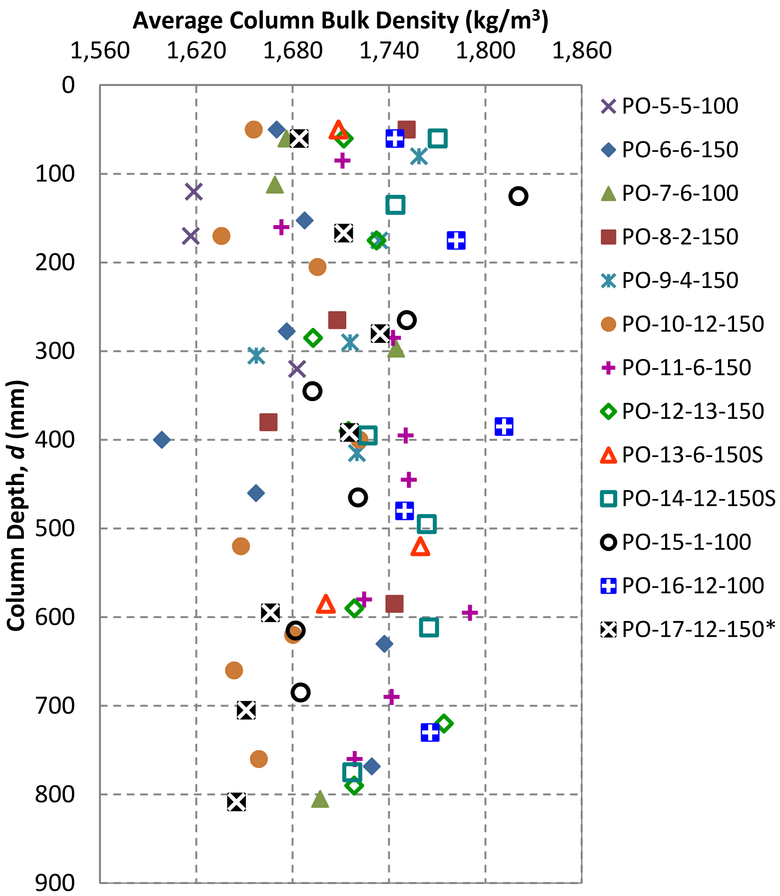

Figure 5-15: Average column density with depth

In Figure 5-16, a & b ρ_{col} is compared to the respective ρ_{mldR} and ρ_{mldT} samples of the mix from which they originated. Column densities are seen to predominantly lie in the range 1.0 to 1.1 times that of their respective mould densities, indicating a greater compactive effort was experienced by the columns than by the mould samples.

Figure 5-17 a & b, show an increasing ρ_{mld} with reducing w_{mix} for the respective 100 kg/m^3 and 150 kg/m^3 binder contents. Also included is an estimation of the stabilised density using Equations 5-1 and 5-2:

$$\rho_{Sleech} = \frac{G_s + w_i G_s}{1 + w_i G_s} \rho_w \qquad \text{5-1}$$

$$\rho_{stab} = \frac{MS + BC}{MS/\rho_{Sleech} + BC/\rho_{OPC}} \left(1 - A_{stab}\right) \qquad \text{5-2}$$

where ρ_{sleech} is the estimated fully saturated *sleech* density (kg/m^3) at a moisture content w_i, G_s is the specific gravity of the unstabilised *sleech*, ρ_w is the density of water (kg/m^3), ρ_{stab} is the estimated density of the stabilised sample (kg/m^3), MS is the mass (kg) of *sleech* in 1 m^3, BC is the mass (kg) of binder added to 1 m^3 of *sleech*, ρ_{OPC} is the density of Ordinary Portland Cement (taken to be 3,150 kg/m^3 (Taylor 1997)) and A_{stab} is the percentage of air in the stabilised *sleech* sample assuming an ideal cylindrical sample volume.

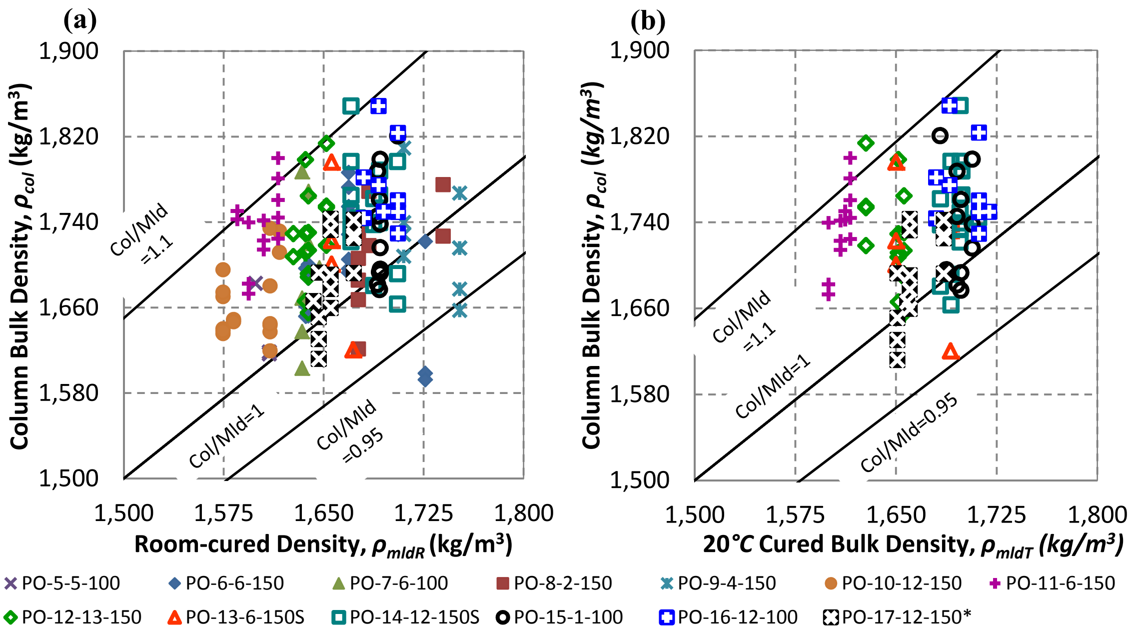

Figure 5-16: Column density with a) room-cured density & b) 20°*C* cured density

Assuming a G_s of 2.73 (from initial classification tests), the data are found to lie within the density bands predicted using A_{stab} values of 6% and 9%, and 6% and 11% applied to 100 kg/m^3 and 150 kg/m^3 binder contents, respectively. The presence of air in laboratory stabilised samples has previously been noted by Åhnberg (2004) where degrees of saturation (S_r) were found to lie between 93% and 98% in 50 mm dia. laboratory stabilised clay samples.

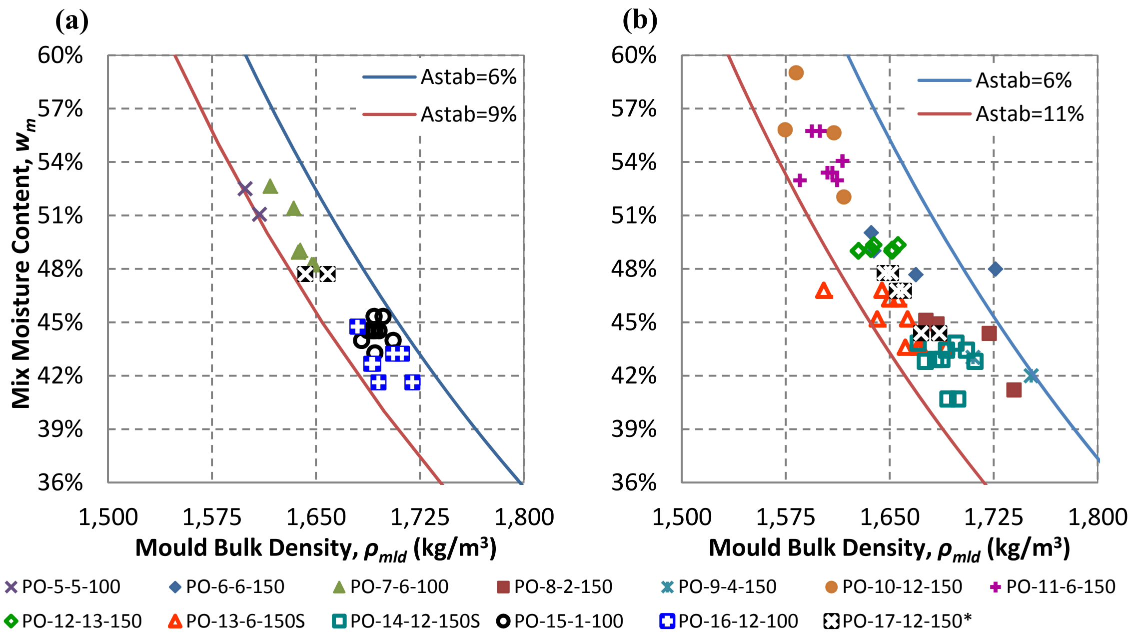

Figure 5-17: Room and 20 °C cured mould sample density with moisture content at binder contents of a) 100 kg/m^3 & b) 150 kg/m^3

Figure 5-18 a & b show the increasing ρ_{col} achieved with reducing w_{mix} for both binder contents used. Greater variations in the predicted density are seen in column samples compared to the mould samples due to the factors set out in Section 3.12, *i.e.*, w_i variations and sample trimming. Again using the A_{stab} value to capture the variation, ranges of 0% to 8% and 0% to 10% can be used to envelope the column density ranges but it should be noted that care needs be taken with the values due to the volumetric measurement issues regarding the column samples.

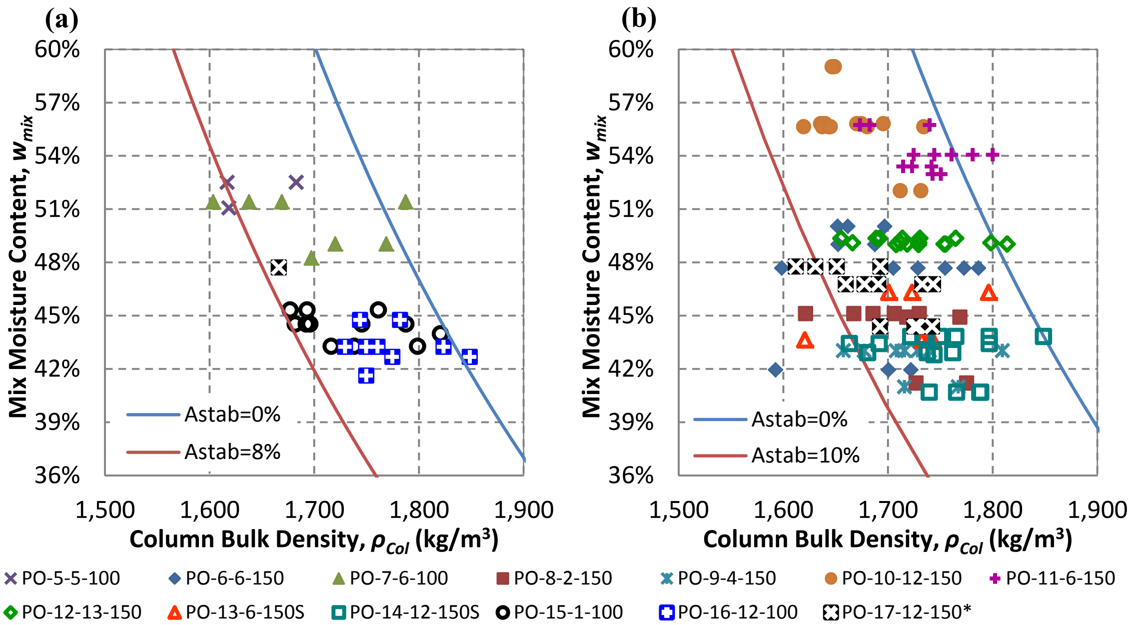

Figure 5-18: Column sample density with moisture content at binder contents of a) 100 kg/m^3 & b) 150 kg/m^3

5.6 PORT Column Stabilised Strength and Stiffness

5.6.1 Introduction

In this section the stabilised UCS and stiffness properties of the laboratory cured mould samples (from each stabilised mix) and samples taken from the exhumed PORT columns are presented. To assess quality and repeatability, comparisons are also drawn between column samples and their respective laboratory mould samples, including samples cured at 20 °C as per standard procedures.

5.6.2 PORT Mould Stabilised Strength

<u>Mould Unconfined Compression Strengths:</u>

Overall, a range of mould UCS values (q_{mld}) was obtained from 143 kPa to 743 kPa by varying the binder content and curing time. Before presenting the strengths achieved, it should be noted that:

- From all stabilised mixtures one 65 mm dia. mould sample was prepared and cured at room temperature. From PO-11 onwards, a second 65 mm dia. sample was created and cured in a water bath at 20 °C.

- Average ambient curing temperatures for room-cured samples range from 13.5 °C to 20.5 °C (see Table 5-1).
- The stabilised mixtures required to produce each column were created over a 5 hour period. Data presented represents the curing time from mid-point of column construction to UCS testing and as such, samples from Mix 1 have actually cured for longer than samples from the final mix.
- The variability of w_i and curing temperature addressed in Section 3.12 will impact upon the strengths achieved but as will be seen later in this section their effect can be accounted for to confirm the high quality of the results.
- Mould samples for the surcharged columns, PO-13S and PO-14S, were cured in the same way as all other mould samples and did not cure under a surcharge.
- No mould samples were created for Mix 2 in PO-9.
- Of the 4 mixes used to construct PI-17*, Mix 2 was stabilised at a binder content of 100 kg/m^3 rather than the 150 kg/m^3 used in the other three mixes.

Figure 5-19 a & b show the increase in UCS for room-cured (q_{mldR}) and 20 °C cured (q_{mldT}) samples with average mould curing time (t_{mld}), respectively, while Figure 5-19 c & d show the same data itemised by the binder content used. Overall strength is seen to increase with time and binder content. Assessing the variations within each column's mould samples, CoVs were found to range from 2.4% to 13.6% (and to 20.4% in PO-5 for which only two samples exist) for room-cured samples and from 4.5% to 14.0% for 20 °C cured samples. On comparison with the CoVs compiled in Section 2.10.3, these values are similar to those for laboratory prepared samples and are less than those seen in field samples.

In all tests, room-cured mould samples are seen to give lower strengths than their respective 20 °C cured samples (see Figure 5-20). q_{mldR} was found to be higher than q_{mldT} for Mix 2 in PO-13S but this is considered to be due to a lesser quality sample as its strength is lower than other samples with similar properties, cured at the same temperature.

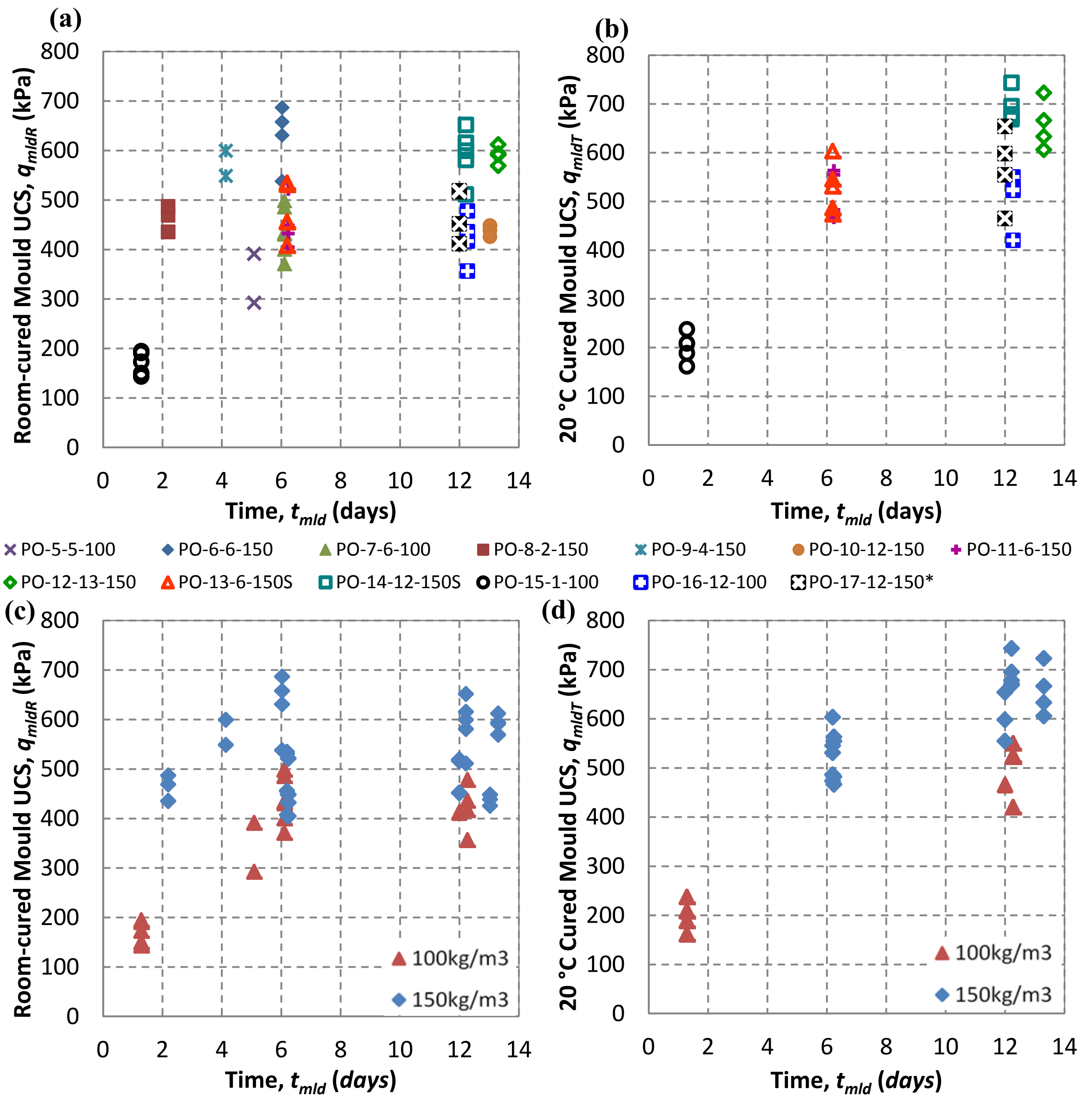

Figure 5-19: Mould UCS with curing time: a) room-cured & b) 20 °C cured. Binder content specific: c) room-cured & d) 20 °C cured

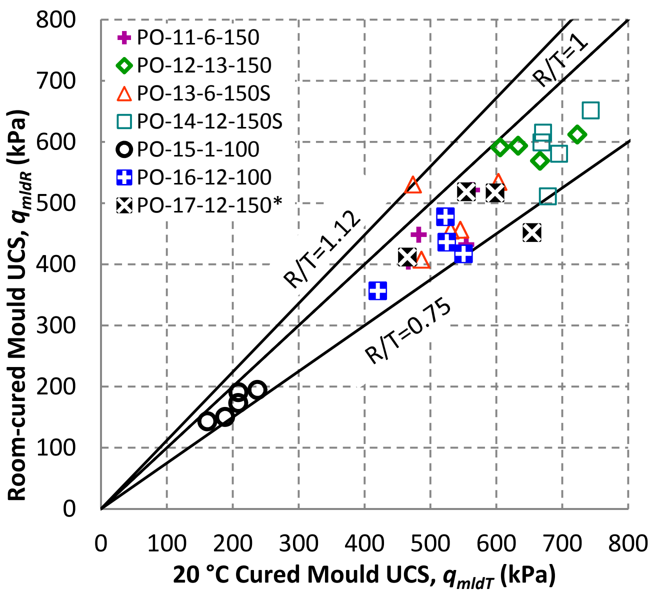

Figure 5-20: Mould room-cured sample UCS with 20 °C cured sample UCS

Accounting for w_i and Temperature Variability:

As will be seen in Section 7.4, the temperature of the mould samples was seen to equalise with that of ambient laboratory temperature soon after stabilisation and therefore it is appropriate to use the average ambient temperature of the laboratory as a measure of curing temperature. Using the method set out in Section 7.5 and Equation 7-3, the curing time of the samples is corrected for temperature variations. This is referred to as the Temperature Corrected Time (*TCT*) and is denoted by TCT_{mld} for all mould samples.

Figure 5-21 shows the average q_{mld} (with standard deviation error bars) of the room-cured and 20 °C cured mould samples with TCT_{mld}; the different binder content samples for Mix 2 in PO-17* are given separate points and are highlighted.

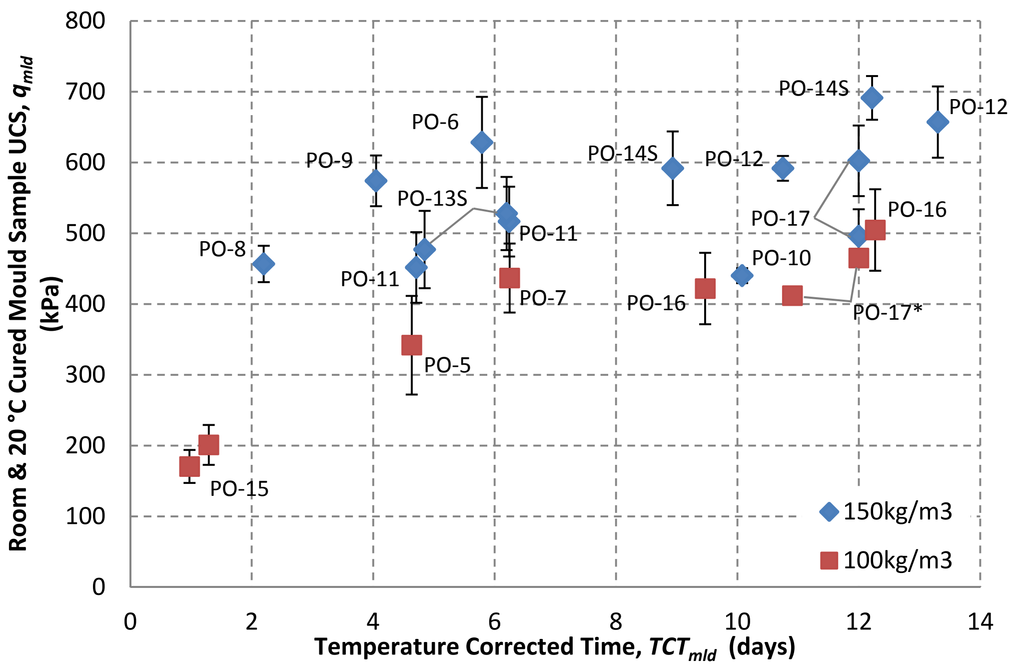

Figure 5-21: Average mould UCS and standard deviation with temperature corrected time

In an additional step to unify the data by including for variations in the moisture content of the unstabilised *sleech* and the different binder contents used, Figure 5-22 shows the average of each samples UCS multiplied by its *WTBR* plotted against TCT_{mld}. This normalisation of UCS by *WTBR* is justified based in the linear relationship between the UCS and 1/*WTBR* that is seen in the OPC stabilised *sleech* samples in Section 4.3.4. Within the limits of the properties observed in this series, Equation 5-3 provides an overall natural logarithmic function fit ($R^2 = 74.8\%$) to the data:

$$UCS \times WTBR = 541.5\ ln(TCT_{mld}) + 1083.0 \quad (1 \leq t \leq 13) \qquad 5\text{-}3$$

The high R^2 fit to the data suggests that the overall quality of mixing and repeatability in mould production has being accounted for successfully by including for the different moisture contents and curing temperatures.

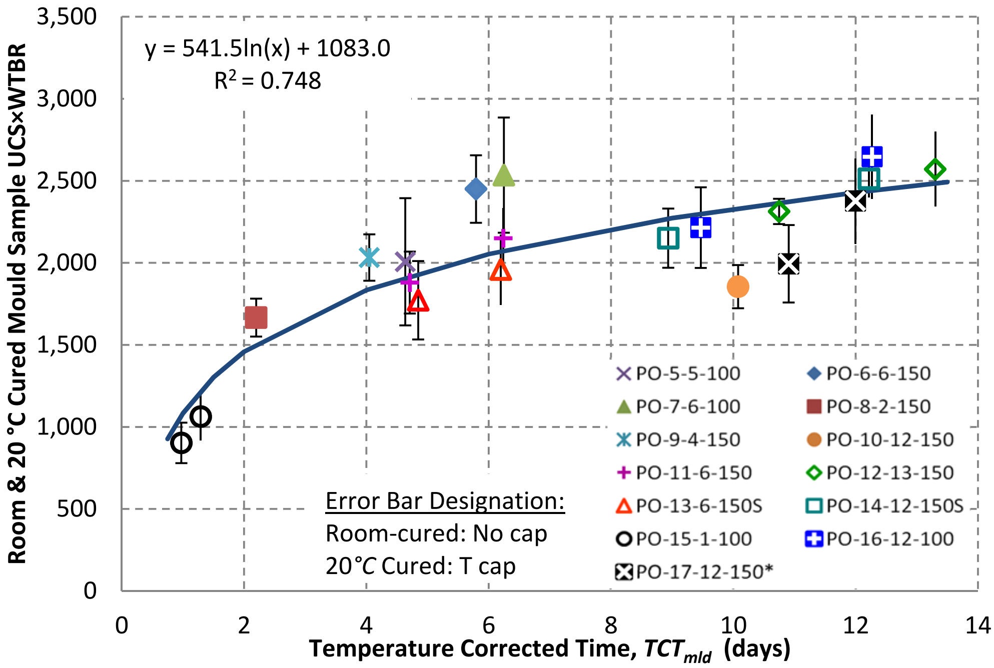

Figure 5-22: Average UCS×WTBR and standard deviation for room and 20 °C cured mould samples with their temperature corrected times

5.6.3 PORT Column Stabilised Strength

Column Unconfined Compression Strengths:

After carrying out the PORT, the column was extracted and trimmed into 50 mm dia. samples for UCS testing. It was typically found that samples did not straddle between two mixes in a single column. Due to cracking within the tested column, the effects of sampling and trimming as well as attempts to maximise the number of samples possible, sample heights ranged from 74 mm to 110 mm.

Figure 5-23 shows the column UCS (q_{col}) with depth for each column, where it can be seen that:

- Strengths obtained from the PORT columns ranged from 116 kPa to 845 kPa, primarily as a result of varying the curing time and binder content.
- The column strength showed good uniformity with depth as a result of the mixing, construction and testing procedures implemented. CoVs for the strength of individual columns were calculated to predominantly lie between 9.1% and 16.3%, although early columns in the test series (PO-5 to PO-7) show higher values of 19.5% to 25.1%. Overall the values typically lie between those observed for field and laboratory samples, as seen in Section 2.10.3.

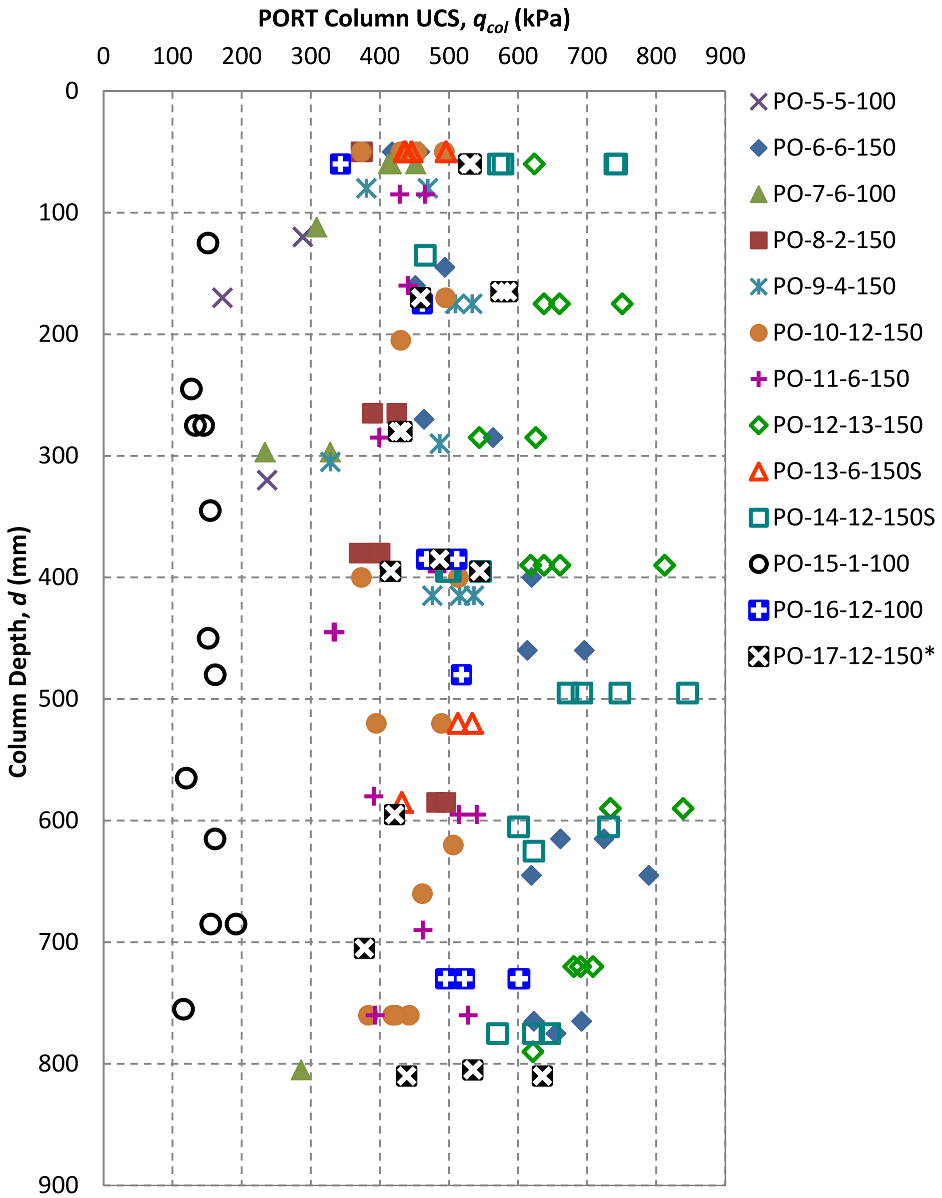

Figure 5-23: PORT column UCS with depth

- The number of samples recovered from each column varied from 7 to 18 as a result of sampling difficulties due to cracking in the mid sections of the column caused by the carrying out of the test. The mid-sections of columns whose strengths were in the range 250 kPa to 400 kPa were found to be the most difficult to obtain full sample profiles from for testing.
- Only one usable sample was obtained from the 100 kg/m^3 Mix 2 (located at depths between 380 mm and 595 mm) in PO-17*, the varied binder content column.

<u>Accounting for w_i and Temperature Variability:</u>

In Section 7.4, the results of an experiment to assess the temperature of the stabilised column during curing are presented and it is seen that the column temperature equalises (within 0.5 °C) with that of the *sleech* surrounding it within 12 hours of construction. In an attempt to account for the different curing temperatures under which each column cured, the temperature corrected time was calculated for each column (TCT_{col}) in the same way that was carried out for the mould samples in Section 5.6.2. In Figure 5-24 the average column UCS (with standard deviation error bars) is shown against TCT_{col} for all columns. As seen with the mould samples, strength can be seen to increase with binder content and curing time following the inclusion of the effect of curing temperature.

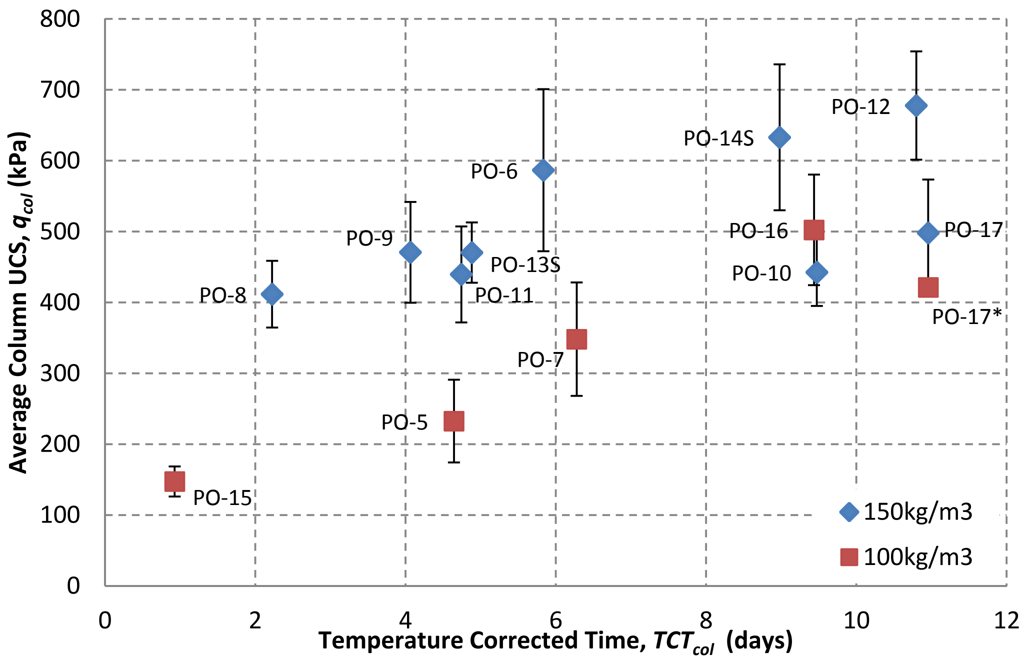

Figure 5-24: Average uncorrected column UCS (and standard deviation error bars) with temperature corrected time

In an additional step to unify the data, the *WTBR* is again used to include for variations in w_i and for the different binder contents. Figure 5-25 shows the average UCS×WTBR (with standard deviation error bars) against TCT_{col} for all the columns. The logarithmic function, set out in Equation 5-4, fits to the data with an R^2 value of 71.6% and successfully unifies the data into one curve.

$$UCS \times WTBR = 621.1 \ln(TCT_{col}) + 846.2 \qquad (1 \leq t \leq 13) \qquad 5\text{-}4$$

This equation will be used later in Section 7.6 to estimate the strength of the column at the time of the PORT, a value required to accurately estimate the N value.

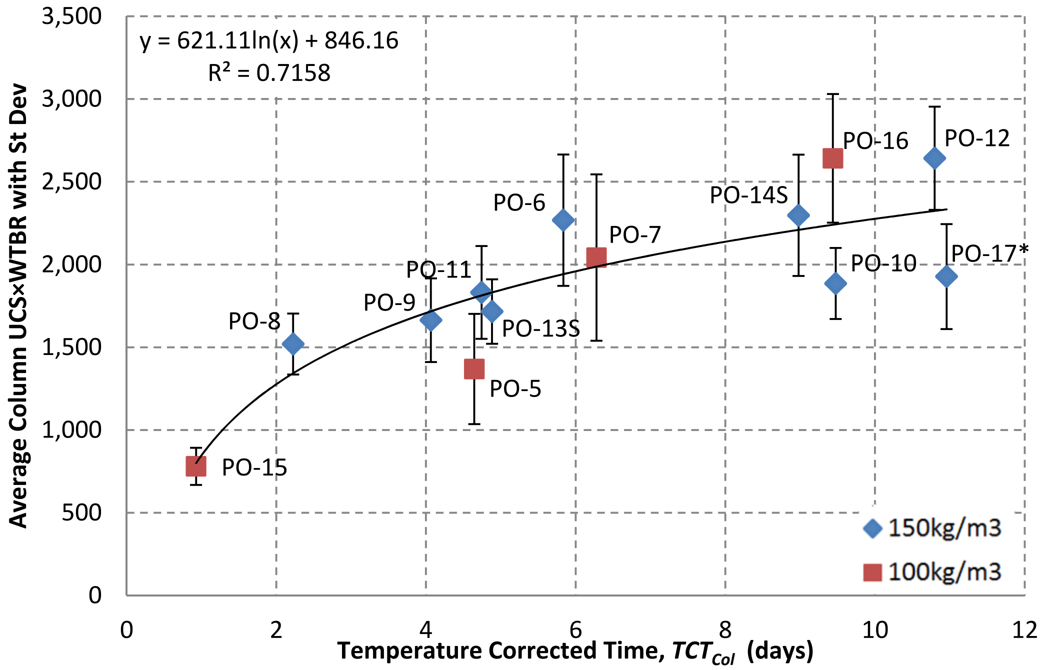

Figure 5-25: Average column UCS×WTBR (and standard deviation) with temperature corrected time

Figure 5-26 a & b show a comparison of q_{col} against their respective q_{mldR} and q_{mldT}. Column strengths are typically seen to lie at a multiple of 0.70 to 1.3 times that of their respective room-cured samples and between 0.60 and 1.25 (predominately in the range 0.60 to 1.0) times that of their respective 20 °C cured samples. Contributing factors to the variation in the q_{mld}-q_{col} ratios have been mentioned in Section 3.12, and include compaction differences, variations in curing temperature, sample trimming and comparisons with only a single mould sample result.

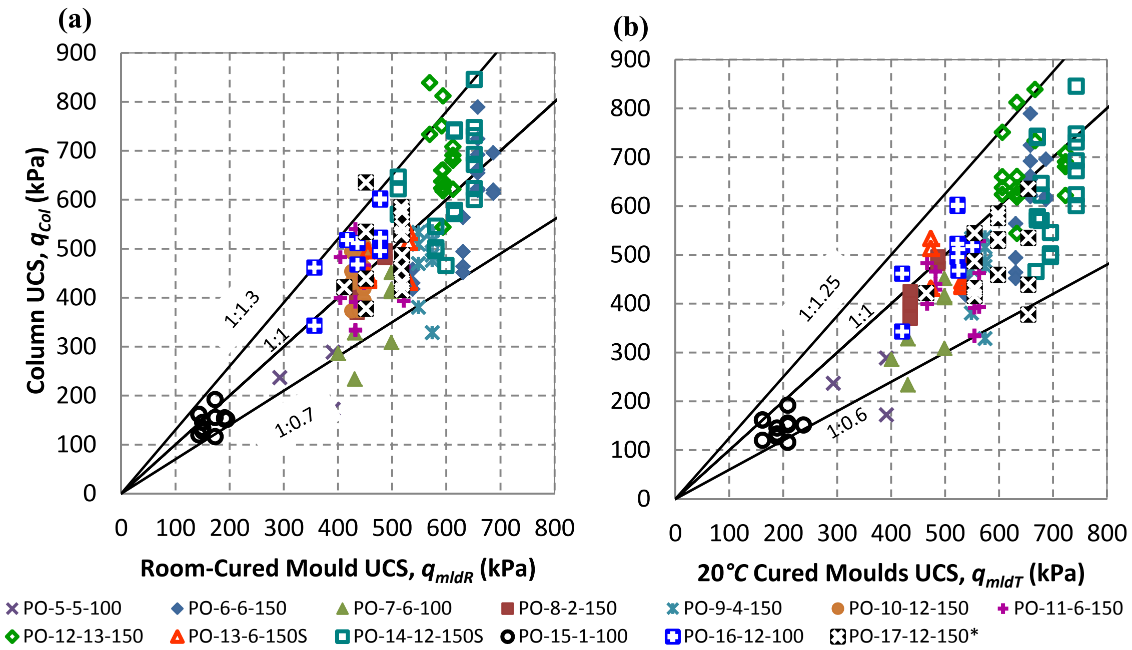

Figure 5-26: Column strength with mould strength: a) room-cured & b) 20 °C cured

5.6.4 PORT Mould and Column Stabilised Stiffness

The secant stiffness was calculated at 50% of the failure strength for each of the room-cured (E_{mldR}), 20 °C cured (E_{mldT}) and column (E_{col}) samples. Figure 5-27 a & b show an increasing E_{mldR} and E_{mldT} with *TCT*, respectively. When itemised by binder content in Figure 5-27 c & d, it appears that increased stiffnesses occur at the higher binder content of 150 kg/m^3. The additional step of incorporating *WTBR*, as carried out for the strength data, was not carried out here as stiffnesses were measured as a characterisation measure only. Values up to 70 MPa were obtained for both room-cured and 20 °C cured samples and in a similar way to that seen with the mould sample strengths, E_{mldR} was seen to lie between 0.5 and 1.3 times E_{mldT} but predominantly between 0.5 to 1.0 times E_{mldT}.

CoV for the secant stiffness of room-cured samples lie between 5.7% and 39.0% and between 13.6% and 36.2% for the 20 °C cured samples, while the number of samples used to calculate each CoV is that which is set out in Table 5-1 for the number of mixes in each column. Although currently there are no E_{50} CoV guidelines in the literature for stabilised soil, values up to 65% are stated by Phoon & Kulhawy (1999) for sands.

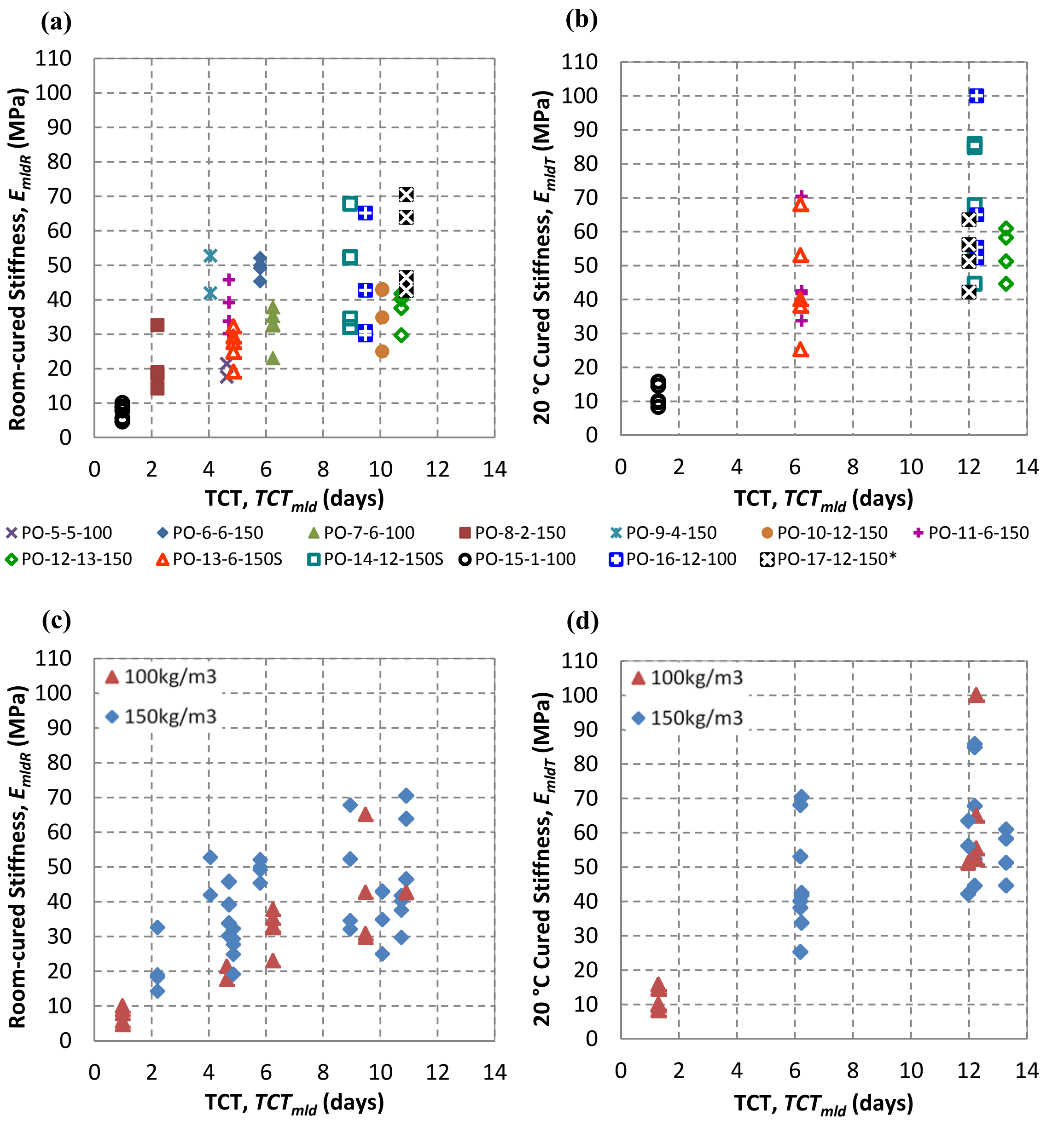

Figure 5-27: Mould secant stiffness with TCT: a) Room-cured, b) 20 °C cured. Binder content specific: c) room-cured & d) 20 °C cured

Figure 5-28 shows the variation in stiffness with depth for each column in the PORT series and column sample stiffnesses ranged up to 90 MPa. In Figure 5-29 stiffness is seen to increase with *TCT* and higher stiffnesses are typically observed at the higher binder content of 150 kg/m^3. Considerable variation in column stiffness is notable, particularly within PO-6, PO-7, PO-9 and PO-16. CoV values for each column are found to range from 23.7% to 38.2%, although PO-7 has a CoV of 51.5% due to two very low E_{col} values.

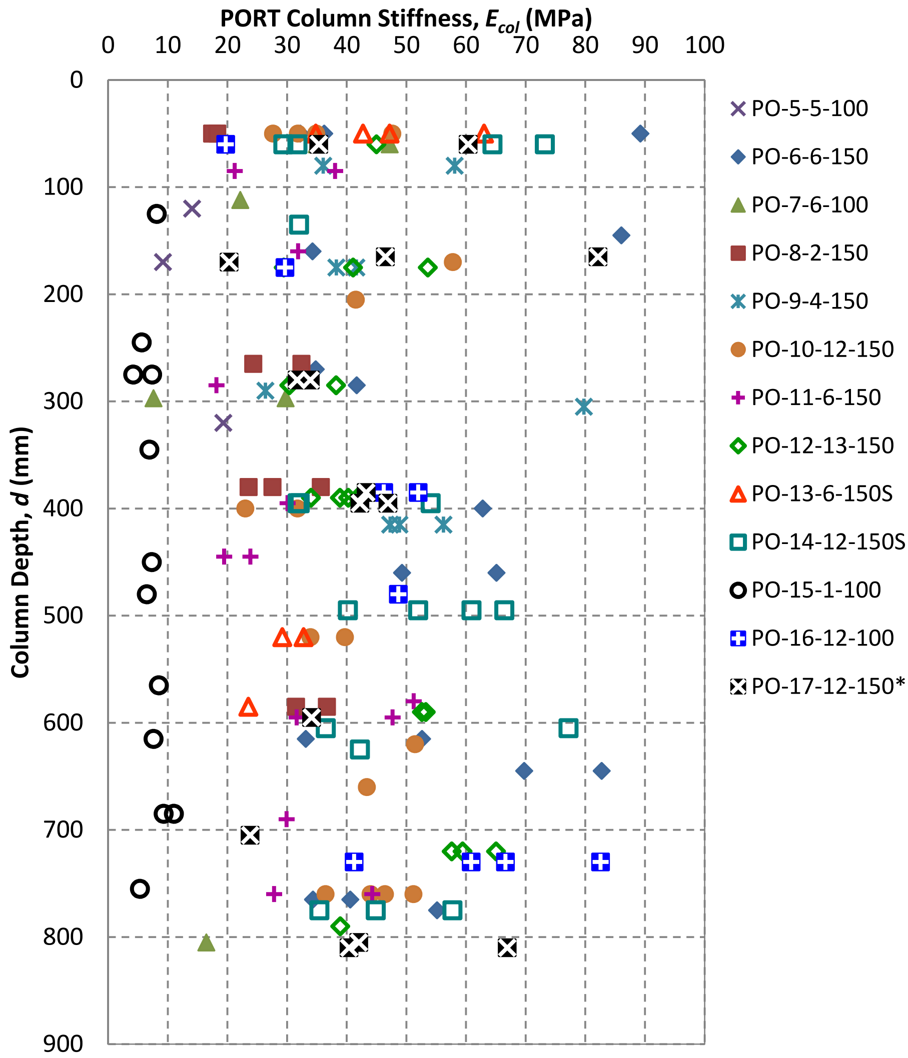

Figure 5-28: PORT column stiffness with depth

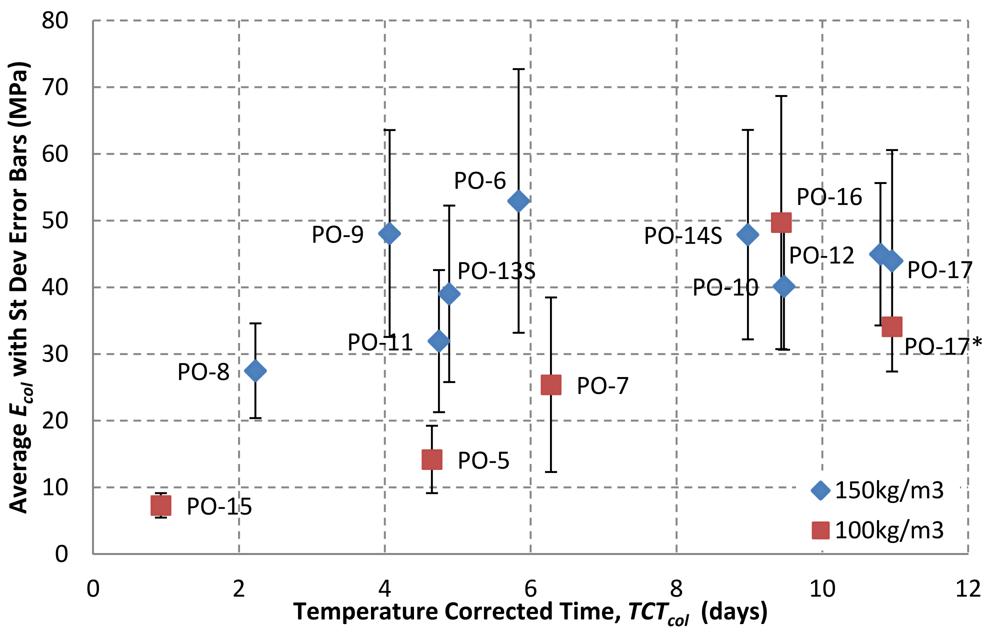

Figure 5-29: Average column stiffness (and standard deviation) with temperature corrected time

The relationship between E_{50} and q was calculated and found to be $E_{50} = [35\text{-}115]q_{mld}$ for mould samples (see Figure 5-30a) and $E_{50} = [45\text{-}125]q_{col}$ for column samples (see Figure 5-30b), comparing favourably with the typical values of between 50 and 150 seen in current literature for stabilised soils (see Table 2-8). Figure 5-31 a & b show E_{50}/c_u against strain to failure ($\mathcal{E}_f$) for mould and column samples. A clear trend of increasing E_{50}/c_u with reducing $\mathcal{E}_f$ can be seen, and is consistent with the stabilisation trials in Chapter 4 and the overall observations during this test series. Although some data from PO-6 lies outside the minimum E_{50}/c_u with $\mathcal{E}_f$ relationship (derived on the basis that $\mathcal{E}_f \geq 2\times\mathcal{E}_{50}$), due to higher than expected E_{50} values, all other data is seen to satisfy the relationship.

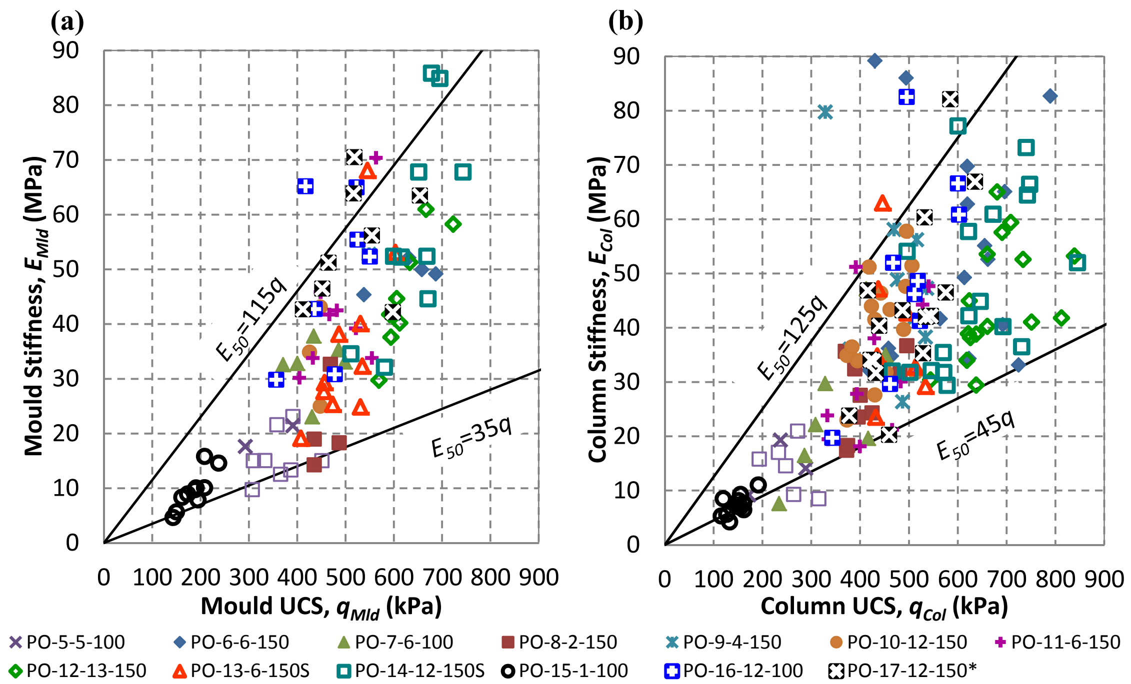

Figure 5-30: PORT column stiffness with UCS: a) mould samples & b) column samples

5.7 PORT SPSS Statistical Analysis

5.7.1 PORT Mould Sample Strength Analysis

The PORT room-cured and 20 °C cured mould data were split for separate analysis due to statistical difficulties in sub-dividing the data within the model for the different curing temperature conditions. However, an analysis of the 20 °C cured mould sample data was not carried out as the number of data samples, 30, was considered too small given the number of covariates that needed to be included in the models.

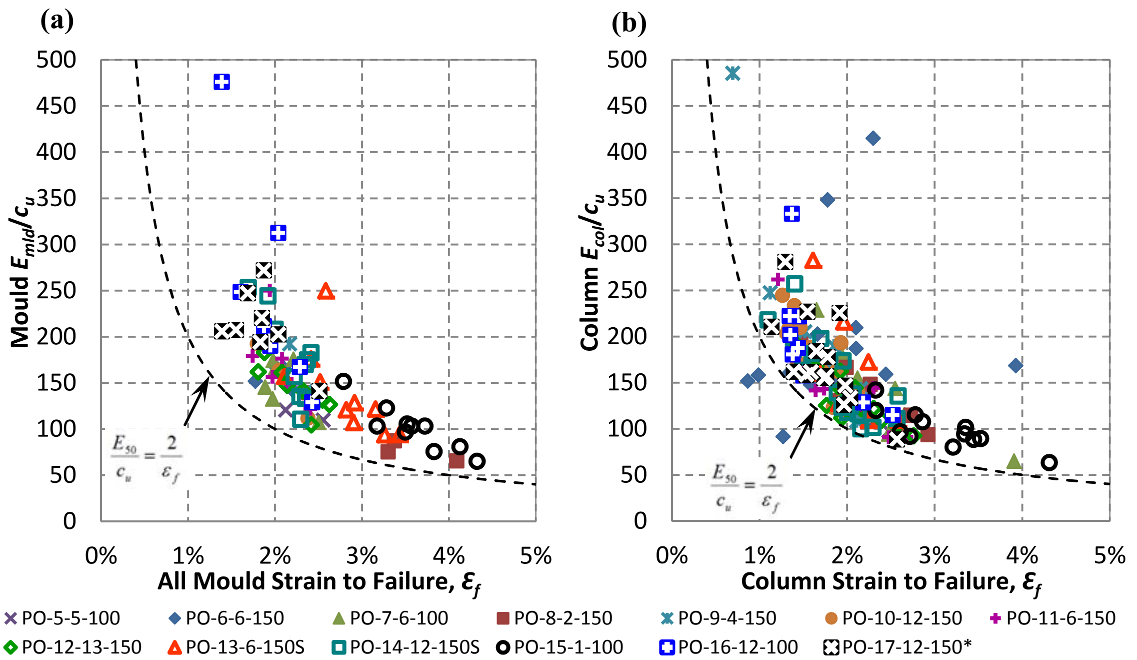

Figure 5-31: E_{50}/c_u relationship with failure strain: a) mould samples & b) column samples

<u>Bivariate Correlation:</u>

In the PORT room-cured mould bivariate analyses (see appendix G.1), the correlation of time and binder content with q_{mld} was found to be highly significant, while the correlation of w_i with q_{mld} was not significant. Density and temperature were found not to be significant and an interaction between w_i and density was observed to a high significance.

<u>Mixed Model Linear Regression Analyses:</u>

The initial mould model show curing time and binder content to have highly significant influences upon *q,* with significance values of 0 produced by the analysis (see Table 5-2); significant *covariates*, *i.e.,* values less than 0.05, are highlighted in bold. The same *covariate* significances are again seen when the natural log of the strength and curing time is applied (thus removing the flaring effect seen in the initial residual versus predicted graphs, see Appendix G.4). With additional *covariates* added to the models, curing time and binder content remained significant and, once included curing temperature was found to be significant in all models. Improved R^2 values are also noted as extra *covariates* are added. Moisture content (w_i) is typically found not to be significant over the range observed, nor was the interaction between w_i and density. A normal distribution of the residuals occurs and its bell shape improves with additional *covariates*, particularly for the PIRT room-cured data.

Table 5-2: PORT room-cured mould model assessment

Analysis:	**1**	**2**	**3**	**4**	**5**	**6**	**7**
R^2	0.535	0.666	0.673	0.829	0.845	0.85	0.854
Output	q	Ln(q)	Ln(q)	Ln(q)	Ln(q)	Ln(q)	Ln(q)
Covariates:	***Significances:***						
Intercept	0.67	**0**	**0**	**0**	**0**	0.606	0.259
Time	**0.002**	-	-	-	-	-	-
Ln(Time)	-	**0**	**0**	**0**	**0**	**0**	**0**
Binder	**0**	**0**	**0**	**0**	**0**	**0**	**0**
w_i	-	-	0.306	-	**0.033**	0.95	0.302
Temperature	-	-	-	**0**	**0**	**0**	**0**
Density	-	-	-	-	-	0.218	0.445
w_i - Density	-	-	-	-	-	-	0.3

5.7.2 PORT Column Sample Strength Analysis

Bivariate Correlation:

As seen in the mould data, highly significant correlations were observed between q_{col} and both the curing time and binder content, as well as an interaction between w_i and density (see appendix G.1). Possible correlations were also seen between binder content, w_i and temperature in terms of the curing time but are again due to the manner in which the tests were scheduled and are not accounted for.

Mixed Model Linear Regression Analyses:

In all PORT column models (see Table 5-3), curing time and binder content were found to have a significant effect on the q value. Again, the natural log was taken of the q value and the curing time to remove the flaring noted in the residual versus predicted graphs. Normal distribution of the residuals again occurs. Addition of w_i and temperature to the PORT column models shows both properties to be highly significant. In the final model, the interaction between w_i and density was found not to be significant, as was seen in the mould analysis. Overall, R^2 values increased from 69.5% to 79.9% as additional *covariates* were added to the models. The SPSS outputs for each PORT column analysis can be found in Appendix G.3.

Table 5-3: PORT column model assessment

Analysis:	**1**	**2**	**3**	**4**	**5**	**6**	**7**
R^2	0.538	0.695	0.74	0.728	0.769	0.798	0.799
Output	q	Ln(q)	Ln(q)	Ln(q)	Ln(q)	Ln(q)	Ln(q)
Covariates:	***Significances:***						
Intercept	**0.023**	**0**	**0**	**0**	**0**	**0.015**	0.245
Time	**0**	-	-	-	-	-	-
Ln(Time)	-	**0**	**0**	**0**	**0**	**0**	**0**
Binder	**0**	**0**	**0**	**0**	**0**	**0**	**0**
w_i	-	-	**0**	-	**0**	**0**	0.341
Temperature	-	-	-	**0**	**0**	**0**	**0**
Depth	-	-	-	-	-	**0.013**	**0.02**
Density	-	-	-	-	-	**0**	0.672
w_i -Density	-	-	-	-	-	-	0.402

5.8 Chapter Summary

Overall, thirteen successful PORT column tests were completed on OPC stabilised *sleech* columns, created using binder contents of either 100 kg/m^3 or 150 kg/m^3. The columns were cured for times of between one and thirteen days before testing, resulting in average column strengths from approximately 200 kPa to 680 kPa, and stiffnesses from 4 MPa to 90 MPa. Two of the columns were tested under a surcharge load, which increased confinement around the top of the column.

In Chapter 8, the data from the PORT column tests presented in this chapter, will be used along with wire friction data and the corrected column strengths, data for both of which are presented in Chapter 7, to calculate the N value for the 150 mm reduced-scale PORT penetrometer used in the these tests. These N values will then be discussed and compared with those in current literature.

CHAPTER 6: PUSH-IN RESISTANCE TEST (PIRT) RESULTS

6.1 Introduction

In this chapter, the results of a series of reduced-scale PIRTs on 200 mm dia. pre-drilled stabilised soil-cement columns are set out. Three preliminary trial columns (PI-1 to PI-3) were constructed specifically to help define the PIRT column construction and testing procedures, but results from these are not considered in this thesis.

The results of 11 no. PIRT (PI-4 to PI-14S), carried out between July and October 2013, are considered hereafter and are summarised in Table 6-1. Each PIRT column experiment is given a full designation *PI-X-Y-Z,* where:

(i) *X* refers to the column test reference number and *PI-X* is used as an abbreviated reference to a test.

(ii) *Y* represents the curing time, rounded to the nearest day, from column construction to PIRT, and ranges from 1 to 12 days to achieve a wide spread of target strengths.

(iii) *Z* represents the binder content (kg/m^3) used to stabilise the *sleech* and was either 75 kg/m^3, 100 kg/m^3 or 150 kg/m^3 of OPC.

The "*" designation for PI-12-12-150* is used to highlight that while most of the column was constructed with a binder content of 150 kg/m^3, one of the four mixes in the column was stabilised with 100 kg/m^3, with the view to establishing the effect of a significant drop in strength within a column. The "S" designation (of PI-9S and PI-14S) signifies columns that were surcharged over the top of the entire basin, with a view to increasing the confinement in the curing basin, particularly around the top of the column.

The alternative descriptor *PI-SL-X* designates a PIRT in the unstabilised *sleech* surrounding a given column, *X*, and *PI-SL-T* is used to reference tests in the *sleech* surrounding the "temperature-monitored" column. The descriptor *C-SL-X* is given to a cone-only penetrometer test performed in the surrounding *sleech*. These tests were carried out to obtain a benchmark for the *PI-X* test series in a very low strength, unstabilised material. The recorded probing forces of all PIRT experiments are presented in Section 6.2, while individual summary sheets and summary statistics on all tests can be found in Appendix E.4 and E.5, respectively.

The relevant properties recorded during construction, curing and testing of each column (and their reference mould samples) are presented in this chapter. The moisture and organic content of the initial *sleech* is detailed in Section 6.3, while Section 6.4 presents the ambient curing temperature, curing stress conditions and the properties of the surrounding *sleech* in which the columns cured. Section 6.5 presents the stabilised moisture content and stabilised density of the mould and column samples, while Section 6.6 presents the strength and stiffness properties of each stabilised column following PIRT and their respective mould samples. Finally, in Section 6.7 the results of a statistical analysis carried out on the mould and column strength sample data are presented.

The same framework as set out in Chapter 5 is again used to account for variability discussed in Section 3.12 and unify the data presented in this chapter.

6.2 Push-In Resistance Test Experiments

6.2.1 PIRT of Stabilised Columns

PIRT probing of stabilised columns was typically carried out in two pushes, designated P_1 and P_2, with a pause in the test required to insert additional sounding bars. Average probing rates for each push were typically between 18 mm/sec and 26 mm/sec and are individually detailed in Table 6-1. Figure 6-1 shows the uncorrected probing force profile (P_1) with height from the basin base (h) for tests PI-4 to PI-14S grouped by similar curing times. Probing forces are presented relative to the leading edge of the PIRT penetrometer wing.

At the beginning of each test, the force increased instantly as the penetrometer began to press into the column. The force peaked and subsequently dropped as the column cracked open ahead of the penetrometer, before rising again to follow a relatively constant trend with depth. In the middle of the column, a temporary reduction in force identifies where the test was paused to insert additional sounding bars. Approaching the base of the column (*i.e.,* within the last 50 mm of column) the force began to drop, believed to be due to a crack extending to the base of the column. On entering the unstabilised *sleech* under the column the probing force showed a reduced magnitude to that recorded in the column. During testing minor buckling of the sounding bars was noted due to their slenderness, resulting in contact with the column, the extent of which cannot be easily quantified.

Table 6-1: PIRT column details

PIRT No.	PIRT Time t_{Pi} days	UCS Time t_{col} days	Binder Content kg/m^3	Column Height, *h*, mm	*Sleech* Moisture Range, w_i, %	Organic Content %	No. Column Samples	Av. Column UCS, *kPa* (*Uncorrected*)	Column UCS St. Dev., kPa	Av. Column UCS, *kPa* *(Corrected)*	Ambient Temp. *T*, °C	Push-In Rates, P_1 & P_2, mm/sec	
PI-1[¤]	*3.09*	*3.18*	*100*	*572/660*	*45-46*	*-*	*7*	*219.4*	*17.5*	*216.4*	*11.2*	30.0	-
PI-2[¤]	*10.99*	*11.17*	*150*	*890*	*38-44*	*-*	*15*	*562.5*	*123*	*559.7*	*13.7*	12.4	11.1
PI-3[¤]	*12.88*	*13.04*	*150*	*790*	*46-48*	*3.1-4.0*	*11*	*798.4*	*98.7*	*796.6*	*21.3*	32.3	32.7
PI-4	1.85	2.10	150	955	42-48	2.6-3.4	14	347.5	60.9	327.8	19.2	18.3	21.1
PI-5	0.93	1.16	100	1,025	45-47	2.4-4.6	16	221.6	24.8	199.1	18.5	31.2	21.3
PI-6	5.93	6.11	150	1,020	46	2.2-3.2	13	474.4	59.0	469.7	18.4	24.9	26.1
PI-7	5.93	6.13	100	1,020	44-47	2.8-2.9	7	397.4	55.5	393.8	18.7	23.5	29.9
PI-8	3.94	4.13	150	1,000	48-52	2.6-3.6	13	459.4	37.7	452.2	17.9	27.4	25.3
PI-9S[†]	5.91	6.11	150	1,000	48-54	2.6-3.4	16	463.2	78.7	458.5	18.3	22.0	30.7
PI-10	11.86	12.19	150	1,010	53-56	2.4-3.8	14	712.5	51.8	708.5	17.8	34.5	26.3
PI-11	11.88	12.18	100	1,010	48-53	3.1-4.1	10	479.4	54.3	476.9	18.7	19.0	28.9
PI-12	11.90	12.22	150*	1,000	47-53	2.5-4.4	15	539.8	54.4	535.8	17.6	19.8	19.9
PI-13	0.88	1.22	75	1,005	48-49	2.6-3.9	16	180.5	22.5	155.7	17.5	22.1	20.5
PI-14S[‡]	11.86	12.33	150	980	48-51	2.9-4.6	22	632.7	35.4	625.4	16.9	18.2	21.6

[¤] PI-1, PI-2 and PI-3 were trial columns built to define the construction and testing methods. See summary sheets for further details

[†] 13.5 kPa surcharge on the basin during curing and testing via a 722 mm dia. loading plate

[‡] 13.8 kPa surcharge on the basin during curing and testing via a 722 mm dia. loading plate

* Mix 2 (height from basin base 420 mm to 615 mm) was stabilised with 100 kg/m^3 rather than the 150 kg/m^3 used in all other mixes in PI-12

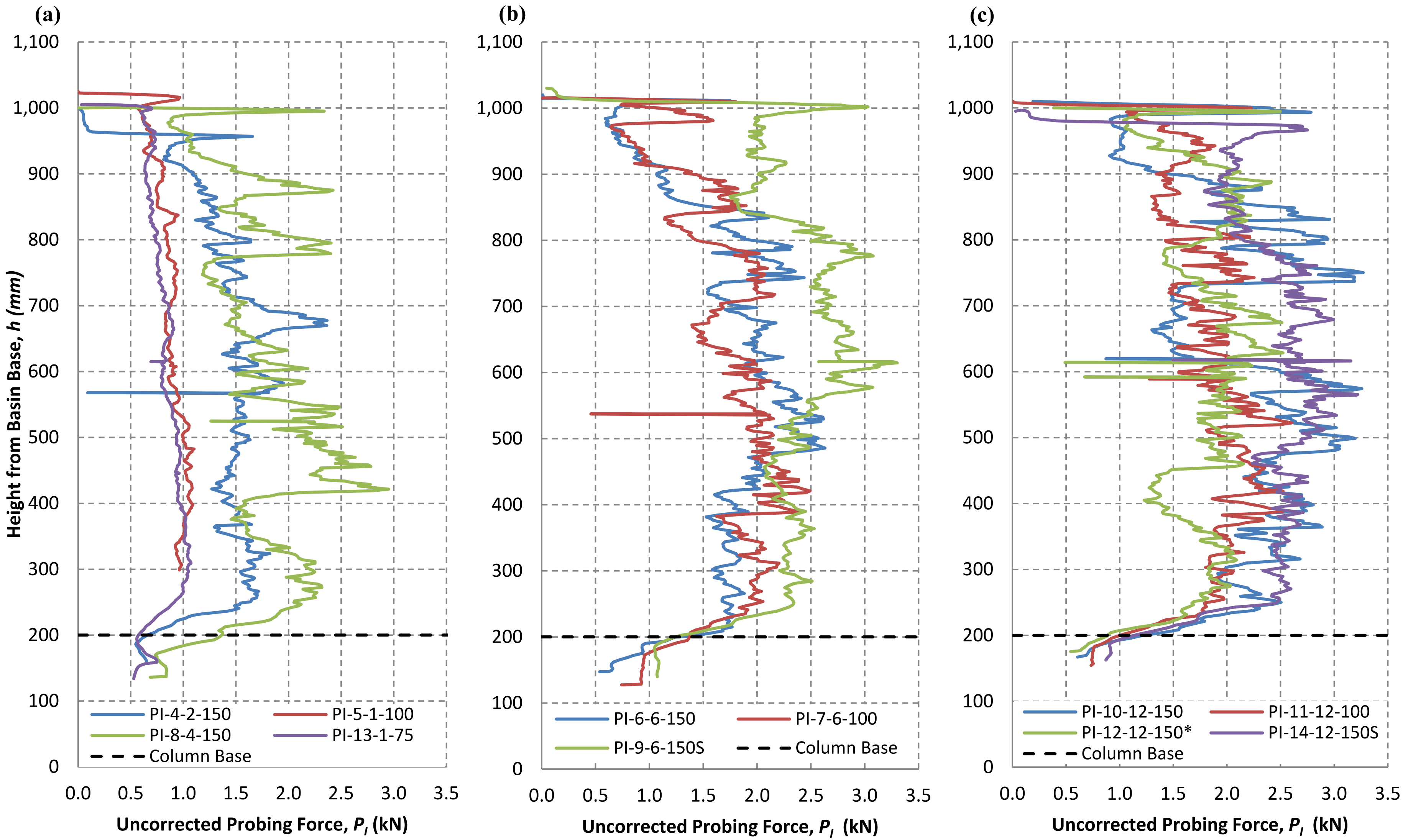

Figure 6-1: Recorded PIRT probing force with height from basin base: a) 1-4 day columns, b) 6 day columns and c) 12 day columns

Columns PI-4, PI-9S and PI-14S all show a low initial probing force due to a thin layer of *sleech* on the top of the column. In PI-12*, the varied binder content column, a reduction in force was recorded between h = 615 mm and h = 420 mm, *i.e.,* the extents of the 100 kg/m^3 Mix 2, and showed a notable drop at $h \approx 450$ mm. All of the stabilised column probing force results in Figure 6-1 are later corrected for cone and sounding bar friction using the results obtained from a series of cone-only penetrometer tests, see Section 7.3.

The application of a surcharge on the column reduced the magnitude of the drop in force that occurred after the initial peak as the penetrometer broke into the column. This is particularly evident in a comparison of PI-10 with PI-14S where similar average column strengths at the time of PIRT were observed in the top 200 mm of the column (688 kPa compared to 634 kPa respectively). In PI-10 the force peaks to 2.8 kN and drops to 1.1 kN, while in PI-14S a similar peak force of 2.8 kN was measured and reduces over a greater distance to 1.9 kN. Interestingly, the recommencement of probing after the addition of sounding bars in these tests does not show similar peaks and drops in force to those seen at the top of the column. It appears that increased confining stresses around the column created by the surcharge limit the amount by which the column can crack open.

Similar cracking patterns were noted throughout all tested columns, generally running from the centre of the column diagonally downwards and out to the face of the column and in places significant cracking was noted over the column's cross-section. As noted for the PORT series, it is likely that this cracking is the explanation for the jaggedness in the P_I profiles. Photographs of a number of exhumed columns and the crack patterns noted in each are presented in Appendix F.5 and are discussed in Section 8.3.3, along with the effect of cracking in the column on the probing force.

6.2.2 PIRT of Unstabilised *Sleech*

Four PIRTs were carried out in the unstabilised *sleech* surrounding a number of columns and Figure 6-2a shows the uncorrected probing force profile plotted against h for each test. PI-SL-13 and PI-SL-14 were both carried out in holes formed by the hole-form bar while both PIRTs around the "temperature-monitored" column (PI-SL-T1 and PI-SL-T2) were carried out without pre-forming a guide hole, and as such all data is presented relative to the leading edge of the PIRT penetrometer wing.

Lower probing forces (typically less than 0.25 kN) than those seen in the stabilised columns were noted and these were seen to increase with depth, in keeping with a mild increase in undrained shear strength, as seen in Figure 6-2b. The adhesive nature of the soil also contributes an additional probing force which increases with depth as *sleech* adheres to the vertical faces of the penetrometer and the sounding bars. The contribution of the additional force from the sounding bars can be interpreted using the cone-only penetrometer test (C-SL-14) data shown on Figure 6-2a. All four tests are later corrected in Section 8.5.2 for sounding bar friction using these results.

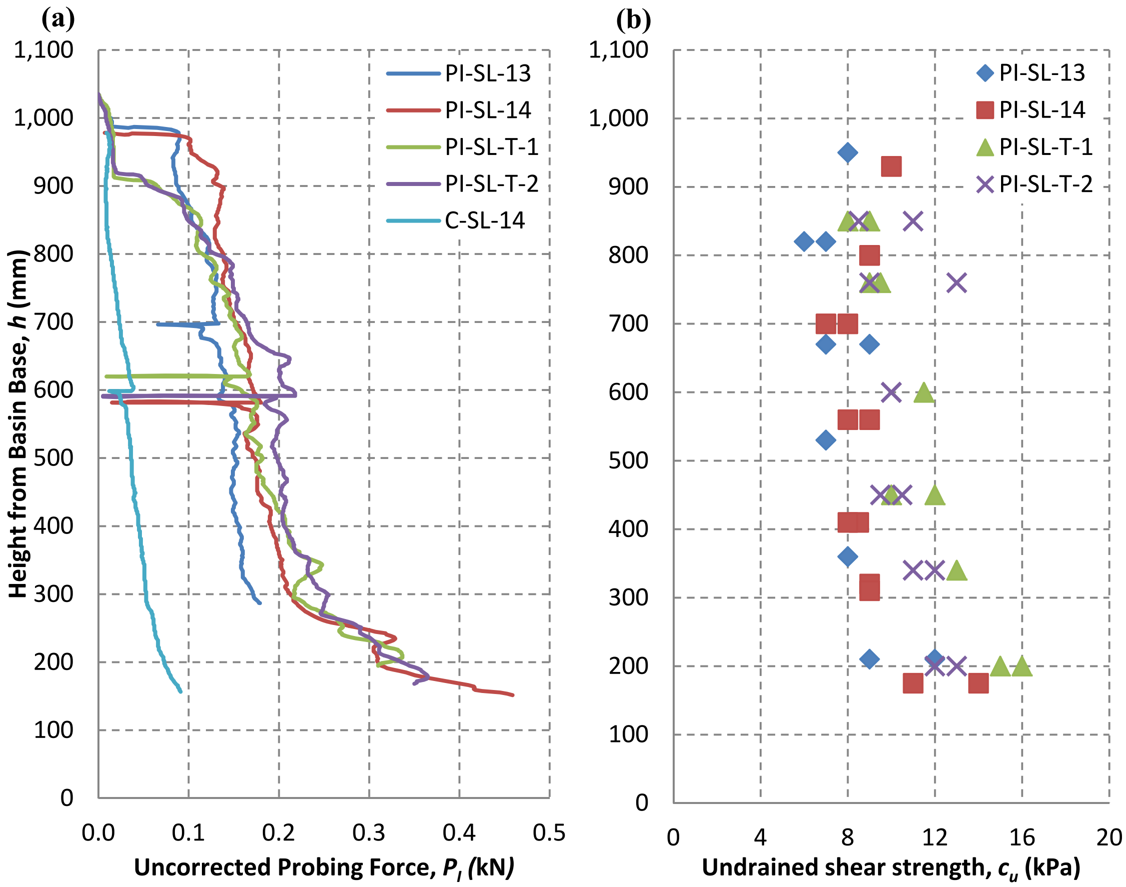

Figure 6-2: a) PIRT in unstabilised *sleech* & b) *sleech* undrained shear strength

6.3 PIRT Column Initial *Sleech* Properties

6.3.1 Introduction

This section presents details of the moisture content and the organic content of the *sleech* used to create each individual stabilised mixture. A consideration of these initial properties is necessary for proper interpretation of the test results.

6.3.2 PIRT Column Moisture Content

Figure 6-3 shows the raw moisture content values (w_i) relevant to each individual PIRT column mix. The values of w_i, each based on samples (n = 2) taken from the homogenised *sleech* from each mix, are plotted at mid-depth for each of the four mixes in a given column. Values lie in the range 42% to 56%, but predominantly lie between 46% and 53%, and cover a narrower range than that observed in the PORT series (46% to 69%), presented in Section 5.3. This was achieved by greater control on the choice of *sleech* for each column, see Section 3.12, *e.g.,* sampling all of the *sleech* for one column from the same location in the storage basin. Coefficients of variation for w_i in a given column were found to range from 1.7% to 6.2% and the CoVs for w_i in each individual column may be found in Appendix E.5.

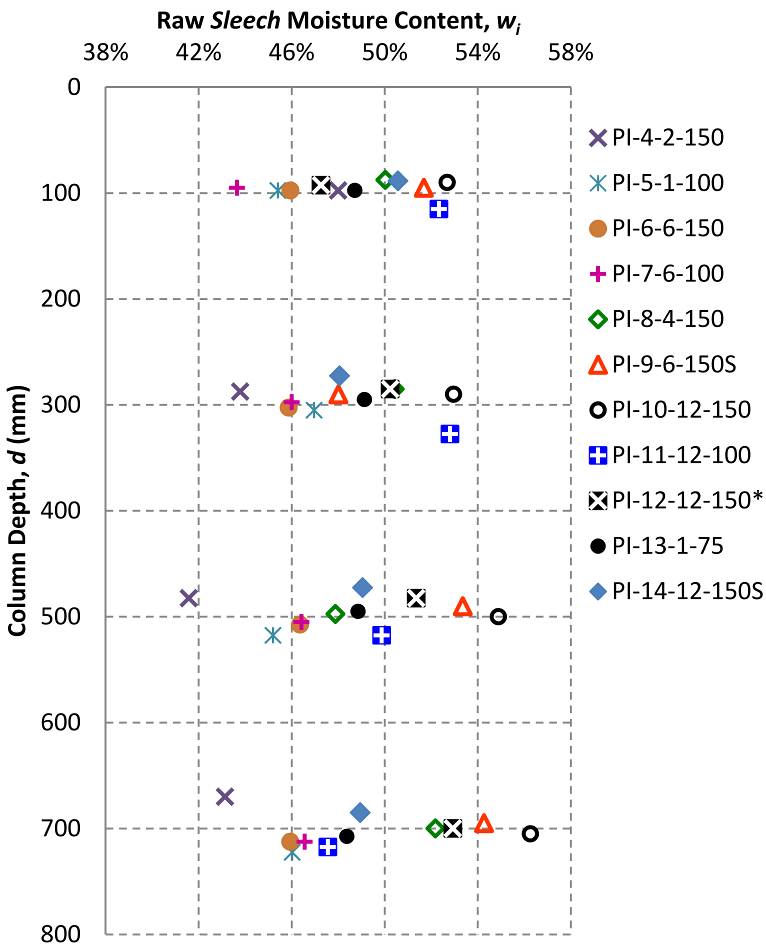

Figure 6-3: PIRT column raw *sleech* moisture content

Reductions in moisture content were observed after the addition of the binder to the raw *sleech* and mixing, see Figure 6-4 a & b where the difference between w_i and the mixed *sleech* moisture content (w_{mix}) is plotted against the mid-depth of each mix. Approximate reductions were typically between 4% and 6% for the binder contents of 75 kg/m^3 and 100 kg/m^3, and as expected, greater reductions typically between 6% and 8% were seen at the higher binder content of 150 kg/m^3. These values are compatible with those measured in the PORT series. The final moisture content of the stabilised *sleech* at the time of UCS testing (*i.e.,* post-curing) is presented in Section 6.5.2 for both mould and column samples.

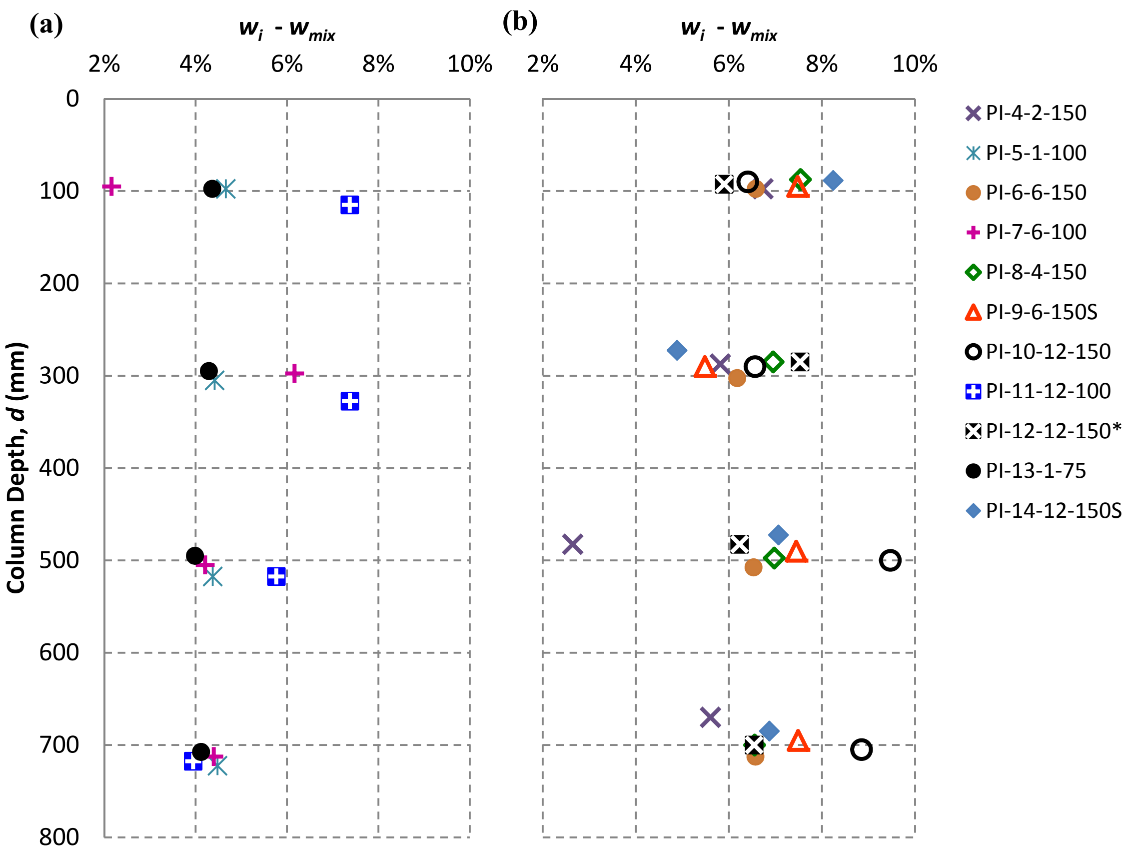

Figure 6-4: Reductions in column moisture content after binder addition and mixing at binder contents of a) 75 kg/m^3 and 100 kg/m^3 & b) 150 kg/m^3

6.3.3 PIRT Column Organic Content

Organic contents were found to range from 2.2% to 4.6%, see Figure 6-5, and overall show a notable difference to the 5.2% obtained in the original classification trials. The organic matter present in the *sleech* originates from the remains of marine animals, shells and fibrous roots, all of which were found in the *sleech* during the test series. Further data on the organic content, in terms of the *sleech* surrounding the columns, is given in Section

5.4.4 and possible reasons for the variation in organic content have been given previously in Section 3.12.

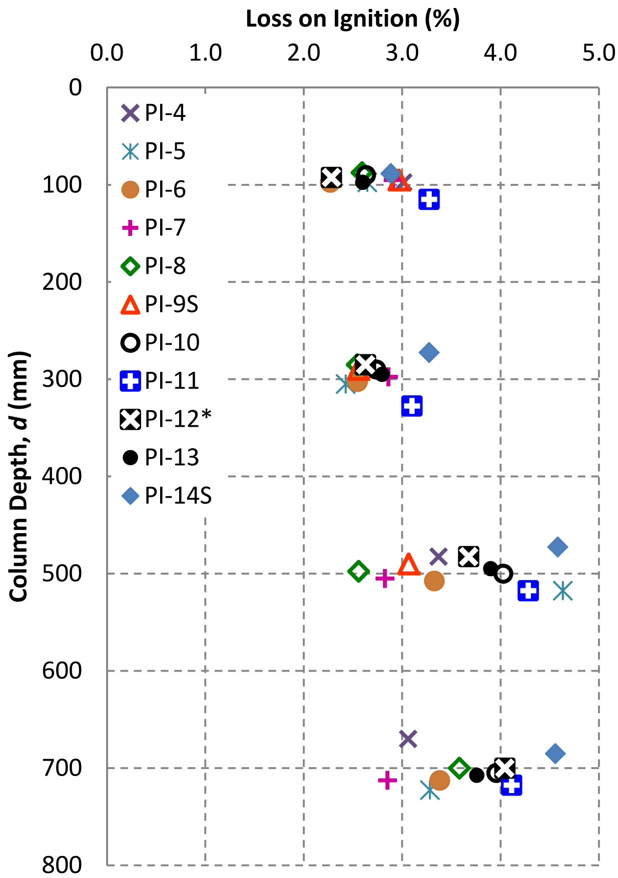

Figure 6-5: Organic content of *sleech* used in each PIRT column

6.4 PIRT Column Curing Conditions

6.4.1 Introduction

This section presents details of the factors that influence the curing conditions of both the laboratory prepared mould samples and the PIRT columns. A consideration of all these properties is relevant to the interpretation of the test results. These are:

(i) The historical ambient temperature variation of the laboratory in which the columns cured.

(ii) The stress conditions to which the columns were subjected during curing and testing.

(iii) The properties of the *sleech* surrounding each column during curing.

6.4.2 Laboratory Temperature

Column basins and one mould sample from each mix were cured at ambient laboratory temperature. Laboratory temperature data were recorded at an hourly rate by the Building Management System (BMS) and Figure 6-6 shows the ambient laboratory temperature variation over the course of the entire PIRT series, with mixing and testing dates for each test superimposed. The average ambient laboratory temperature (T) over the curing period of each column was calculated and these were found to lie between 16.9 °C and 19.2 °C, see Table 6-1. Where temperature data were not recorded by the BMS (during part of the curing period of PI-6 and all of PI-8), best estimates were made using the trends seen in the outside air temperature and the laboratory temperature either side of missing data.

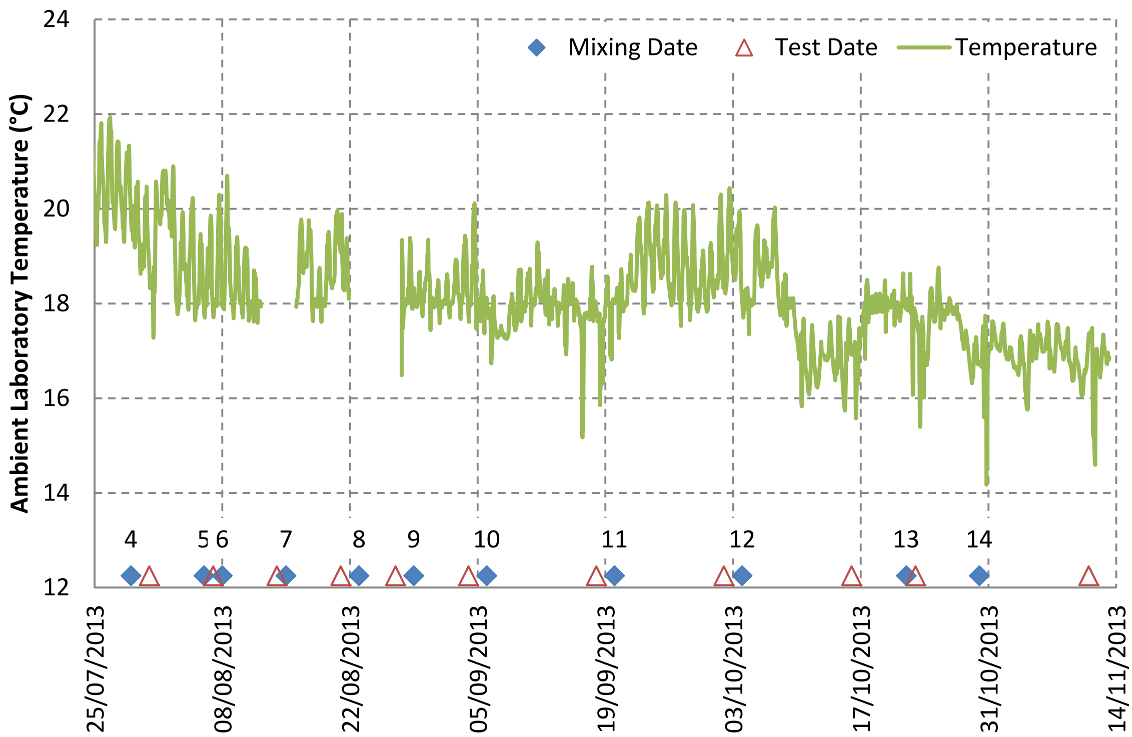

Figure 6-6: Ambient laboratory temperature during PIRT column series

6.4.3 Surcharged PIRT Columns

To increase confinement throughout the basin, particularly around the top of the column, PI-9S and PI-14S were loaded with surcharges of 13.5 kPa and 13.8 kPa respectively over the entire top of the column and surrounding *sleech*. The surcharges were applied immediately after construction of the columns and remained in place during the PIRT. Mould samples from the surcharge tests were cured under the same conditions as all other tests and were not stressed in any way. This should be borne in mind in the comparison of column and mould strengths presented subsequently in Figure 6-26.

The increase in stress with depth induced by the surcharge for PI-9S and PI-14S, was approximated using the Boussinesq vertical stress distribution and was superimposed upon that due to the self-weight of the *sleech* in Figure 6-7. The inclusion of a surcharge on the basins is seen to increase the stresses throughout the entire basin depth. At the top of the basin, where an increased confinement was sought, the increased stresses are comparable to those at a depth of 0.80 m in a non-surcharged column scenario.

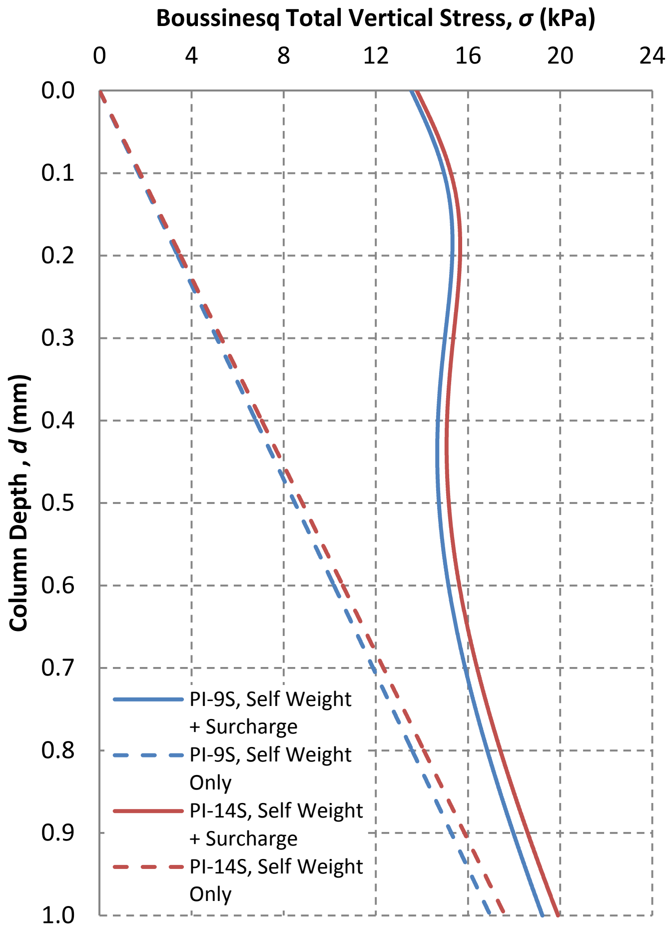

Figure 6-7: Boussinesq vertical stress distribution

6.4.4 PIRT Column Surrounding *Sleech* Properties

During construction each column was surrounded by unstabilised parent *sleech* and Figure 6-8 a & b show the average moisture content and average bulk density profiles determined from 50 mm dia. by 50.5 mm long cylindrical core samples (typically n = 3) after PIRT of the column.

Average surrounding *sleech* moisture contents (w_{ss}), determined by drying the whole bulk density sample, lie between 42% and 50% and vary due to loss of moisture due to repeated remoulding during the column construction process and during storage. LOI values for the surrounding *sleech* vary between 2% and 5%, see Figure D-2 in Appendix D. Average compacted *sleech* densities (ρ_{ss}) varied between approximately 1,700 kg/m^3 and 1,900 kg/m^3 (see Figure 6-8b), compared to the in situ field densities of 1,550 kg/m^3 to 1,750 kg/m^3 (w_i range 48% to 80%) seen in Section 3.12. In Figure 6-9, individual ρ_{ss} values are seen to be a function of their w_{ss} values. The spread at a particular w_{ss} may be the result of small pieces of stone, shell or small air pockets in the sampled cores.

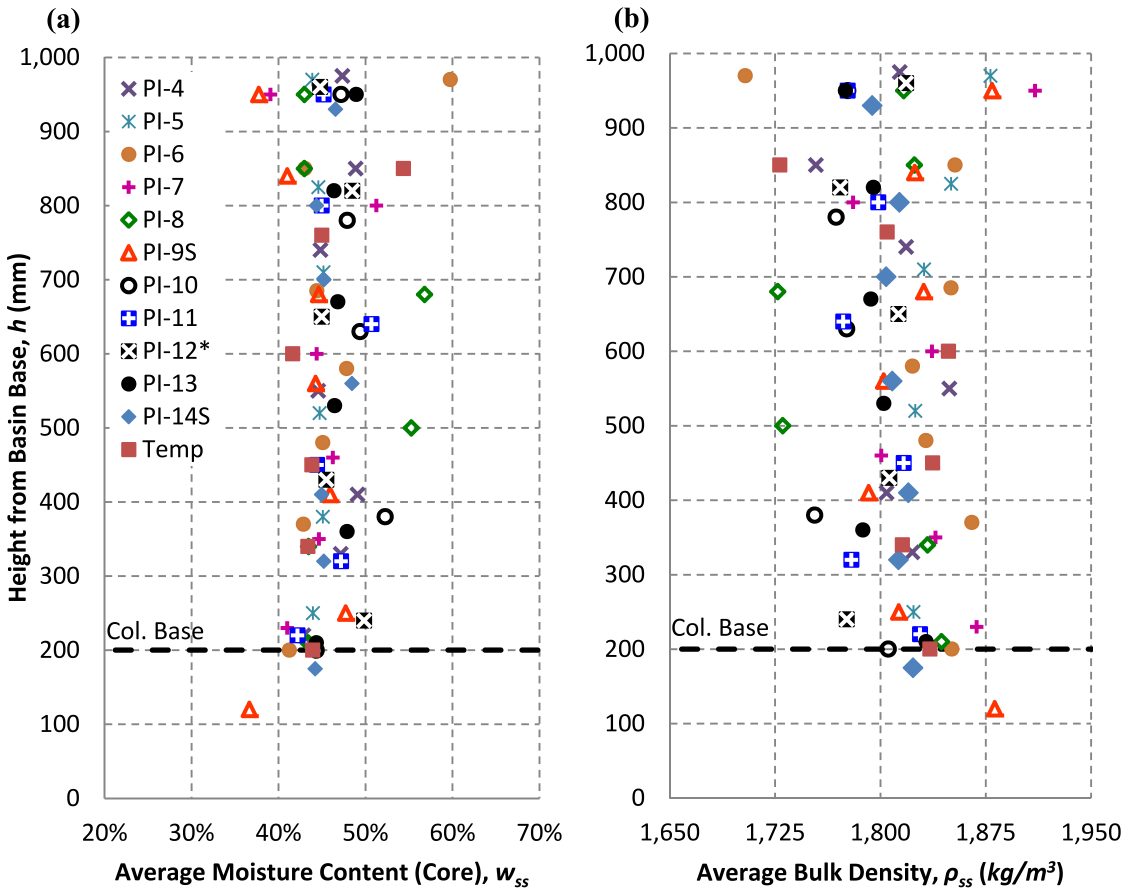

Figure 6-8: Unstabilised surrounding *sleech*: a) average moisture content, b) average bulk density

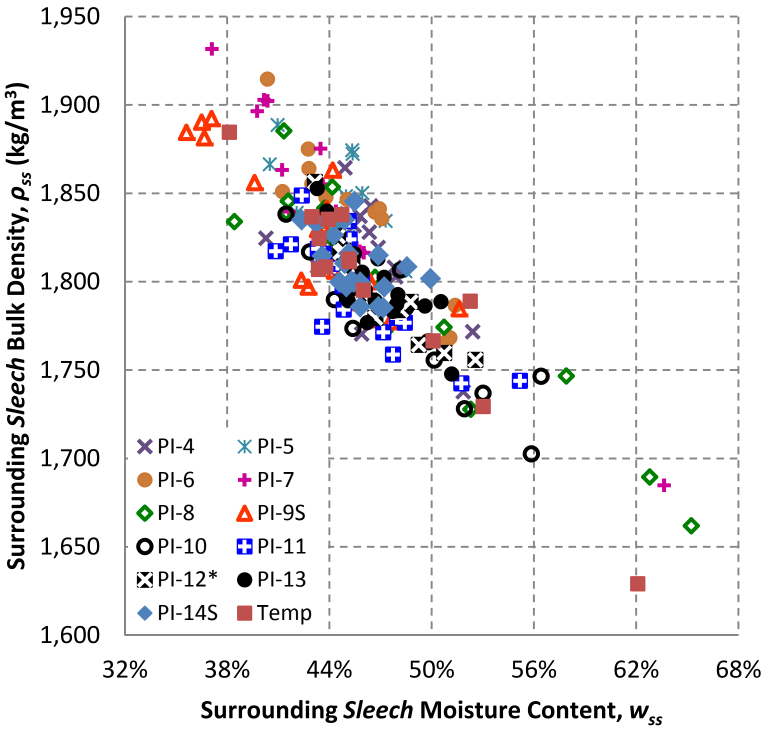

Figure 6-9: Surrounding *sleech* compacted density with moisture content

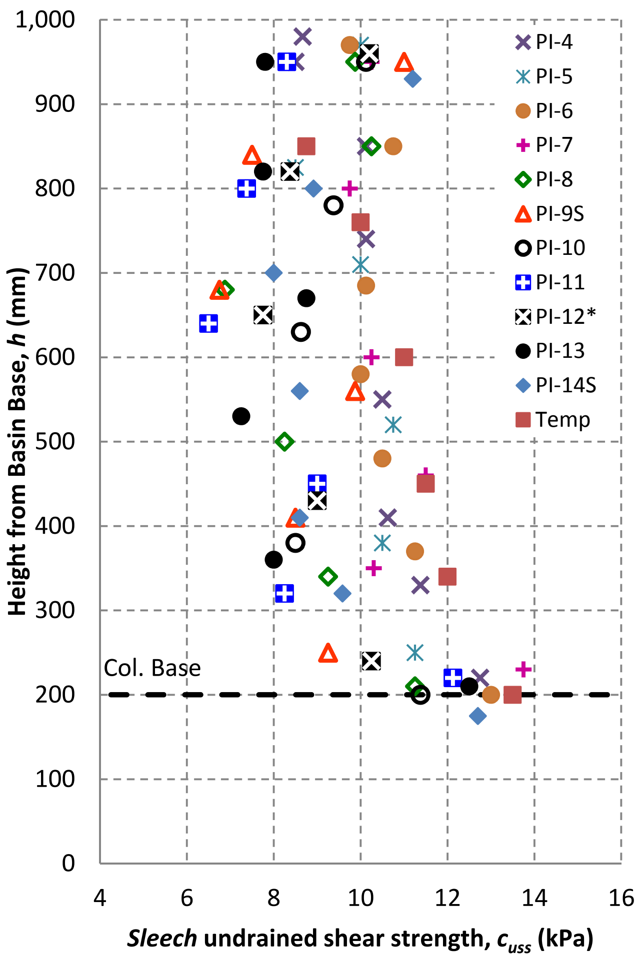

Figure 6-10: Average undrained shear strength of surrounding *sleech*

Average undrained shear strengths of the surrounding *sleech* (c_{uss}) (n = 3-4), determined with a pocket shear vane, typically show a mild increase with depth with overall strengths between 7 kPa and 14 kPa, see Figure 6-10. Strengths lie between the values of 4.5 kPa (remoulded) and 15 kPa (undisturbed) obtained in the laboratory during initial classification tests using a fall cone. In general lower strengths are seen to reflect greater moisture contents as shown in Figure 6-11, but the relationship is not as clear as was seen in the corresponding PORT series.

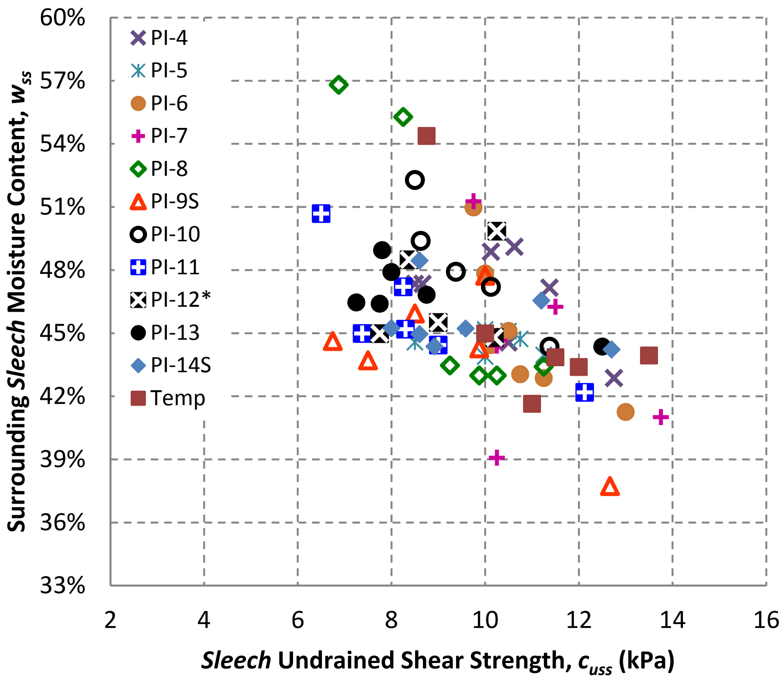

Figure 6-11: Surrounding *sleech* average undrained shear strength with average moisture content

To investigate the possibility of lateral migration of moisture within the surrounding *sleech* after curing and PIRT, moisture content samples were taken at the basin wall (r = 375 mm, where r = radius from column centre), mid-way between the wall and the column (r = 240 mm) and at the column face (r = 100 mm) using a soil profile sampler. No systematic trend could be identified in terms of the radial movement of moisture within the *sleech* surrounding the column during curing, as was the case around the PORT columns. Once again, a zone of increased plasticity approximately 10 mm in thickness was noted around the columns and this *sleech* was discarded from future tests.

6.5 PIRT Column Stabilised Moisture Content & Density

6.5.1 Introduction

In this section the stabilised moisture content and the stabilised density of the 65 mm dia. laboratory prepared mould samples (from each stabilised mix) and 50 mm dia. samples taken from exhumed columns are presented. In view of repeatability of column production comparisons are drawn between column sample densities, which tend to be underestimated due to necessity to trim the column into cylindrical samples by hand, and their associated room-cured samples, as well as samples cured at 20 °C to EuroSoilStab (2002) requirements.

6.5.2 PIRT Mould and Column Stabilised Moisture Content

For each individual mix, the stabilised moisture contents (w_{mld}) for the room-cured and 20 °C cured mould samples were similar and no systematic trend in w_{mix} - w_{mld} over the curing periods could be seen. The actual stabilised moisture contents may be found on the summary sheets in Appendix E.3 and Figure D-2 presents the w_{mld} and w_{col} values with depth.

Figure 6-12 a & b show the reduction in moisture content of the column during curing, *i.e.,* the difference between w_{mix} and the moisture content of the 50 mm dia. stabilised column samples (w_{col}). Although a general trend of greater reductions with curing time occurs, minor variations in the mixed *sleech,* losses in moisture due to evaporation during mould and column construction, and the small numerical differences between w_{mix} and w_{mld} or w_{col} mean that again, it is difficult to fully quantify the exact change in moisture content during curing.

As presented in Section 5.5.2, Equation 2-16 calculates an estimated stabilised moisture content (w_{se}) and Figure 6-13 a & b show a comparison of w_{mld} and w_{col} with w_{se}, respectively. Using a sum of least squares calculation, a non-evaporable moisture content of 0.21 was found to fit the data best and again, is at the lower limit of values quoted in the literature as seen in Section 5.5.2.

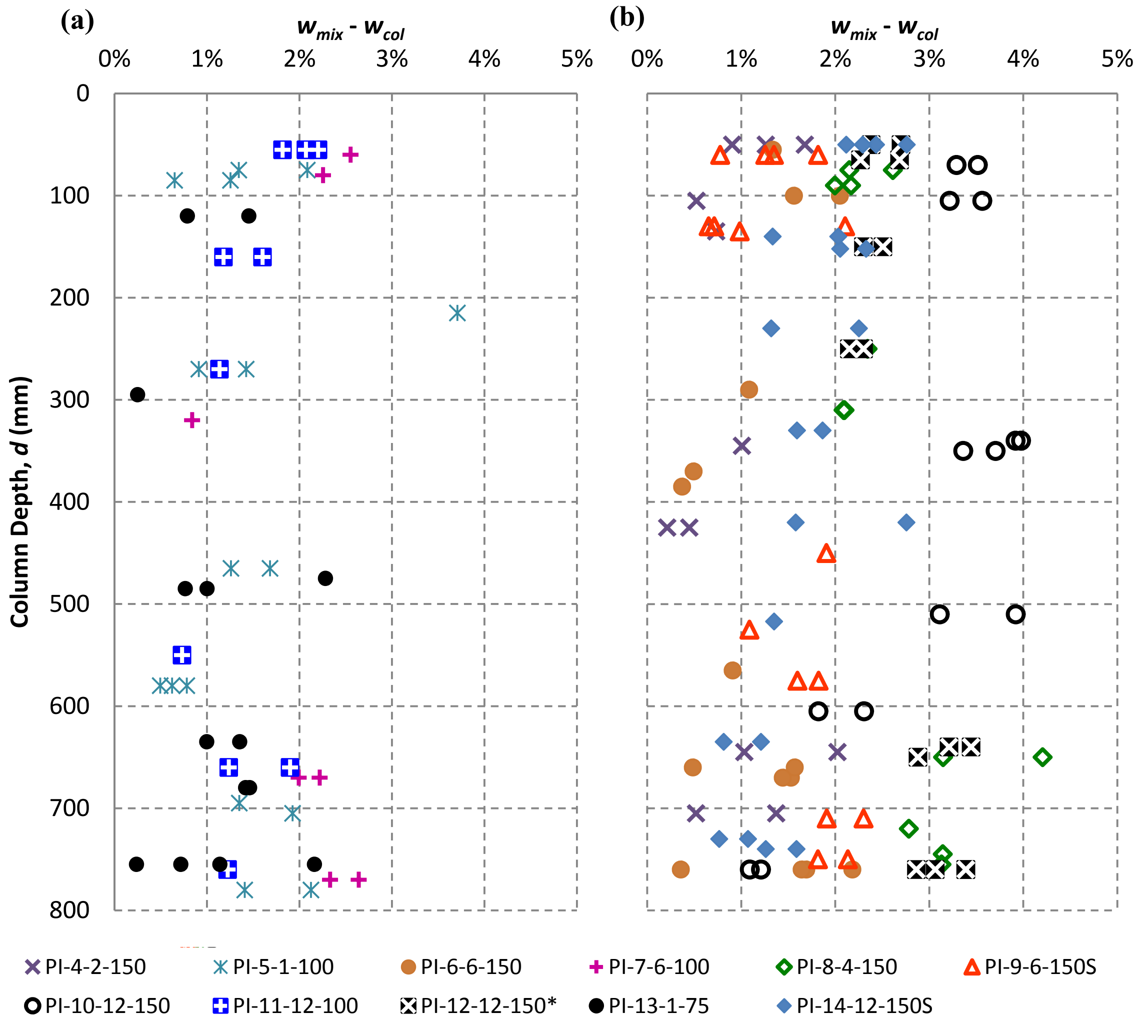

Figure 6-12: Reductions in column moisture content during curing at binder contents of a) 75 kg/m^3 and 100 kg/m^3 & b) 150 kg/m^3

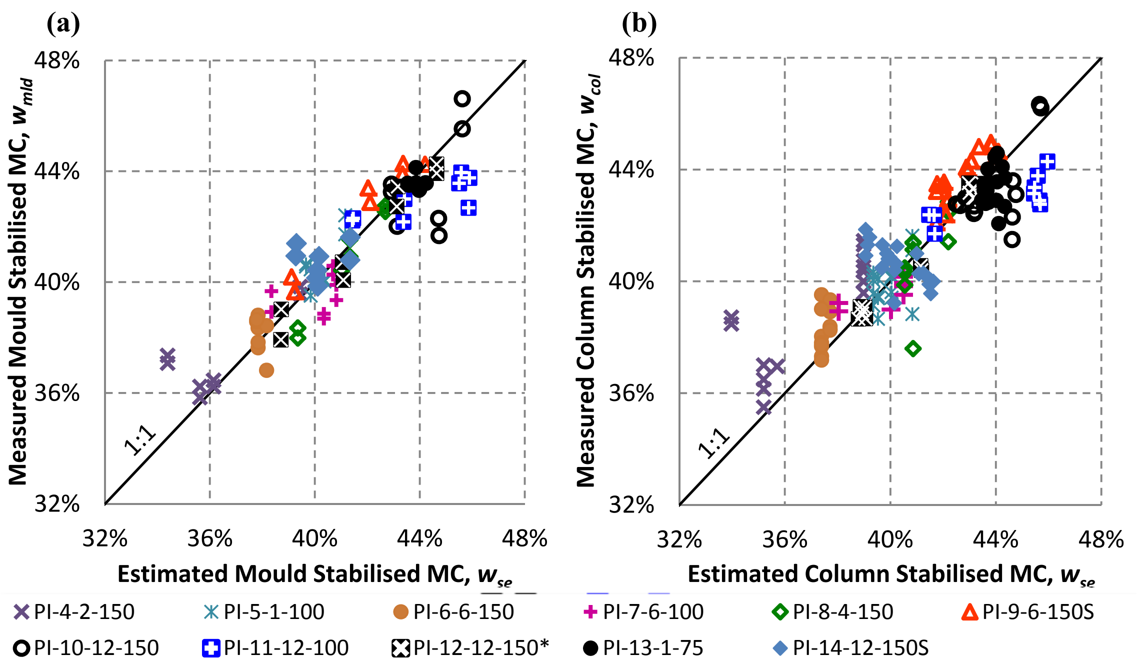

Figure 6-13: Estimated and measured stabilised moisture content: a) mould samples & b) column samples

6.5.3 PIRT Mould and Column Stabilised Density

Figure 6-14 shows a comparison of the room-cured sample density (ρ_{mldR}) against its respective 20 °C water-bath cured sample density (ρ_{mldT}). In keeping with that found in Section 2.11.2 and seen for the PORT series in Section 5.5.3, a general 1:1 trend between room-cured and 20 °C cured sample density is visible although room curing temperatures are generally close to 20 °C (see Table 6-1). It should be noted that mould sample data relates to one sample only and small discrepancies in the results are primarily due to minor voids on the face of the sample. Coefficients of Variation (CoV) for both the four room-cured and the four 20 °C cured samples created for a given column were found to be less than 1.4%, see Appendix E.5.

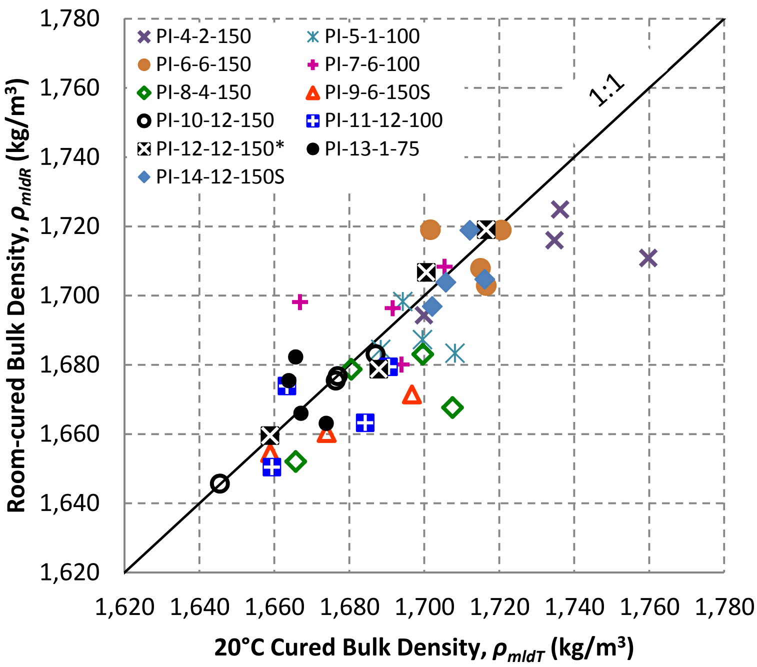

Figure 6-14: Room and 20°*C* mould sample density comparison

Figure 6-15 shows the average column density (ρ_{col}) with depth; samples whose centre's depths were within 25 mm of each other in any one column were averaged. Average densities ranged from 1,675 kg/m^3 to 1,900 kg/m^3 due to the factors set out in Section 3.12 and all individual column sample densities can be found in Appendix E.4. The CoV for ρ_{col} associated with a given column was found to be no more than 3.5% and the number of samples used in its determination is stated in Table 6-1.

In Figure 6-16 a & b, ρ_{col} samples are compared to the respective ρ_{mldR} and ρ_{mldT} samples of the mix from which they originated. Overall ρ_{col} was found to lie in the range of 1.0 to

1.12 times the density of their respective ρ_{mldR} and ρ_{mldT} samples, indicating that slightly greater densities were achieved in the columns compared to the moulds. This ratio is in keeping with that established in the PORT series.

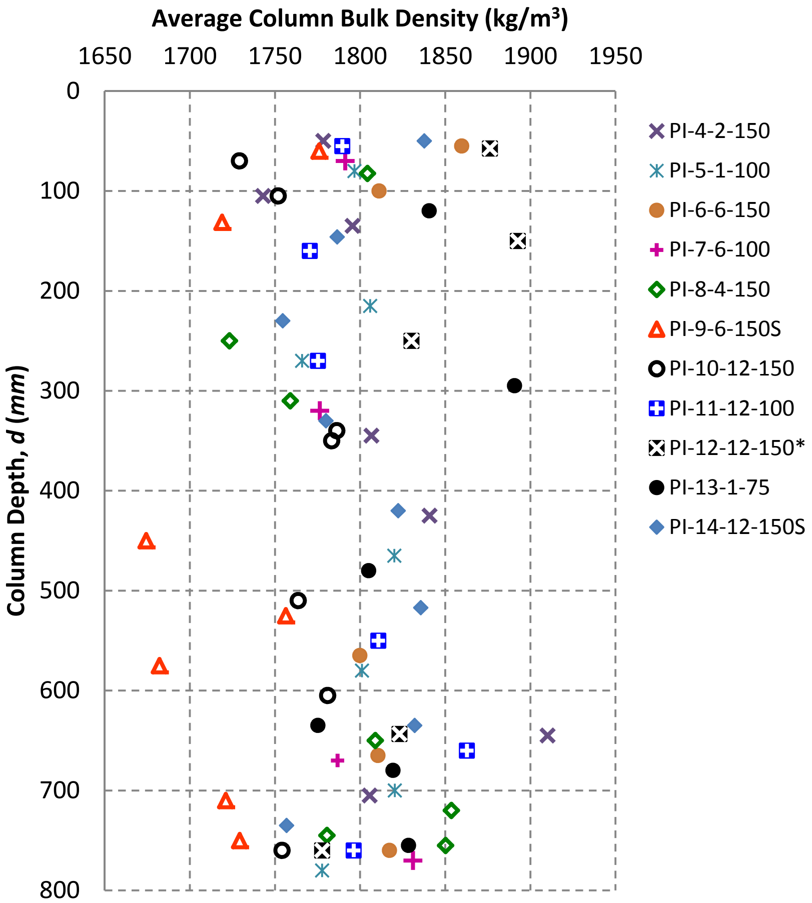

Figure 6-15: Average column density with depth

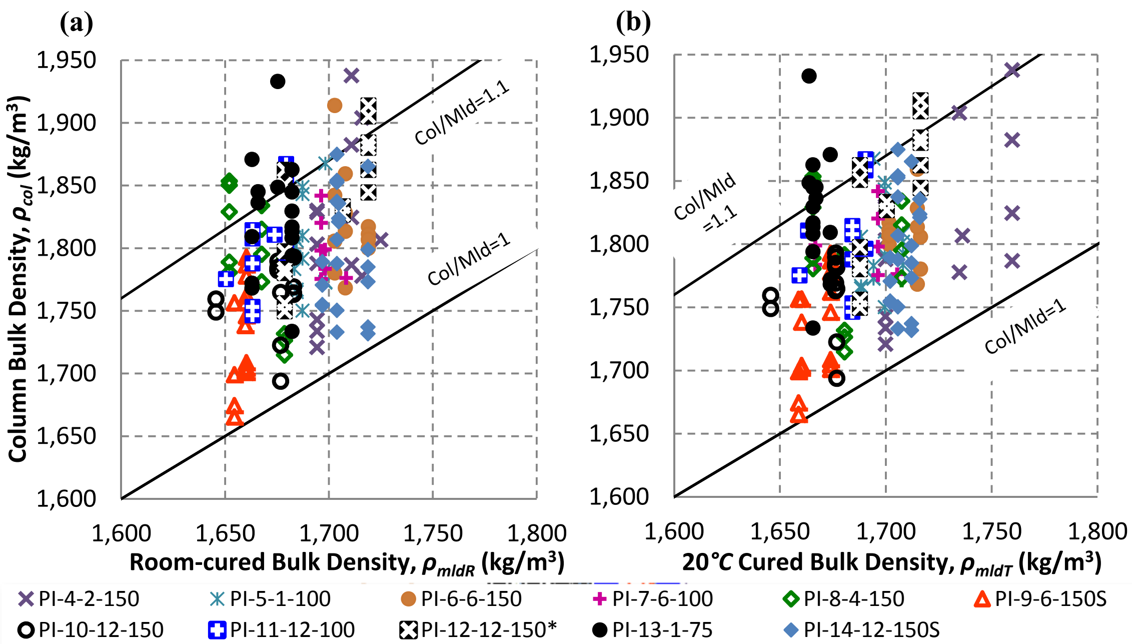

Figure 6-16: Column density with a) room-cured density & b) 20 °C cured density

Trends of increasing ρ_{mld} with reducing w_{mix} are seen in Figure 6-17 a & b, indicating that the variation in stabilised mould density over all tests can be attributed largely to variations in moisture content rather than variations in compaction of the mould samples. In Figure 6-17 a & b values of A_{stab} are chosen to predict the range of mould sample densities at binder contents of 100 kg/m^3 and 150 kg/m^3 respectively, calculated using Equations 5-1 and 5-2. At a G_s of 2.73 (from initial classification tests) the data is found to lie within the density ranges predicted assuming A_{stab} values of 7% and 10.5% and are similar to those seen in the PORT columns, see Section 5.5.3.

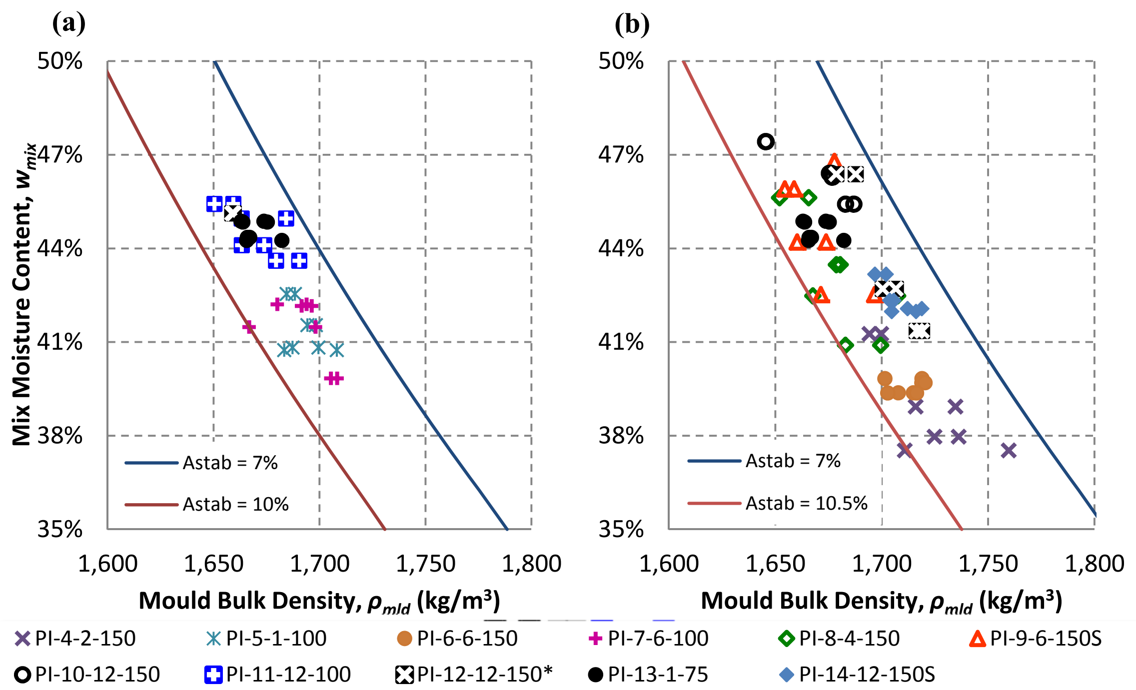

Figure 6-17: Room and 20°C cured mould sample density with mixed moisture content at binder contents of a) 75 kg/m^3 and 100 kg/m^3 & b) 150 kg/m^3

The variation of ρ_{col} with w_{mix} shown in Figure 6-18 highlights a wider spread of densities than for the moulds shown in Figure 6-17. This is thought to be the result of the volumetric column sample measurement issues previously mentioned in Section 3.12. Figure 6-18 a & b also provide an estimate of the column density, calculated using a G_s of 2.73 and air contents of 0% and 6% for 100 kg/m^3 binder contents and 0% and 8% for 150 kg/m^3. The reduced air content for column samples, compared to mould samples, is thought to be the result of a greater compactive effort having being applied to the column than to the moulds during compaction but again care should be taken with the values of A_{stab} due to volumetric column sample measurement issues.

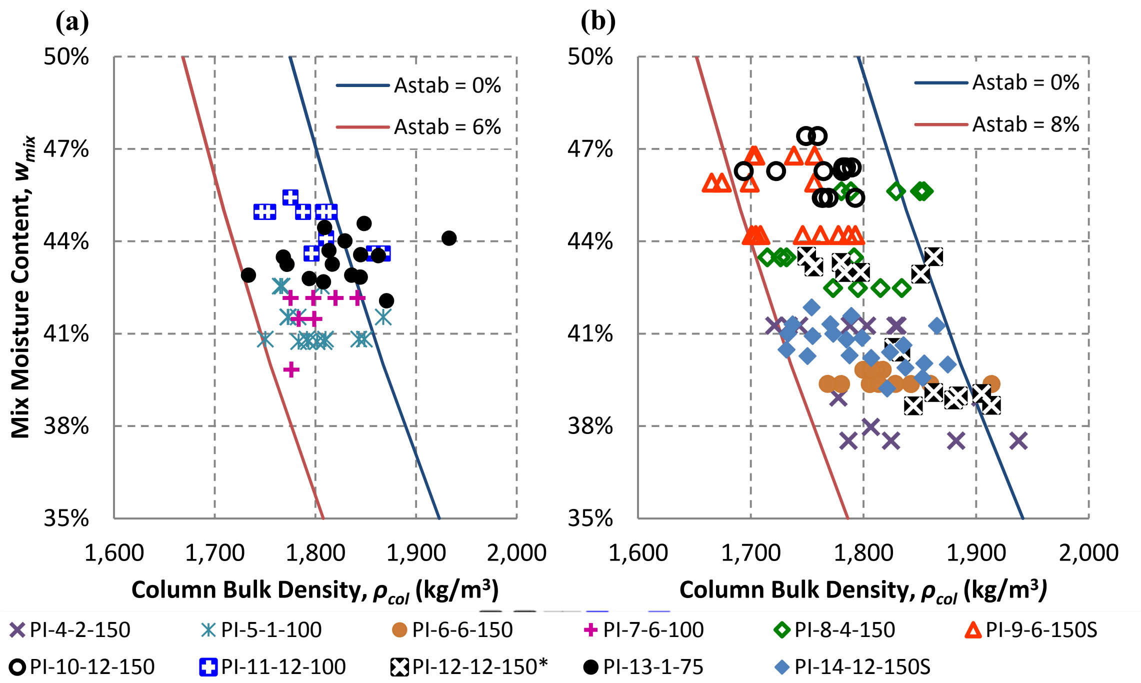

Figure 6-18: Column sample density with mixed moisture content at binder contents of a) 75 kg/m^3 and 100 kg/m^3 & b) 150 kg/m^3

6.6 PIRT Column Stabilised Strength and Stiffness

6.6.1 Introduction

In this section, the stabilised strength and stiffness properties of both the laboratory-cured mould samples (from each PIRT column stabilised mix) and samples taken from exhumed columns are presented. To show the quality and repeatability of the testing, comparisons are also drawn between column samples and their respective laboratory mould samples, including samples cured at 20 °C as per standard procedures.

6.6.2 PIRT Mould Stabilised Strength

<u>Mould Unconfined Compression Strength:</u>

The chosen range of binder contents and curing times had the effect of producing mould UCS values between 138 kPa and 610 kPa. Before presenting the mould sample strength data it is important to bear in mind the following:

- For each mix, two 65 mm dia. mould samples were prepared, one cured at room temperature and one in a water bath at a constant temperature of 20 °C.

- Average curing temperatures for room samples range from 16.9 °C to 19.2 °C; see Table 6.1.
- The stabilised mixtures required to produce each column were created over a 5 hour period and all samples were strength tested over a 1 hour period. Curing times presented are calculated from the midpoint of column construction until UCS testing and as such samples from Mix 1 have cured for longer than samples from the final mix.
- Mould samples for the surcharged columns, PI-9S and PI-14S, were cured in the same way as all other mould samples and did not cure under a surcharge.
- In PI-9S, the room-cured sample from Mix 1 has been excluded as a notable localised failure occurred during its UCS test at a strain of 0.7%; see PI-9S summary sheet in Appendix E.4.
- Of the four mixes used to construct PI-12*, Mix 2 was stabilised with a binder content of 100 kg/m^3 rather than the 150 kg/m^3 used in the other three mixes.

Figure 6-19 a & b present the room-cured (q_{mldR}) and 20 °C cured (q_{mldT}) mould sample UCS with average curing time (t_{mld}) respectively, while Figure 6-19 c & d show the same data itemised by the binder content used. It is clearly visible that increased strengths were achieved at higher binder contents and that strength increases with curing time. Also visible is the rapid increase in strength achieved in the early stages of curing for the 150 kg/m^3 binder content.

The CoV for the mould strengths in each column was calculated using the results of the four mould samples tested, apart from PI-9S where only three room-cured samples are considered. The CoV for q_{mldR} associated with a given column was found to range from 2.4% to 8.4% and from 1.4% to 11.8% for q_{mldT} and compare very well with the values compiled in Section 2.10.3. Compared to the PORT series, the same trends are observed and the improved controls applied are seen to reduce the overall variability.

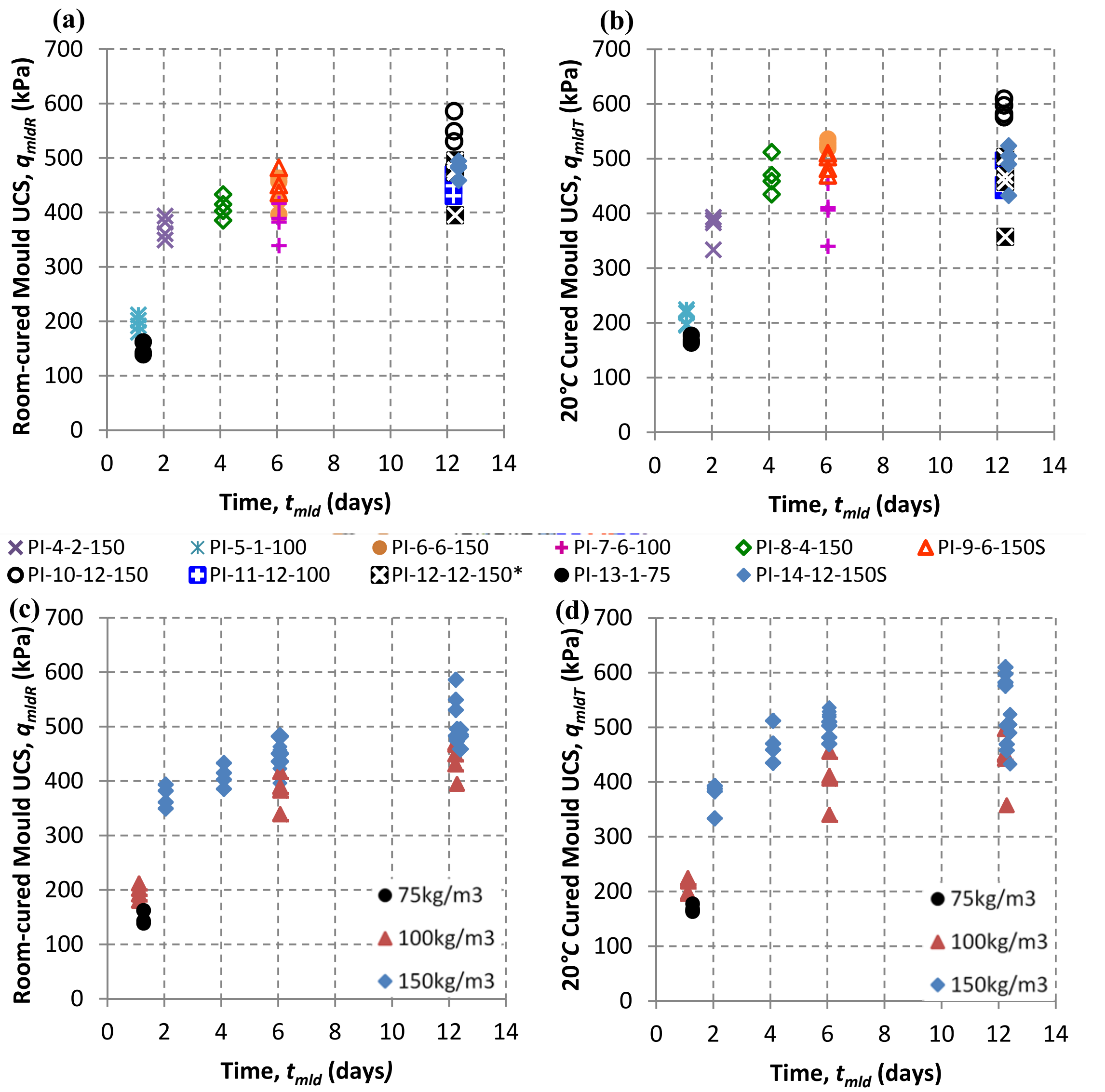

Figure 6-19: Mould UCS with curing time: a) Room-cured, b) 20 °C cured. Binder content specific; c) room-cured & d) 20 °C cured

Figure 6-20 shows a comparison of q_{mldT} with q_{mldR}, where increased strengths were seen in the 20 °C cured samples compared to the room-cured samples. q_{mldR} was found to lie within the range of 0.8 to 1.12 times q_{mldT}, with an average ratio of 0.93 and a standard deviation of 0.08. This is in keeping with that set out in Section 2.9.2 that greater strengths are achieved at higher curing temperatures due to the increased rate of strength gain caused by the greater number of hydration reactions occurring.

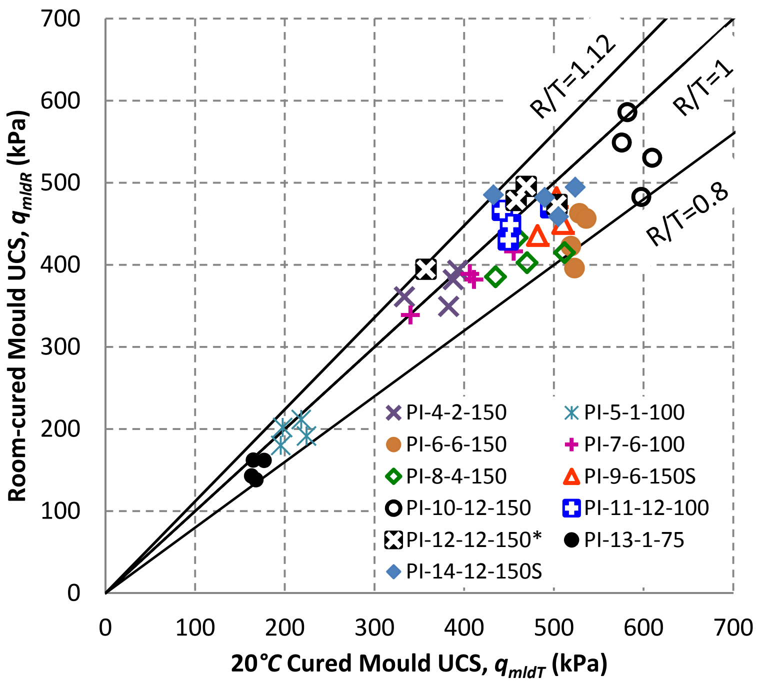

Figure 6-20: Comparison of mould cured sample UCS with 20 °C cured sample UCS

<u>Accounting for w_i and Temperature Variability:</u>

Variations in the curing temperature are accounted for using the *TCT* term as set out later in Section 7.5 and previously as used in Section 5.6 for the PORT column results. Figure 6-21 shows the average mould strengths with the standard deviation error bars, against their TCT_{mld} and the different binder content samples for Mix 2 in PI-12* are given separate points. The relative strength gains for the different binder contents are clear in this figure.

In an additional step to unify the data by including for variations in the moisture content of the unstabilised *sleech* and the different binder contents, Figure 6-22 shows UCS multiplied by the *WTBR* plotted against TCT_{mld}. Equation 6-1 provides an overall natural logarithmic function ($R^2 = 76.1\%$) to the PIRT mould data:

$$UCS \times WTBR = 427.6 \ln(TCT_{mld}) + 1005.2 \quad (1 \leq t \leq 12) \qquad 6\text{-}1$$

The improved fit to the data suggests that the variables of w_i and curing temperature can be accommodated within this frame work. This equation will later be used in Section 7.6 to estimate the strength of the column at the time of the PIRT.

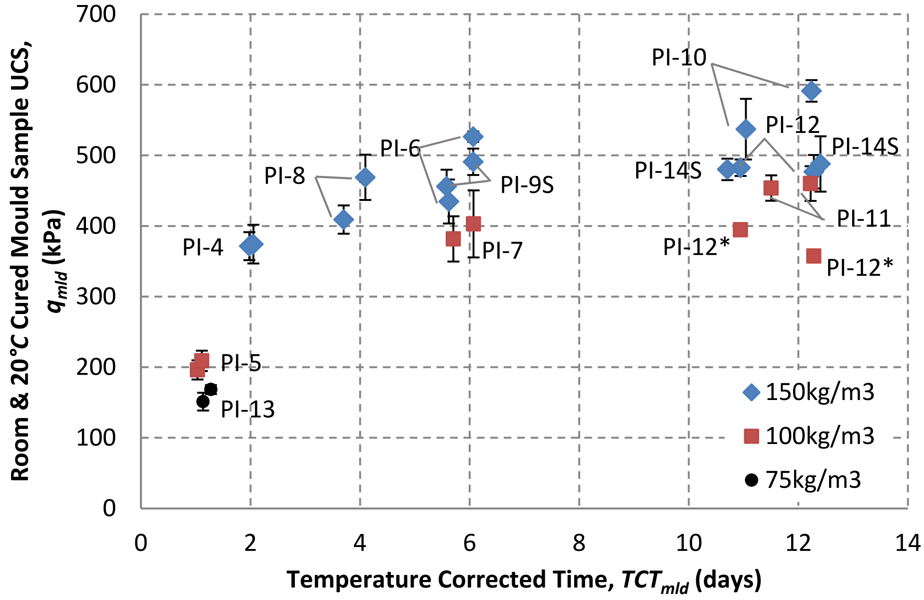

Figure 6-21: Average mould UCS and standard deviation with temperature corrected time

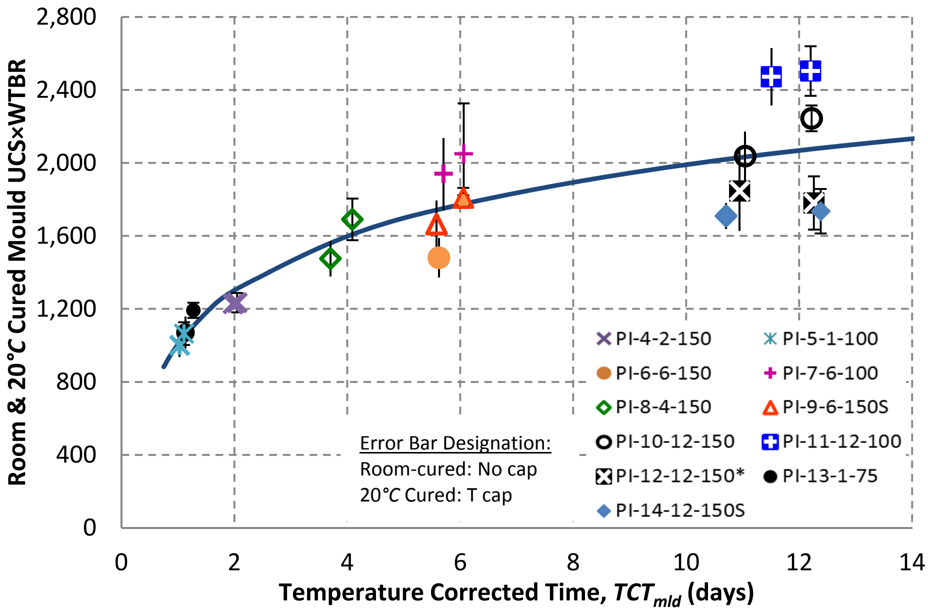

Figure 6-22: Average UCS×WTBR and standard deviation for room and 20 °C cured mould samples with their temperature corrected times

6.6.3 PIRT Column Stabilised Strength

Mould Unconfined Compression Strength:

Samples obtained from the column were typically found to be taken from within a single mixture, *i.e.,* samples did not straddle between two mixes, and sample heights were between 75 mm and 108 mm. The column sample UCS (q_{col}) with depth for each column is shown in Figure 6-23, where it can be seen:

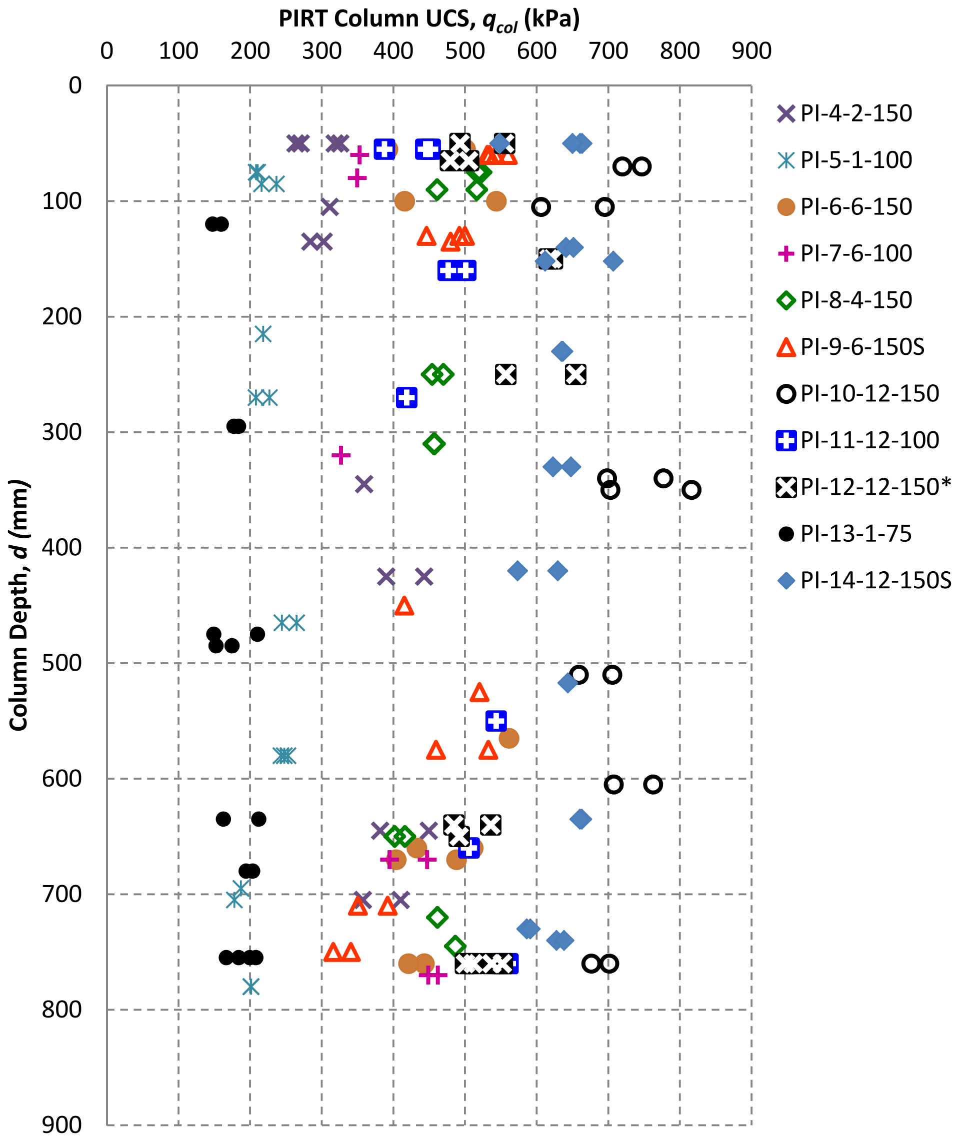

Figure 6-23: Uncorrected PIRT column UCS with depth

- A range of column UCS values have been obtained between 148 kPa and 816 kPa by varying the binder content and curing time.
- By attempting to maintain uniformity of the *sleech* used for each column and uniform mixing, column strengths show good uniformity with depth. Coefficients of variation for the strength from a given column are typically below 12.5% (but for PI-4, PI-7 and PI-9S were up to 17.5%) and show improved values compared to those seen in the PORT series. In some columns, strengths near the column base are notably lower than strengths at higher levels and this is particularly clear in PI-5 and PI-9S and is thought to be due to poor compaction of the first layers of stabilised *sleech* placed during construction as their mould strengths do not show reduced strengths.

- The number of samples obtained from each column ranged from 7 to 22 with column cracking (caused by the PIRT) affecting the number of samples retrieved. This occurred mostly in the mid-sections of columns, whose q_{col} lay approximately between 300 kPa and 450 kPa. Further details on column cracking are presented in Section 8.3.3 and crack pattern diagrams and photographs of exhumed columns are presented in Appendix F.4 and F.5.
- Due to column cracking, no samples were recovered from Mix 2 (h = 420-615 mm), the lower binder content mix in PI-12*.

Figure 6-24 a & b show a comparison of q_{col} against their q_{mldR} and q_{mldT} counterparts. Column strengths are typically seen to lie by and large in the range 0.8 to 1.2 times the strength of their respective mould samples, although higher column strengths again, were seen in the two 12 day-150 kg/m^3 columns. These ranges are narrower than those observed in the PORT series, of 0.6 to 1.3, primarily as a result of the experience gained during that series and the efforts applied to reduce the variability highlighted in Section 3.12.

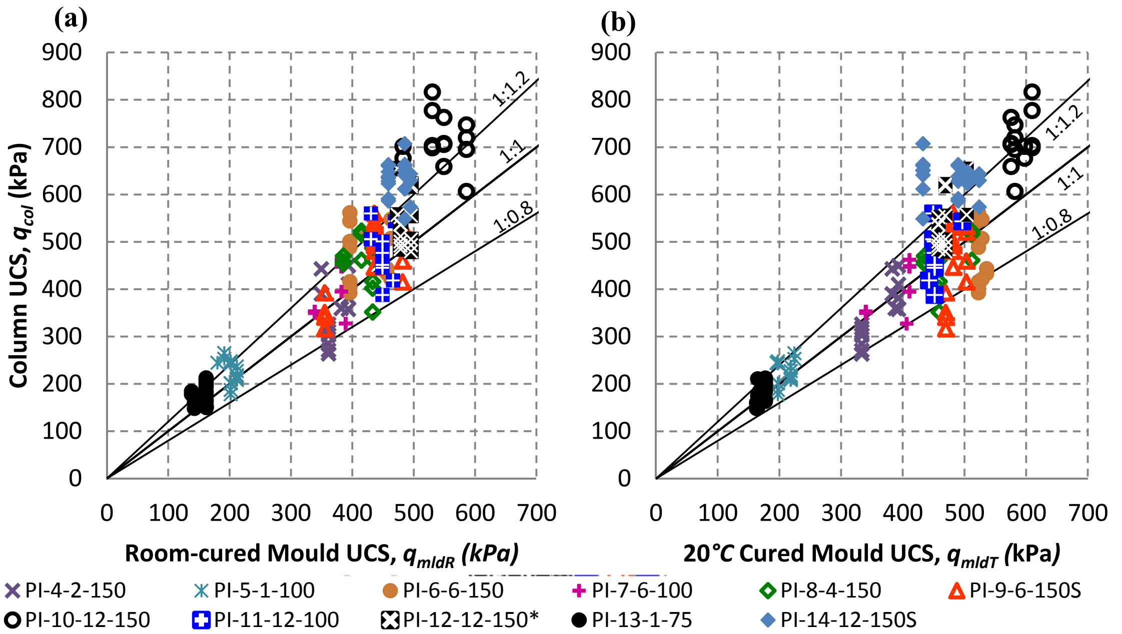

Figure 6-24: Column strength with mould strength: a) room-cured & b) 20 °C cured

<u>Accounting for w_i and Temperature Variability:</u>

The average column strength (with standard deviation error bars) are plotted against curing time (t_{col}) in Figure 6-25 and to further unify these data, Figure 6-26 shows the average UCS×WTBR of the column plotted against TCT_{col}, as used in Section 5.6.3. The logarithmic function set out in Equation 6-2 fits to the column strength data with an R^2 value of 0.787 and successfully unifies the parameters into one curve. This equation is later used in Section 7.6 to estimate the column strength at the time of PIRT.

$$UCS \times WTBR = 531.78\ ln(t) + 1010 \quad (1 \leq t \leq 12) \qquad 6\text{-}2$$

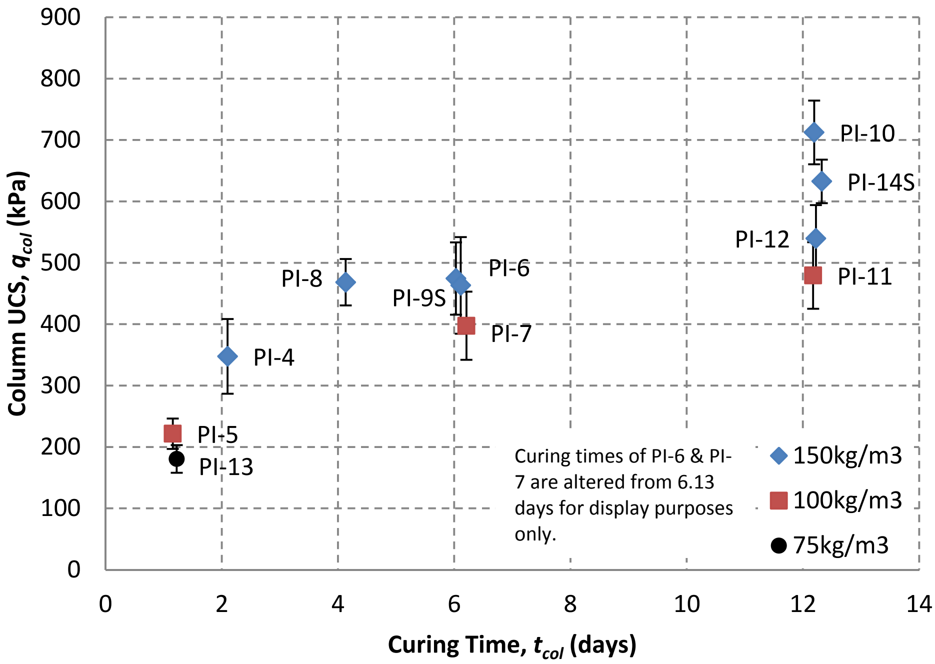

Figure 6-25: Average column UCS and standard deviation with time

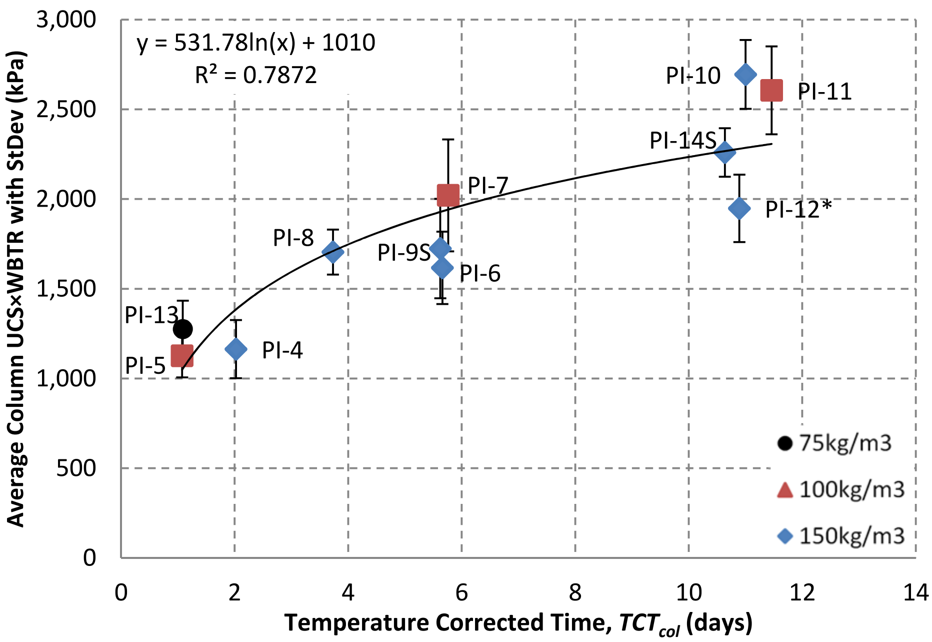

Figure 6-26: Average column UCS×WTBR and standard deviation with temperature corrected time

6.6.4 PIRT Mould & Column Stabilised Stiffness

The secant stiffness was calculated at 50% of the failure strength for each of the room-cured (E_{mldR}), 20 °C cured (E_{mldT}) and column (E_{col}) samples. In Figure 6-27 a & b, a general increase in mould sample stiffness with *TCT* is visible and in Figure 6-27 c & d, where the data are itemised by binder content, the increasing stiffness at higher binder contents is apparent. As with the PORT data, the additional step of incorporating *WTBR* is not carried out as stiffnesses are presented for characterisation and quality purposes only. CoV for each of the four room-cured samples were found to range from 6.0% to 21.9% (and up to 54.2% in PI-10) and from 10.6% to 35.3% for the 20 °C cured samples. In a

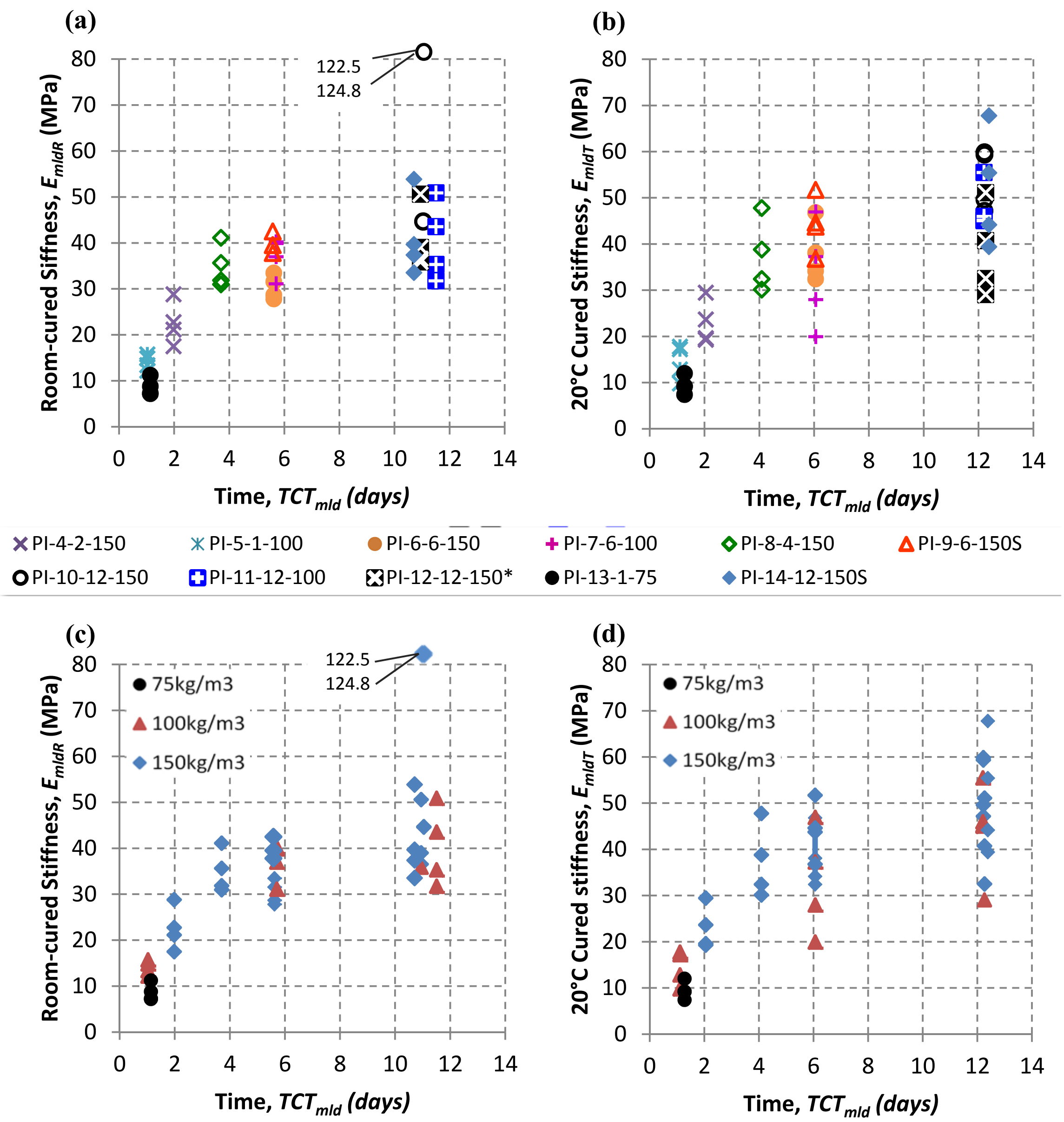

Figure 6-27: Mould secant stiffness with TCT: a) Room-cured, b) 20 °C cured. Binder content specific: c) room-cured & d) 20 °C cured

comparison of the mould stiffness values, E_{mldT} was found predominately to be between 0.66 and 1.0 times E_{mldR}, indicating higher stiffnesses were achieved in the samples cured at the higher constant 20 °C temperature. In PI-10 very high stiffnesses are seen in two of the room-cured samples and although higher strengths are noted, no significant difference is noted in the initial parameters.

Figure 6-28 shows the column sample stiffness with depth for each individual column. No clear trend of varying stiffness with depth can be identified but variations in stiffness for samples at the same depth are clear, particularly in PI-10. In Figure 6-29 it can be seen that stiffness increased with increasing binder content and with *TCT*. Within each column, CoV values were found to range between 19.7% and 40.5%. At the base of columns where poorer strengths were observed, little difference in stiffness is seen compared to those throughout the rest of the column.

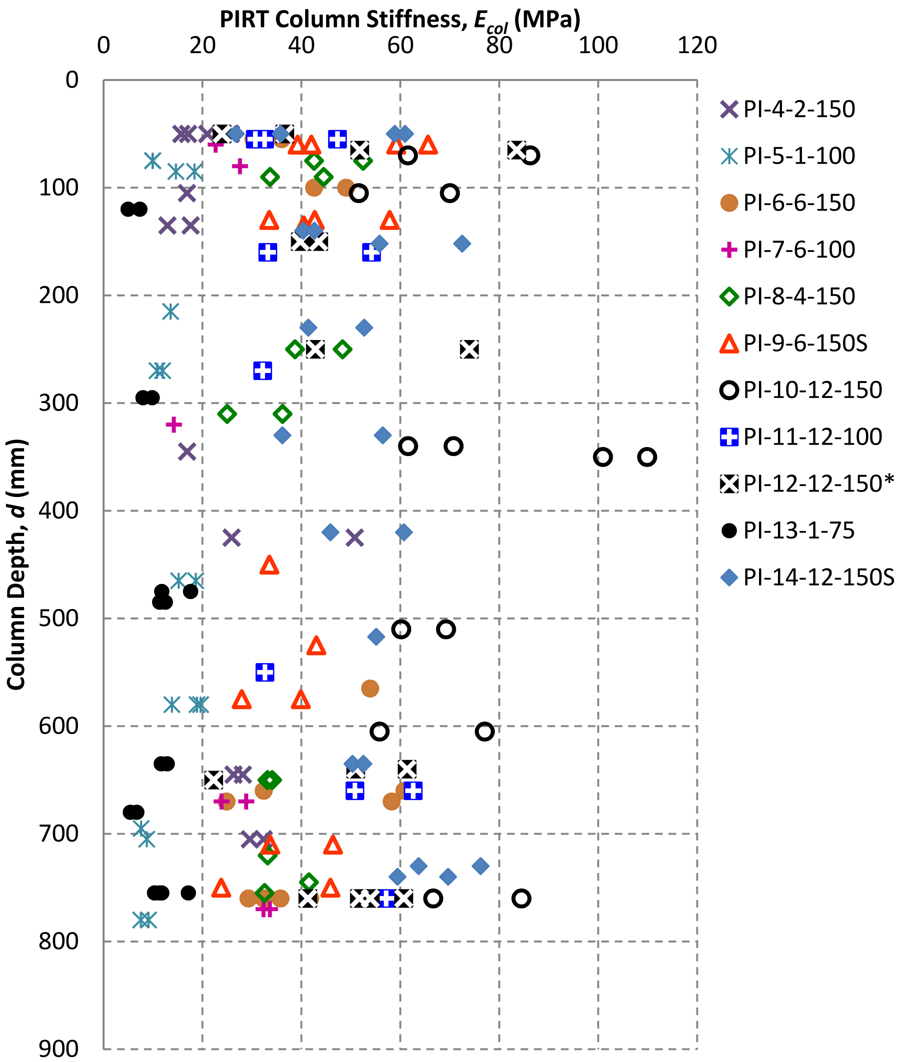

Figure 6-28: PIRT column stiffness with depth

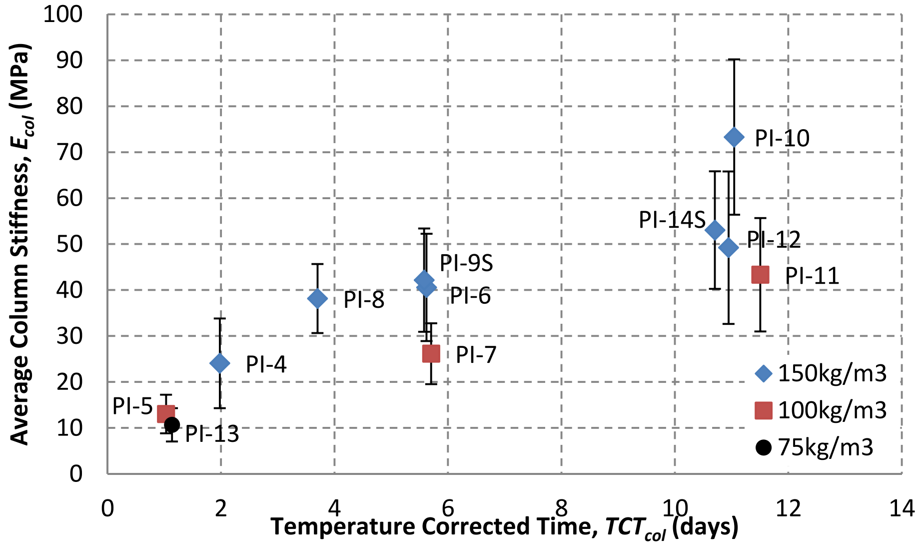

Figure 6-29: Average column stiffness (and standard deviation) with temperature corrected time

The E_{50} - q relationship was found to be E_{mld} = [50-125]q_{mld} for mould samples (see Figure 6-30a) and E_{col} = [45-130]q_{col} for column samples (see Figure 6-30b), comparing favourably with the typical values of between 50 and 150 seen in current literature for stabilised soils, see Table 2-8 and the values obtained during the PORT column tests, see Section 5.6.4. Figure 6-31 a & b show E_{50}/c_u against $\mathcal{E}_f$ for each respective mould and column sample, where a clear trend of increasing E_{50}/c_u with reducing strain to failure can be seen, which again satisfies the minimum E_{50}/c_u with $\mathcal{E}_f$ relationship (derived on the basis that $\mathcal{E}_f \geq 2 \times \mathcal{E}_{50}$).

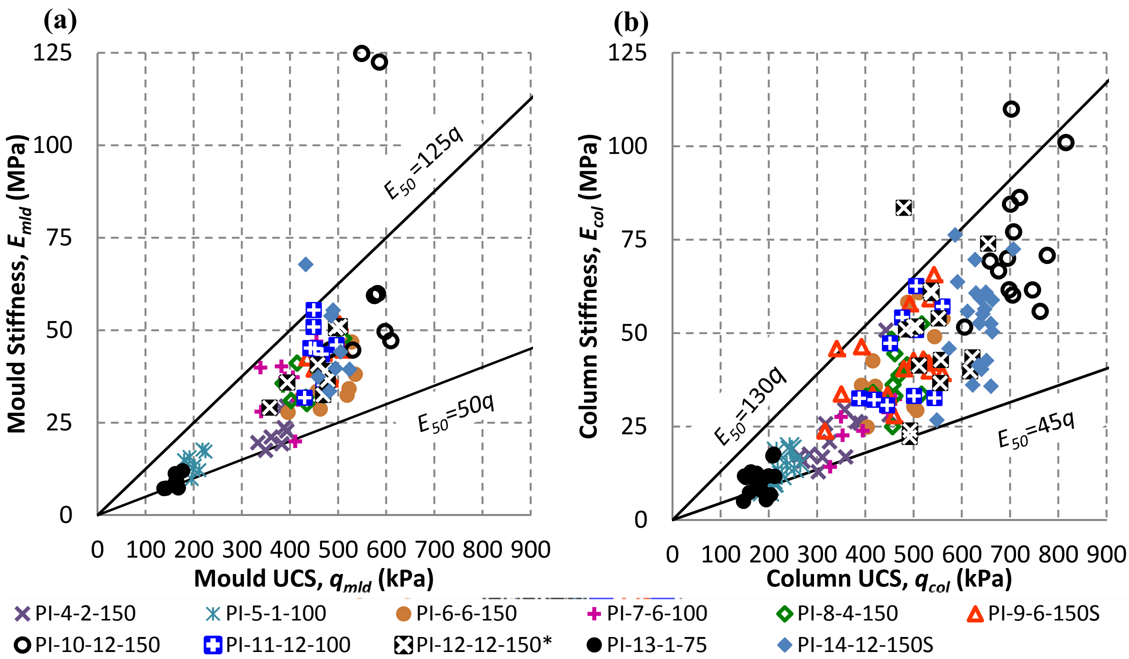

Figure 6-30: PIRT column stiffness with UCS: a) mould samples & b) column samples

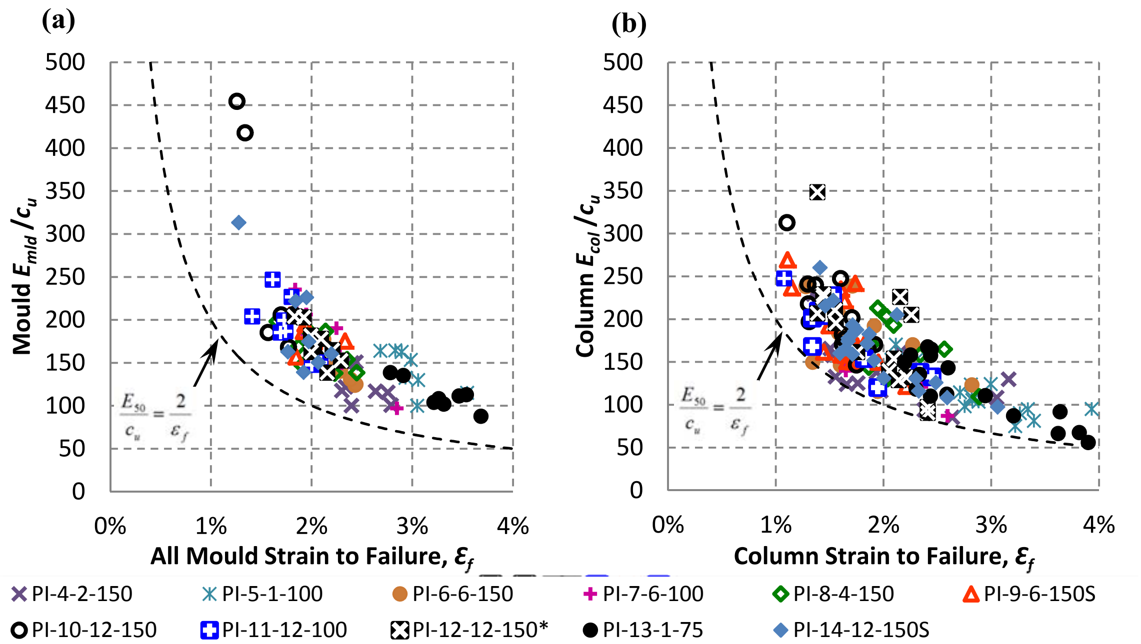

Figure 6-31: E_{50}/c_u relationship with failure strain: a) mould samples & b) column samples

6.7 PIRT SPSS Statistical Analysis

6.7.1 PIRT Mould Sample Strength Analysis

The PIRT room-cured and 20 °C cured mould sample data were split into separate analysis due to statistical difficulties in sub-dividing the data within the model for the different curing temperature conditions.

Bivariate Correlation:

In both PIRT mould data analyses, the correlation of time and binder content with q_{mld} was found to be highly significant, as was the correlation of w_i with q_{mld}. Each correlation table can be found in Appendix G.1. Density, temperature and organic content were found not to be significant, while the existence of an interaction between w_i and density was observed to a high significance. Other correlations, such as w_i with time and temperature with time, were observed but are due to the manner in which the tests were scheduled and are not included for.

Mixed Model Linear Regression Analyses:

All initial mould models show curing time and binder content to have highly significant influences upon q with significance values of 0 produced by the analyses, see Table 6-2 and Table 6-3; significant *covariates*, *i.e.,* values less than 0.05, are highlighted in bold. The same *covariate* significances are again seen when the natural log of the strength and curing time is applied (thus removing the flaring effect seen in the initial residual versus predicted graphs). Higher R^2 values are noted in the PIRT data compared to the PORT data results from Chapter 5, due to the greater care taken during testing to reduce the variability in the data.

As additional *covariates* are added to the models, curing time and binder content remain significant, and once included, curing temperature is found to be significant in the room cured models. Improved R^2 values are also noted as extra *covariates* are added. Moisture content is typically found not to be significant in the room cured mould data, however, in the final 20 °C data model, when an interaction between moisture content and density is added, all covariates are found to be significant and an R^2 value of 91.7% is obtained. A normal distribution of the residuals occurs and its bell shape improves with additional covariates, particularly for the PIRT room-cured data.

Table 6-2: PIRT 20 °C cured mould model assessment

Analysis:	**1**	**2**	**3**	**4**	**5**	**6**
R^2	0.811	0.897	0.903	0.904	0.905	0.917
Output	q	Ln(q)	Ln(q)	Ln(q)	Ln(q)	Ln(q)
Covariates:	***Significances:***					
Intercept	0.716	**0**	**0**	**0.004**	**0.005**	0.054
Time	**0**	-	-	-	-	-
Ln(Time)	-	**0**	**0**	**0**	**0**	**0**
Binder	**0**	**0**	**0**	**0**	**0**	**0**
w_i	-	-	0.123	0.114	0.151	**0.023**
Density	-	-	-	0.495	0.548	**0.026**
w_i - Density	-	-	-	-	-	**0.021**
Organics	-	-	-	-	0.595	-

6.7.2 PIRT Column Sample Strength Analysis

<u>Bivariate Correlation:</u>

As seen in the mould data, highly significant correlations were observed between the q_{col} and both the curing time and binder content but now also included a temperature correlation (see appendix G.1). An interaction between w_i and density was also seen and possible correlations between binder content, w_i, temperature and organic content in terms of the curing time were observed but are due to the manner in which the tests were scheduled and are not accounted for.

Mixed Model Linear Regression Analyses:

In all models for the PIRT columns (see Table 6-4) curing time and binder content were found to have a significant effect on the *q* value. Again, the natural log was taken of the *q* value and the curing time to remove the flaring noted in the residual versus predicted graphs. Normal distribution of the residuals again occurs. Addition of w_i and temperature to the PIRT column models shows both properties not to be significant. In the PIRT models, following inclusion of the natural log data, all models show similar R^2 values of approximately 92%. The impact of w_i and temperature, and the higher R^2 values are believed to be due to the lower variability in the PIRT column data compared to the PORT column data, as highlighted in Section 3.12.

6.8 Chapter Summary

Eleven successful PIRT column tests were completed on stabilised *sleech* columns created using OPC at binder contents of either 75 kg/m^3, 100 kg/m^3 or 150 kg/m^3. The columns were cured for times of between one and twelve days before testing, resulting in average strengths from approximately 180 kPa to 710 kPa, and stiffnesses from 5MPa to 110 MPa. Two of the columns were tested under a surcharge load which was found to increase confinement around the top of the column, reducing the amount by which is split open at the beginning of the test. Four PIRT and one cone-only test were also carried out in the unstabilised *sleech* that surrounded the two of the columns.

In Chapter 8, the data from the PIRT column tests presented in this chapter will be used along with cone-only penetrometer and sounding bar friction data and the corrected column strength data, both of which are presented in Chapter 7, to calculate the N value for the 150 mm reduced-scale PIRT penetrometer. These N values will then be discussed and compared with those in current literature.

Table 6-3: PIRT room-cured mould model assessment

Analysis:	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
R^2	0.878	0.909	0.916	0.968	0.969	0.97	0.971	0.97	0.971
Output	q	Ln(q)	Ln(q)	Ln(q)	Ln(q)	Ln(q)	Ln(q)	Ln(q)	Ln(q)
Covariates:	***Significances:***								
Intercept	0.85	**0**	**0**	**0**	**0.002**	**0.021**	0.253	**0.025**	0.236
Time	**0**	-	-	-	-	-	-	-	-
Ln(Time)	-	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Binder	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
w_i	-	-	0.079	-	0.674	0.488	0.363	0.48	0.337
Temperature	-	-	-	**0**	**0**	**0**	**0**	**0**	**0**
Density	-	-	-	-	-	0.174	0.317	0.181	0.295
w_i - Density	-	-	-	-	-	-	0.371	-	0.345
Organics	-	-	-	-	-	-	-	0.594	0.532

Table 6-4: PIRT column model assessment

Analysis:	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
R^2	0.868	0.919	0.919	0.92	0.92	0.921	0.921	0.923	0.921
Output	q	Ln(q)	Ln(q)	Ln(q)	Ln(q)	Ln(q)	Ln(q)	Ln(q)	Ln(q)
Covariates:	***Significances:***								
Intercept	0.076	**0**	**0**	**0**	**0**	0.26	**0**	0.289	0.216
Time	**0**	-	-	-	-	-	-	-	-
Ln(Time)	-	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Binder	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
w_i	-	-	0.914	-	0.869	0.066	0.931	0.08	**0.044**
Temperature	-	-	-	0.308	0.306	0.64	0.278	0.534	-
Organics	-	-	-	-	-	-	0.81	0.664	-
Density	-	-	-	-	-	0.069	0.819	0.084	**0.046**
Depth	-	-	-	-	-	-	0.326	0.464	-
w_i - Density	-	-	-	-	-	0.066	-	0.081	**0.043**

CHAPTER 7: FRICTION TESTS, TEMPERATURE MONITORED COLUMN AND DATA CORRECTIONS

7.1 Introduction

The PORT probing forces reported in Chapter 5 are the result of a combination of bearing on the penetrometer and friction between the pull-out wire and the stabilised column. Similarly, the PIRT forces, reported in Chapter 6, are due to a combination of bearing on the penetrometer wings, bearing and friction between the PIRT cone and the stabilised column, and friction between the sounding bars and the column. However, N values reported for PORT and PIRT testing strictly relate to the bearing components of the penetrometer only, so a separate programme of testing was required to deduce the additional components so as they may be deducted from the total forces. The results of these additional tests are detailed in this chapter.

In Section 7.2, the results from a series of 8 no. wire friction tests, carried out to ascertain the magnitude of friction between the PORT penetrometer pull-out wire and the stabilised column, are presented. The initial properties of the *sleech* used in the tests are presented along with the stabilised density, strength and stiffness of the cured columns. Each wire pull-out test is labelled W-*X*-*Y*-*Z*, where W designates a wire pull-out test, *X* is the column test reference number, *Y* the curing time (days) and *Z* the OPC binder content (kg/m^3); wire tests are generically referred to as W-*X*. The results from a series of 7 no. 14mm dia. cone-only penetrometer tests, carried out to estimate the bearing and friction forces between the stabilised column and the 14 mm dia. cone tip and the sounding bars during PIRT of a 200 mm dia. column are presented Section 7.3. Supporting information includes the initial properties of the *sleech* used and the properties of the stabilised columns. A similar reference system, using C-*X*-*Y*-*Z* and the shortened version C-*X*, is used to designate the cone-only penetrometer tests.

A column was constructed specifically with-a-view to recording temperature variations following stabilisation and during curing due to exothermic hydration reactions and ambient laboratory temperature variations. The recorded temperature data from the column and surrounding *sleech* are presented in Section 7.4, along with temperature data for the mould samples. These data form the basis of a method to account for the variations in the ambient temperature of the laboratory in which the tests were carried out.

Since there was an unavoidable lag from PORT/PIRT and the friction tests to UCS testing of the column samples, the strengths obtained had to be corrected to reflect those prevailing at the time of the column test. These corrections are carried out in Section 7.6 and are used in Section 8.5.2 to accurately calculate the PORT/PIRT N value at the time of the column test.

7.2 PORT Wire Friction Tests

7.2.1 Introduction

In this section, the results of a series of 8 no. wire pull-out tests (W-1 to W-8), carried out to quantify the magnitude of friction between the PORT penetrometer pull-out wire and the stabilised column, are presented. Table 7-1 provides details of each test. The columns were constructed using a single OPC mix at binder contents of either 100 kg/m^3 or 150 kg/m^3 between November 2013 and January 2014. Columns cured in 800 mm long, 104 mm dia. PVC-U pipes and the base of the pipe was sealed with a blanking plug (see Section 3.7.4), with the wire typically extended 40 mm to 50 mm beyond the base of the plug.

The columns were allowed to cure for various curing times between 1.2 days and 12 days, targeting strengths similar to those achieved in the 200 mm dia. PORT column series. The column was restrained by a bearing plate to prevent it being pulled out from the curing pipe and movement of the plate was found to be no more than 1.5 mm. Pull-out of the wire was carried out in a single pull with no pauses and average rates were between 16.6 mm/sec and 17.4 mm/sec (see Table 7-1). From the columns, 50 mm dia. and 38 mm dia. cylindrical samples were obtained and tested but the 38 mm dia. sample results are not considered here due to the greater difficulty in trimming them to the required size. Summary sheets for each wire test may be found in Appendix E.7 and E.8 and photographs of some columns are shown in Figure F-7.

7.2.2 Wire Pull-Out Force

Figure 7-1a shows the overall pull-out force with depth for each of the 8 tests carried out, while Figure 7-1b shows a magnified version omitting the P_o peaks at the column base. At the beginning of the test, the peak pull-out force was observed immediately as the bond between the wire and the column was overcome. In the 100 mm or so of movement after the peak, P_o dropped rapidly as material adhered to the wire was removed as it passed through the column, after which the force gradually reduced to zero at the top of the column. In the upper section of the column (*i.e.,* d < 200 mm), monitoring of the P_o and the displacement was effected as the draw wire gauge wire reeled in and this added a very small additional force to the load cell at this stage.

Table 7-1: Wire friction experiment summary data

PORT Wire No.	W-1	W-2	W-3	W-4	W-5	W-6	W-7	W-8	
Curing Time, t_{Po}:	5	6	4	1.2	12	12	1.6	6.6	days
Binder Content:	150	100	150	100	150	100	150	150	kg/m^3
Column Height, h:	800	800	800	770	800	800	800	800	mm
***Sleech* MC, w_i:**	45.5	51.5	48.8	46.9	46.6	46.9	47.1	45.9	%
Mixed MC, w_{mix}:	40.4	46.1	41.5	42.2	39.9	41.3	40.1	38.9	%
Loss on Ignition:	3.3	2.6	3.9	2.8	4.1	3.3	3.5	2.7	%
No. Column Samples†:	7 (+7)	7 (+6)	7 (+7)	7 (+5)	7 (+6)	7 (+6)	7 (+4)	7 (+6)	-
Average Column UCS, q_{col}:	555.5	405.0	558.9	188.9	698.8	517.6	321.2	674.1	kPa
Standard Deviation:	42.7	54.9	71.0	23.6	109.0	59.6	38.8	37.1	kPa
Corrected Average Column UCS, q_{cor}:	548.6	401.7	549.7	172.5	696.1	516.0	304.6	657.2	kPa
Ambient Temperature, T:	15.8	16.0	16.6	16.7	17.2	17.2	15.7	15.1	°C
Average Pull-Out Rate:	16.6	17.0	16.8	16.8	17.4	17.4	17.2	17.0	mm/sec
Max Pull-Out Force:	2.33	1.94	2.71	0.78	3.89	1.39	1.73	4.05	kN

† Figure in brackets denotes number of 38 mm dia. samples

The initial peak forces observed during the wire pull-out tests are significantly higher than the initial forces seen in the PORT penetrometer pull-out tests (see Figure 5.1). This is thought to be related to the different construction times required for the 104 mm dia. wire columns (30 minutes) and the 200 mm dia. PORT columns (5-6 hours) and disturbances that occur during column construction. Any disturbance to the wire bond in the 104 mm dia. column is thought to be short term, as the bond may have the opportunity to reform in the fresh mix. In the case of the 200 mm dia. columns, the bond is less likely to reform as the mix was not as fresh. However, these differences in initial peak forces have no implication for this test series as their purpose was to estimate the pull-out wire's friction within the column as the PORT penetrometer cut though the stabilised column.

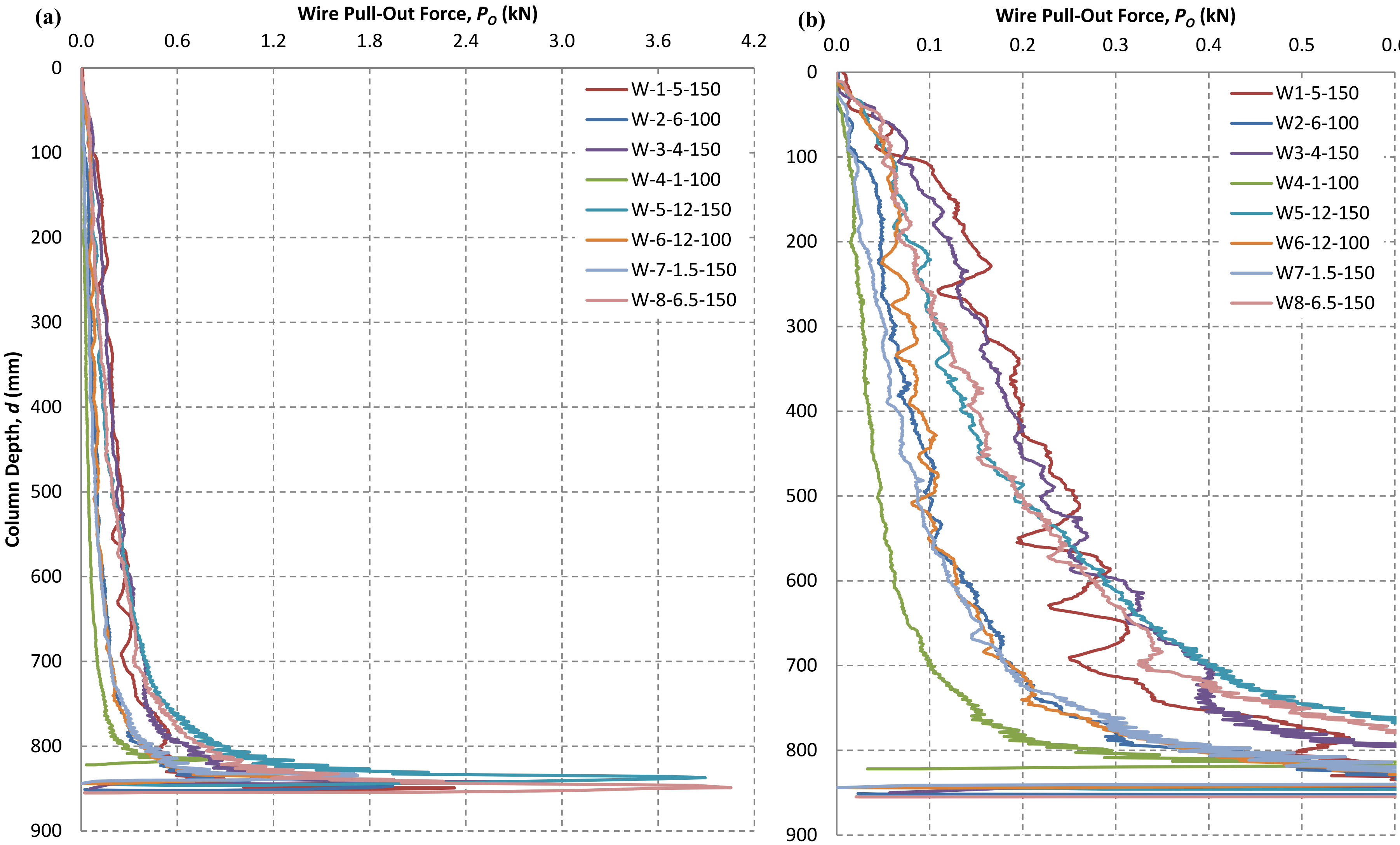

Figure 7-1: Wire pull-out force profile: a) overall pull-out force profile & b) magnified view of the pull-out forces within the column

7.2.3 Laboratory Curing Temperature

The wire columns, and their associated room-cured mould sample, were cured at laboratory room temperature. Figure 7-2 shows the variation in laboratory temperature, recorded by the BMS, over the course of the wire friction test series, from which average ambient laboratory temperatures were found to range from 15.1 °C to 17.2 °C (see Table 7-1). Due to a lack of recorded temperature data during the curing period of W-8, average ambient laboratory temperatures were estimated using the outside air temperature and trends seen in the laboratory temperature either side of the missing data.

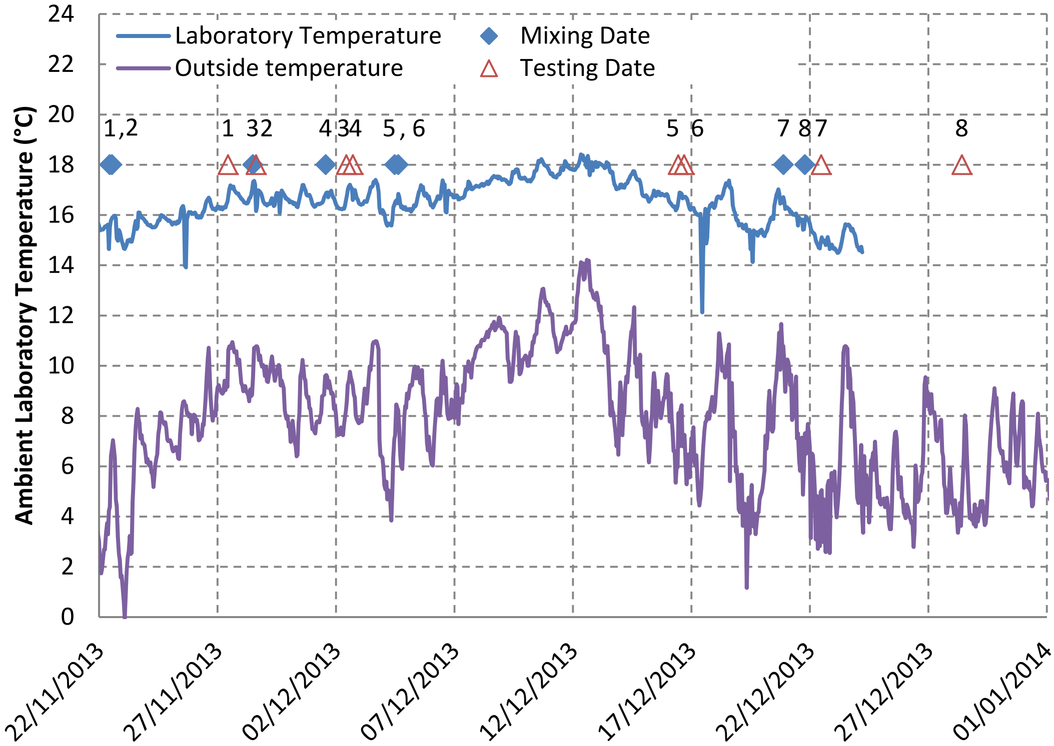

Figure 7-2: Laboratory temperature during wire friction test series

7.2.4 Moisture Content, Organic Content & Density

The *sleech* used in all wire friction experiments was sampled from a single location in a storage basin prior to any tests being carried out and had previously been used to surround PIRT columns during curing (see Section 3.12). The initial moisture content of the *sleech* (w_i) used ranged from 45.5% to 51.5% and organic contents for the sleech used ranged from 2.7% to 4.1% (see Table 7-1). After addition of the binder and mixing, moisture content reductions of approximately 5% and 7% were noted in the mixed *sleech* (w_{mix}) for the 100 kg/m^3 and 150 kg/m^3 binder contents, respectively. Following curing, the difference between w_i and stabilised moisture content (w_s) was found to be 6-7% for 100 kg/m^3 and 7-9% for the 150 kg/m^3 binder contents.

As shown in Figure 7-3a, very minor variations in density were seen between the room-cured (ρ_{mldR}) and 20 °C cured (ρ_{mldT}) mould densities, with the overall range of densities due to the different w_{mix} values. Similar trends of increasing sample density with reducing w_{mix} to those seen in Sections 5.5.3 and 6.5.3 were noted. Predictions of the stabilised density, calculated as presented in Section 5.5.3, were obtained using an A_{stab} of approximately 8%.

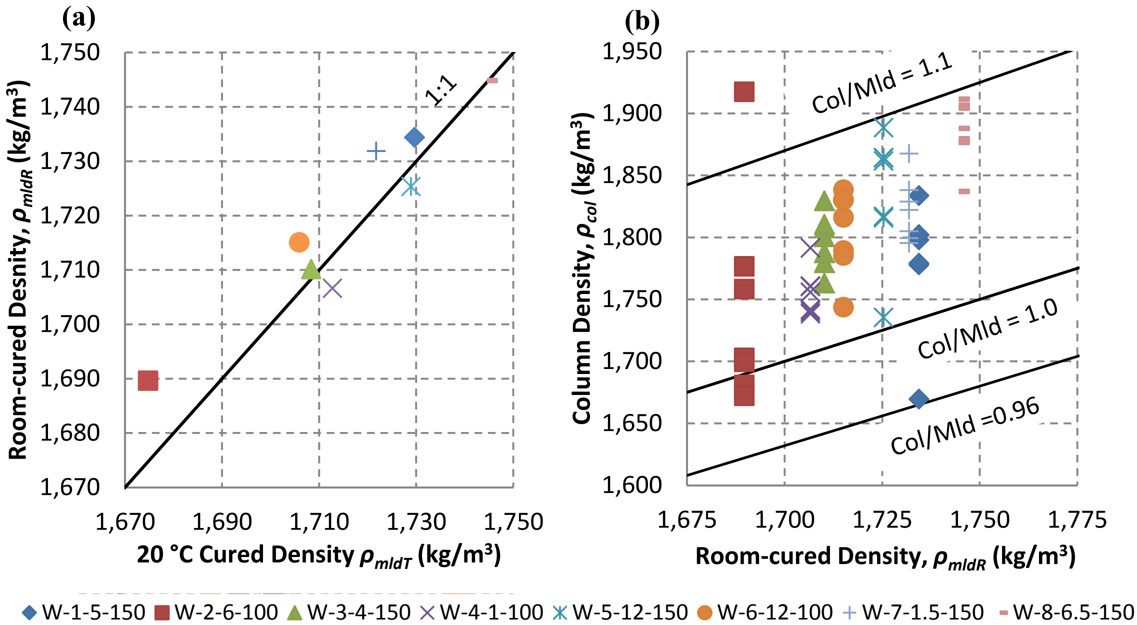

Figure 7-3: a) Mould sample density comparison & b) Column to room-cured mould density comparison

Once again, column densities were found to be 1.0 to 1.1 times that of their room-cured counterparts (see Figure 7-3b) in keeping with that observed in the PORT series. Figure 7-4 shows the density of each column sample (ρ_{col}) at its respective depth (d) and variations in density within a given column are primarily due to increased compaction with depth and sample trimming effects (see Section 3.12). Unlike the 104 mm dia. columns constructed for the cone-only penetrometer experiments, presented later in Section 7.3.4, a reduction in the density is not seen at the column base as the blank plug acted as a firm platform for compacting the mixed *sleech*. The maximum CoV for the density of the 50 mm samples was 4.9% seen in W-2, but typically CoVs of less than 2.9% were seen in all other columns. CoV for each individual column's density can be found in Appendix E.8, along with the CoV of the stabilised column strength and stiffness. As previously seen, ρ_{col} was again found to follow a trend of increasing density with reducing w_{mix} and when a predicted density curve was fitted to the data, an approximate A_{stab} value of 4.5% was found to best suit both binder contents.

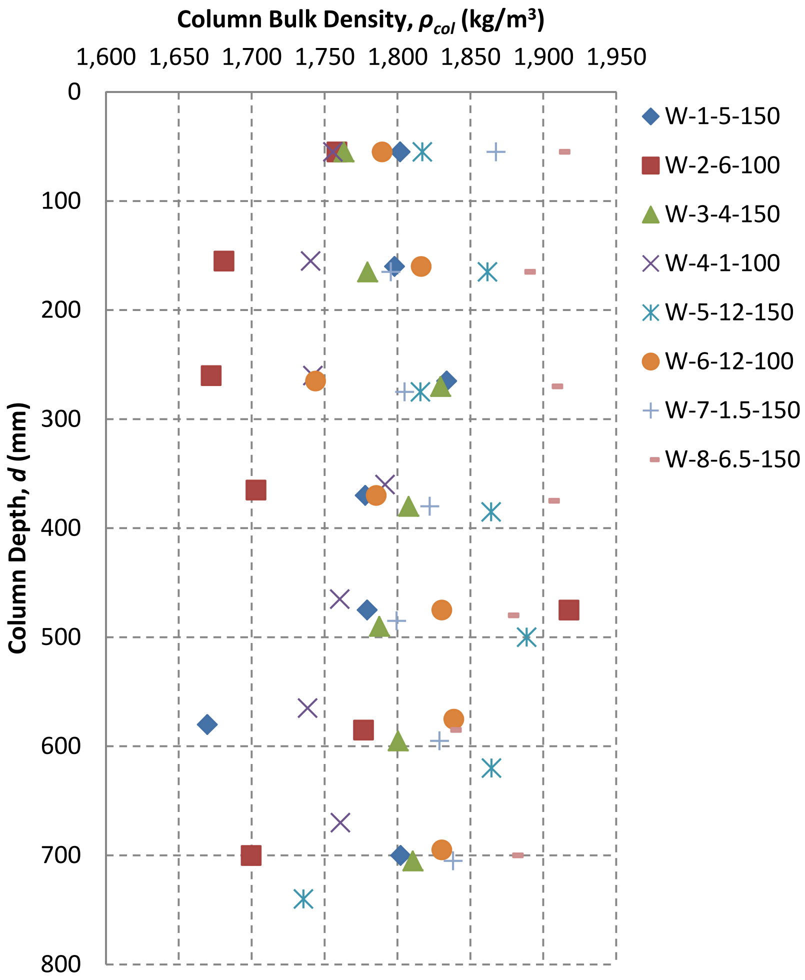

Figure 7-4: Wire friction column density with depth

7.2.5 Stabilised Mould and Column Strength

Figure 7-5a shows the increase in strength of all mould samples (q_{mld}) with curing time (t_{mld}), where values up to 570 kPa were achieved. As expected, stabilisation with 150 kg/m^3 binder contents produced higher strengths than the 100 kg/m^3 binder content and all room-cured samples were found to have lower strengths than their respective 20 °C cured samples (see Figure 7-5b). Similar patterns of increasing column UCS (q_{col}) with curing time (t_{col}) and binder content were noted for column samples (see Figure 7-6a). q_{col} was found to range from 141 kPa to 821 kPa and the CoV within each column lay between 5.5% and 15.6%. Figure 7-6b shows column strengths to be 0.95 to 1.4 times that of their room-cured mould samples, again similar to that observed in the PORT series. The difference in strength is possibly a result of increased column compaction and the greater temperatures occurring due to the hydration reactions in the larger stabilised column mass. As can be seen in Figure 7-7, strengths show a slightly increasing trend with depth and is considered to be due to the increased compaction experienced by the column at depth.

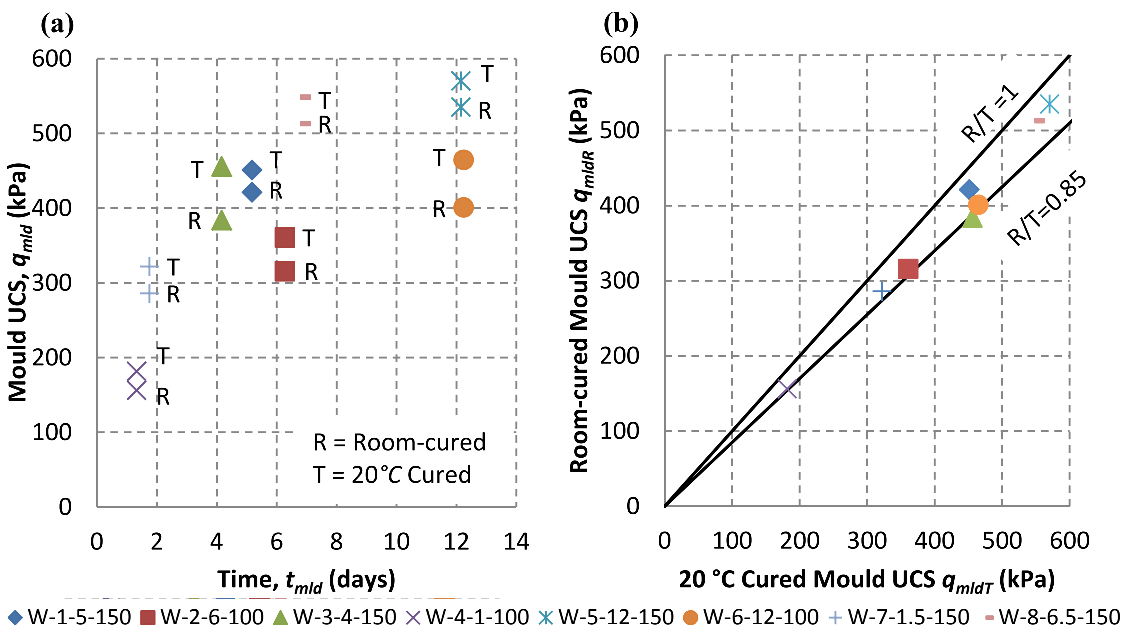

Figure 7-5: Wire friction column: a) Mould UCS with curing time & b) Mould sample comparison

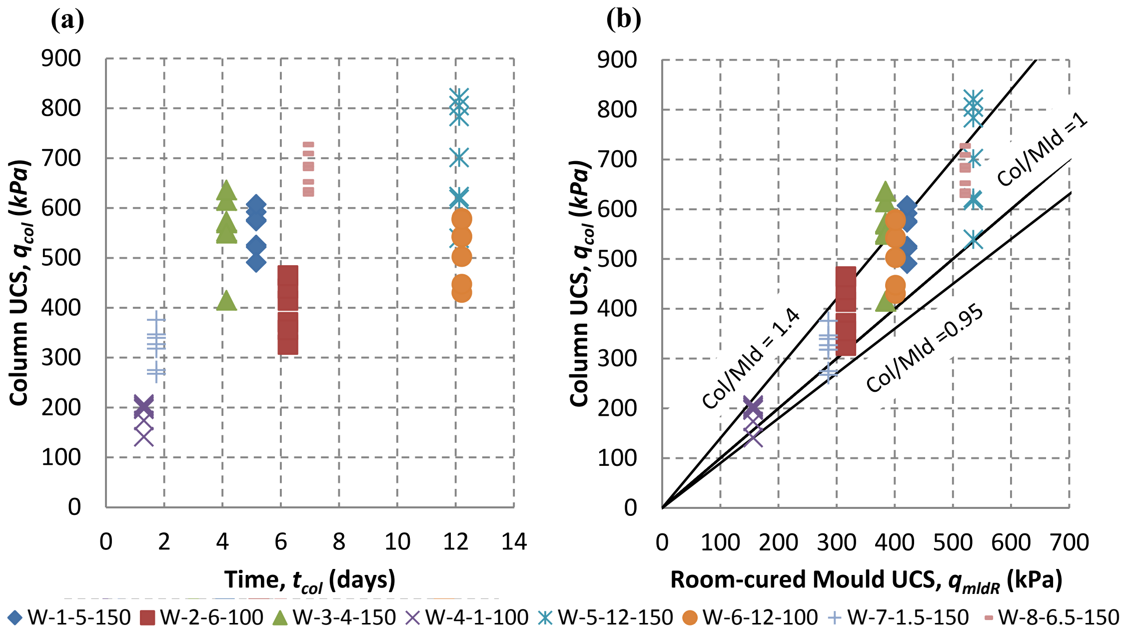

Figure 7-6: Wire friction column: a) Column sample UCS with curing time & b) Column to room-cured mould UCS comparison

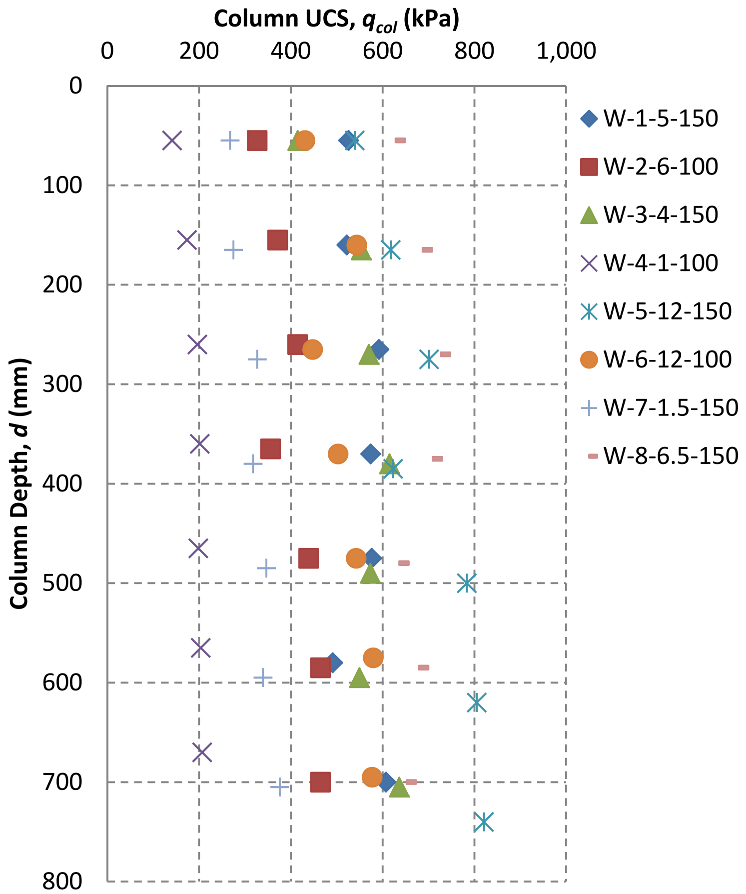

Figure 7-7: Wire friction column UCS profile

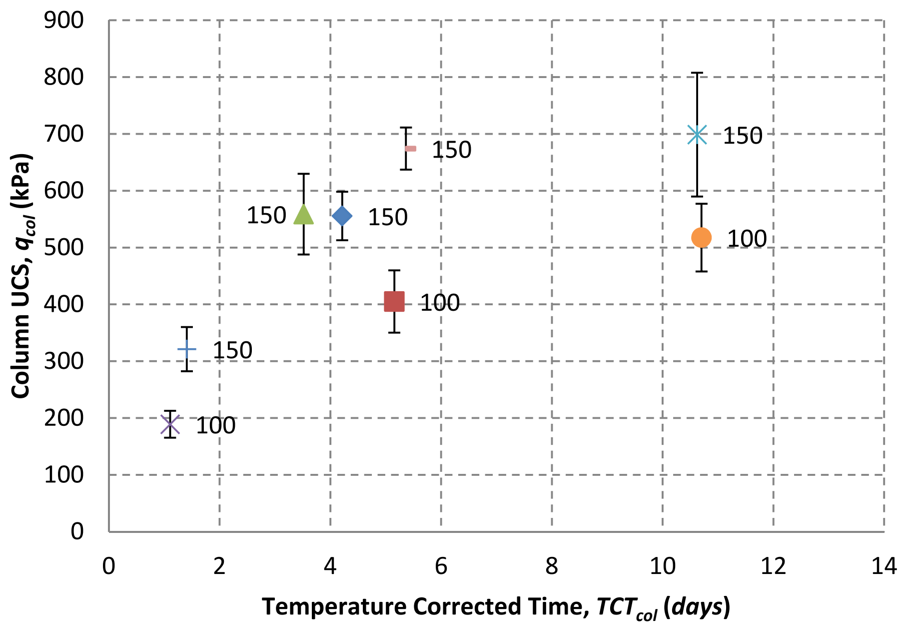

Figure 7-8: Column UCS with temperature corrected time for all wire friction tests

Figure 7-8 shows the average column strength (and standard deviation error bars) with temperature corrected time (TCT_{col}), thus taking into account the variation of ambient temperature in the laboratory. The effect of increased binder content and curing time on strength can be seen. Figure 7-9 shows the q_{col} multiplied by the specimens *WTBR* and plotted against TCT_{col}. Equation 7-1 was fitted to the data and produces a very high R^2 value of 95.1%:

$$UCS \times WTBR = 713.14 ln(TCT_{col}) + 944.67 \qquad 7\text{-}1$$

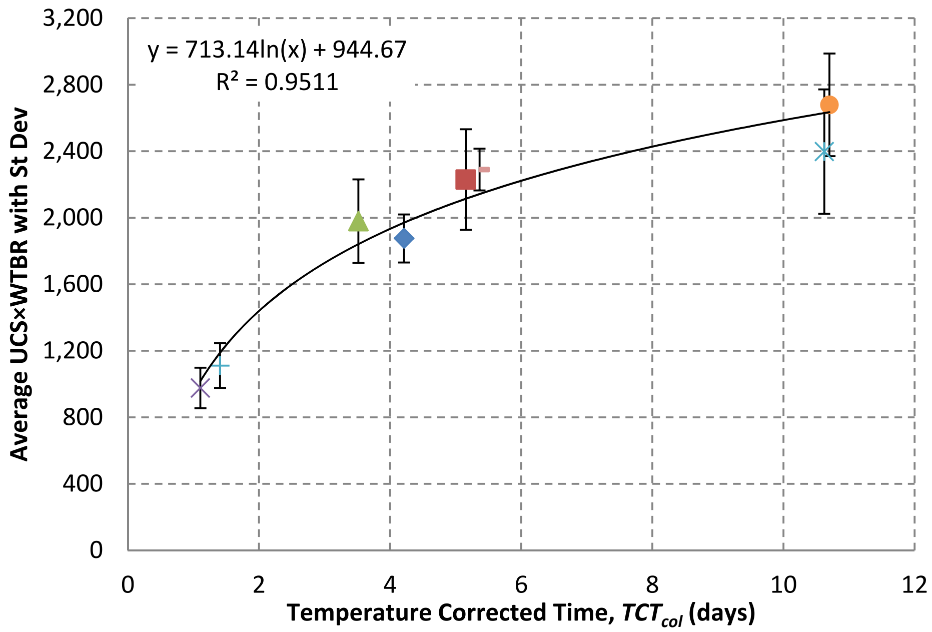

Figure 7-9: Column UCS×WTBR with temperature corrected time

7.2.6 Mould and Column Stabilised Stiffness

The secant stiffness was calculated at 50% of the failure stress for each mould (E_{mld}) and 50 mm dia. column (E_{col}) sample tested, and E_{50} graphs for both mould and column samples may be found in Appendix D.3. E_{mld} was seen to increase with both curing time and binder content up to values of 88 MPa after 12 days and in the majority of cases, the 20 °C samples show higher stiffnesses than their room-cured counterparts. In a similar way to q_{col}, E_{col} was seen to increase with depth, possibly as a result of increasing compaction that occurred during construction and had CoVs of between 14.1% and 42.1%. The relationship between E_{50} and q was found to lie predominately in the range E_{mld} = [60-125]q_{mld} for the mould samples and E_{col} = [75-150]q_{col} for the column samples and these ranges compare very well with those seen in the literature and in the previous chapters. As seen in the previous chapters, strain to failure ($\mathcal{E}_f$) was again found to lie between 1% and 4% for all samples, reducing with increasing strength.

7.3 PIRT Cone-Only Penetrometer & Sounding Bar Friction Test

7.3.1 Introduction

In this section, the results from the 7 no. PIRT cone-only penetrometer and sounding bar tests, carried out to quantify the combined friction between the PIRT cone tip and the sounding bars with the stabilised column, are presented. The overall force will also include some bearing as the diameter of the cone is 14 mm and the pre-formed hole is 13 mm. Some friction between the sounding bars and the plastic sounding bar guide on the CPT rig is also expected. Table 7-2 provides a summary of the test details, in which reduced-scale stabilised soil-cement columns were constructed using a single OPC mix at binder contents of either 100 kg/m^3 or 150 kg/m^3 between November 2013 and January 2014. Columns cured in 900 mm long, 104 mm dia. PVC-U pipes with the 13 mm dia. hole-form bar inserted to replicate pre-drilling (see Section 3.8.4) and were between 730 mm and 750 mm in length, with the remainder of the pipe comprising *sleech* to represent unstabilised material beneath the column.

Table 7-2: Cone-only penetrometer experiment summary data

PIRT Cone Test No.	C-1	C-2	C-3	C-4	C-5	C-6	C-7	
Test Time, t_{Pi}:	1	2	6	6	12	1.6	12.7	days
Binder Content:	100	150	100	150	150	150	100	kg/m^3
Column Length:	750	745	730	747	730	740	740	mm
***Sleech* MC, w_i:**	45.8	46.0	49.1	49.2	47.0	47.2	45.5	%
Mixed MC, w_{mix}:	40.3	38.9	43.7	41.8	38.0	40.1	40.8	%
Loss on Ignition:	4.1	4.1	4.4	4.8	4.3	4.1	3.1	%
No. Column Samples†:	6 (7)	7 (7)	7 (5)	7 (7)	6 (6)	7 (6)	7 (6)	-
Average Column UCS, q_{col}:	226.6	389.8	390.9	506.9	788.2	301.0	562.3	kPa
Standard Deviation:	22.9	49.1	31.3	41.0	29.0	23.7	40.4	kPa
Corrected Average Column UCS, q_{cor}:	208.0	373.7	387.7	501.3	785.5	285.9	561.4	kPa
Ambient Temperature, T:	16.7	15.7	16.2	16.6	17.1	16.0	14.5	°C
Average Push-In Rate: P_1 & P_2	17.8	19.6	12.9	13.1	16.5	14.2	15.7	mm/sec
	19.3	22.6	15.0	15.0	19.4	19.1	18.1	mm/sec

† Figure in brackets denotes the number of 38 mm dia. samples

The columns were allowed to cure for various durations between 1 day and 12.7 days, targeting strengths similar to those achieved in the 200 mm dia. PIRT column series, after which probing was carried out. From the columns, 50 mm dia. and 38 mm dia. cylindrical samples were obtained and tested but again only the 50 mm dia. samples are considered due the greater difficulty in trimming 38 mm dia. samples to the required size. An initial trial column was constructed to define the appropriate set up but is excluded from the analysis due to issues encountered when the test was paused to insert additional sounding bars and cracking in the exhumed column. Results from a cone-only penetrometer test in unstabilised *sleech* have previously been presented in Section 6.2.2.

7.3.2 PIRT Cone-Only Penetrometer Probing Force

Probing of the pre-drilled cone-only penetrometer columns with the 14*mm* dia. cone was carried out in two pushes, labelled P_1 and P_2, with a pause in the test required to insert additional sounding bars. Typically this occurred at a depth of approximately 450 mm. Probing rates for each push were targeted to be 20±4 mm/sec but due to the manual rate control of the CPT rig and varying push-in forces, average rates were between 12.9 mm/sec and 22.6 mm/sec (see Table 7-2).

Figure 7-10 shows the recorded probing force (P_i) with column depth (d) for each of the cone-only penetrometer tests. All P_i profiles rise instantly as the cone penetrometer begins to press into the pre-formed hole and then shows a near constant trend with depth. A temporary reduction in the P_i is visible where the test was paused to insert additional sounding bars. Accentuated peaks in P_i are visible in C-3, C-4 and C-5, but no foreign material or stones were found in the exhumed column to explain their occurrence. The probing force drops off near the base of the column due the increased diameter of the hole caused by rotation of the hole-form bar during construction and curing. Once in the raw *sleech* under the column, P_i further drops and in general shows a constant trend as the cone approaches the bottom of the *sleech* layer.

The lack of an increasing P_i with depth indicates that the majority of the recorded force was a result of bearing and friction only between the cone tip and the stabilised column, *i.e.,* little to no friction occurred between the column and sounding bars. Evidence of bearing of the cone in the pre-formed hole was found in some columns in the form of a stabilised soil plug ahead of the cone which was formed as stabilised material was shaved from the column by the cone during the test (see Figure F-15e). Probing forces were significantly lower (less than 0.3 kN) than the range of forces from 0.7 kN to 3.2 kN observed in PIRT of the 200 mm dia. columns. As a result, buckling of the sounding bars observed during PIRT column probing was not seen in these tests, and thus the tests are thought not help to quantify any friction between the sounding bars and the column during full PIRT. However, they do help quantify friction between the cone and the column and between the sounding bars and the plastic sounding guide.

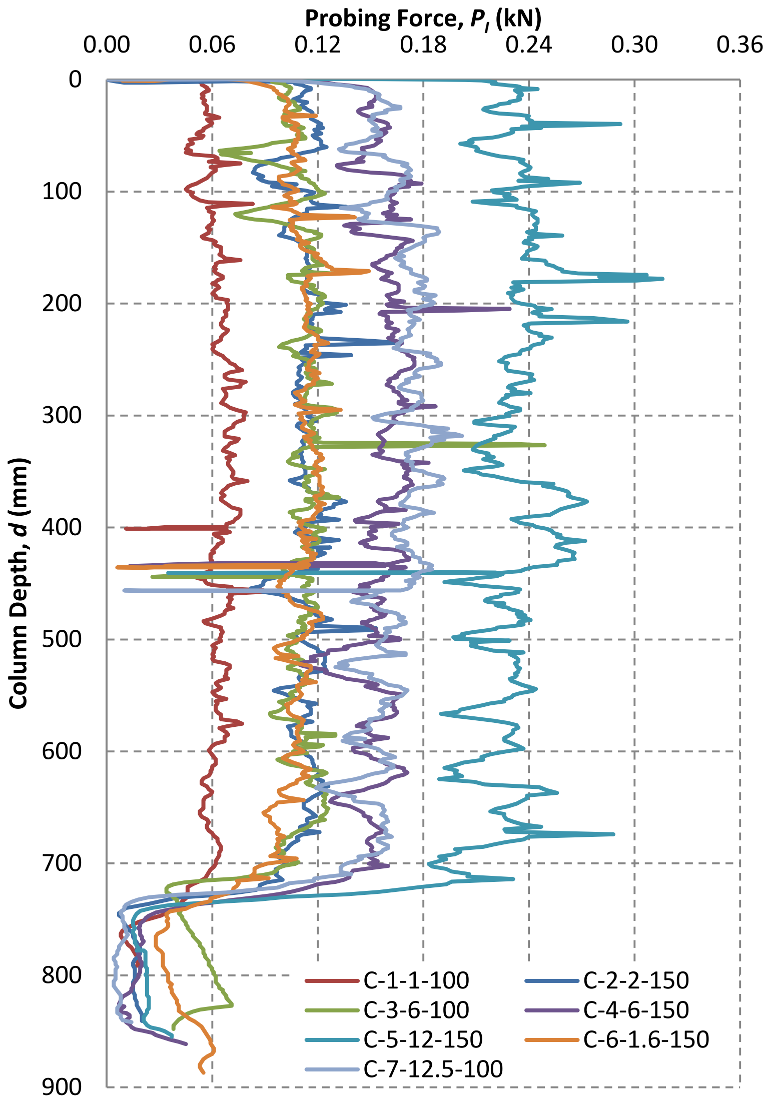

Figure 7-10: PIRT cone penetrometer probing force with depth

7.3.3 Laboratory Curing Temperature

All cone penetrometer columns, and their associated room-cured mould sample, were cured at laboratory ambient room temperature. Figure 7-11 shows the variation in ambient laboratory temperature, recorded by the BMS, during the cone-only penetrometer test series, from which average ambient laboratory temperatures (T) were found to range from 14.5 °C to 17.1 °C (see Table 7-2). Due to a lack of recorded temperature data during curing of C-7, T was estimated using the outside air temperature and trends seen in the laboratory temperature either side of the missing data.

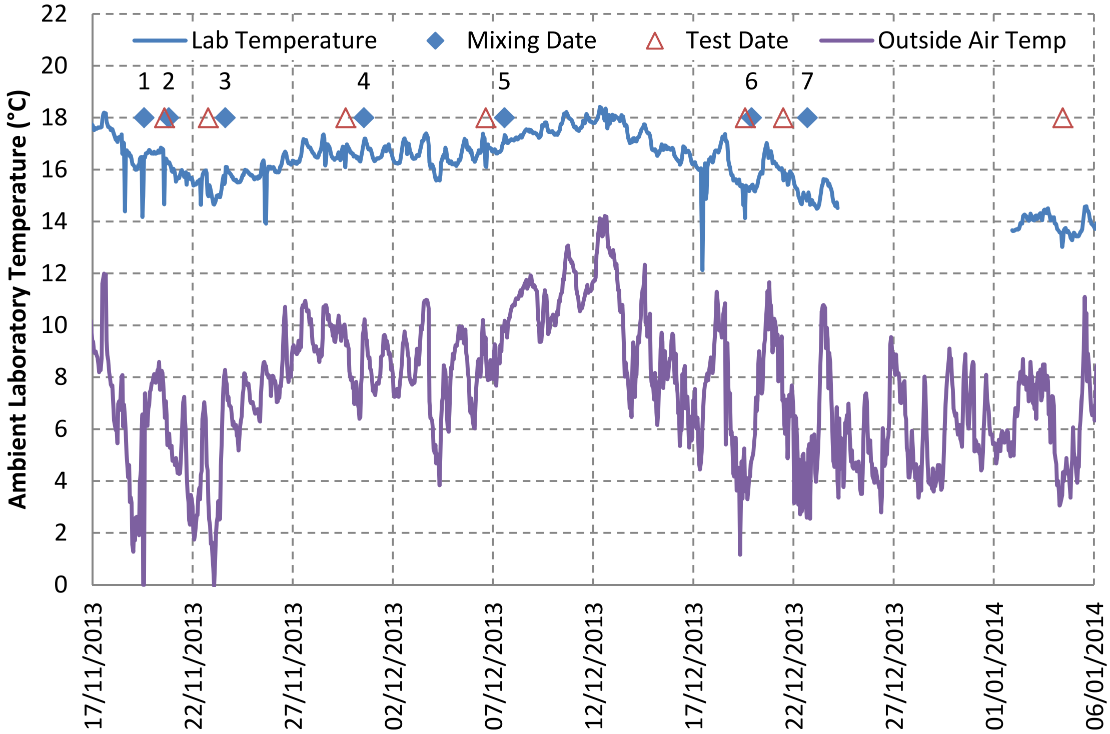

Figure 7-11: Laboratory temperature during cone-only penetrometer test series

7.3.4 Moisture Content, Organic Content and Density

All *sleech* used for the cone penetrometer tests was sampled from a single location in a storage basin prior to all tests and had previously been used to surround PIRT columns during curing. Initial moisture contents (w_i) were between 45% and 49% and low variations were seen in the organic content, with values ranging from 3.1% to 4.8% (see Table 7-2). Addition of the binder to the *sleech* and mixing was seen to reduce the moisture content by approximately 5% for 100 kg/m^3 and 7% for 150 kg/m^3 binder contents. Stabilised moisture contents were 6-7% and 9-10% lower than the initial moisture content of the *sleech* for the 100 kg/m^3 and 150 kg/m^3 binder contents, respectively.

Again, negligible differences in density are seen between room-cured (ρ_{mldR}) and 20 °C cured (ρ_{mldT}) mould samples as shown in Figure 7-12a, with the spread due to different w_{mix} values. Once again, a greater compactive effort was experienced in the columns compared to the moulds with column densities found to be 1.0 to 1.12 times that of their room-cured counterparts (see Figure 7-12b). These are similar to the ratios seen in the PIRT columns. Both ρ_{mld} and ρ_{col} again showed a dependence on w_{mix} and A_{stab} values of approximately 8% and 6% were fitted for the mould and column samples, respectively. Figure 7-13 shows the variation in column density (ρ_{col}) with depth, where the greatest densities are seen to occur in the mid-section of the column rather than at the base, as the *sleech* under the column acted to dampen compactive efforts. CoVs for the column density were found to be up to 2.8%.

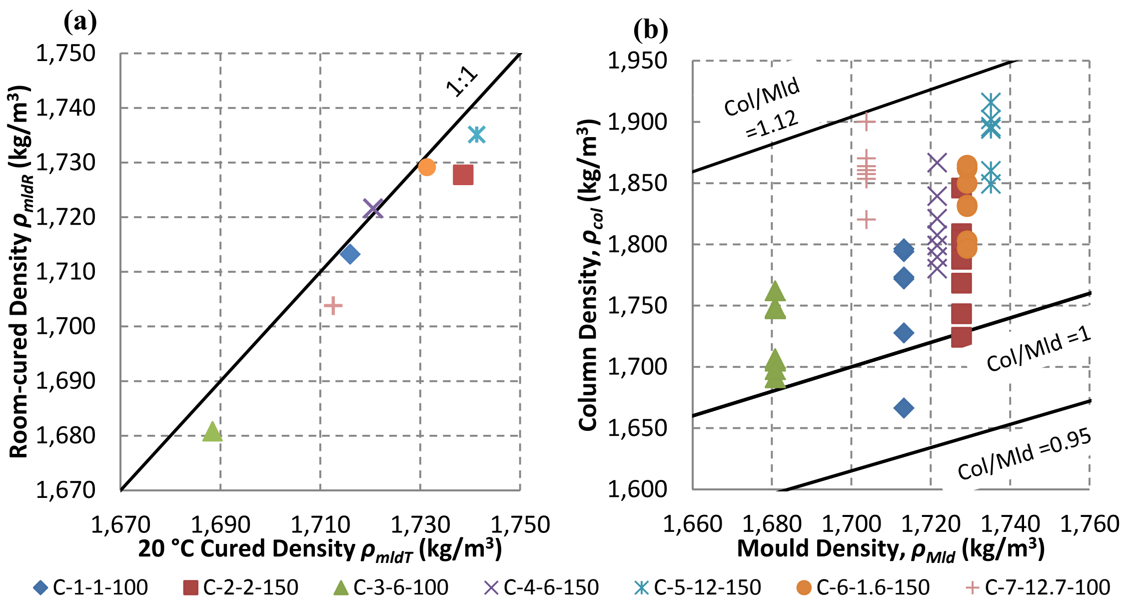

Figure 7-12: a) Mould sample density comparison & b) Column to room-cured mould density comparison

7.3.5 Stabilised Mould and Column Strength

Figure 7-14a shows the increase in mould strength (q_{mld}) with time for all mould samples, where strengths are seen to range from 154 kPa to 693 kPa. As expected, higher strengths were seen with the 150 kg/m^3 binder content and, room-mould cured sample strengths are 0.8 to 1.0 times that of 20°C cured counterparts (see Figure 7-14b). Similar trends of increasing strength with curing time and binder content are also seen for the column samples (see Figure 7-15a) with strengths seen to range from 195 kPa to 839 kPa. Figure 7-15b shows that most of the column strengths are 1.0 to 1.4 times those of their respective room-cured sample strengths, as was seen in the PIRT and wire series columns. This is thought to be due to the increased levels of compaction observed in the column sample density and the greater temperatures occurring due the hydration reactions in the larger stabilised column mass.

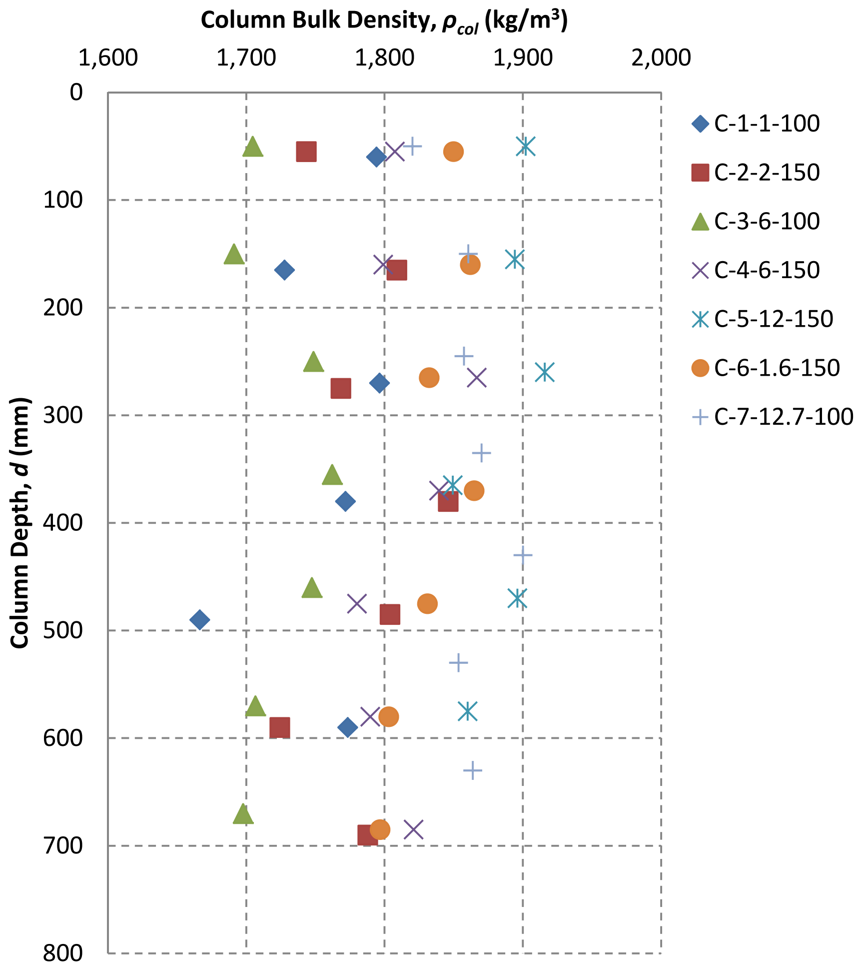

Figure 7-13: Cone-only penetrometer column density with depth

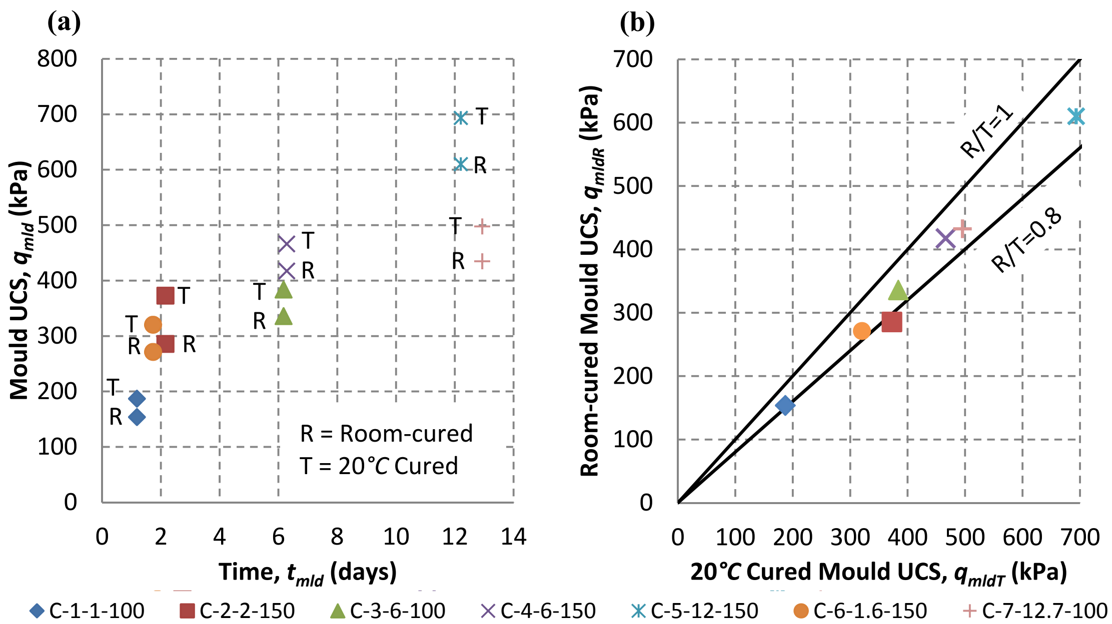

Figure 7-14: Cone-only friction column: a) Mould UCS with curing time & b) Mould sample comparison

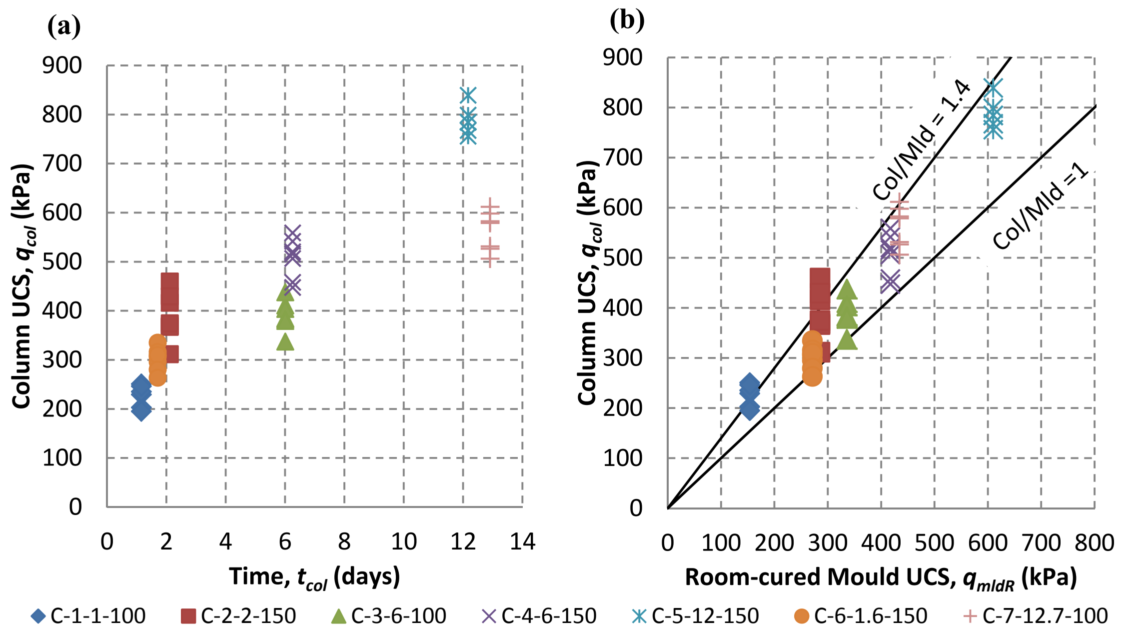

Figure 7-15: Cone-only friction column: a) Column sample UCS with curing time & b) Column to room-cured mould UCS comparison

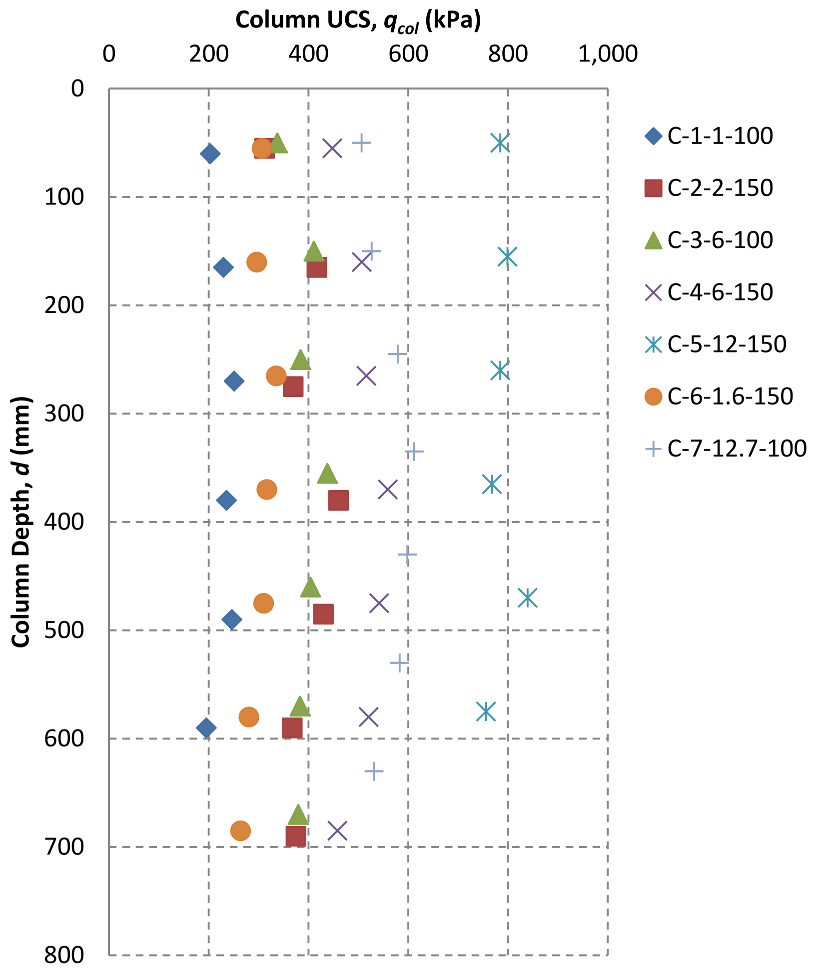

Figure 7-16: Cone-only penetrometer column UCS with depth

Figure 7-16 shows the column strength (q_{col}) profile with depth for each of the cone-only penetrometer test columns. Similar strength with depth trends to those observed in the larger 200 mm dia. PIRT columns are also seen, *i.e.,* a lower strength near the base of the column. As seen with the column density, this is thought to be due to the presence of the *sleech* under the column during construction. CoV of the column strength within a given column were a maximum of 12.6%.

Figure 7-17 shows the average q_{col} (and standard deviation error bars) with TCT_{col}, thus taking into account the variation in the ambient temperature of the laboratory in which the columns cured and the effect of increasing binder content and curing time is clearly visible on the strength. Figure 7-18 shows the average of each specimen's UCS multiplied by its WTBR and plotted against the TCT_{col}, thus incorporating the main variables of moisture content, binder content, strength, time and temperature. Equation 7-2 was fitted to the data and produces a very good R^2 of 92.0%:

$$UCS \times WTBR = 729.53 \ln(TCT_{col}) + 932.82 \qquad \text{7-2}$$

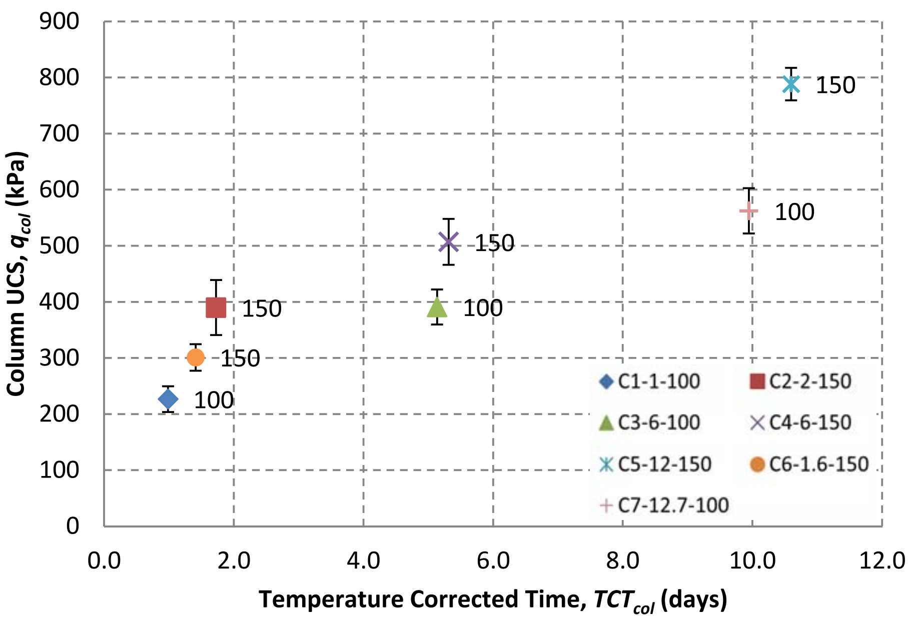

Figure 7-17: Column UCS with temperature corrected time for all cone-only penetrometer tests

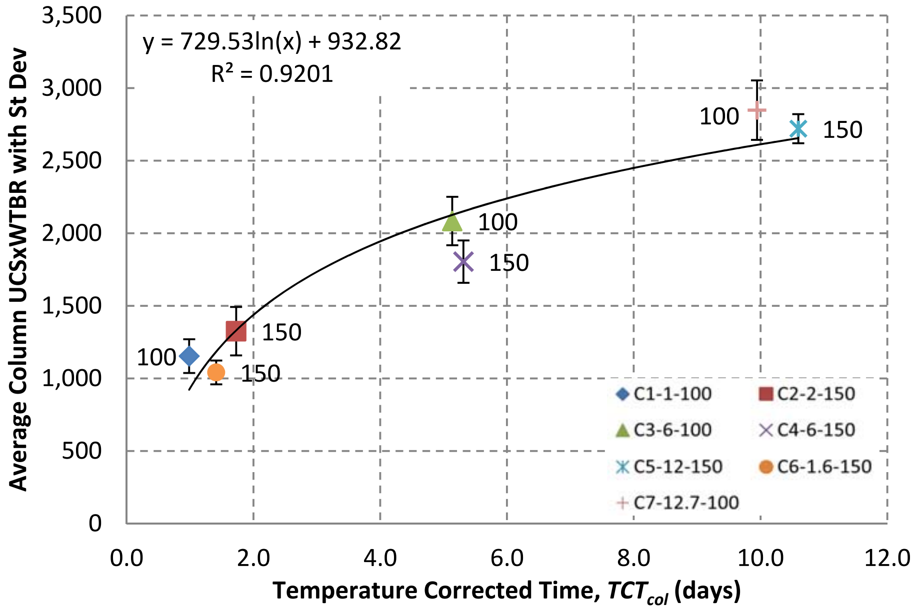

Figure 7-18: Column UCS×WTBR with temperature corrected time

7.3.6 Mould and Column Stabilised Stiffness

Mould stiffnesses (E_{mld}) were again seen to increase with both curing time and binder content, reaching a maximum value of 103 MPa after 12 days and samples cured at 20 °C showed increased values over their room-cured counterparts. E_{50} graphs for both mould and column samples may be found in Appendix D.4. Column stiffness (E_{col}) profiles with depth showed trends of increasing E_{50} from the top of the column to the lower-middle section and a reduction thereafter, a shape similar to that seen with the density and strength profiles. Increased E_{col} values, up to 107 *MPa,* were noted compared to the E_{mld} values, thought to be due to the increased compaction experienced by the column during construction. E_{col} CoV's were between 18.1% and 42.2%. The relationship between E_{50} and q_{col} was found to be E_{mld} = [70-125]q_{mld} for mould samples and E_{col} = [60-125]q_{col} for column samples and compare very well with those seen in the literature and with the results from the other columns tested in this thesis.

7.4 Temperature Monitored Column

7.4.1 Introduction

To investigate the variations of temperature due the exothermic hydration reactions in the column and the effect of the ambient laboratory temperature, a designated column was constructed. The column was built to a height of 905 mm in four mixes (see Figure

7-19). Mixes 1 and 2 were stabilised with 150 kg/m^3 of OPC and Mixes 3 and 4 with 100 kg/m^3 of OPC. Initial moisture contents (w_i) for the *sleech* used were between 46% and 48%. The location of each thermistor is shown in the cross-section in Figure 7-19 with co-ordinates provided in Table 7-3. The column was allowed to cure for 12 days before exhumation and testing.

Based on their location in the basin, column thermistors are labelled *X-Y-Z,* while surrounding *sleech* thermistors are labelled *X-Z*, where:

(i) *X* represents the radial location; *CC*: column centre, *CQ*: column quarter-point, *CF*: column face, *SM*: *sleech* mid-basin and *SW sleech* at the basin wall.

(ii) *Y* represents the binder content, either 100 kg/m^3 or 150 kg/m^3 of OPC

(iii) *Z* represents the mix number

The labels M*X*R and M*X*T are used to reference room-cured and 20 °C cured mould samples from Mix *X*, respectively.

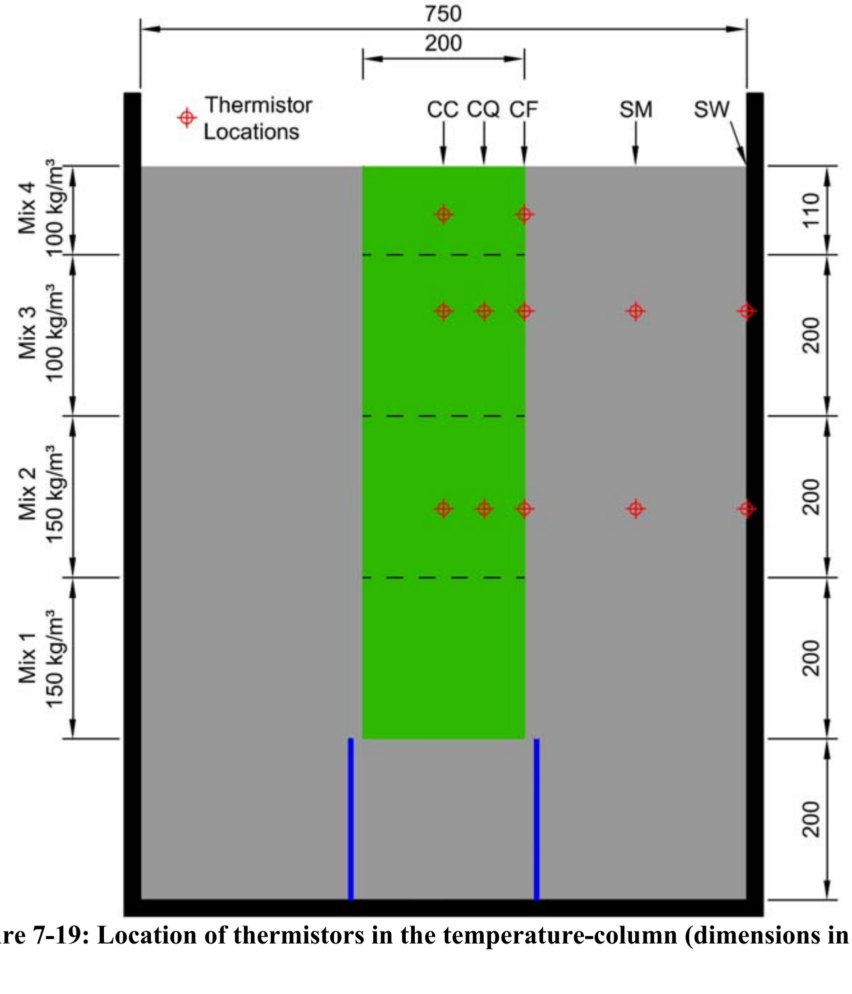

Figure 7-19: Location of thermistors in the temperature-column (dimensions in mm)

Table 7-3: Temperature column thermistor details

Label	Radial Location	Radius from Column. Centre, mm	Depth, mm	Mix*	Binder Content kg/m^3
CC-150-2	Column centre	0	420	2	150
CQ-150-2	Column quarter	50	410	2	150
CF-150-2	Column face	100	430	2	150
SM-2	*Sleech* middle	240	430	(2)	-
SW-2	Basin wall	375	430	(2)	-
CC-100-3	Column centre	0	180	3	100
CQ-100-3	Column quarter	50	170	3	100
CF-100-3	Column face	100	190	3	100
SM-3	*Sleech* middle	240	180	(3)	-
SW-3	Basin wall	375	175	(3)	-
CC-100-4	Column centre	0	50	4	100
CF-100-4	Column face	100	70	4	100

*Brackets denote thermistors in *sleech* at that mix's level

7.4.2 Recorded Temperatures

Figure 7-20 a, b & c illustrate the variations in temperature at each of the three levels of thermistors in the basin, their associated stabilised mould samples, the ambient laboratory temperature (labelled *Room*) and the temperature of the water bath (labelled *Water Bath*) in which mould samples cured. Figure 7-21 shows the variation of temperature in the first 24 hours of curing recorded by all thermistors. From the graphs, the following conclusions are made:

<u>Ambient Temperatures:</u>

Relative to the temperature in which the column cured:

- The ambient laboratory temperature shows daily variations due to the outside temperature and the temperature control of the laboratory by the BMS.
- Ambient temperatures in the laboratory rise steadily between day 2 and 7 of the test and from day 7 to day 12 the ambient temperature drops.
- A significant drop in temperature can be seen after 35 hours when the laboratory ambient temperature drops by 2 °C. This is thought to be due to the opening of a large outside door in the laboratory and the effects of the drop in temperature are seen across all thermistors.

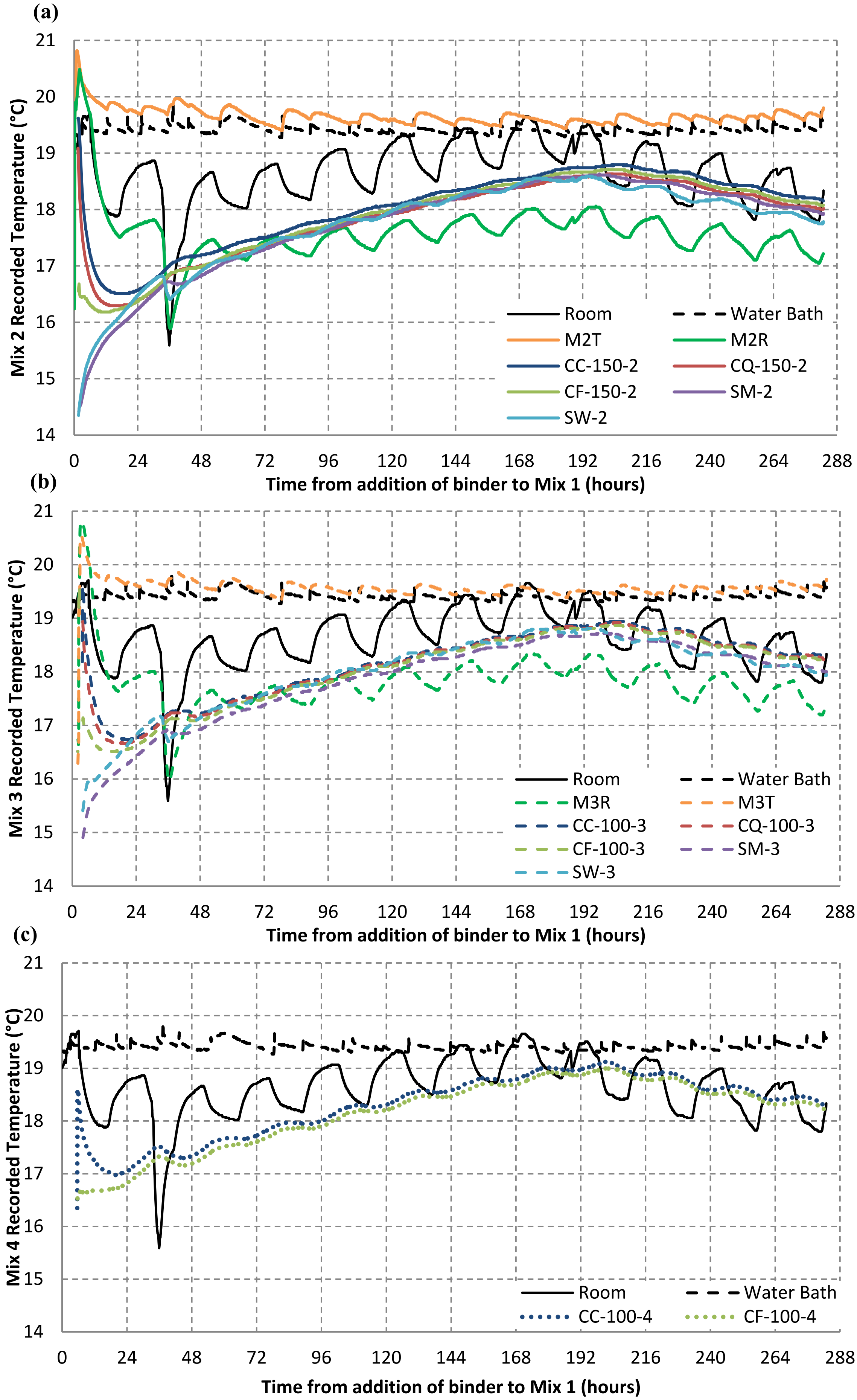

Figure 7-20: Recorded temperature variations in a) Mix 2, b) Mix 3 & c) Mix 4

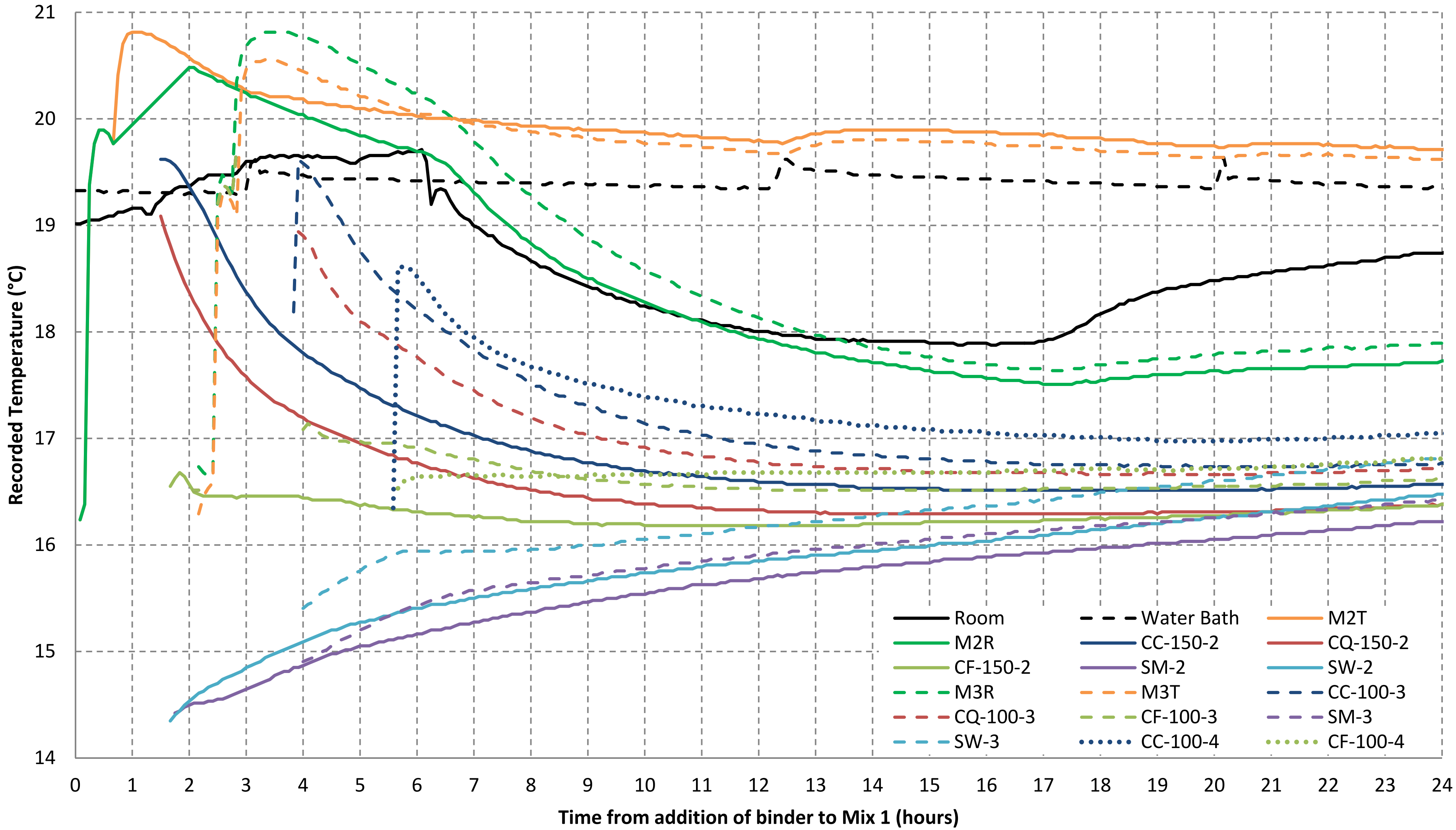

Figure 7-21: Temperature variations within the column in the first 24 hours from all thermistors

It should be noted that this column was cured in the Concrete Laboratory and not the Wet Soils Laboratory where the *sleech* used to construct the column was stored, as were all other columns during construction and curing. As such, the *sleech* was not in equilibrium with the temperature of the Concrete Laboratory at the start of the test and thus the column's temperature is compared to the temperature of the surrounding *sleech*, not the ambient laboratory temperature, when determining the time at which equalisation of the column and surrounding *sleech* occurs.

Stabilised Column and *Sleech* Temperatures:

Within the stabilised column and the surrounding *sleech*:

- The highest temperatures in the stabilised soil are seen to occur within approximately 1 hour of stabilisation in all cases.
- From an unstabilised *sleech* temperature of 14 °C (measured before the experiment), mould samples reached highest temperatures of 20.8 °C, reducing to ambient temperature within 6 to 7 hours. Mould samples cured in the water bath were found to have water around the thermistor after curing and so do not reflect the temperature within the sample correctly.
- In the centre of the column, heat of hydration increased the temperature to 19.6 °C in Mixes 2 and 3 (despite different binder contents), and similarly at 50 mm into the column peak temperatures of 19.1 °C and 18.9 °C were recorded. The highest temperature in Mix 4, stabilised with 100kg/m^3, was found to be 18.6 °C at the column centre.
- After 12 hours, the temperature of the column and surrounding *sleech* show similar values.
- Up to day 7, the temperature of the laboratory increases and the column and surrounding *sleech* rise in a similar manner. Similarly, reductions in temperature are seen throughout the curing basin as the ambient temperature drops after day 7.

Higher temperatures have been noted in the literature for OPC stabilised soil (see Section 2.9.2) and in theory higher temperatures would be expected in the column compared to the moulds, due to the greater size of the stabilised mass (Van Impe & Verástegui Flores 2006). The time required for mould preparation and column construction influences when the thermistors can be placed at the desired location and this may have resulted in temperature losses (*e.g.,* lack of surrounding *sleech* to insulate the stabilised soil). Also, the peak temperature may have occurred before the thermistors were put in place. This is supported by fact that the mould samples show higher peak temperatures than the column at its centre due to the short delay between stabilisation and placement of the thermistors.

Temperature Equalisation:

Both column and surrounding *sleech* temperatures are seen to equalise within 12 hours of stabilisation and follow similar trends thereafter. It is thought that in a scenario where the *sleech* temperature was the same as the ambient temperature at the start of the test (as was the case in the PORT, PIRT and friction column series), equalisation of the column temperature with ambient laboratory temperature would have occurred earlier than 12 hours. Thus, it is concluded that the average ambient laboratory temperature can be justifiably used as an estimate of the curing temperature within the column.

7.4.3 Extracted Column

Following extraction, the column was cut into sections and the thermistors were recovered (see Figure 7-22 and Figure 7-23). Samples were taken from the cut sections to investigate the variation of strength over the column cross-section and the variation in strength due to the effects of different sample lengths, *i.e.,* L/D ratios.

Column Quality:

As the PORT/PIRT columns are split vertically during their testing, the actual column diameter cannot be accurately verified. However, it was possible to measure the actual cross-sectional dimensions of the extracted temperature-monitored column at a number of locations along its length. The lengths of two perpendicular diameter chords at five locations over the column length are shown in Table 7-4, the upper four of which indicate good uniformity. Figure 7-24 shows the column base (inverted), where notable bulging and a concave shape can be seen. This is thought to be due to the compaction of the column from Mix 2 onwards which caused the base of the column to bulge out into the surrounding *sleech*. Exhumed columns after PORT and PIRT were noted to show similar local bulging at their bases.

Table 7-4: Perpendicular column cross-sectional diameter dimensions

Location:	Dimensions:
Top	197×210 mm
Middle upper	200×194 mm
Middle lower	194×202 mm
Base (above bulging)	197×200 mm
Base (bulged)	217×218 mm

Figure 7-22: Temperature-column during extraction

Figure 7-23: Thermistor locations within Mix 3

Figure 7-24: Bulging and bowling at the column base

Column Strengths:

Four samples were taken from two depths (see Table 7-5) in Mix 3 of the extracted column and trimmed with extra care to various lengths of between 75.5 mm and 100.5 mm. Assessments were carried out to investigate the variation in strength at different L/D ratios, referred to as L/D Test. In order to provide a baseline to judge the L/D tests, further assessments investigated the variation in similar sample size strengths across at a particular depth, referred to as UCS Spatial. To remove any possible effects of different construction or curing conditions, samples for each assessment are from the same depth. Figure 7-25 shows the column sample UCS plotted against its bulk density and the annotations on the graph refer to the sample length.

Table 7-5: Temperature column sample UCS assessment

Assessment:	Depth mm	Max UCS kPa	Min UCS kPa	Max-Min kPa	Average kPa	St.Dev kPa	UCS CoV
UCS Spatial	155	520.9	440.0	80.9	478.4	38.0	7.9%
L/D Test	235	518.1	490.4	27.7	505.1	12.8	2.5%

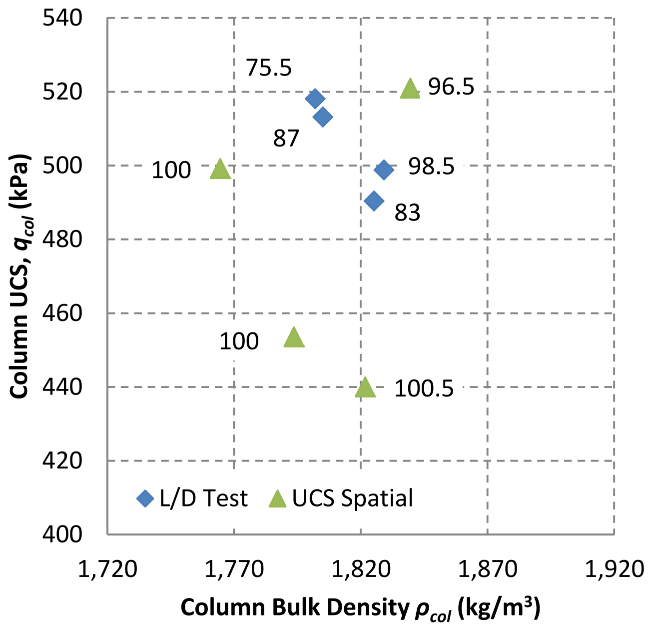

Figure 7-25: Exhumed column sample UCS with bulk density including sample height label

In the L/D Test, where sample lengths varied from 75.5 mm to 98.5 mm, no systematic trend of strength with sample length is visible, while a CoV of 2.5% was calculated for q_{col} and 0.8% for ρ_{col}. As a baseline comparison, UCS Spatial shows a higher variability in q_{col} with a CoV of 7.9% for sample lengths of approximately 100 mm and L/D Test q_{col} values all lie within the q_{col} values seen in the UCS Spatial assessment. Overall, it is thought variations in sample length have little effect on the strength obtained, agreeing with the findings of Wilson (2013) set out previously in Section 3.4.3 and this is considered later in Section 7.6 when estimating the strength to be used to calculate the N values for the PORT and PIRT penetrometers.

7.5 Temperature Correction

Over the duration of the testing programme, the ambient temperature of the laboratory was found to vary seasonally. The PORT column series was carried out over a twelve month period and the columns cured at average ambient temperatures (*T*) of 13.5 °C to 20.5 °C. The PIRT column series was carried out over a six month period, during which time columns cured at a narrower range of *T* of between 17.5 °C and 19.2 °C. In Section 2.9.2 and throughout the previous chapters, the effect of temperature on strength has been highlighted. Account for the curing temperature is carried out by adjusting the curing time using Equation 7-3 (*i.e.,* Equation 2-15 written in terms of the parameters used in this thesis) and the adjusted time is referred to as the Temperature Corrected Time (*TCT*).

$$TCT = \sum_{i=1}^{n} e^{-\left(4000/[273+T]-13.65\right)} \times t \qquad 7\text{-}3$$

where *T* is the average ambient temperature (°C) over a curing period of *t* (days). Using the hourly temperature data recorded by the BMS for the (Wet Soils) laboratory in which the columns cured, *T* was determined for each individual column. The analysis in Section 7.4.2 has shown *T* to be an appropriate measure of the temperature at which the columns cured as it was seen that the column temperature equalises with that of the surrounding *sleech* within 12 hours of stabilisation and thereafter shows a similar trend to that of the ambient laboratory temperature. This justifies the calculation of *TCT* using *T* as carried out in Sections 5.6, 6.6, 7.2.5 and 7.3.5.

7.6 Prediction Models & Strength Corrections

7.6.1 Introduction

During the PORT/PIRT series, the time between the column test and UCS testing of samples from the column was up to 11 hours as the columns had to be exhumed and trimmed into suitable sample sizes for testing. As has been shown in the results of the PORT, PIRT, wire friction and cone-only Penetrometer series, strength was seen to increase with time. Before the N value, *i.e.,* the relationship between column strength and probing resistance, may be calculated, it is important that the probing resistance is related to the strength of the column at the time of probing and not the strength of the samples at the time of UCS testing. The strengths at the time of probing are subsequently referred to as the corrected column UCS (q_{cor}). In this section, the manner in which q_{cor} is calculated is set out for each of the four test series, and calculated q_{cor} values are presented. This adjustment is only carried out on q_{col} values for the purpose of calculating the N values in Chapter 8 and obviously will have the most effect on early age samples where the rate of strength gain is high.

7.6.2 Strength Correction Method

As has been presented in Sections 5.6, 6.6, 7.2.5 and 7.3.5, equations of the form of that shown in Equation 7-4 have been fitted to the average mould and column data of each test series in an aim to include for the effects of binder content, curing time, initial moisture content and curing temperature on the strength. Details of the coefficients of these equations for each column series are compiled in Table 7-6 and their similarities are discussed in Section 8.3.1.

$$UCS \times WTBR = A \ln(TCT) + B \qquad \text{7-4}$$

Table 7-6: UCS×WTBR Prediction Models

UCS×WTBR = Aln(TCT) + B	**PORT**		**PIRT**		**Wire**		**Cone-Only & Sounding Bar**	
	Mould	***Column***	***Mould***	***Column***	***Mould***	***Column***	***Mould***	***Column***
A	541.5	621.1	427.6	532.7	544.7	713.1	641.9	729.5
B	1,083.0	846.2	1,005.2	1,005.8	772.2	944.7	726.1	932.8
R^2 Fit	74.8%	71.6%	76.1%	78.7%	91.3%	95.1%	93.0%	92.0%

Using Equation 7-4, the UCS×WTBR was estimated for each column at the PORT, PIRT or friction test average *TCT* (TCT_{Po} or TCT_{Pi}) and at the column UCS test average *TCT* (TCT_{col}). The difference between these values is referred to as the correction factor ΔUCS×WTBR ($\Delta q\eta$) (see Figure 7-26). The corrected UCS values (q_{cor}) were calculated for each individual UCS test sample using to Equation 7-5:

$$q_{cor} = q_{col} - \frac{\Delta q\,\eta}{WTBR_S} \qquad \text{7-5}$$

where q_{col} is the column sample UCS at the time of the UCS testing (kPa), $\Delta q\eta$ is the ΔUCS×WTBR correction factor for the column from which the sample originates and $WTBR_S$ is the sample's actual $WTBR$ (calculated using Equation 4-1). In subsequent sections, this procedure is used to estimate the strength of each individual column sample at the time of the column test for all four series.

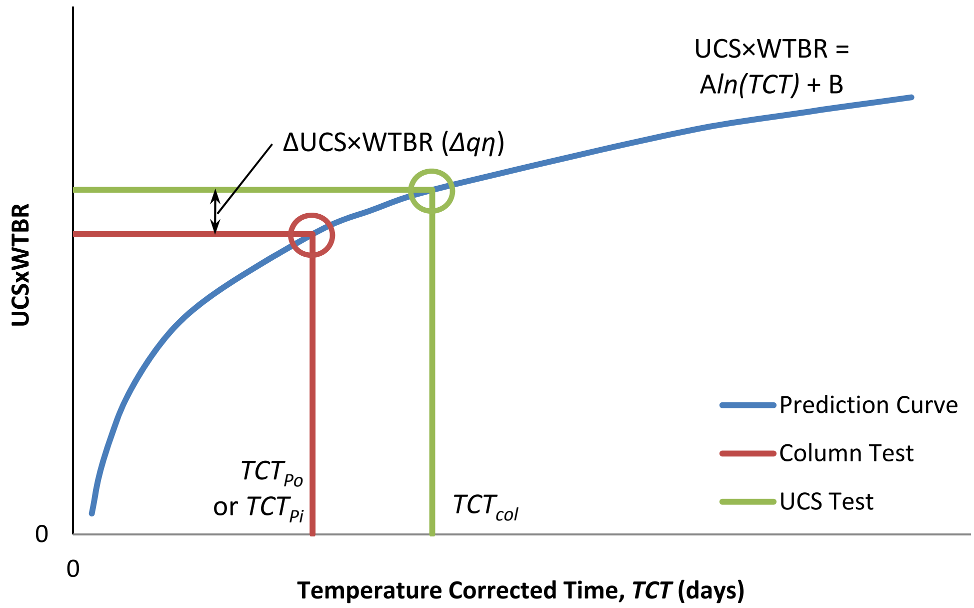

Figure 7-26: Adjustment of strength with time for N value calculations

7.6.3 Sample Length-to-Diameter Ratio

The recommended length-to-diameter ratio (L/D) for cylindrical UCS test samples is two-to-one (BSI 1994). As can be seen on the summary sheets for each test in Appendix E, the length of the tested mould samples overall ranged from 125 mm to 131 mm (average 129 mm) and varies little from the desired sample height of 130 mm (with the exception of PO-13S). As a result of trimming the column by hand the desired sample height of 100 mm was not achieved in all cases and overall, column sample heights ranged from 74 mm to 110 mm (average 94 mm). In Section 7.4.3, the results of a two separate L/D tests on samples (UCS up to approximately 800 kPa) obtained from the temperature-monitored column are presented in consideration of an L/D strength correction and it was concluded that within the range of 74 mm to 107 mm the differing height had little effect on the achieved strength. Following from these findings and those set out in Section 3.4.3, no correction has been applied to adjust the achieved strength for differing L/D ratios.

7.6.4 Corrected PORT Column Strength

The time between PORT of the column and UCS testing of samples taken from the column was between 4 and 10 hours depending on the number of samples obtained. Based on the correction method set out in Section 7.6.2, Table 7-7 and Figure 7-27 show the correction factors and the corrected PORT column strengths, respectively. The greatest adjustments are made to samples where the curing time is short as the rate of increase of strength is high, *e.g.,* PO-8 and PO-15, and in long duration columns the adjustment is near negligible. Corrected column strengths are seen to range from 86*kPa* to 841 kPa.

Table 7-7: PORT column strength adjustment factors

PORT Column No.	*TCT* to PORT, TCT_{Po} days	Column UCS *TCT*, TCT_{col} days	Predicted PORT UCS×WTBR kPa	Predicted Column UCS×WTBR kPa	Column ΔUCS×WTBR $\Delta q\eta$, kPa
PO-5	4.51	4.65	1,781.7	1,800.1	18.5
PO-6	5.65	5.84	1,921.2	1,941.8	20.6
PO-7	6.10	6.28	1,968.9	1,987.2	18.3
PO-8	1.95	2.23	1,261.9	1,343.0	81.1
PO-9	3.87	4.07	1,686.3	1,717.3	31.0
PO-10	9.26	9.47	2,228.3	2,242.8	14.5
PO-11	4.44	4.74	1,772.4	1,813.0	40.6
PO-12	10.47	10.80	2,304.7	2,324.0	19.2
PO-13S	4.66	4.88	1,802.1	1,831.1	29.0
PO-14S	8.77	8.98	2,194.5	2,209.4	14.9
PO-15	0.72	0.93	639.5	799.5	160.0
PO-16	9.20	9.44	2,224.6	2,240.4	15.8
PO-17*	10.73	10.96	2,320.3	2,333.0	12.7

7.6.5 Corrected PIRT Column Strength

In practice the time between PIRT of the column and the UCS testing of column samples was between 5 and 11 hours. Again, based on the correction method set out in Section 7.6.2, Table 7-8 and Figure 7-28 provide the correction factors and corrected strengths for each PIRT column, respectively. PIRT column strengths at the time of PIRT are estimated to lie between 123 kPa and 812 kPa, and similar trends in terms of correction factors are observed to those seen in the PORT series.

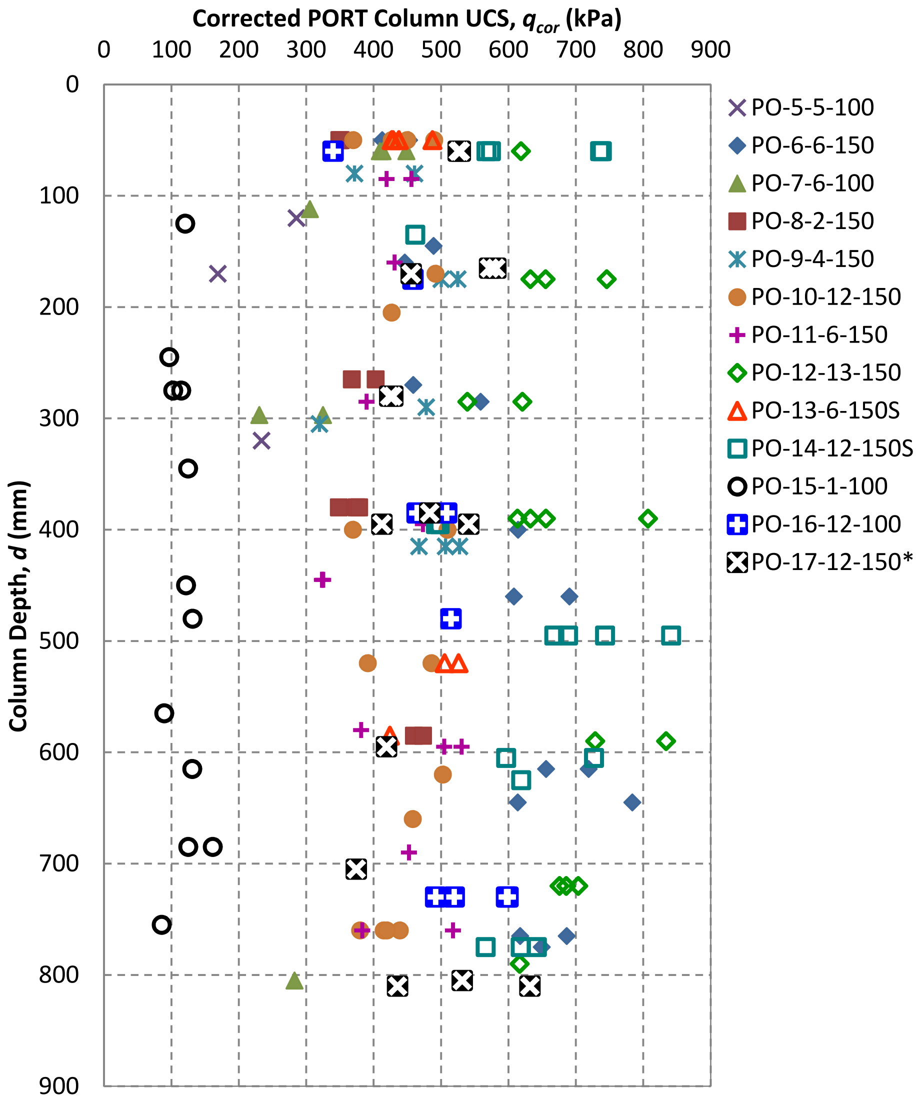

Figure 7-27: Corrected PORT column UCS with depth

Table 7-8: PIRT column strength adjustment factors

PIRT Column No.	*TCT* to PIRT, TCT_{Pi} days	Column UCS *TCT*, TCT_{col} days	Predicted PIRT UCS×WTBR kPa	Predicted Column UCS×WTBR kPa	Column ΔUCS×WTBR $\Delta q\eta$, kPa
PI-4	1.79	2.02	1,315.0	1,381.5	66.5
PI-5	0.87	1.08	930.2	1,044.5	114.3
PI-6	5.49	5.66	1,913.3	1,929.3	16.0
PI-7	5.57	5.76	1920.7	1,938.8	18.1
PI-8	3.56	3.73	1,681.5	1,707.5	26.0
PI-9S	5.44	5.62	1,908.0	1,925.7	17.7
PI-10	10.70	11.00	2,268.4	2,283.2	14.8
PI-11	11.18	11.46	2,291.6	2,305.0	13.3
PI-12	10.60	10.89	2,263.5	2,277.9	14.4
PI-13	0.78	1.09	875.0	1,050.6	175.6
PI-14S	10.24	10.64	2,244.8	2,265.3	20.5

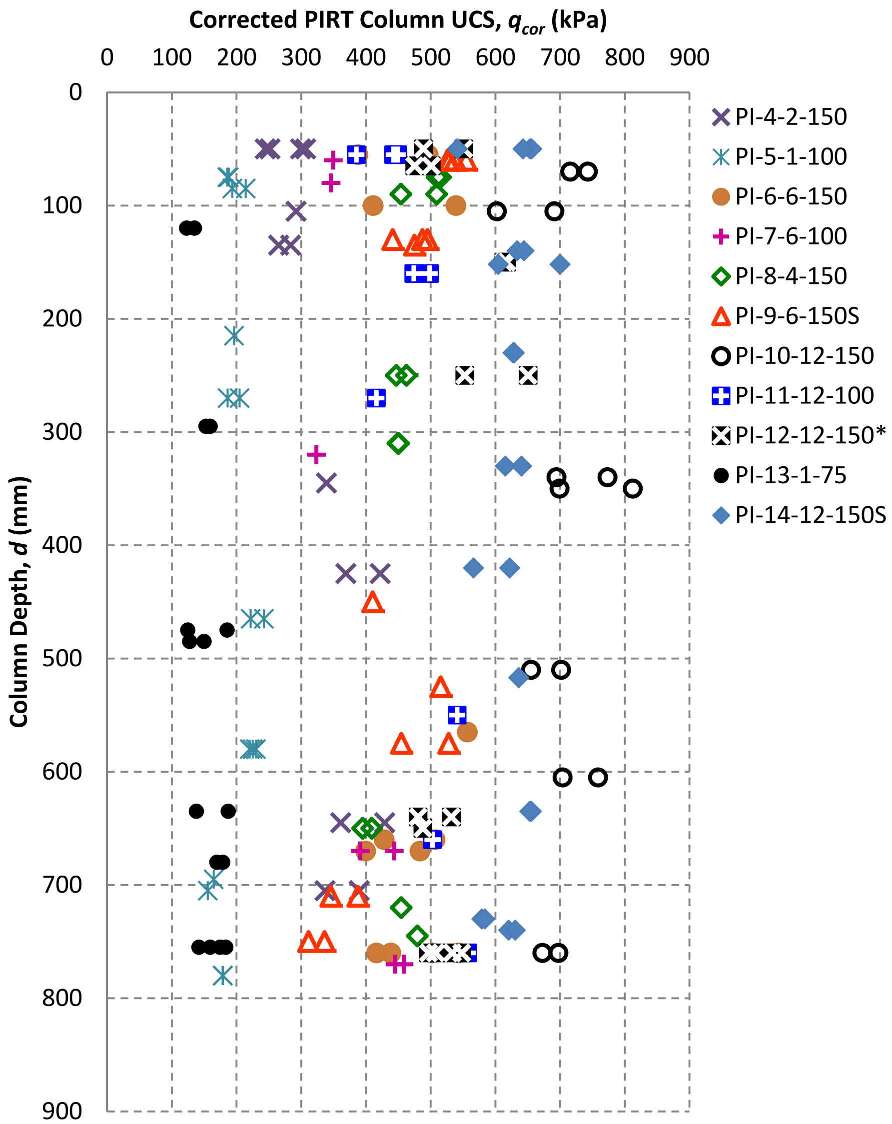

Figure 7-28: Corrected PIRT column UCS with depth

7.6.6 Corrected Friction Column Strength

A shorter delay of less than 4 hours occurred between the friction column test series and the UCS testing of their samples due to the lesser amount of work required to extract and sample the 104 mm dia. columns, and the absence of surrounding *sleech* to be profiled. Using Equation 7-1 for the PORT wire friction tests and Equation 7-2 for the cone-only penetrometer friction tests, ΔUCS×WTBR correction factors were calculated for each column using Equation 7-4. Table 7-9 shows the PORT wire friction test adjustments and Table 7-10 shows the adjustments to the cone-only penetrometer tests. q_{cor} values for both test series are shown in Figure 7-29 a & b, respectively. Due to the short delay between the column test and testing of its UCS samples, strength adjustments are minimal in the case of both columns, but nonetheless are required to estimate the column strength at the time of testing, which will be used to apply friction corrections in Sections 8.5.2 to the PORT and PIRT data.

Table 7-9: Wire column strength adjustment factors

Wire Column Test No.	Wire Column *TCT*, TCT_{Po} days	Column UCS *TCT*, TCT_{col} days	Predicted Wire UCS×WTBR kPa	Predicted Column UCS×WTBR kPa	Column ΔUCS×WTBR $\Delta q\eta$, kPa
W-1	4.08	4.21	1,947.2	1,970.4	23.2
W-2	5.02	5.16	2,095.9	2,114.2	18.3
W-3	3.36	3.52	1,809.2	1,841.7	32.5
W-4	0.98	1.11	932.4	1,017.3	84.9
W-5	10.48	10.62	2,620.5	2,629.8	9.4
W-6	10.58	10.70	2,626.8	2,635.1	8.3
W-7	1.30	1.41	1,131.3	1,188.8	57.4
W-8	5.24	5.36	2,125.5	2,142.6	17.2

Table 7-10: Cone-only penetrometer column strength adjustment factors

Cone Column Test No.	Cone Column *TCT*, TCT_{Pi} days	Column UCS *TCT* TCT_{col} days	Predicted Cone UCS×WTBR kPa	Predicted Column UCS×WTBR kPa	Column ΔUCS×WTBR $\Delta q\eta$, kPa
C-1	0.86	0.98	826.9	921.7	94.8
C-2	1.60	1.73	1,276.3	1,331.0	54.6
C-3	5.02	5.14	2,109.6	2,126.5	16.9
C-4	5.17	5.31	2,131.2	2,151.3	20.1
C-5	10.46	10.60	2,645.5	2,654.9	9.4
C-6	1.31	1.41	1,132.1	1,184.4	52.4
C-7	9.82	9.94	2,599.7	2,608.6	8.9

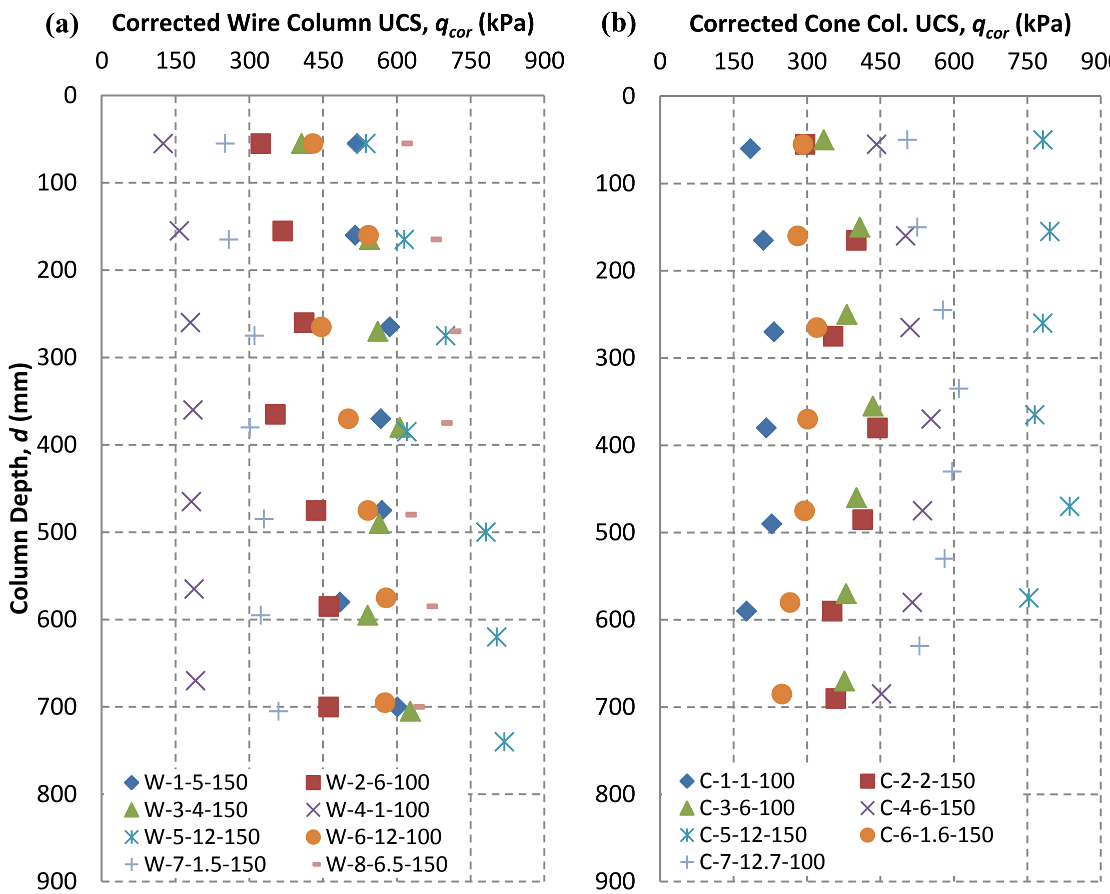

Figure 7-29: Corrected column UCS at the time of a) wire pull-out testing & b) cone-only penetrometer testing

7.7 Chapter Summary

Overall, eight no. wire friction tests and seven no. cone-only penetrometer and sounding bar friction tests were successfully carried out at strengths similar to those obtained from the respective PORT and PIRT columns. The temperature of a specific column was monitored, and was found to equalise with that of the laboratory ambient temperature within 12 hours, justifying the use of the average ambient temperature when calculating the temperature corrected time. Finally, the strength of each column sample at the time of the column test was estimated using the results of the UCS×WTBR *versus TCT* framework, thus accounting for any delay between the column test and UCS testing of that column's samples.

In Chapter 8, the results of the friction tests and the corrected column strengths will be used in conjunction with the data presented in Chapters 5 and 6 to calculate the respective PORT and PIRT N values for the penetrometers used in this study.

CHAPTER 8: DISCUSSION

8.1 Introduction

The goal of this chapter is to derive and discuss N values applicable to the PORT and PIRT techniques for the reduced-scale columns in this thesis. Prior to this however, a discussion on quality control and on consistency of trends across the entire test programme is necessary and some data corrections are presented. The chapter content is as follows:

- Section 8.2 presents a comparison of the CoV of variables within the four column test series, as well as drawing together the results from statistical analyses, carried out in Chapter 5 and 6 on their respective strength data.
- In Section 8.3, data from across all four column series are compiled and compared to demonstrate consistency across the test programme. The equations fitted to the UCS×WTBR against *TCT* graphs for each column series are compared. From the exhumed columns, the predominant cracking patterns are discussed.
- Section 8.4 provides a comparison between the reduced-scale PORT and PIRT of the laboratory columns and full-scale versions of the field test.
- In Section 8.5, the procedure for calculating the corrected probing force relevant to each PORT and PIRT column sample is presented, as well as for the respective tests in unstabilised *sleech*.
- Finally in Section 8.6, the PORT and PIRT N values are presented along with a summary of the factors which influence them.

8.2 Overall Statistical Analysis

8.2.1 Coefficient of Variation Comparison

An assessment of the acceptability of variation was carried out by examining the CoV of the initial moisture content (w_i), stabilised density (ρ), stabilised UCS (q) and stabilised stiffness (E_{50}). Table 8-1 compiles the range of CoV values observed within each column from each column test series, and all values may be found in the summary statistics sheets in Appendix E.

Moisture content CoVs within each column were typically less than 6.2%, and although not directly comparable to the field, the values are below the guideline range of 8% to

30% detailed by Phoon & Kulhawy (1999) for *in situ* clay and silt samples. Stabilised densities all show very good CoV values of less than 2.5% for mould samples and less than 3.9% for column samples. The higher column variation is due to the sample preparation factors given in Section 3.12. All density CoVs are within the limit of 10% also quoted by Phoon & Kulhawy (1999) for natural clay and silt samples.

Investigation of the stabilised mould sample strengths (q_{mld}) CoV corresponding to a column demonstrated that values typically lie below 14%. This is above the values quoted in the literature for laboratory stabilisation trials (values up to 7%) and is below the lower limit of those for *in situ* field samples (see Section 2.10.3). However, it should be remembered that q_{mld} values are a comparison of data from a number of stabilised mixtures (*i.e.,* the initial properties of the *sleech* used in a given column can differ) rather than a number of samples from the same stabilised mix to which the 7% refers. Stabilised column strengths (q_{col}) were typically found to show very good CoV values compared to field values (approximate values of 15% to 60%), with CoVs typically below 16%. Stabilised stiffnesses show the highest CoV of the data with values typically up to 40% observed. No guideline CoV data for stabilised E_{50} is available in the literature but values of up to 65% are quoted by Phoon & Kulhawy (1999) for *in situ* sand data.

Table 8-1: Coefficients of variation ranges observed within individual columns

Property:	PORT:	PIRT:	Wire:	Cone-Only:
w_i	< 5.1 (12)%	< 6.2%	-	-
ρ_{mldR}	< 2.5%	< 1.2%	-	-
ρ_{mldT}	< 2.0%	< 1.4%	-	-
ρ_{col}	< 3.9%	< 3.5%	< 2.9(4.9)%	< 2.8%
q_{mldR}	2.4-13.6 (20.4)%	2.4-8.4%	-	-
q_{mldT}	4.5-14%	1.4-11.8%	-	-
q_{col}	9.1-16.3 (25.1)%	5.6-12.5 (17.5)%	5.5-15.6%	3.7-12.6%
E_{mldR}	5.7-39%	6.0-21.9 (54.2)%	-	-
E_{mldT}	13.6-36.2%	10.6-35.3%	-	-
E_{col}	23.7-38.2 (51.5)%	19.7-40.5%	18.1-42.2%	14.1-42.1%

*Value in brackets denotes an isolated high CoV outside the typical range observed

Overall, across all four column series, similar CoVs were noted for each property, implying very good construction and testing repeatability was achieved, given the variations described in Section 3.12. Improved CoV ranges are seen in the PIRT, Wire and Cone-Only column data as a result of the experience gained during the PORT column series and the improved controls applied to those series.

8.2.2 SPSS Statistical Analyses Assessment

Overall, given the variability set out in Section 3.12, the mixed linear regression analyses models on the PORT and PIRT data from Chapter 5 and 6 (see Sections 5.7 and 6.7) show curing time and binder content to be highly significant in terms of the UCS values achieved. Normal distributions are seen in the residual histograms and improve with additional covariates, as do the R^2 values to the actual q *versus* the predicted q plots.

All PORT and PIRT room-cured mould models showed the curing time and binder content to be significant but that w_i, density and organic content were not significant within the range of w_i values observed. Temperature was also found to be significant in both room-cured models. Within the PORT column data, improved models are achieved once the w_i and temperature are included for, both of which are highly significant. This shows that these two parameters are a factor in the observed variability in q and allowance for them increases confidence in the actual results. In the PIRT column data, curing time and binder content are again highly significant but the lesser variability in w_i and temperature, achieved by improved procedures, results in them not having a significant effect on the q value.

These analyses show that the variations in the achieved q values in terms of curing time and binder content alone are influenced by the different w_i and temperature values. This statistical study, carried out alongside the UCS×WTBR and *TCT* framework in Chapters 5, 6 and 7 confirms the need for this framework within those chapters.

8.3 Overview of the Column Test Series

8.3.1 Comparability between Testing Programmes

Following from the CoV comparison provided in Section 8.2.1, Table 8-2 provides a compilation of the relationships between the mould and column sample data for all four column series, as well as the relationship between strength and stiffness of the stabilised samples. Mould samples created from the same mixture but cured under different conditions were found to give very similar densities. Over the four column series, the column density was found to be 0.95 to 1.12 times that of the mould density. Higher column densities are due to the greater compactive efforts that were applied to the columns compared to the moulds and this may also be seen in the values of A_{stab} back figured.

Table 8-2: Observed mould and column sample comparisons

Property:	PORT:	PIRT:	Wire:	Cone-Only:
ρ_{mldR}/ρ_{mldT}	0.98-1.03	0.98-1.02	0.99-1.0	1.0-1.01
ρ_{col}/ρ_{mldR}	0.95-1.11	1.01-1.12	1.0-1.1	1.0-1.12
ρ_{col}/ρ_{mldT}	0.96-1.11	1.0-1.12	1.0-1.1	1.0-1.11
Mould A_{stab}	6-11%	7-10%	8%	8%
Column A_{stab}	0-10%	0-8%	4%	4%
q_{mldR}/q_{mldT}	0.75-1.0	0.8-1.12	0.85-0.95	0.77-0.92
q_{col}/q_{mldR}	0.7-1.3	0.8-1.2	0.8-1.4	0.85-1.3
q_{col}/q_{mldT}	0.6-1.25	0.8-1.2	0.8-1.4	0.85-1.3
E_{mld}/q_{mld}	35-115	50-125	60-125	70-125
E_{col}/q_{col}	45-125	45-130	75-150	60-125

The variation in q between the room-cured and the 20 °C cured mould samples was found to predominantly lie in the range of 0.75 to 1.0, with samples cured at temperatures below 20 °C producing lower strengths. However, 12-day mould data from the PIRT series shows values up to 1.12. Column strengths were found to range from 0.6 to 1.4 times that of the respective mould strengths over the series but predominantly lie between 0.8 and 1.2. The variations in the ratios are due to the different temperatures at which they cured, the different stabilised densities that occurred and also the effects of trimming the column samples. The E_{50}/q_t relationship for the column and mould data was found to lie within the limits of 35 to 150 and is comparable with the E_{50}/q_t values for laboratory and field data compiled in Section 2.10.4.

For all four column series, the UCS×WTBR *versus TCT* framework has been used to account for the variations in binder content, curing time, initial moisture content and curing temperature on the achieved mould and column strengths. These four equations, previously compiled in Table 7-6, were used to adjust the column strength for UCS testing delays. In Figure 8-1, good agreement can be seen between the models for the mould sample data for each column series, with R^2 values of between 75% and 93%. This shows the variability due to moisture content and curing temperature can be captured well within this framework. A comparison of the models obtained from the PORT and PIRT column data (see Figure 8-2) again shows very good agreement with R^2 values of 72% to 95% and similarly, very good agreement is seen between the two friction column models.

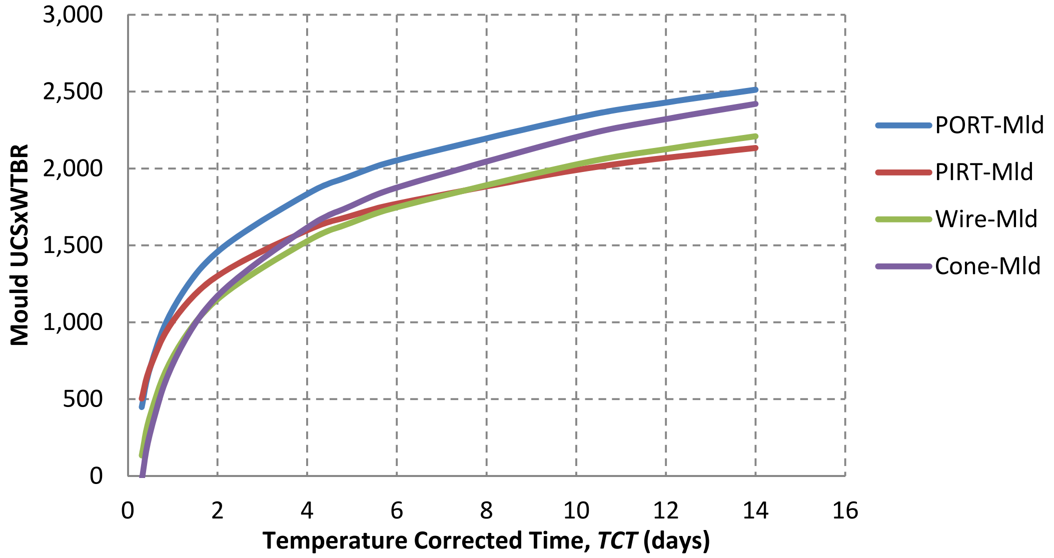

Figure 8-1: Mould sample prediction models

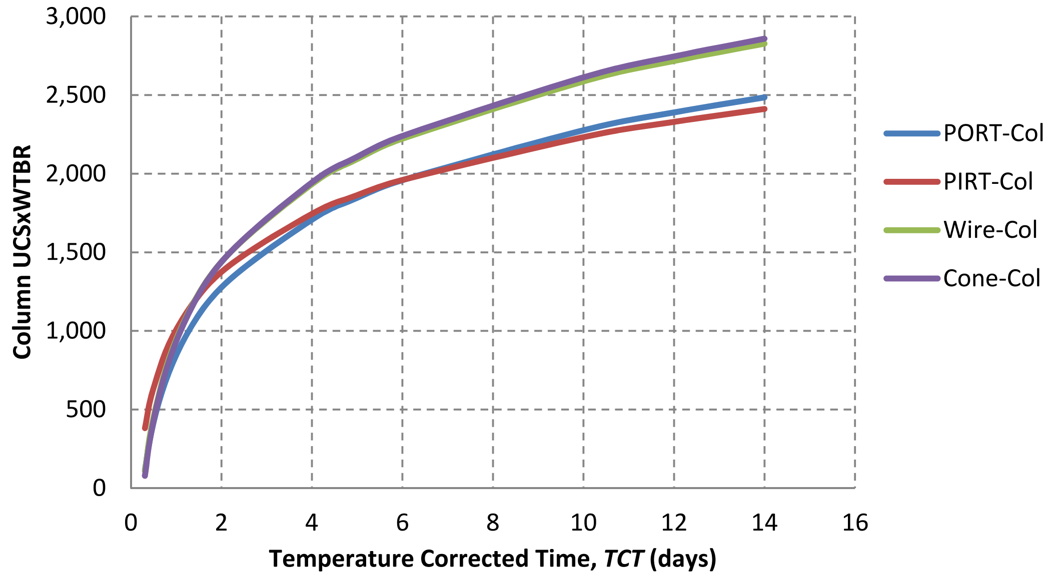

Figure 8-2: Column sample prediction models

Likewise, similarity can also be seen between the PORT/PIRT and the friction columns. The minor difference between the PORT/PIRT columns and friction column models is believed to be a result of the different construction procedures used and the different conditions in which they cured. Improvements in the R^2 fits of these models also reflect increasing experience over the experimental programme and the application of better controls applied as the series progressed.

8.3.2 Preliminary Stabilisation Trials - Column Mould Sample Comparison

A comparison of the strengths achieved during the column test series with those of the preliminary stabilisation trials in Chapter 4, reveals a notable difference. Figure 8-3 shows a comparison of data from the preliminary stabilisation trials with some data from the 20 °C cured mould samples of the PORT (PO-12, PO-13 & PO-16) and PIRT series (PI-7, PI-9, PI-10 & PI-11). The UCS×WTBR against *TCT* framework is used to account for differences in moisture content and binder content. Although all samples were cured at 20 °C, the *TCT* is used for consistency with the framework. As differing curing times apply, the 7-day stabilisation trial data are benchmarked against 6 day PORT/PIRT mould data and likewise, 28-day samples are compared with 12-day samples.

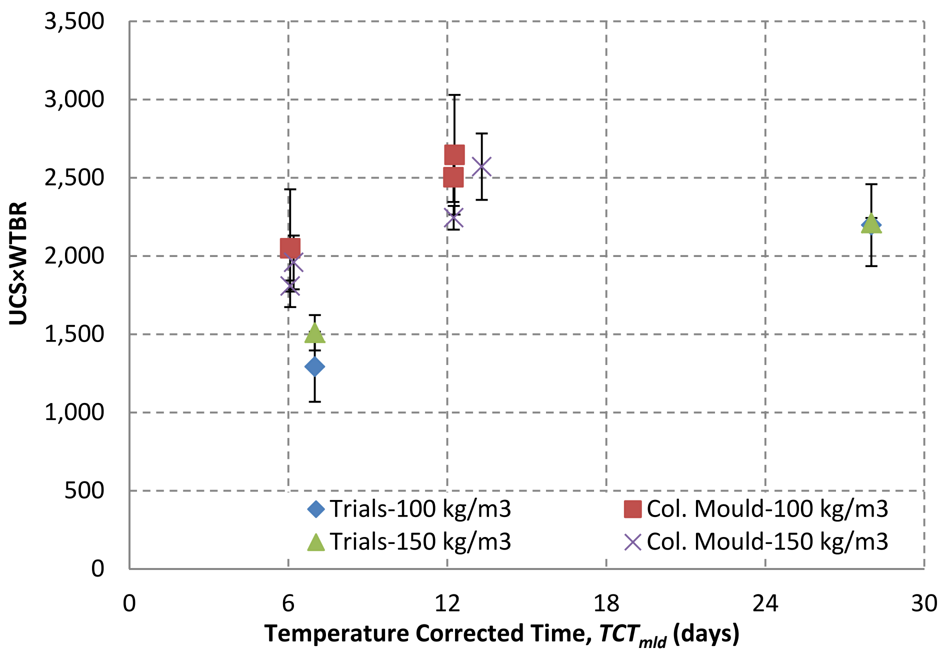

Figure 8-3: Stabilisation trial and 20 °C cured column series data compared under the UCS×WTBR against *TCT* framework

It is clearly seen that a difference exists between the 6-day and 7-day data and, the 12-day data shows higher values than the 28-day data. The most probable cause of these variations is changes in the properties of the *sleech* during storage. It has already been shown that variations in the moisture content occurred during storage and testing, but variations in the organic content were also recorded. It is believed that the changes in the organics within the sampled *sleech*, noted in the PIRT and friction column tests as set out in Section 3.12, resulted in the increased strengths achieved. As has been reviewed in Section 2.6.3, increased organic contents can inhibit strength gain and Strick van Linschoten (2004) observed changes in Kinnegar *sleech* organics, purporting them to occur between storage and testing of the samples. Variations or changes in the pH of the soil may also have influenced the increased strengths but pH data were not recorded for any of the *sleech* used in the column series.

8.3.3 Exhumed Columns and Column Cracking

In all PORT columns, the penetrometer was found to pull-out through the centre of the column and at no stage did it leave the column. In some columns, some rotation (<10°) of the penetrometer about the pull-out wire was noted during exhumation of the column (see Figure F-3b). On the cut face of the extracted columns, the route of the penetrometer was clearly visible (see Figure F-2 and Figure F-3). In all PIRT columns tested, where pre-drilling was replicated, no deviation of the penetrometer from the centre of the column was noted as the pre-drilled hole provided a guide for the penetrometer tip to follow. Again the route of the penetrometer was clearly visible in the extracted column (see Figure F-11). In soft columns the penetrometer left a smooth path, *e.g.,* Figure F-11 where a section of PI-13 is shown. In stronger columns, the cut face showed a rough broken surface, *e.g.,* in Figure F-3a and Figure F-5a.

During column exhumation, two types of crack patterns were typically discovered:

(i) Horizontal cracks occurring at the interface between mixes where a weak plane formed due to the time difference between compaction of each mix.
(ii) Diagonal cracks running from the cut face of the column to the outer face of the column caused during PORT/PIRT probing.

The first and last mixes of each column were typically found to exhibit little cracking and were extracted in whole as horizontal-cylindrical segments. Diagonal cracking primarily occurred in the mid-sections of the columns at an approximate angle of 45°. In PORT columns the diagonal cracks ran upwards and out in the direction of probing to the outer face of the column, while in the PIRT columns the direction of cracking was noted to be downwards to the outer face of the column. The locations of the cracks and their orientation may be found in Appendix F where photographs and cracking diagrams of the exhumed columns are presented. These cracks affected sampling rates to such an extent that samples were only obtained from the top and bottom of some columns, *e.g.,* PO-13S and PI-7, and were most prevalent in columns with q_{cor} values between 300 kPa and 450 kPa.

Vertical cracking is also believed to have occurred within the column ahead of the penetrometer. This was evident at the top of the columns and visible in the PIRT columns during testing as the column split open and is thought to be due to the lack of confinement around the top of the column which allowed tensile failure to occur rather than shear failure to which the N value relates. This was most noticeable in columns with q_{cor} values over 300 kPa. It is also believed to have occurred within the mid-sections of some columns. A vertical crack is also considered to occur in the PIRT columns when the penetrometer is approximately 50 mm from the base of the column and its occurrence is thought to be shown by the drop in probing force that occurs as the final section of the column fails in a tensile manner. This is further discussed in Section 8.5.2 when determining the appropriate probing force relative to samples at the base of the PIRT columns.

PI-10 provides examples of a number of different crack patterns in a PIRT column. At the beginning of the test the P_i profile peaked at 2.8 kN as the penetrometer began to bear on the column (see Figure 8-4). P_i then dropped rapidly by 1.8 kN as the penetrometer broke into the column causing it to split open and the drop in force is believed to be due to the lesser resistance experienced as the penetrometer passed through the cracked section of column. After approximately 100 mm, P_i began to rise to near that of the initial peak but still shows a jagged profile. At h = 830 mm, P_i shows a sudden drop from 2.9 kN to 1.7 kN believed to be due to a weak layer between Mixes 3 and 4.

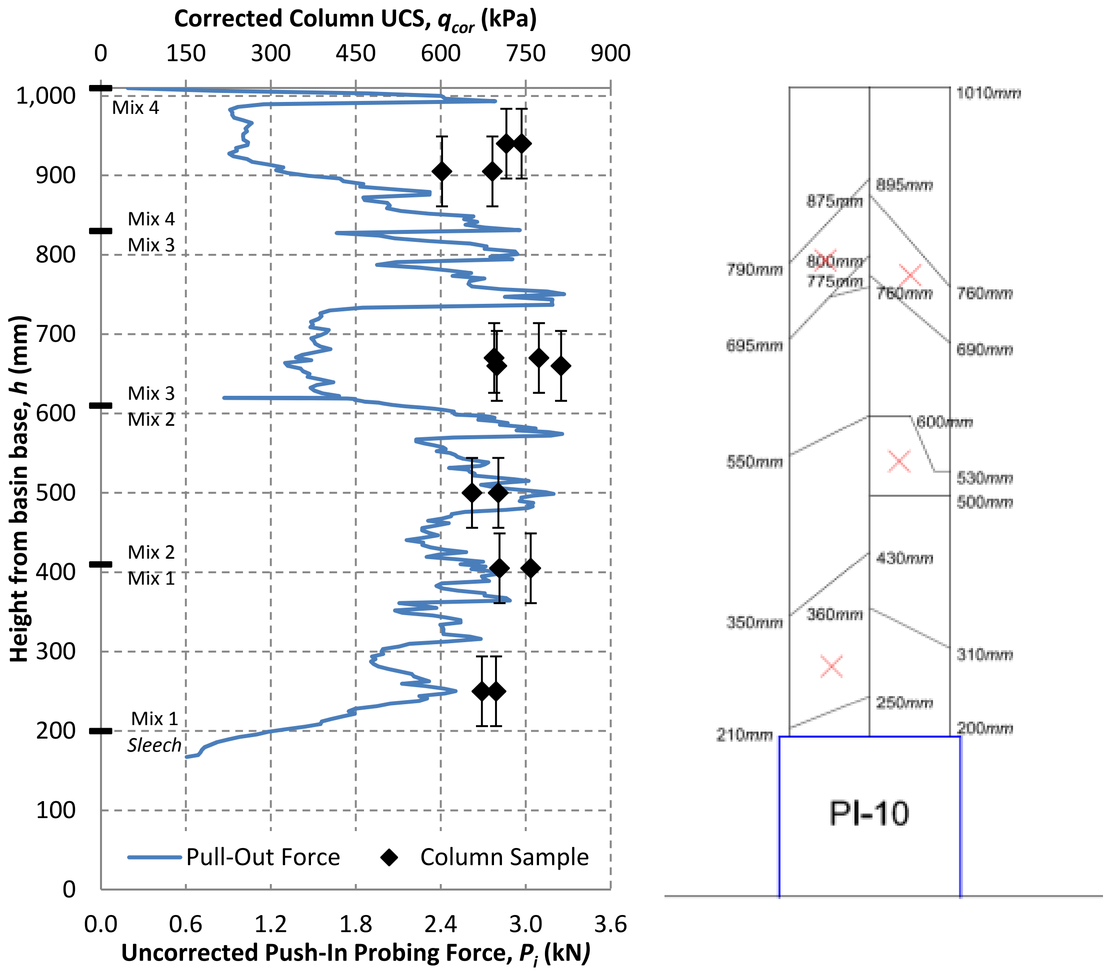

Figure 8-4: PIRT 10 probing profile with column cracking diagram

At a height of 730 mm, P_i dropped instantly from 3.2 kN to 1.6 kN and continues at this level until it reaches the interface between Mix 2 and Mix 3. Column samples recovered from the level of this crack show similar strengths to the rest of the column and thus the drop in force is believed to be due to a vertical crack. The crack is prevented from continuing by either the interface layer between Mixes 2 and 3 or the pause in the test which also occurred at this level. When restarted, the P_i rose to a similar magnitude to that before the assumed crack.

Comparisons may also be made between the jaggedness of the push-in force profile with the crack pattern diagram alongside it. At a number of locations, sudden reductions in the push-in force can be seen to occur where the beginning of a diagonal crack was noted, *e.g.,* at heights of 360 mm, 775 mm and 880 mm. For comparison, Figure 8-5 shows the push-in force profile and corrected column strength for PI-13, a soft column, alongside its cracking diagram. The smooth profile of P_i is visible as is the lesser number of cracks throughout the column. At the base of the column, a steep diagonal crack is seen to occur and is thought to cause the drop off in P_i that begins at a height of approximately 270 mm.

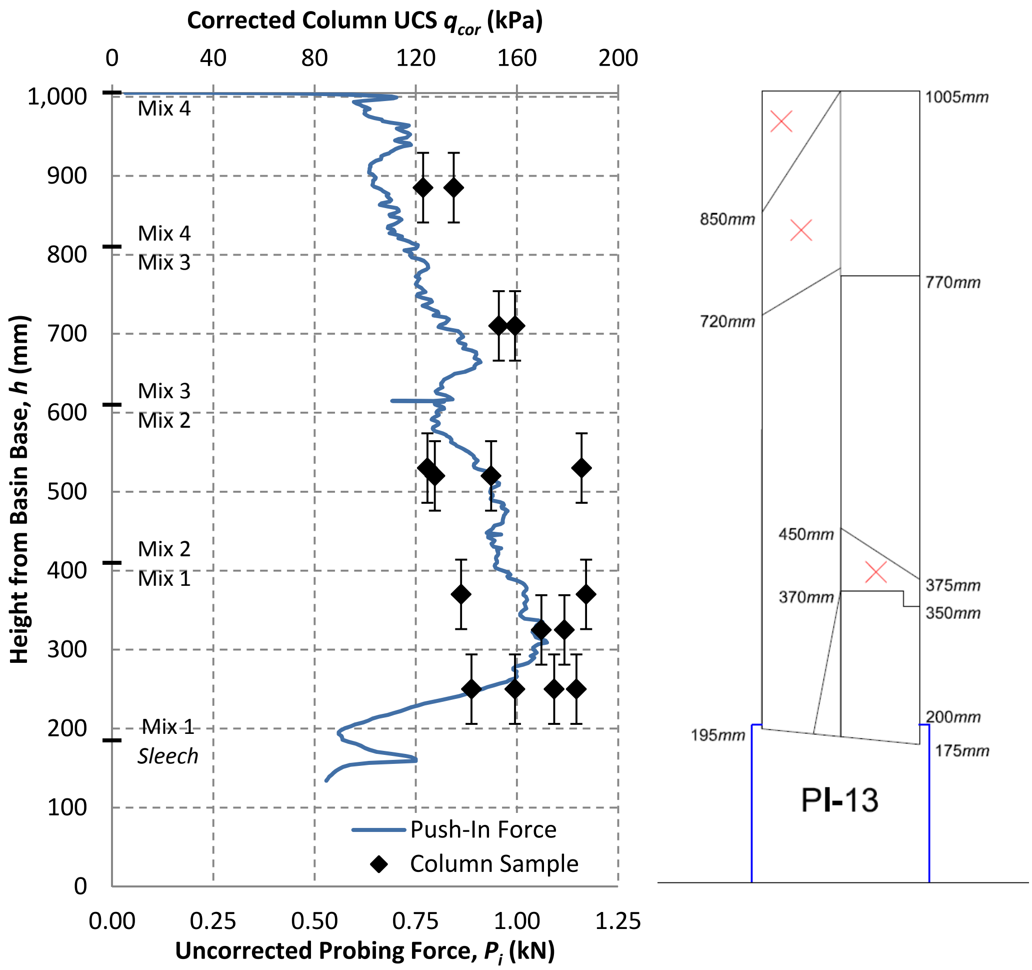

Figure 8-5: PIRT 13 probing profile with column cracking diagram

8.4 Laboratory and Field PORT/PIRT Comparison

8.4.1 PORT Probing Force Field Comparison

Comparing the pull-out force profile obtained from the reduced-scale PORT and the reduced-scale PORT wire test series, with some field test results (see Figure 8-6) (courtesy of Keller Grundläggning AB) and Figure 8-7, the following similarities can be seen (it should be noted that the strength profiles will greatly influence the profile shape and may not be the same):

- Overall, greater pull-out forces are observed in the field due to the large penetrometer frontal area and pull-out wire area in contact with the column than their reduced-scale counterparts. The magnitude of these forces is also greatly influenced by the column strengths and length.
- At the beginning of a field PORT, a high-short peak in the force is observed as bond between the column and wire is broken. In the reduced-scale PORT this peak is not seen but is observed in the wire tests. It is believed this is as a result of the construction procedures used in the reduced-scale PORT and wire tests (see Section 7.2.2).
- In the unstabilised material under the column in both field and laboratory PORT, low pull-out forces are observed. Field results show a reduction from the peak to the short plateau as adhering material to the PORT wire is removed.

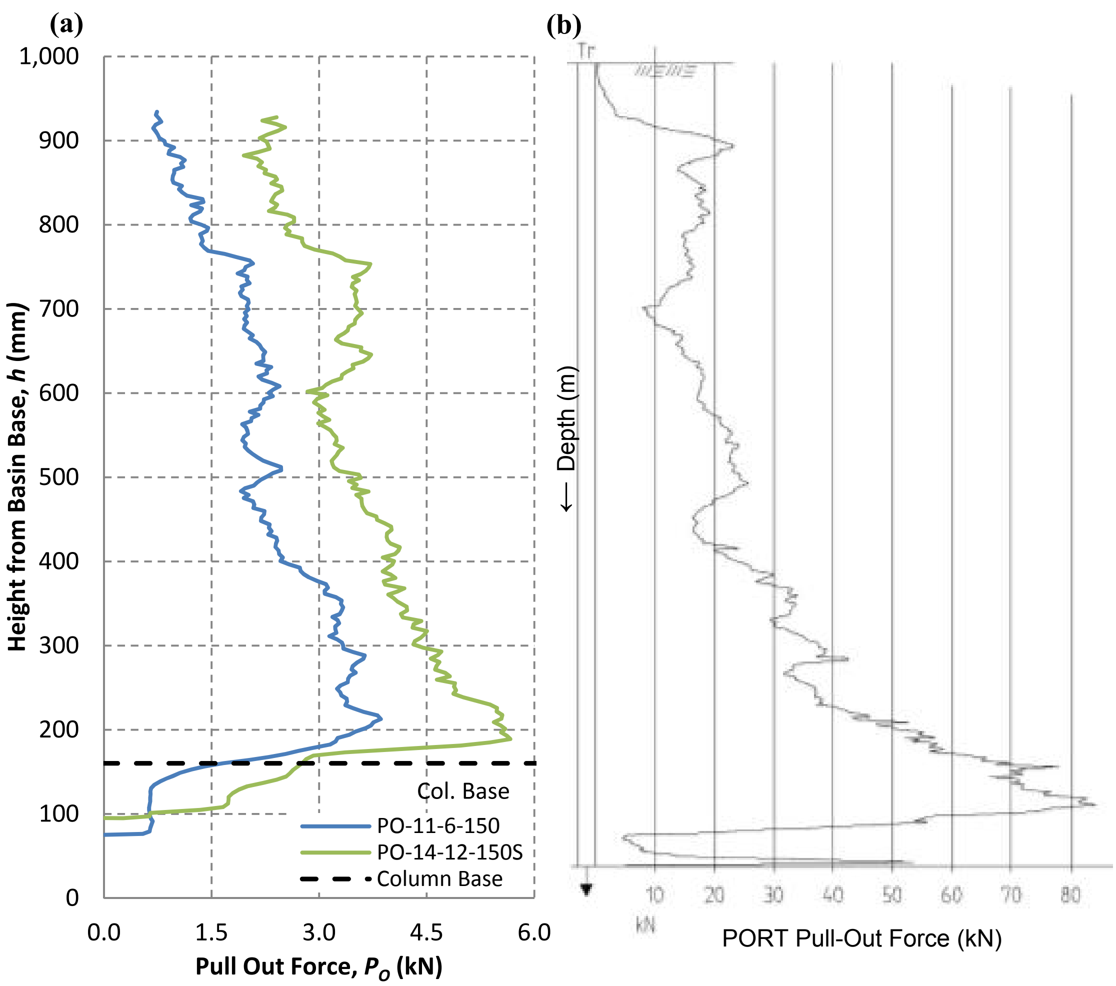

Figure 8-6: PORT pull-out force profiles: a) PO-11 & b) field PORT of a lime-cement stabilised clay column (courtesy of Keller Grundläggning AB)

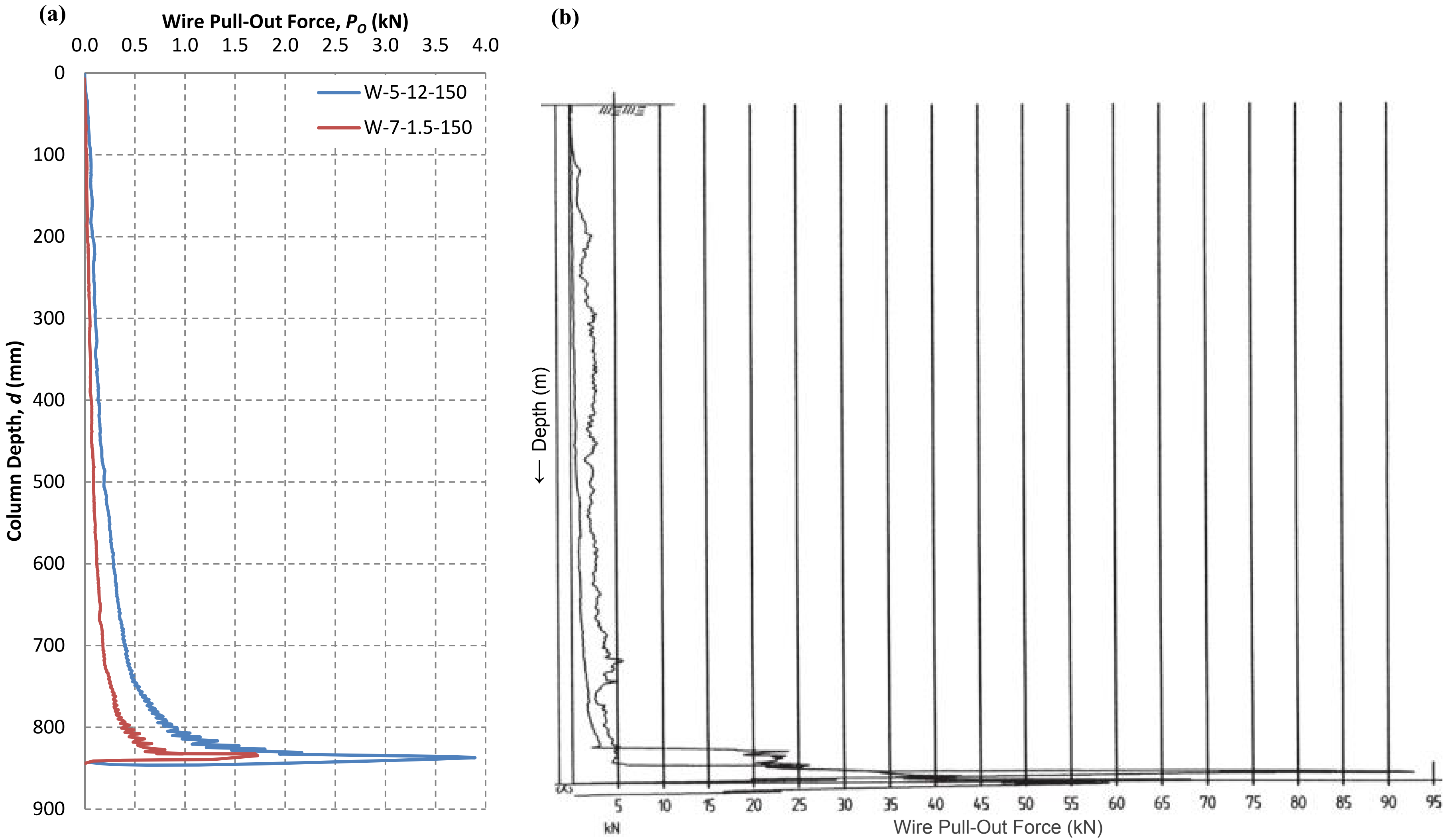

Figure 8-7: Laboratory and field wire pull-out test comparison: a) W-5 and W-7 wire column tests & b) after Carlsten & Ekström (1996)

- In both cases, as the penetrometer approaches the base of the column and the wings make full contact with the column, the force rises to a peak before reducing with depth until the surface is reached.
- Although little published field wire test data exist, Figure 8-7 a & b provide a comparison of some laboratory tests from this thesis with two field tests (Carlsten & Ekström 1996). The high peak forces are visible in both as the wire's bond is broken, as is the reduction in friction as material adhered to the wire is removed and the wire pulled out.

The absence of the initial pull-out force peak in the reduced-scale PORT is thought not to have a significant effect on the friction test results as any material on the wire would be removed within 50 mm to 100 mm of wire displacement.

8.4.2 PIRT Probing Force Field Comparison

In Figure 8-8 some laboratory pre-drilled PIRT from this thesis are compared with some field PIRT of floating cement-lime stabilised clay columns (after Nilsson (2005)) and some similarities may be seen. These include:

- As with the PORT, greater probing forces are observed in the field due to the large penetrometer frontal area in contact with the column than their reduced-scale counterparts. The magnitude of these forces is also greatly influenced by the column strengths.
- Although strength profiles for the tests are not comparable, within the column, both graphs show consistent profiles with depth.
- The location of pauses to insert additional sounding bars is visible in both graphs.
- At the base of the graphs, the probing force reduces as the penetrometer enters the unstabilised material beneath the column.

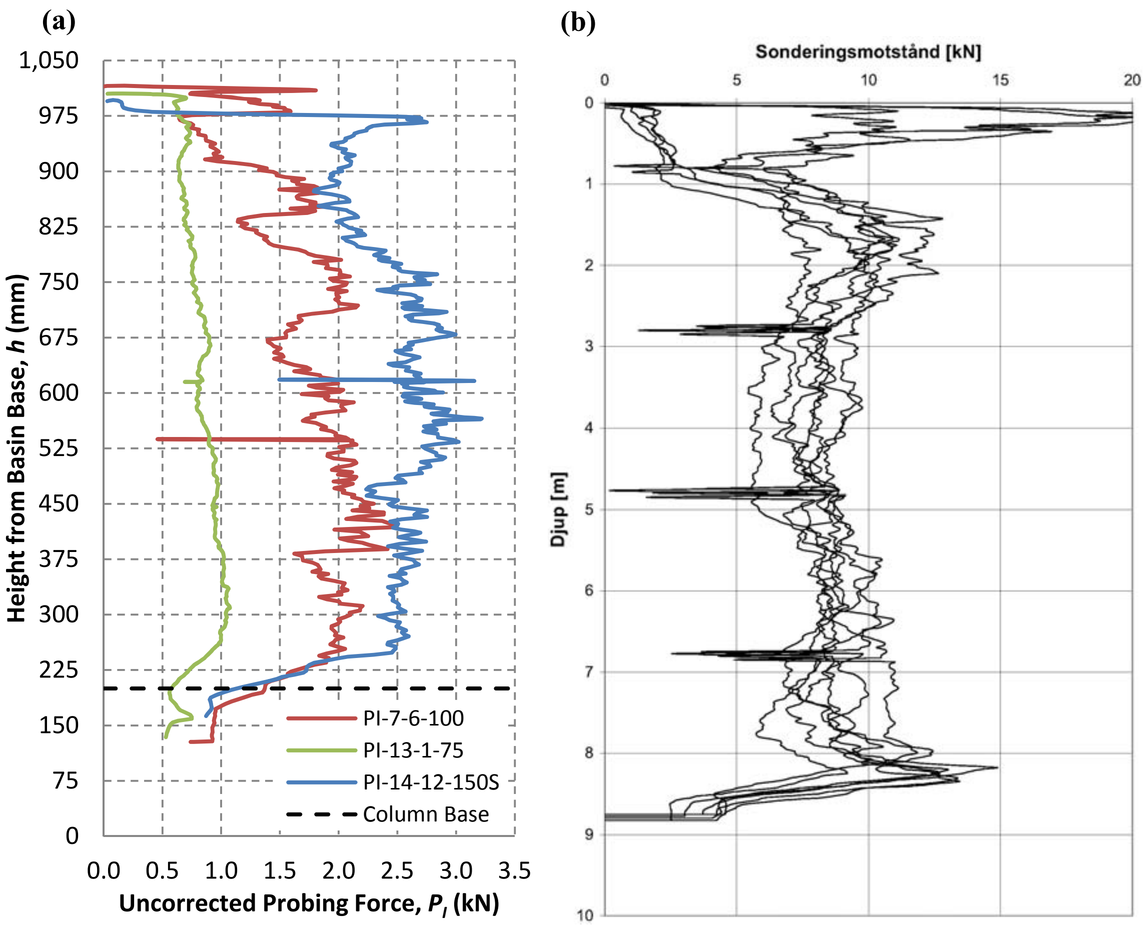

Figure 8-8: Laboratory and field PIRT comparison: a) PI-7 and PI-13 & b) after Nilsson (2005)

8.5 N Value Determination

8.5.1 Introduction

In this section, the N values relevant to each column sample are reported for both PORT and PIRT series. To this end, a number of stages relevant to determining the correct force to use for the calculations are presented. These are:

(i) Extracting the portion of the probing force profile relevant to the original position of the sample in the column.
(ii) Applying the friction correction to the PORT series.
(iii) Applying the friction correction to the PIRT series.

In addition, reference N values in unstabilised *sleech* are also determined.

8.5.2 Probing Force and Friction Force Corrections

PORT and PIRT Sample Probing Force:

From the PORT and PIRT probing force profile, the average probing force (P_a) over the depth range originally occupied by each sample was determined (P_{oa} for PORT and P_{ia} for PIRT). Average probing forces for samples at the base of the columns were adjusted as follows so as to represent more fairly the strength of the sample:

(i) For samples located near the base of the PORT column, P_{oa} was calculated from the point at which the peak force occurred to the top of the sample. Forces below the peak are considered not to represent the strength of the column base due to the bowling noted in Figure 7-24 and failure to account for this would underestimate P_{oa} relative to the strength at the column base.

(ii) Similarly, at the base of the PIRT columns, the probing force begins to reduce approximately 50 mm from the base (see Figure 6-1) and it is thought that this is due to the final 50 mm of the column splitting open during the test. Again, the force beyond this point is not comparable to the strength of the column base and so the P_{ia} is calculated from the top of the sample to the point at which a clear drop off in the push-in force profile occurs.

PORT Friction Adjustment:

The forces recorded during PORT are a combination of resistance on the penetrometer and friction between the 4 mm pull-out wire and the stabilised column. As is performed in practice with full-scale PORT column tests, the pull-out forces recorded during each PORT are adjusted for wire friction and this is achieved using the results of the wire friction tests detailed in Section 7.2.

The wire frictional stress (μ_w) profiles were calculated for each wire column test using Equation 8-1 and are shown in Figure 8-9:

$$\mu_w = P_o / 2\pi r_w d \qquad \text{8-1}$$

where P_o is the pull-out force (kN), r_w is the radius of the wire (m) and d is the depth at which P_o was recorded (m).

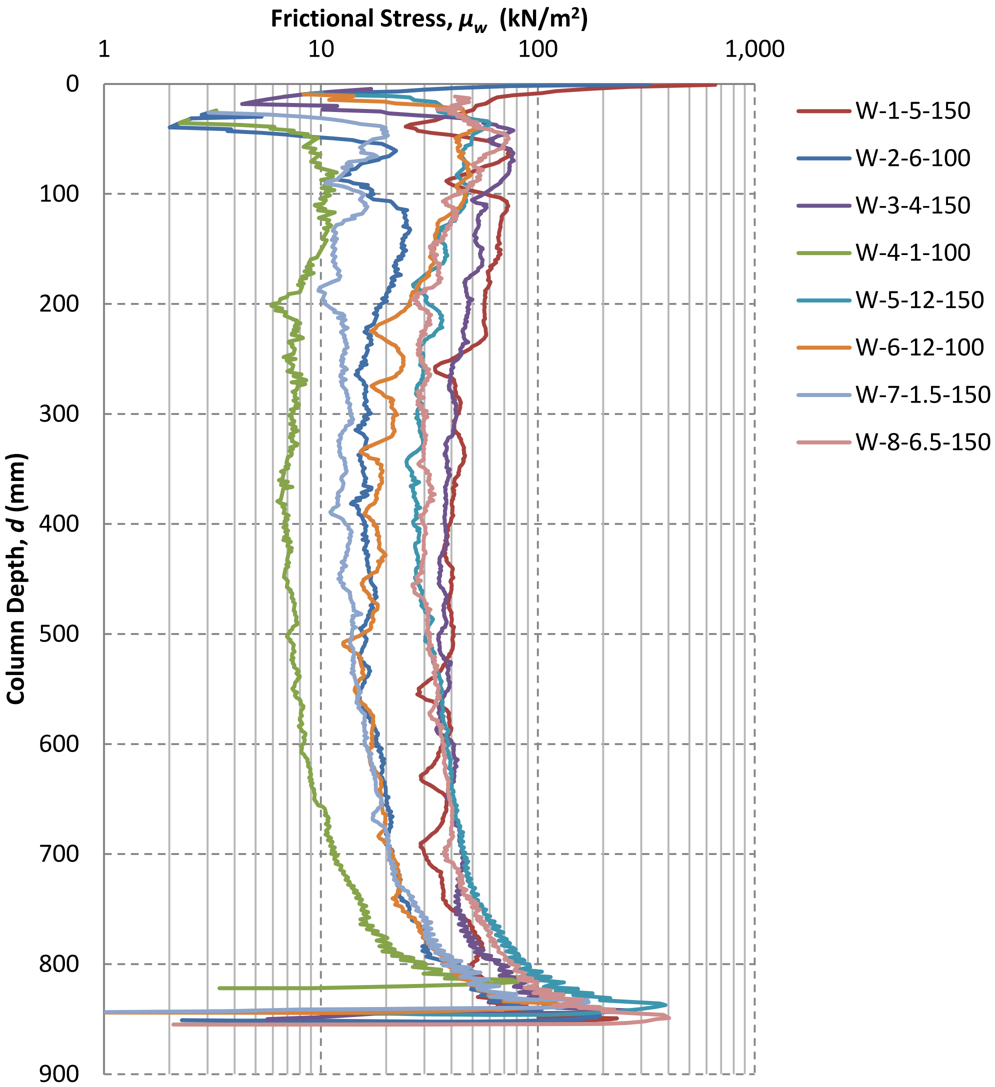

Figure 8-9: Pull-out wire frictional stress with column depth

From Figure 8-9, high μ_w values can be seen at the beginning of the test (*i.e.,* at the base of the profile) where the bond between the wire and column is broken and material adhered to the wire is removed. Towards the end of the test (*i.e., d* < 300 mm), μ_w increases due the effects of the draw wire gauge on the recorded data mentioned in Section 7.2.2. The effect of the additional force caused by the draw wire gauge is magnified by the small area of wire remaining in the column and the very small forces on the load cell at this stage. In the middle sections of the column (d = 300-650 mm), μ_w shows a near constant value with depth and a wire friction correction factor (P_{wc}) was calculated by multiplying the average μ_w between d = 300-650 mm by the curved surface area of wire in a 1 m length. It is deemed appropriate to use P_{wc} to correct for wire friction as this portion of the data relates to a condition where material adhered to the wire has been removed and the effects of the draw wire gauge, which would not occur in PORT of a column, are little to none.

Table 8-3: Wire column allocation to PORT columns

PORT No	Binder Content, kg/m^3	PORT Time, t_{Po} days	q_{cor} *kPa*	Wire No	Binder Content, kg/m^3	Wire Time, t_{Po} days	q_{cor} kPa	Wire Friction Correction, P_{wc} kN/m
PO-5	100	4.95	232.6	W-7	150	1.59	304.6	0.177
PO-6	150	5.88	586.6	W-1	150	4.99	548.6	0.451
PO-7	100	5.96	348.2	W-7	150	1.59	304.6	0.177
PO-8	150	1.95	411.6	W-2	100	6.08	401.7	0.208
PO-9	150	3.95	470.7	W-6	100	12.07	516.0	0.218
PO-10	150	11.97	442.5	W-2	100	6.08	401.7	0.208
PO-11	150	5.89	439.6	W-2	100	6.08	401.7	0.208
PO-12	150	12.95	677.8	W-5	150	11.96	696.1	0.400
PO-13S	150	5.96	470.3	W-1	150	4.99	548.6	0.451
PO-14S	150	11.98	633.0	W-5	150	11.96	696.1	0.400
PO-15	100	0.95	147.4	W-4	100	1.15	172.5	0.095
PO-16	100	11.92	502.5	W-6	100	12.07	516.0	0.218
PO-17*	150*	11.81	493.0	W-6	100	12.07	516.0	0.218

q_{cor} strength profiles for the pull-out wire experiment series (see Section 7.6.6) were overlain on the q_{cor} profiles from the PORT series (see Section 7.6.4) and each PORT column was assigned a wire column test based primarily on strength similarity, but also on binder content and curing time. Table 8-3 details the wire tests allocated to each PORT column. The pull-out force acting on the PORT penetrometer alone (P_{oac}) was calculated for each column sample using its depth (d) and the μ_{wc} value assigned to its column (see Equation 8-2).

$$P_{oac} = P_{oa} - P_{wc}d \qquad 8\text{-}2$$

<u>PIRT Friction Adjustment:</u>

Using the results of the cone-only friction column tests a composite estimate of the frictional resistance between the PIRT penetrometer cone tip, the sounding bars, the plastic sounding bar guide and the stabilised column during PIRT of the 200 mm dia. columns was calculated.

From Figure 7-10 the average push-in force (P_{ia}) was calculated over the length of each individual sample recovered from the column. Figure 8-10 shows q_{cor} (see Section 7.6) for all 50 mm dia. samples plotted against their corresponding P_{ia}. Equation 8-3 represents the best fit to all the data and shows a high R^2 value of 92.6%:

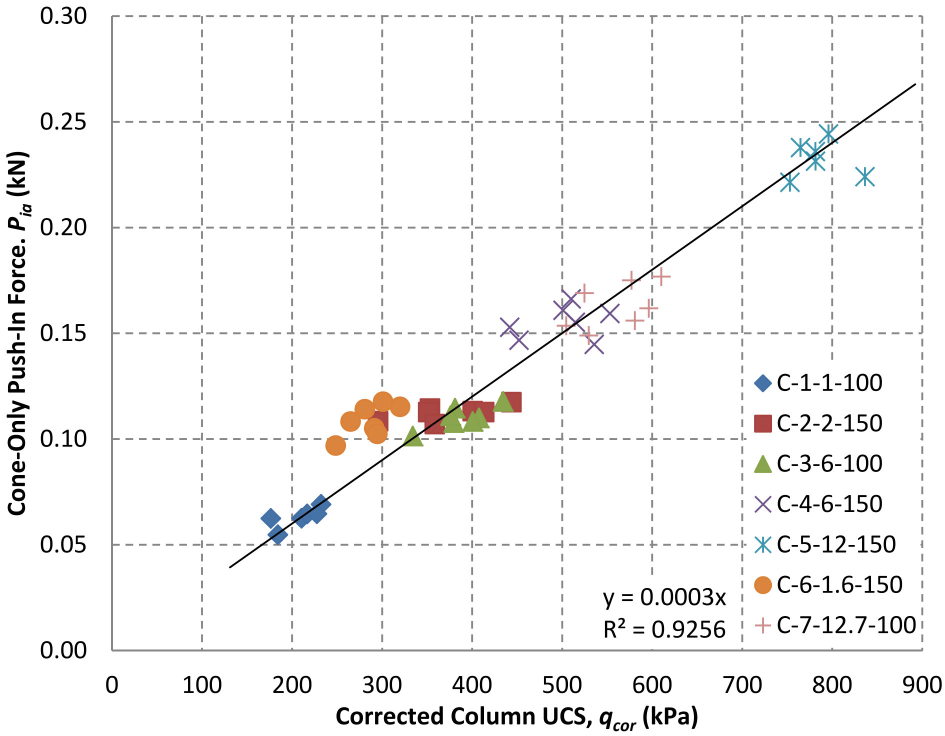

Figure 8-10: Corrected column UCS with cone-only probing force

$$P_{ic} = 0.0003q_{cor} \tag{8-3}$$

where P_{ic} is the PIRT friction correction (kN). Using Equation 8-4 the probing resistance on the PIRT penetrometer wings (P_{iac}) excluding sounding bar friction, plastic sounding bar guide friction, cone tip friction and cone bearing was calculated for each sample.

$$P_{iac} = P_{ia} - 0.0003q_{cor} \tag{8-4}$$

The cone-only tests, presented in Section 7.3, were found to show a near constant P_i with depth indicating that minimal friction between the sounding bars and the columns occurred. As it is near impossible to determine how much contact occurred between the PIRT sounding bars and the column due to the different buckling behaviour of the sounding bars previously described in Section 7.3.2, their friction cannot be properly included for but the adjustment is still applied to include for cone tip friction and bearing, and the minimal friction between the sounding bars and the plastic sounding bar guide on the CPT rig.

8.5.3 Stabilised Column N Value Calculation

N values were determined for each PORT and PIRT strength sample tested using Equations 8-5 and 8-6, respectively, a rewritten form of the relationship, previously detailed in Equation 2-5:

$$N = \frac{1}{c_{cor}} \times \frac{P_{oac}}{A} \qquad 8\text{-}5$$

$$N = \frac{1}{c_{cor}} \times \frac{P_{iac}}{A} \qquad 8\text{-}6$$

where N is the bearing capacity factor, c_{cor} is the corrected undrained shear strength at the time of PORT/PIRT (kN/m^2) (calculated as half of the q_{cor}, see Sections 2.10.3 and 7.6), P_{oac} is the corrected pull-out force (kN), P_{iac} is the corrected push-in force (kN) and A is the plan area of the penetrometer in contact with the column (m^2).

The PORT plan area was determined as the sum of the penetrometer wing plan area plus the plan area of the top of the PORT shaft in contact with the column (see Appendix C where all penetrometer dimensions are provided). For all PORT column tests the same penetrometer was used, having A = 0.000903 m^2. PIRT penetrometer plan areas were determined as the penetrometer width minus the diameter of the cone penetrometer multiplied by the wing thickness. All PIRT columns and PI-*Sleech*-T1 were tested with PIRT penetrometer no. 1 (A = 0.00082 m^2), while PIRT penetrometer no. 2 (A = 0.00080 m^2) was used in all other unstabilised *sleech* PIRTs.

8.5.4 Unstabilised *Sleech* N Value Calculation

From Figure 5-2 a & b the PORT penetrometer pull-out force in unstabilised *sleech* was determined at the location of each of the pocket shear vane test results. No adjustments were made to the pull-out force in terms of wire friction as, following from the results seen for the wire friction in a column, friction with the *sleech* alone was deemed to be very small. From Figure 6-2 a & b the PIRT penetrometer push-in force in unstabilised *sleech* was determined at the location of each of the pocket shear vane test results relative to the penetrometers wings and was corrected for cone and sounding bar friction based on the cone-only (C-SL-14) test results (see Section 6.2.2). PI-SL-13 and PI-SL-14 were pre-formed in pre-drilled holes and A values stated in Section 8.5.3 were used to calculate N using Equation 8-6. PI-SL-T1 and PI-SL-T2 were carried out in unstabilised *sleech* and A values used were 0.000997 m^2 and 0.000982 m^2 for PIRT penetrometers no. 1 and 2 respectively.

8.6 N Value Results and Discussion

8.6.1 PORT N Value

Figure 8-11a shows the calculated PORT N value variation with depth within each stabilised column and in unstabilised *sleech*, where a wide variation in N can be seen as well as a general increase with depth in all columns. However, column strength, penetrometer-column friction and confinement of the column during testing are deemed responsible for the wide variation in N values. Further interrogation of the variation in the data shows the N value to reduce with an increasing c_{cor}; see Figure 8-11b where N is itemised by arbitrary strength divisions of c_{cor} < 150 kPa, 150 kPa < c_{cor} < 250 kPa and c_{cor} > 250 kPa similar to those highlighted in Section 2.3.

In the low-strength, early age columns (c_{cor} < 150 kPa), the stabilised material is soft and adhesive in nature. As the penetrometer passes through the column, material adheres to the vertical faces of the penetrometer wing (see Figure 8-14 for a PIRT penetrometer, although also noted on the PORT penetrometers) as a result of:

- The difference between the outside of the leading edge bulb and the wing's vertical face on the reduced-scale penetrometer, a distance of 1 mm, is thought not to be great enough to displace the material far enough away from the wings for them to avoid contact with the column during the test.
- Any minor deviations off vertical will allow the wing's vertical faces to make contact with the column.

As the probing force includes both bearing and friction components, and N values relate to bearing only, this results in higher than representative N values. As the stabilised strength increases, the material becomes less adhesive in nature and its behaviour changes from ductile to brittle (c_{cor} > 150 kPa).

Confinement of the columns also influences the N values obtained, particularly around their upper region and in stronger columns:

- At the top of the columns, N values of between 3 and 10 are seen due to the low confining stresses which allow the column to split open and fail in a tensile manner rather than by shear, thus resulting in a lower than representative pull-out force.
- Comparing PO-6 and PO-12 with their comparative surcharged columns, PO-13S and PO-14S, increased N values are seen at the top of the column due to the increased confining stresses (more in keeping with those deeper in the columns) induced by the surcharge (see Section 5.4.3).
- Below a depth of 200 mm, the N value increases reaching values in the range of 10 to 24 at the base of the column with the spread due to the c_{cor} dependence already described.

Figure 8-12 shows the N value variation with depth excluding data where splitting open or cracking of the column (*i.e.,* c_{cor} > 150 kPa at d < 200 mm) influences the N value. The dependence on depth remains visible and reasons for this within a column are thought to relate to the manner in which the pull-out wire friction was accounted for. These include:

- The difference in moisture content between the PORT column (w_{col} range 44-56%) and its associated wire column test (w_{col} range 37-44%), as columns with an increased w_{col} may provide additional frictional resistance to the wire during pull-out.
- Although care was taken to ensure the PORT penetrometer wire ran through the centre of the column, any curvature in the wire or inclination of the column would result in an increased friction as the wire cut into the column as the penetrometer was pulled out.
- Additional friction occurring with depth due to the build-up of stabilised material on the bearing face of the penetrometers shaft where the wire exits the top at the PORT penetrometer.

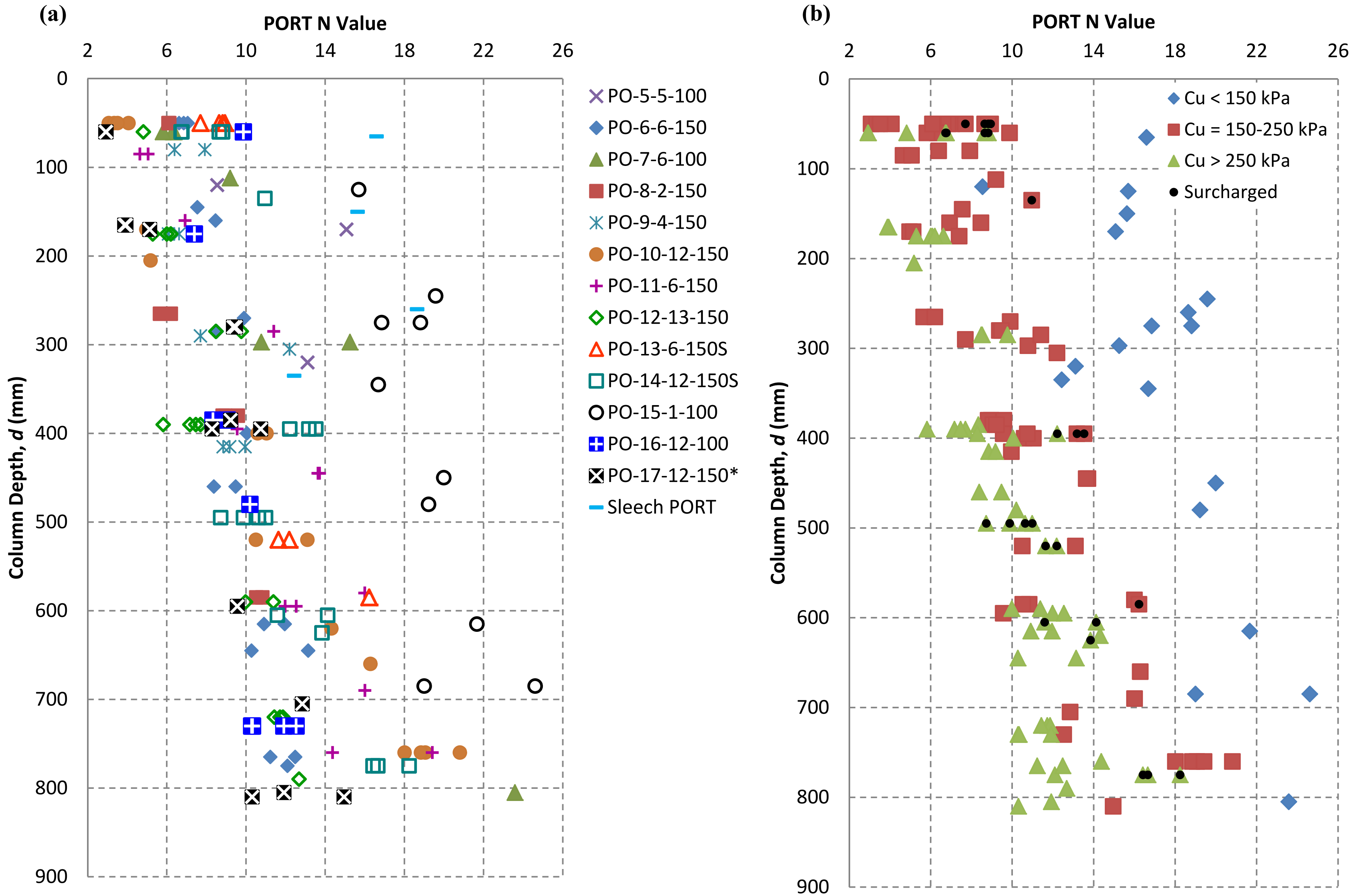

Figure 8-11: PORT column and *sleech* N value with depth: a) Itemised by column & b) itemised by shear strength

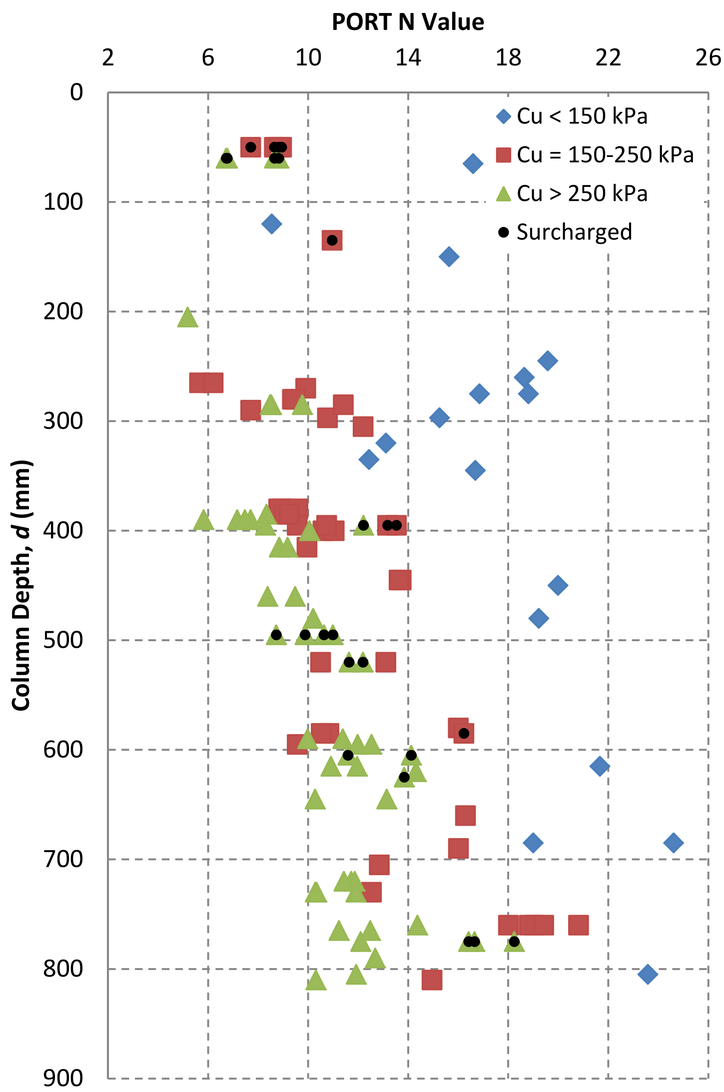

Figure 8-12: PORT column N value with depth excluding non-surcharged data at *d* < 200 mm

8.6.2 PIRT N Value

Figure 8-13a shows the calculated PIRT N value with depth for each stabilised pre-drilled column, itemised by column test number, where again a wide variation in N can be seen. However, as with the PORT N values, confinement, column strength and friction influence the magnitude of the calculated N values. At the top of the column low N values, 7 and less, are observed due to the splitting open of the column previously mentioned. Again this is believed to be due to the low confining stresses around the top of the column which allow it to split open and fail in a tensile manner rather than a shear failure. The application of the surcharge to PI-9S and PI-14S has been seen to increase the confining stresses (see Section 6.4) and when calculated, the N values were found to be higher than those in the comparable columns PI-6 and PI-10.

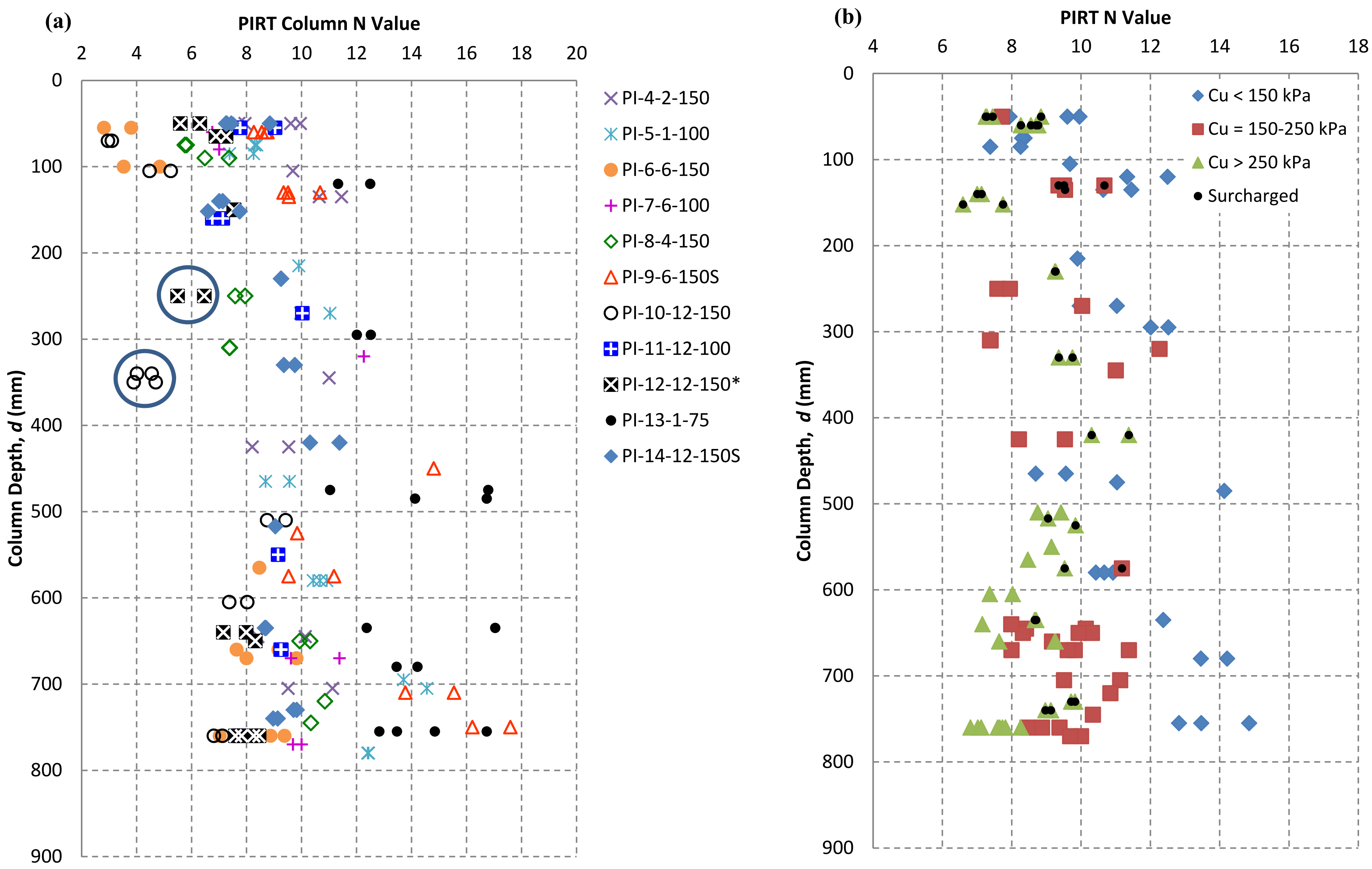

Figure 8-13: a) All PIRT column N value with depth & b) PIRT column N value with depth excluding spurious data itemised by strength

For a few of the data points presented in Figure 8-13a, issues with sample strengths and column cracking which impacted upon in the N value, were identified. These included:

- In PI-5 and PI-9S, samples near the base of the column (and at a depth of 450 mm in PI-9S) show notably lower strengths than samples from the rest of the column, (see Figure 7-30) but interestingly P_i does not show a significant reduction. E_{col} values for the samples at the base of PI-5 show notably lower values than the samples immediately above them, while the spurious data in PI-9S shows the lowest ε_f for that column.
- Data from PI-10 and PI-12 are highlighted where the effect of a significant drop in the probing force, believed to be due to a vertical crack in the column occurring during testing, results in low N values. (In PI-10, if the P_i were to have followed the trends seen above 730 mm and below 600 mm, *i.e.,* an average value of 3.0 kN, N values of approximately 8.3 to 9.8 would have been obtained as opposed to the actual values calculated of between 3.9 and 4.7).

As such all of these samples are removed from further N value consideration. Figure 8-13b shows column N values with depth where values at d < 200 mm for non-surcharged columns have been excluded due to the splitting open of the top of the column, as have values where cracking is deemed to have affected the probing force profile. From this graph:

- N values at c_{cor} > 150 kPa are seen to range from approximately 7 to 12 and are constant with depth.
- The data from PI-13 (the softest stabilised column tested) shows an increasing N value with depth and is believed to primarily be due to additional probing force occurring due to friction between the vertical faces of the penetrometer's wings in a similar manner to that set out for the PORT in Section 8.6.1 above. Adhesion of material to the vertical faces of the PIRT penetrometer in PI-5, a soft column, can be seen in Figure 8-14.
- Friction with the sounding bars also accounts for additional probing force but to a lesser extent. When data from the cone-only test in *sleech* (C-SL-14), considered to have a higher sounding bar friction than a stabilised column would have, is used to attempt to account for sounding bar friction in PI-13, only marginally

lower N values of 10.6 to 16.2 are observed, compared to the 11 to 17 without the correction (see Figure 8-15a).

In the unstabilised *sleech* N values between 10 and 15 are typically seen at d < 100 mm (see Figure 8-15b). Below this N starts to increase due to additional probing force occurring due to friction as the *sleech* begins to come in contact with the vertical faces of the penetrometers. Beyond depths of approximately 200 mm, full contact between the penetrometer and the *sleech* is believed to have occurred and the N value shows a constant trend with depth with most values between approximately 16 and 22. As friction with the sounding bars has been properly accounted for using the data from C-SL-14, theses N values are believed to be the upper limit of those which will occur as a result of friction between the penetrometer and the *sleech*.

In Section 7.3, it was suggested that the cone-only friction tests did not account for sounding bar friction with the column. As such, a further calculation of the column N value without the inclusion of the cone-only friction correction and using an A that includes for bearing on the cone tip (A = 0.000867 m^2), was found to show very similar N values to those obtained with the correction. This further justifies the belief that the cone-only tests do not include for sounding bar friction but are nonetheless included.

Figure 8-14: PIRT penetrometer at final location in PI-5 with stabilised *sleech* adhered to the penetrometer's wings

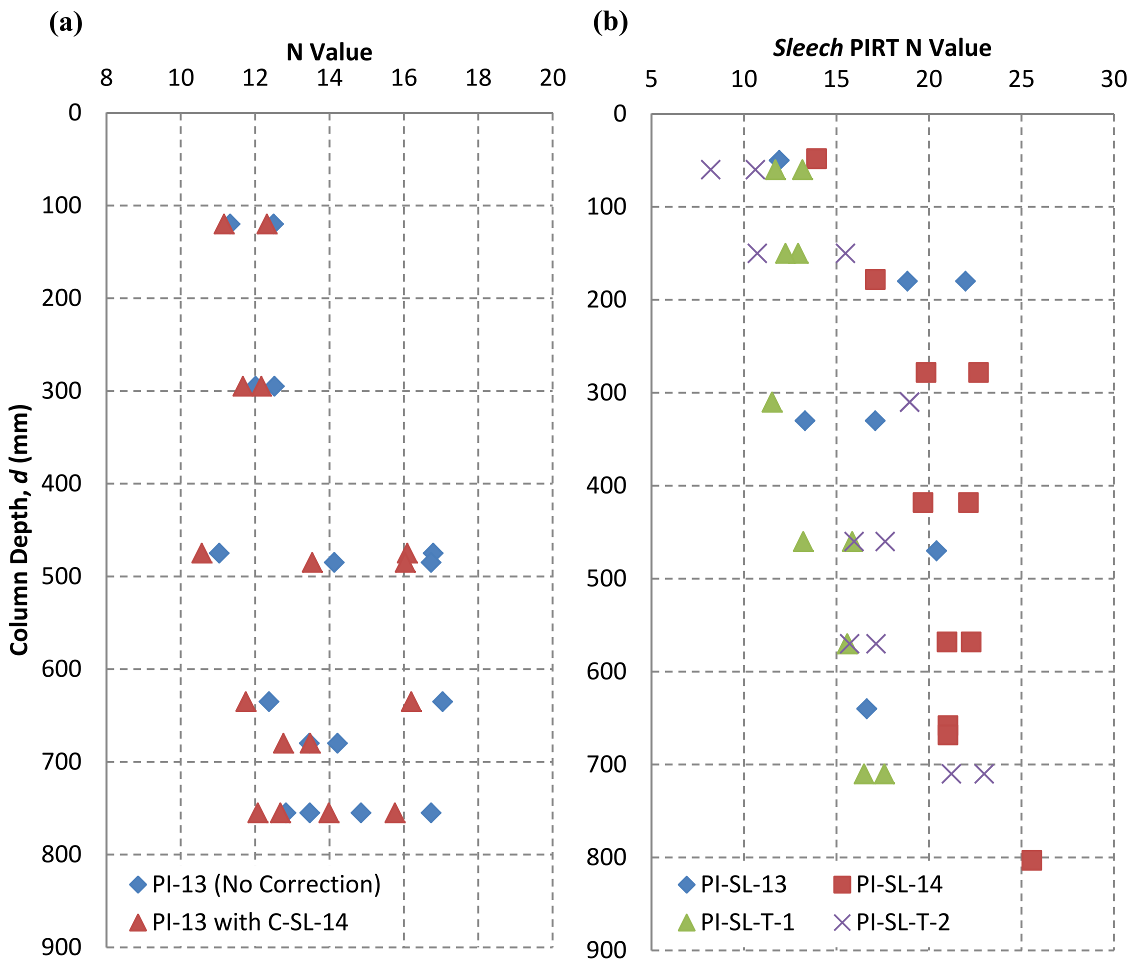

Figure 8-15: a) PI-13 N values with and without C-SL-14 correction & b) unstabilised *sleech* PIRT N values with depth

Figure 8-16 shows the average N value for each column against average c_{cor} of the data in Figure 8-13b with standard deviation error bars. Overall, a slight reduction in N is seen to occur with a reducing c_{cor} with values typically lying between 8 and 12. In similar strength columns, the application of the surcharge is seen to increase the average N.

8.6.3 N Value Summary

In Section 2.4.4 it was found that current guidance suggests the use of an N value of 10 while results from field tests show values predominantly ranging from 8 to 15 and even up to 20. In the PORT and the PIRT column series average N values (d > 200 mm) were found to range from approximately 9 to 20 and 8 to 13, respectively. The factors which influence the spread in N are now summarised.

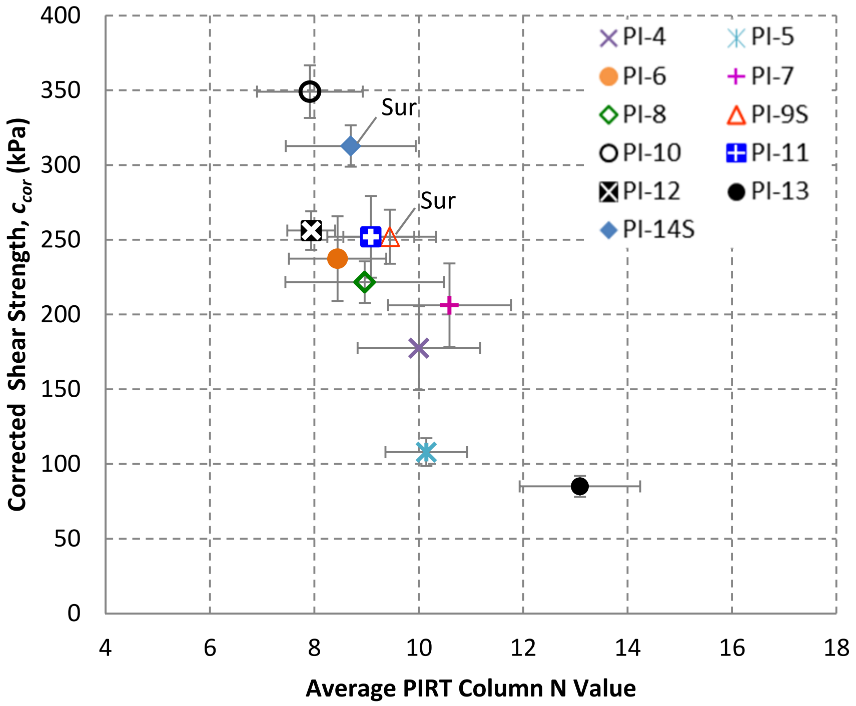

Figure 8-16: Average PIRT column N values with corrected shear strength

Influence of Binder Content, Curing Time and Curing Temperature:

The column strengths achieved are primarily a function of the binder content and curing time but are also influenced by the curing temperature and as such, it is inappropriate to compare N values based on only curing time or binder content alone. Where similar strengths were achieved using different binder content-curing time combinations, it was found that similar N values were observed. Within these tests, this indicates binder content and curing time do not have a direct effect on the N values alone but do influence N through the strengths they produce. However, it is considered that binder contents outside of the particular range used in this thesis could influence N.

Influence of Confinement and Depth:

Low confinement of the column was found to result in lower than representative probing forces and as confinement increased with depth, and through the surcharge column tests, increased N values were observed.

Influence of Friction:

The probing force is thought to be influenced by friction occurring between the penetrometer and the material being tested. This was particularly evident in the soft columns (c_{cor} < 150 kPa) and the unstabilised *sleech,* where the material is adhesive and provides additional probing resistance. Comparing the shape of the PORT and PIRT N value graphs, *i.e.,* Figure 8-11 with Figure 8-13, it could be suggested that the increasing N trend with depth for the PORT is a result of the wire friction tests having not fully accounted for friction which was minimal for the PIRT.

<u>Influence of Cracking:</u>

In a number of columns, particularly columns with strengths over c_{cor} values 150 kPa, vertical cracking and a tensile failure has resulted in reduction in the probing force relative to the actual column strength at that location, thus resulting in a low calculated N value. This occurs at three particular locations:

(i) At top of both the PORT and PIRT columns where the confining stress is low, the column is allowed to split open ahead of the penetrometer.

(ii) In the middle of some columns (PI-10 and PI-12) vertical cracking occurred ahead of the penetrometer and was noted by a sudden drop in the probing force.

(iii) At the base of the PIRT columns the probing force began to drop off approximately 50 mm from the base, believed to be due to a vertical crack again forming ahead of the penetrometer. However, this type of crack was accounted for by excluding the probing force below the location at which the crack is believed to have formed.

Diagonal cracking was noted in both the PORT and PIRT columns, with the direction of the crack pattern related to the direction of probing. This type of cracking, which can be seen in Appendix F, is believed to be the cause of the jaggedness of the probing profile in columns with strengths over c_{cor} > 150 kPa and the extent to which it influences the probing force requires further investigation, as does the possibility of its occurrence in field testing.

<u>Overall N Value Summary:</u>

Despite the fact that these unique reduced-scale column tests are specific to this soil type, the binder contents used and the scaling applied, N values are typically within the ranges of those in the literature (*i.e.,* 8 to 15) and it has been found that:

- The N value for PORT penetrometer lies in the region of 8 to 15, with the spread in values a result of the factors above, in particular friction.
- The N value for PIRT penetrometer is approximately 8 to 12 but greater values can occur due to frictional force contributions on the penetrometer.
- Low column confining stresses can significantly influence the N value as splitting open of the column during the test, resulting in lower than representative probing forces relative to the column's strength.

Further work is required to accurately quantify the frictional force contributions to the reduced-scale PORTs and also to understand the effect of different confining stresses and column cracking have on the probing force. To this end some recommendations are made later in Section 9.4.

CHAPTER 9: CONCLUSIONS AND RECOMMENDATIONS

9.1 Background

Dry soil mixing is a form of ground improvement that can be used to improve the properties of very soft and organic soil profiles through the addition of dry cementitious and pozzolanic binders. However, due to the inherent variability of soils and differences in the *in situ* mixing and curing conditions, *in situ* strength verification is required to ensure that the minimum design strength is achieved. Two methods to do this are the Push-In Resistance Test (PIRT), and to a lesser extent, the Pull-Out Resistance Test (PORT). PIRT is the more commonly used test method but issues with penetrometer deviation can require the stabilised columns to be pre-drilled to prevent deviation of the penetrometer from the column. PORT allows for the testing of longer columns than PIRT and although penetrometer deviations are not a problem, issues with pulling out of the penetrometer mean the test can be difficult to perform. In this chapter an overview of the research carried out in this research is presented along with the key findings and recommendations for future reduced-scale testing.

9.2 Thesis Overview

In this thesis two series of reduced-scale PORT and PIRT penetrometer tests were undertaken to investigate the relationship between the probing force and the stabilised column strength, quantified by the N value. Methods were developed for the construction of high quality 200 mm dia. stabilised soil-cement columns and a total of 31 columns were produced, on which either reduced-scale PORT or PIRT were subsequently carried out. PIRT could only be performed following replication of pre-drilling by forming a hole in the column during the construction process. Subsequent to probing, the columns were exhumed, sampled and strength tested. To account for additional frictional forces acting on the penetrometers during the tests, a further series of 17 no. 104 mm dia. friction column tests, including two initial trial columns, were carried out. For quality and repeatability purposes, the effect of ambient curing temperature on the column strength was also investigated by monitoring the temperature throughout a column and its test basin during curing. Using the results of the column testing series, N values for both the reduced-scale PORT and PIRT penetrometers were back-calculated and compared with each other and values currently used in practice.

9.3 Research Conclusions

9.3.1 Novelty of Research

It is believed that the reduced-scale PORT and PIRT experiments in this thesis are the first of their kind to be carried out on stabilised soil-cement columns in a laboratory. To this end, the following original experimental equipment and procedures were developed:

(i) A number of reduced-scale (1:4) PORT and PIRT penetrometers were designed and manufactured based on full-scale penetrometers.

(ii) Procedures to successfully construct reduced-scale stabilised columns in the laboratory were developed following some initial trial tests.

(iii) After some initial trials, procedures for reduced-scale PORT and PIRT were developed to test the stabilised columns. To allow for successful testing, the following issues were addressed as set out below:

a. To prevent pull-out of the column from its curing basing during a PORT, a loading was required to be placed on top of the column.

b. To prevent penetrometer deviation, replication of column pre-drilling was performed by forming a hole in the column during construction.

(iv) Two additional series of column construction and testing procedures were developed to assess the contribution of wire or sounding bar friction to the respective reduced-scale PORT and PIRT.

Later in Section 9.4, the overall experience gained during this thesis is used to suggest some additions and alterations to the methods, which may further enhance the quality of the data obtained in future tests.

Due to the variability of the parent soil, a new framework (in which the strength data are presented on plots of unconfined compression strength times water-to-binder ratio (UCS×WTBR) against temperature corrected time (*TCT*)) was developed to account for the effects of the intended variables of curing time and binder content, as well as the unintended variables of moisture content and curing temperature. The use of the average ambient curing temperature of the laboratory within this framework to account for curing temperature variations on the column strengths was shown to be appropriate based on measurements taken in a specific temperature monitored column. The framework was then later used to account for any strength gain occurring in the time between probing of the column and UCS testing of the column samples recovered, a correction essential for calculating time-consistent N values.

9.3.2 Experimental Results

At the outset, two series of stabilisation trials were carried out to define an appropriate soil type, binder type and binder content for use in the reduced-scale column tests. Two Irish soils, a H3 peat and a soft organic clayey silt (or *sleech*), were successfully stabilised and overall, cement and cement-GGBS binders were found to provide best improvements in both soils. From the experience and results gained in the trials the *sleech*, stabilised with either 100 kg/m^3 or 150 kg/m^3 of OPC, was chosen for the reduced-scale column series. Although PORT and PIRT of stabilised peat columns was not pursued, the peat stabilisation data has been compiled with that of other Irish peats to provide a useful database of achievable stabilised strengths.

In total, 39 no. high quality stabilised soil-cement columns were successfully constructed and tested. These included:

- 13 no. PORT columns
- 11 no. pre-drilled PIRT columns
- 8 no. wire pull-out friction columns
- 7 no. cone-only penetrometer friction columns
- 1 no. temperature monitored column

From analyses of the data obtained on the stabilised columns, the following findings were arrived at:

(i) Stabilised column strengths up to approximately 800 kPa were achieved by varying the binder content (100 kg/m^3 or 150 kg/m^3 of OPC) and curing time (1 to 13 days). Strengths were also influenced by moisture content and curing temperature.

(ii) Across all four column series the quality of the columns was found to be very consistent, as CoV values for the principal properties were typically below guideline ranges in the literature, and in particular strength CoV values were less than those seen in field column data given the variability of the *sleech* used.

(iii) The benefit of the experience gained during the PORT column series was evident in the improved CoV ranges seen in the subsequent PIRT, wire and cone-only column series.

(iv) Similar stiffness-strength relationships were seen in each column series and are comparable to those of laboratory and field data in the literature.

(v) Comparisons with the mould samples prepared and cured using standard practices show consistency with similar density and strength ratios observed in all test series.

(vi) The quality of the PORT and PIRT columns was further justified through linear mixed model statistical analyses which showed curing time and binder content to significantly influence the stabilised strength, while moisture content and curing temperature also had a significant influence on the PORT series data where greater variability occurred.

From analysis of the data obtained in the reduced-scale probing tests and the N values calculated for each column using the corrections determined from the friction test, the following key findings were established:

(i) Both the PORT and PIRT probing force profiles observed show similarities to their respective field tests in the literature, as do the wire pull-out tests.

(ii) In both PORT and PIRT, the calculated N values were found to be influenced by a number of factors:

a. *Column confinement:* Low confining stresses, particularly clear at the top of the column where the column split open as the penetrometer progressed, resulted in a lower than representative probing force relative to the column strength, which in turn gave a low N value. Increased confining stresses were found to increase the N value, demonstrated through tests with and without imposed surcharge loadings.

b. *Column strength:* As the column strength increased the material behaviour changed from ductile to brittle with tensile failures occurring. Again, this was seen at the top of the columns with c_{cor} >150*kPa* and particularly where c_{cor} > 250 kPa. In soft columns additional probing force was generated due to the adhesive nature of the stabilised material producing the highest N values.

c. *Friction effect*s*:* It is believed that additional probing force occurred due to contact between the vertical faces of the penetrometers and the stabilised column as the leading edge did not displace the column far enough so as to avoid contact occurring.

(iii) In the PORT columns, N is seen to increase with depth from 7 to 15. However this is believed to be due to an under estimation of the friction occurring between the column and the pull-out wire, and the spread in N is due to the factors mentioned above, such as strength and confinement.

(iv) In the PIRT column data, below a depth of 200 mm, N values tend to show a constant trend with depth of approximately 8 to 10, while higher values up to 15 are seen in columns with c_{cor} < 150 kPa and in the unstabilised *sleech*.

(v) In general the magnitude of the N values is typically within the range of those reviewed in Section 2.4.4 (*i.e.,* 8 to 15). However, evidence that N depends on confinement and is influenced by strength are new findings from this reduced-scale testing programme.

Overall, a series of high quality stabilised soil-cement columns have been successfully constructed and tested for the first time in the laboratory using reduced-scale PORT and PIRT methods. Although some additional work is needed to investigate further the factors that have been found to influence N, the work presented in this thesis provides the procedures, knowledge and interpretation framework required to do so, as well as providing confidence when determining the strength of dry soil mixed columns.

9.4 Recommendations for Additional and Future Reduced-Scale Laboratory Testing

Since this study was the first of its kind to be conducted at laboratory scale and required original procedures, it is to be expected that a number of additions and alterations might be recommended for future testing to further improve the quality and consistency of the column construction and testing procedures. These are set out below.

9.4.1 Column Construction

(i) Measures should be taken to reduce the variability of the initial properties of the parent soil used, in particular the moisture content. It is preferable to avoid using soil previously used to surround the column during curing for later column construction.

(ii) To remove the effects of temperature variations on the achieved strengths, all columns should be cured at a constant temperature, as should the parent soil used so as any temperature variations are solely due to hydration reactions.

(iii) A greater number of mould samples could be created to increase confidence in their results. This may be achieved using larger stabilised batches or smaller 50 mm dia. by 100 mm long moulds.

(iv) To reduce the occurrence of layering in the columns two methods are proposed:

   a. Obtain a lower rate of strength gain which will allow better binding between mixes by reducing the binder content, although this would then require longer curing periods to achieve desired strengths.
   b. Increase the speed of column construction by creating larger stabilised batches than those created in this thesis. Longer and larger diameter columns may also be constructed using this method.

(v) The construction of longer columns is deemed to be possible using techniques similar to those used in this thesis, but in which the columns are created in progressively longer form pipes. During construction, the pipes are removed and replaced by longer form pipes and the next section of column is then formed. The process is repeated until the desired height of column is created, at which point the column is carefully surrounded with parent soil.

9.4.2 Column Testing

(i) Column testing using different penetrometer sizes, in particular investigating the effects of different column diameter-to-penetrometer width ratios and different penetrometer leading edge width-wing thickness ratios. Stronger sounding bars are also required to ensure the bars do not bend or buckle under the push-in probing force and if a method of ensuring the bars do not deviate can be found, it may be possible to probe columns without the necessity to replicate predrilling.

(ii) One method of increasing the confinement around the column is to use a series of semi-circular pipes which surround the column during the PIRT. The short semi-circular sections would surround the column over its length during testing and be linked by a series of springs which would replicate the *in situ* confining stresses. Instrumentation on the springs would record variations in the confining stresses during the PIRT. The extent of column cracking and the influence of column confinement could also be investigated.

(iii) To investigate the N value for a PORT penetrometer alone without the effects of the PORT wire friction with the column, a tubular metal sleeve around the PORT wire during construction and removed prior to testing, could be used to minimise friction. The tubular metal sleeve would also ensure the wire remained straight within the column and help in maintaining the column's verticality during construction.

9.4.3 Additional Testing

(i) As has been stated the wire tests are thought to under estimate the wire friction during a PORT. A better representation of the friction may be obtained by the following alterations:

a. Parent soil used should have similar properties to the PORT column to which it relates, particularly moisture content, *i.e.,* μ_{wc} might not be assigned based on strength alone.

b. A series of further tests in which the pull-out wire friction due to the build-up of material at the top of the penetrometer shaft is assessed.

(ii) Under controlled conditions, an in-depth investigation of the UCS×WTBR with *TCT* framework through a series of stabilisation trials. Samples, from batches of a parent soil at different moisture contents, should be stabilised with different binder contents and separate samples then cured for different curing times under different curing temperatures before UCS testing.

(iii) If the amount of contact between the vertical faces of the penetrometer's wings and the stabilised columns can be estimated and a number of tests carried out to determine column-penetrometer friction factors (α), the principles of dynamic penetrating anchors (see Section 2.4.2) may be applied to the data to better estimate the strength based on the probing force.

(iv) It may also be possible to carry out centrifuge testing to investigate the N value, in a similar way to that carried out for dynamic penetration anchors (see Section 2.12), although difficulties in accurately fabricating the leading edge of the PORT/PIRT penetrometer wing and penetrometer deviations may be encountered.

9.4.4 Field Testing

Although expensive, the most accurate method deemed by the author to determine the N value is through field testing in which a number of stabilised columns would be created, probed and extracted using a column sampler (see Section 2.3.4). Samples would be taken throughout the extracted column for immediate strength testing. An assessment may also be made as to the extent to which cracking of the columns occurs in the field. A number of binder contents and curing times should be used to achieve a range of column strengths and any PORT performed should be accompanied by wire pull-out tests.

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Appendix A: Publications

Experiences of Dry Soil Mixing in Highly Organic Soils

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Experiences of dry soil mixing in highly organic soils
Timoney, McCabe and Bell

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Experiences of dry soil mixing in highly organic soils

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Soil mixing, or soil stabilisation, is a method of enhancing the geotechnical properties of suitable host soil through the addition of cementitious and/or pozzolanic binders in either dry or slurry forms. In dry soil mixing, the binder is injected into the soil in powder form using compressed air. Published laboratory experiences of stabilising highly organic soils in dry soil mixing laboratory trials are collated in this paper. A large database of stabilised strengths is compiled from which it emerges that cement and a cement/ground granulated blast furnace slag combination are the most suitable binders for peat soils, and that the ratio of mass of water to mass of binder and the von Post classification H value are important indicators of stabilised strength. The data provide a useful frame of reference for practitioners wishing to select an appropriate binder type and content for mixing trials in peat. Stabilised strength gain over time is discussed, as are issues such as soil temperature, binder temperature sensitivity and prestressing.

1. Introduction

Soil stabilisation/mixing is a form of ground improvement in which cementitious and/or pozzolanic materials are introduced to a soil, with the goal of improving strength and deformation characteristics (e.g. EuroSoilStab, 2001) or confining/remediating contaminated soils (e.g. Al-Tabbaa *et al.*, 2009). Stabilisation can be achieved using either the dry mix method, with air as the medium used to carry the binder, or the wet mix method, where water is the transport medium.

Dry soil mixing (DSM), the focus of this paper, is implemented in the field using either of two main methods: deep dry soil mixing (DDSM) and mass stabilisation. DDSM is a relatively new process developed in Sweden and first used in the 1970s (Bredenberg, 1999) in which stabilised columns are created in soft clays, peats and other weak soils. Using a rig similar to that shown in Figure 1, compressed air is used to inject a binder material into the soil in a dry powder form through holes in a purpose-built mixing tool mounted on a rotating kelly bar, which mixes the binder with the parent soil. The natural water content of the soil initiates the chemical reactions of the hydration process, leading to increased shear strength and reduced compressibility and permeability of the soil mass. Typically, columns have diameters between 0·5 m and 1·0 m in European practice and columns up to 1·5 m in diameter have been formed in Japan; they can be constructed as single units, in rows or in interlocking panels. Treatment depths have exceeded 30 m in Europe and treatment to 70 m has been achieved in Japan. In recent years, mass stabilisation has emerged as an efficient means of stabilising large areas of soft ground to shallow depths of up to 5 m. Stabilisation is carried out in blocks using a mixing tool mounted on the end of an excavator's arm, with mixing occurring horizontally as well as vertically (EuroSoilStab, 2001). In the same way as DDSM, the binder is fed to the mixing tool from a shuttle unit tailing the excavator. Mass stabilisation can also be used in combination with DDSM, for example, where a soft soil profile is particularly soft at shallow depths requiring complete treatment (EuroSoilStab, 2001).

Organic soils comprise a significant portion of the land area of some European countries, for example 17·2% of Ireland and 33·5% of Finland are covered by peat (Hobbs, 1986). Stabilisation offers an alternative solution to 'dig and replace' methods of ground improvement in these soils. However, the stabilisation of organic soils is more challenging than that of inorganic soils, given their inherent variability and the tendency of humic acids to hinder the hydration processes and related reactions required for the development of strength following stabilisation (Axelsson *et al.*, 2002). Although the results of many laboratory dry mixing trials have been published, there is little collated guidance to be drawn upon by geotechnical engineers planning a stabilisation scheme in organic soils and it is generally necessary to resort to site-specific pre-contract binder trials for each new project to

Figure 1. Keller Geotechnique's DDSM rig

appraise technical and economic feasibility. As a first attempt to improve this process, existing European and Japanese laboratory experiences in stabilising highly organic (mainly peat) soils are summarised, primarily from conference proceedings (Bredenberg *et al.*, 1999; Kitazume and Terashi, 2009; Rydell *et al.*, 2005), journal publications and published data from the Swedish Deep Stabilisation Research Centre (SDSRC). In particular, a large database of laboratory trials is used to investigate some of the factors that influence stabilised strength, thereby providing additional guidance for the design of stabilisation schemes.

2. Peat properties and characteristics

Those with experience of testing peat soils will be familiar with the irregularity in classification and property determination owing to the material's natural variability and the high level of subjectivity that is commonly encountered when trying to use seemingly straightforward classification systems. Two different laboratories may classify the same peat in two different ways. With this in mind, some of the most relevant characteristics of peat are discussed in this section.

2.1 Peat humification

Peat is a highly organic soil type, with a substantial natural water content, formed by the decay of the dead remains of organic material rich in carbohydrates into humus (referred to as humification). Hartlén (1996) classifies peat into three simple categories.

(*a*) Fibrous peat which has a low degree of humification. This form will have a distinct plant structure and will produce a brown to colourless, cloudy to clear water when squeezed.
(*b*) Pseudo-fibrous peat has a mid to high degree of humification. The plant structure is now less identifiable and a mushy mass will be extruded when squeezed.
(*c*) Amorphous is the classification used for the most highly humified peat. Very little, if any, of the plant structure remains and on squeezing no free water is released.

More detailed classification systems include the von Post (1922) classification and the Canadian classification proposed by Radforth (MacFarlane, 1969). von Post (1922) provides a very detailed classification based on a range of characteristics, including degree of humification, water content and fibre type and content. Von Post's degree of humification, H, is a scale ranging from H1 (least humified) to H10 (most humified); with fibrous peat in the range H1–H4, pseudo-fibrous in the range H5–H7 and amorphous between H8 and H10. The exact classification of H value can be subjective, and can vary locally within a sample. Hobbs (1986) provides a detailed description of the classification and suggests an extension to include tensile strength, plasticity, organic content, smell and acidity, thereby acknowledging the role that soil science can play in characterising a material that is not easily characterised by traditional engineering parameters.

Humic decay may be either aerobic, that is organic matter is oxidised in the presence of oxygen, or anaerobic, that is material is broken down under conditions of no oxygen. Aerobic decay occurs at a higher rate than anaerobic decay; this is evident in that humification of the acrotelm, that is the upper 0·1 m–0·6 m of a peat profile, occurs at a higher rate than that of the oxygen-deficient catotelm beneath it. After full decomposition there will be no evidence of the original plant structure; all the organic matter will have been broken down and the peat will now have a granular rather than a fibrous form. The rate of humification is higher in peats with higher temperatures (optimum 35–40°C) and a basic nature (that is, pH $> 7{\cdot}0$), as the organisms that break down the organics are more active under these conditions (Hobbs, 1986).

2.2 Water content

The standard geotechnical definition of natural water content w_i is shown in Equation 1 where m_w and m_s are the mass of water and solids respectively

$$w_i(\%) = 100 \frac{m_W}{m_S} \quad (1)$$

The value of w_i for peat can range up to many hundreds and even thousands of per cent, as evident in the database summary in Table 1, and can vary within a single peat sample. Fibrous peats with low degrees of humification have higher water contents than more humified granular amorphous peats (Hobbs, 1986). Within a peat, water is stored in three ways (Hartlén, 1996): (i) within large cavities in the peat, (ii) within smaller cavities but held by capillary action, and (iii) held by the physical, chemical and osmotic processes. The proportions of water held by each will depend upon the degree of decomposition of the peat. Fresh peats have high void ratios, with values up to 25 reported (MacFarlane, 1969) and water is found within cavities, whereas amorphous peat void ratios are lower and water mainly exists bound to the particles within the peat. If a peat is dried out, significant shrinkage will occur and oxidation of the peat results in a permanent change to the material. Shrinkage is not as significant in fibrous peats as in amorphous peats, as the fibres act to resist against shrinkage. A peat will not return to its original water content nor will further decomposition occur if it is re-submerged in water.

Another difficulty in comparing moisture contents from different reports is that there is little consensus on the oven temperature to be used in determining the moisture content. General practice for determining the moisture content of a soil is to dry the soil at 105°C ± 5°C (ASTM, 2007; BSI, 1996) but drying organic soils at these temperatures can result in charring and oxidation of the organics, resulting in a higher apparent moisture content (O'Kelly, 2005). Skempton and Petley (1970) endorse the use of 105°C but O'Kelly shows from a series of tests on organic soils, ranging from organic silts to peat (3% to 93% organics), that a temperature of 80°C provides reductions similar to those seen in inorganic soils (evaporation of water rather than charring of organics). Notwithstanding this uncertainty, moisture content is considered to be a primary indicator of changes in peat state as bulk density is notoriously difficult to determine accurately; pore water can be lost owing to the forces applied in sampling, loss of pore gas results in reduced volumes and disturbances can arise in storage and transportation of the sample to the laboratory (Landva *et al.*, 1983).

2.3 Shear strength

In terms of its shear strength, fibrous peat does not act like other soil types. Fibres in the peat act to reinforce the soil and their

Reference	Location	Soil type	w_i: %	ρ: kg/m^3	OC: %	von Post H	pH	Source:
Raheenmore	Raheenmore, Ireland	Peat	1200	1075	98–99	2	5·3	(Hebib and Farrell, 2003)
Ballydermot	Ballydermot, Ireland	Peat	850	1125	94–98	6–9	4·9	(Hebib and Farrell, 2003)
Hernandez	Ireland	Moss Peat	210, 500, 1000	294, 446, 1014	94	6	–	(Hernandez-Martinez and Al-Tabbaa, 2005)
Hömla	Hömla, Sweden	Gyttja	220	1230	10	–	8·5	(Åhnberg and Johansson, 2005)
Söderhamn	Söderhamn, Sweden	Peat	869	–	89	–	5·8	(Lahtinen *et al.*, 1999)
Arlanda (T3)	Arlanda, Sweden	Peat	442	1000	73	8	–	(Axelsson *et al.*, 2002)
Örebro (T1)	Örebro, Sweden	Peat	1308	1000	99	2–3	–	(Axelsson *et al.*, 2002)
Örebro (T2)	Örebro, Sweden	Peat	1413	1000	97	2–6	–	(Axelsson *et al.*, 2002)
Örebro (G1)	Örebro, Sweden	Gyttja	151	1200	8	–	–	(Axelsson *et al.*, 2002)
Arlanda (G2)	Arlanda, Sweden	Gyttja	205	1200	17	–	–	(Axelsson *et al.*, 2002)
Örebro 2	Örebro, Sweden	Peat	1350	980	99·1	–	–	(Axelsson *et al.*, 2002)
Örebro 3	Örebro, Sweden	Peat	1290	980	98·9	–	–	(Axelsson *et al.*, 2002)
Dömle P1	Dömle, Sweden	Peat	1600	950	97	5–7	4·3	(Åhnberg and Holm, 1999)
Adria	Adria, Italy	Peat	375	1070	72	6	6·9	(Cortellazzo and Cola, 1999)
Correzzola	Correzzola, Italy	Peat	690	1075	71	5	4·6	(Cortellazzo and Cola, 1999)
Kivikko	Kivikko, Finland	Peat	668	–	95	–	4·7	(Lahtinen *et al.*, 1999)
Grimsäs	Grimsäs, Sweden	Peat	1022	970	98	4-6	4·3	(Åhnberg and Holm, 2009)
Quigley	Mayo, Ireland	Peat	1019	1000	98	7–8	–	(Quigley and O'Brien, 2010)

Table 1. Compiled data on the stabilisation of peat and gyttja soils and their properties

horizontal orientation provides shear resistance in the vertical direction. In addition, a fresh peat with a high fibre content coupled with a sufficiently high moisture content can have a density below that of water.

Although research in the 1950s by Hanrahan suggested that remoulded peat was purely cohesive (that is, a friction angle of zero), subsequent testing by Hanrahan and Walsh disproved this initial theory by showing that peat was in fact frictional (Long, 2005). The effective friction angle was shown to increase with reducing water content. Long (2005) concludes that the friction angle of peat when tested in triaxial compression ranges widely from 40° to 60°, but that lower angles are obtained from ring shear and direct simple shear tests, noted to be as a result of the reinforcing effect of fibres with a horizontal orientation. Mesri and Ajlouni (2007) provide a table of friction angles for fibrous peats tested in triaxial tests; all are shown to fall between 40° and 60°.

2.4 Gyttja

Gyttja is the Swedish term used for an organic mud-like soil formed in lakes and seas from the deposition of the remains of plants and animals with a high fat and protein content, as opposed to the carbohydrate-rich origin of peats (Hartlén, 1996). Depending upon its origin it can be grey, reddish-grey or greenish-grey when formed in nutritious waters. Organic contents are typically less than 20% with 50% considered as the upper limit (Hansen, 1959). Values of w_i for gyttjas are lower than those seen in peats, lying typically below 300%. Like peat, this soil type shrinks when dried and forms hard clumps. Although gyttjas do not hold the same international interest as peats, some stabilised strength data are available which are included in the strength database to help put some context on the peat results.

3. Binders and stabilisation issues

3.1 Binders

In the early days of DSM, lime was the first binder used but cement binders became popular owing to the greater strength gains achievable. Today, many binders including various cements, ground granulated blast furnace slag (GGBS), gypsum, fly ash and even fillers such as silica sand and limestone are used in soil stabilisation with binder contents ranging between 100 kg/m^3 and 300 kg/m^3 (and greater) depending upon the soil type.

When cement is mixed with an organic soil it reacts with the water within it, starting the hydration process in which calcium (C; CaO) silicate (S; SiO_2) hydrate (H; H_2O) ($C_3S_2H_4$ (CSH)) is formed during hydraulic reactions (Janz and Johansson, 2002). The CSH gel binds the soil particles together, filling voids and becoming stronger and denser with time. Initially the rate of strength gain will be controlled by the temperature; the higher the temperature, the more reactions that take place, leading to better strength gains. In time, the CSH gel formed will hinder the rate of strength gain as the gel slows the release of calcium ions. The ratio of tricalcium silicate (C_3S) to dicalcium silicate (C_2S) within the cement affects the rate of hydration; a high ratio results in greater CSH production and hence greater strengths. Also, the gypsum content of the cement will serve to delay the setting process.

Two forms of lime are used in stabilisation; quick lime (calcium oxide (CaO)) and hydrated lime (calcium hydroxide ($Ca(OH)_2$). When mixed with water, quick lime will react to form hydrated lime but this will not result in any strength gain. The hydrated lime then reacts with the pozzolanic material in the soil and more water to produce CSH, which contributes to strength gain. Lime provides an initial dewatering effect and an increase in pH, but stabilisation results can be poor as humic acids inhibit strengthening reactions. In some cases, failure of the stabilised mass to solidify has been observed (Hayashi and Nishikawa, 1999).

GGBS is a by-product of iron and steel manufacturing processes. It contains a certain amount of lime but requires activation, generally by cement or lime. This allows the latent hydraulic reactions to begin, after which its own lime content provides the calcium hydroxide required for the reactions. The temperature generated during these reactions is low, resulting in slow strength gains, and changes in the temperature of the soil mass can affect the rate of reactions. Thus, initial strengths can be lower than those of mixes using other binders but long-term strengths can be significant. Pulverised fly ash (PFA) is obtained from flue gas in coal-fired power generation plants. PFA, like GGBS, requires activation owing to its low calcium oxide content, achieved using either cement or lime, and is also a temperature-sensitive binder. Its reactivity depends upon its fineness, vitreosity and rate of cooling following manufacture. The calcium hydroxide provided by the added cement or lime reacts with water and the pozzolanic material present in the PFA to start the strengthening process. Reaction rates are low and depend on the amount of calcium hydroxide available and CSH gel with a low tricalcium silicate content is formed, resulting in lower strengths than other binders.

Filler binders such as silica sand and limestone can be used to increase the stiffness of the soil but unlike other binders are practically inert and do not provide any strengthening reactions. They reduce the amount of costly binders required and when used in peat soils they augment the number of solid particles available to be bound together (Axelsson *et al.*, 2002). However, checks need to be carried out to ensure that the increased density of the soil profile and the resulting higher stress states do not lead to excessive subsidence or heaving problems in neighbouring untreated soils. Geosynthetic fibres offer an alternative binder additive to improve strength gains. In a series of laboratory tests Kalantari and Huat (2008) used Portland cement and 12 mm long polypropylene fibres at an optimum 0·15% content in the stabilisation of a H4–H5 peat. Stabilised sample strengths with fibres were observed to be slightly higher than those stabilised without fibres.

3.2 Effect of organics

The organic contents (OC) of peats and gyttjas reported in the literature are given in Table 1. During the stabilisation of organic soils, calcium hydroxide reacts with the humic acids to form insoluble products which coat the particles in the soil. Hebib and Farrell (2003) and Hernandez-Martinez and Al-Tabbaa (2005) inspected stabilised peat samples under an electron microscope and found that there was little or no interaction between the strengthening products created during hydration and the organic material of the stabilised peat. Finnish studies have proposed a binder threshold below which no increase in strength will occur (Axelsson *et al.*, 2002). It is suggested that once this threshold is passed, there is enough binder to cause the pH to increase, neutralising the acids present. Hebib and Farrell (2003) noted the minimum binder quantity for strength improvement to be 150 kg/m^3 for two Irish peats.

Hebib and Farrell (2003) also showed that for a given binder type and content, stabilised strengths can differ from one peat to another; samples from Raheenmore (H2) stabilised with cement showed higher strengths than those from Ballydermot (H6–H9). Likewise, when a GGBS–gypsum binder was used, Raheenmore samples showed excellent strengths reaching nearly 1200 kPa after 28 days with a 250 kg/m^3 content, whereas very poor results were obtained for the Ballydermot peat. The differences in strength of the peats were attributed by the authors to the differences in their extents of decomposition.

3.3 Temperature

Axelsson *et al.* (2002) report that some binders are temperature sensitive, that is the temperature of the soil mass to be stabilised can have a significant effect on the number of reactions that take place and the rate of strength gain. This is not an issue with cement or lime binders, where significant heat is created during the cementitious and pozzolanic reactions; Halkola (1999) reports a temperature of 70°C temperature in lime columns and CIRIA C573 (CIRIA, 2002) notes surprisingly high temperatures of 300–400°C recorded in the centre of lime columns created using the Japanese method up to 3 hours after mixing. Binders such as GGBS produce less heat during the exothermic reactions, and are consequently more susceptible to temperature changes in the soil being stabilised, resulting in fewer reactions and lower initial strengths.

Kido *et al.* (2009) measured the strength of peat stabilised using cement with a high gypsum content and a blast furnace slag cured at temperatures between −20°C and 20°C. Samples cured below 0°C showed little strength improvement using either binder, while samples tested above 0°C showed good strength improvements, especially at 20°C. Analysis of the amount of ettringite formed after 7 days showed very small amounts at low temperatures but large amounts of longer crystals at higher temperatures. Åhnberg and Holm (1999) showed that high curing temperatures can result in lower strength gains. Cement–lime and cement–slag samples cured at 40°C were found to have lower strengths than samples cured at 20°C. They suggest that this may be due to humification under the increased temperatures as gyttja stabilisation under similar conditions showed increasing strength with increasing temperatures.

3.4 Prestress loading

In the field a layer of fill, up to 1 m deep, is generally placed over the stabilised area to compact and remove air entrained in the soil during mixing. Investigations carried out by Åhnberg *et al.* (2001) on the effect of prestress loading on a stabilised peat showed that loading of the freshly stabilised soil was vital in attaining good strength improvements. Samples stabilised with cement–lime and cement–slag at 100 kg/m^3 were loaded with 0 kPa, 9 kPa, and 18 kPa at 45 min (standard delay), 4 h and 24 h after mixing. It was observed that the samples with delayed loading had reduced strengths – in the region of 25% after 45 min and 75% after 24 h when compared to the samples loaded immediately. One possible reason for this is that when the loading is delayed, bonds are created between the soil particles and the effect of the prestress in compressing the void is reduced. Voids will still remain within the stabilised mass, although some will be filled with products from the reactions mentioned earlier. It was also noted that lower strengths were observed in samples with larger diameters and heights than in smaller sized samples from the same stabilised batch. This was thought to be attributable to the larger sample volume and the high variability of peat.

Hebib and Farrell (2003) showed from tests on Irish peats that the permeability of the stabilised samples was reduced by prestressing, whereas the permeability of samples not subjected to prestress was the same as that of the parent peat.

3.5 Laboratory against field results

In most cases, strengths achieved in laboratory tests will not be representative of strengths achieved in the field. In the case of laboratory testing, the unstabilised mass will be mixed to create a uniform homogeneous mass which may not represent the in situ soil throughout its depth. Moreover, any mismatch between the water content of the soil used in the laboratory and that in situ at the time of stabilisation will result in strength differences. In most laboratory tests, the curing temperature used will be in the region of 20°C but the field curing temperature may be much lower, depending upon the location. The lower temperature of the ground to be stabilised will result in a lower reaction rate between the binder and soil; as mentioned earlier, this may have a significant effect on certain binder blends.

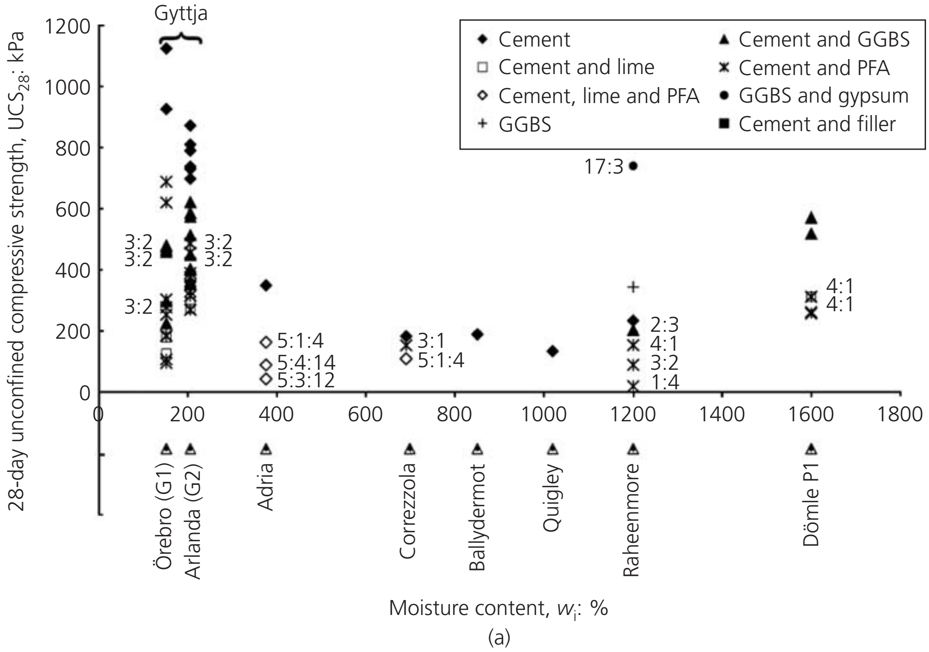
Hayashi and Nishikawa (1999) conducted a series of stabilisation tests on a peat soil using various mixing times and rates, and showed that with increased mixing levels, better strength uniformity can be achieved. The authors detailed the ratio of laboratory to field strengths to lie in the range 2–5, with 3 used as the average ratio in practice. Increased mixing in laboratory tests resulted in a closer correlation between laboratory strengths and the evaluated field strengths.

4. Stabilised strength database

4.1 Unconfined compressive strength and moisture contents

Unconfined compressive strength (UCS) is the most commonly used gauge of the strength of stabilised soil samples in the laboratory. The authors have developed a database comprising almost 600 measurements of the UCS of laboratory stabilised peats and gyttjas which have been cured for periods of between 7 and 365 days and at various temperatures.

The largest and most useful subset of this data is reproduced in Figure 2, which presents UCS values measured at 28 days, UCS_{28} (and cured at either 20°C or 21°C under an 18 kPa prestress)



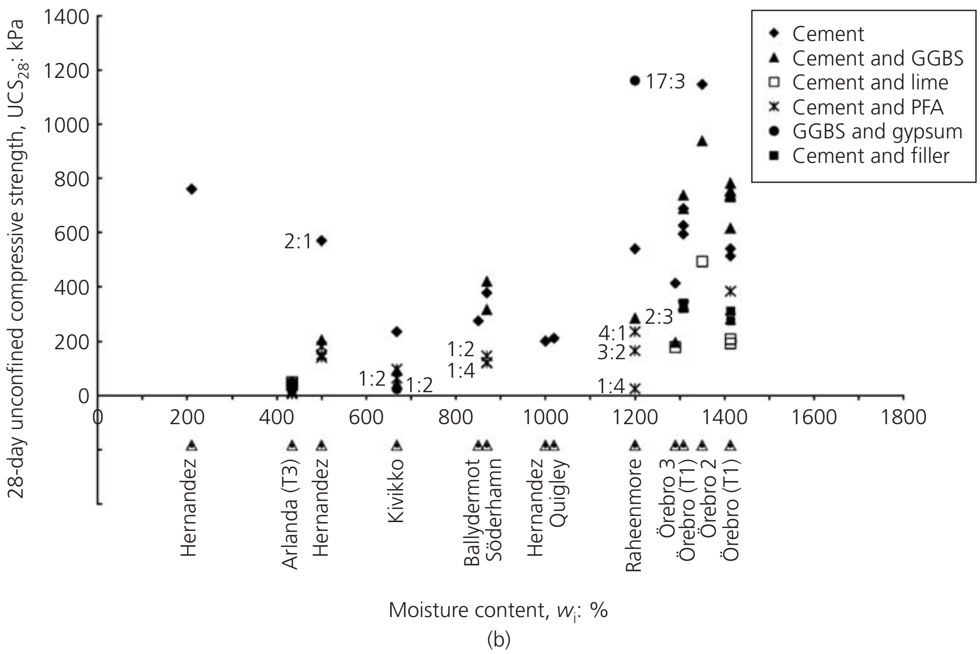


Figure 2. Graphs of unconfined compressive strength against moisture content (a) at 200 kg/m^3 after 28 days' curing; (b) at 250 kg/m^3 after 28 days' curing. Note: all compound binder proportions are split evenly, except where otherwise detailed

plotted as a function of w_i. Two popular binder dosage rates are shown: 200 kg/m^3 Figure 2(a) and 250 kg/m^3 (Figure 2(b)). The sites from which the data have been sourced are annotated on Figures 2(a) and 2(b) and may be cross-referenced with Table 1. All data represent stabilised peats with the exception of those marked as gyttja in Figure 2(a). A careful examination and comparison of these figures reveals the following.

(*a*) UCS_{28} values of stabilised peat and gyttja of up to and beyond 1 MPa are achievable.
(*b*) Higher UCS_{28} values are obtained by using higher binder contents, as expected.
(*c*) Cement and cement–GGBS binders produce consistently higher UCS_{28} values when mixed with peat than other binders. Cement–lime and cement–PFA binders yield poorer strengths.
(*d*) The lower organic content of gyttjas results in higher stabilised strengths, and the database confirms that lower binder contents are sufficient; cement binders appear to be most effective, followed by cement–GGBS blends (Figure 2(a)).

The apparent increase in UCS_{28} with w_i in Figure 2(b) is perhaps misleading as the data for the four highest moisture contents all derive from the same (Örebro) site. Taking the Arlanda and Örebro data from Figure 2(b) in isolation, Axelsson *et al.* (2002) concludes that an increased strength with moisture content may be attributable to the ample availability of water in the soil, allowing for a larger proportion of the binder to be utilised. However, as expected, the general consensus differs; Hernandez-Martinez and Al-Tabbaa (2005) showed reducing strength with increasing moisture content for cement-stabilised Irish moss peat tested at $w_i = 210\%$ and further induced moisture contents of 500% and 1000%. Likewise Hayashi and Nishimoto (2009), who tested three peats of varying moisture and organic contents, demonstrated reducing strengths with increasing moisture and organic content. It appears from Figures 2(a) and 2(b) that moisture content on its own is insufficient as a predictor of stabilised UCS.

4.2 Water to binder ratio

An alternative parameter, the water to binder ratio (η), is defined in Equation 2 as the mass of water per unit volume (m_w) divided by the mass of (active) binder per unit volume (m_b). The mass of water is a function of w_i for DSM as no additional water is added during mixing. Using trials for which w_i, the density of the peat (ρ) and the mass of binder per unit volume (m_b) were all available, η values were calculated using Equation 2 and plotted against respective UCS_{28} values in Figure 3(a) for binders incorporating cement and/or GGBS. For the few data points where the stabilised soil contained some inactive binder content, no adjustments were made to the values of ρ or w_i for calculating η. The references for the data in Figure 3(a) are provided in Table 2

$$2. \quad \eta = \frac{m_w}{m_b} = \frac{\rho}{m_b[1 + (1/w_i)]}$$

Figure 3(a) shows a prevalence of η values in the range 4 ± 1; indicative of the most popular mixing proportions. Importantly, a general trend for UCS_{28} to reduce with increasing η (for $\eta > 3$ approximately) is apparent for both cement and cement–GGBS mixes; the trend for the cement-GGBS (50:50) mixes is the better defined of the two. From this exercise, it is clear that η is a better indicator of stabilised strength than w_i.

4.3 von Post classification

The data in Figure 3(a) having von Post H values are reproduced in Figure 3(b) to investigate the extent of humification on the UCS_{28} values. The data are grouped according to the H1–H4, H5–H7 and H8–H10 categories defined in Section 2.1; however, two intermediate groups are created for data where the degree of humification range quoted in the literature spans two of those categories. Figure 3(b) shows an approximate yet noteworthy tendency (given the variables involved) for UCS_{28} to decrease with increasing humification. In particular, it is clear that stabilising peats with highest H values (i.e. Axelsson *et al.* (2002) at Arlanda, Quigley and O'Brien (2010), and Hebib and Farrell (2003) at Ballydermot) is most challenging, with stabilised strengths generally falling below 200 kPa.

It is clear that the von Post H value is another important variable. Figures 3(a) and 3(b) used in combination provide a useful means of estimating the UCS_{28} values to be expected from pre-contract trials on peaty soils.

4.4 Statistical analysis

Minitab statistical software was used to perform a regression analysis to investigate the significance of η, organic content and von Post H on the UCS_{28} values with H values included on Figure 3(a). The natural log of the UCS was taken so as to condense the numerical range of the data, and statistical p values were used to test the strength of the relationship between the predictor and response (p values lie between 0 and 1 with values closer to 0 indicative of stronger correlation). The results of the analyses are shown in Table 3, and these must be considered in the context of the following limitations

(*a*) the limited dataset for which all three of the aforementioned variables were available
(*b*) the need to take an average H value where only a range was quoted
(*c*) the absence of information on other relevant parameters, such as mixing energy and the temperature used in ascertaining w_i.

Where more than one UCS_{28} value was available for a given mix, an average was taken.

An analysis on all the data (without distinction between binders) showed H to be the least significant parameter. However, when carried out on cement data alone, the analysis gives η a very high significance with equal significance for organic content and

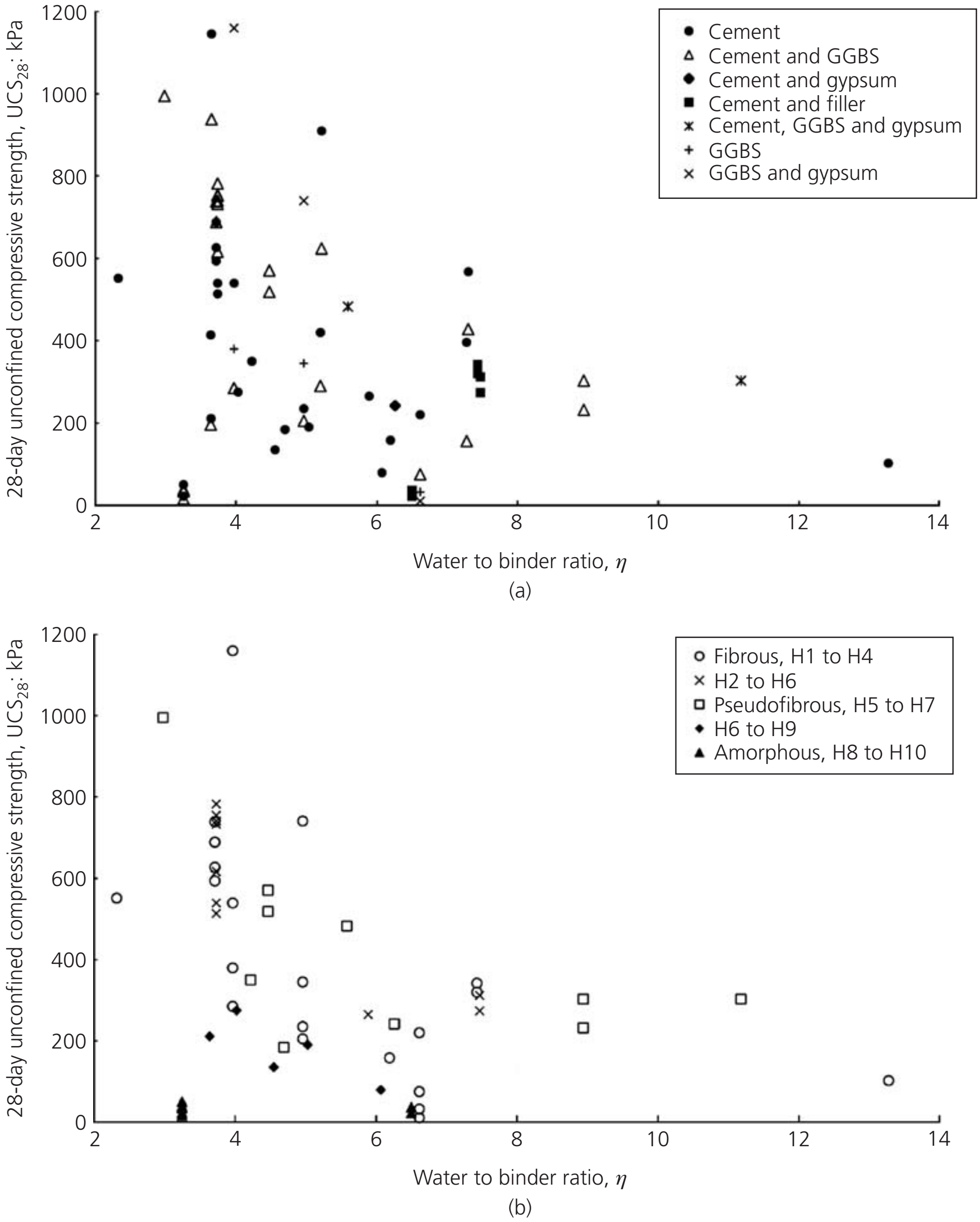


Figure 3. Graphs of unconfined compressive strength against water binder ratio: (a) for cement and GGBS binders in peat; (b) with von Post classification

von Post H; with a coefficient of regression $r^2 = 0{\cdot}548$. When carried out on the cement/GGBS binders equally high significances were seen across η, organic content and von Post H with a higher coefficient of regression $r^2 = 0{\cdot}926$; this stronger correlation is expected given the stronger trend noted between UCS_{28} and η in Figure 3(a). The authors feel that it is inappropriate to provide regression equations given the stated limitations of the analysis; however, this work shows potential for future correlations if adequate and accurate data can be captured from future trials.

4.5 Strength gain over time

Available data showing UCS gain over time (in the form of UCS normalised by the UCS_{28}) are shown in Figure 4. It can be seen that cement and cement-GGBS continue to exhibit strength gain well beyond 28 days, whereas the strength gain from lime is virtually complete after 28 days. Although the cement binders show greater continued strength gain long term, the UCS_{28} values for the cement–GGBS mixes were in fact very high (e.g. UCS_{28} of nearly 1000 kPa was reported for Dömle P1B1 300 kg/m^3). However, there is a need for further data tracking strength gain over time.

Authors' reference:	Binder: (1:1 unless stated)	Quantity: kg/m^3	UCS$_{28}$: kPa	η	Authors' reference:	Binder: (1:1 unless stated)	Quantity: kg/m^3	UCS$_{28}$: kPa	η
Adria1	Cement	200	350	4·22	Arlan T3-4	Cement and GGBS	250	38	3·25
Arlan T3-1	Cement	250	50	3·25	Arlan T3-4	Cement and GGBS	250	15·4	3·25
Arlan T3-1	Cement	250	22	3·25	Arlan T3-6	Cement and GGBS	250	38	3·25
Bally 1	Cement	200	190	5·03	Arlan T3-6	Cement and GGBS	250	34	3·25
Bally 2	Cement	250	275	4·03	Dömle P1 C	Cement and GGBS	200	571	4·47
Corr 1	Cement	200	184	4·69	Dömle P1 B1	Cement and GGBS	100	303	8·94
Grimsås1	Cement	150	265	5·89	Dömle P1 B1	Cement and GGBS	100	232	8·94
Oreb T1-1	Cement	70	102	13·27	Dömle P1 B1	Cement and GGBS	200	519	4·47
Oreb T1-1	Cement	150	158	6·19	Dömle P1 B1	Cement and GGBS	300	995	2·98
Oreb T1-1	Cement	250	626	3·72	Oreb T1-3	Cement and GGBS	250	738	3·72
Oreb T1-1	Cement	250	688	3·72	Oreb T1-3	Cement and GGBS	250	688	3·72
Oreb T1-1	Cement	400	552	2·32	Oreb T2-4	Cement and GGBS	250	754	3·74
Oreb T1-5	Cement	250	594	3·72	Oreb T2-4	Cement and GGBS	250	752	3·74
Oreb T2-1	Cement	250	514	3·74	Oreb T2-5	Cement and GGBS	250	740	3·74
Oreb T2-1	Cement	250	540	3·74	Oreb T2-5	Cement and GGBS	250	616	3·74
Oreb2-1	Cement	125	568	7·30	Oreb T2-7	Cement and GGBS	250	782	3·74
Oreb2-1	Cement	175	910	5·21	Oreb T2-7	Cement and GGBS	250	732	3·74
Oreb2-1	Cement	250	1146	3·65	Oreb2-2	Cement and GGBS	125	428	7·30
Oreb3-1	Cement	125	396	7·28	Oreb2-2	Cement and GGBS	175	624	5·21
Oreb3-1	Cement	175	420	5·20	Oreb2-2	Cement and GGBS	250	938	3·65
Oreb3-1	Cement	250	414	3·64	Oreb3-2	Cement and GGBS	125	156	7·28
Quig1	Cement	150	79	6·07	Oreb3-2	Cement and GGBS	175	290	5·20
Quig2	Cement	200	135	4·55	Oreb3-2	Cement and GGBS	250	196	3·64
Quig3	Cement	250	211	3·64	Rah 6	Cement and GGBS (2:3)	150	75	6·62
Rah 4	Cement	150	220	6·62	Rah 6	Cement and GGBS (2:3)	200	205	4·96
Rah 4	Cement	200	235	4·96	Rah 6	Cement and GGBS (2:3)	250	285	3·97
Rah 4	Cement	250	540	3·97	Arlan T3-3	Cement and filler	250	36	3·25
Corr 4	Cement and Gypsum (3:1)	200	242	4·69	Arlan T3-3	Cement and filler	250	22	3·25
Rah 5	GGBS	150	32	6·62	Oreb T1-2	Cement and filler	250	342	3·72
Rah 5	GGBS	200	345	4·96	Oreb T1-2	Cement and filler	250	320	3·72
Rah 5	GGBS	250	380	3·97	Oreb T2-3	Cement and filler	250	274	3·74
Rah 7	GGBS and Gypsum (17:3)	150	10	6·62	Oreb T2-3	Cement and filler	250	312	3·74
Rah 7	GGBS and Gypsum (17:3)	200	740	4·96	Dömle P1 F	Cement, GGBS and gypsum (2:2:1)	100	303	8·94
Rah 7	GGBS and Gypsum (17:3)	250	1160	3·97	Dömle P1 F	Cement, GGBS and Gypsum (2:2:1)	200	483	4·47

Table 2. Unconfined compressive strength and water to binder ratio for stabilised peats

In 2001, 'EuroSoilStab: Development of design and construction methods to stabilise soft organic soils' was published – the result of collaborative research between six European countries to investigate the stabilisation of organic soils and provides details of the design, testing and construction of soil stabilisation projects in organic soils. The findings of this work provide further support to those detailed in Table 6·1 of EuroSoilStab (2001).

5. Conclusions

Peat soils are problematic in terms of their low strength, high compressibility and high moisture and organic contents. DSM

Binder	No. of data	r^2	p-values		
			η	OC	H
All binders	39	0·329	0·013	0·003	0·776
Cement only	14	0·548	0·021	0·157	0·152
Cement/GGBS only	12	0·926	0·000	0·000	0·001

Table 3. Regression analysis results using Figure 3(b) data

provides an alternative approach to the conventional dig and replace methods used today, with the potential for improved strength and settlement properties, as well as ground remediation in contaminated soils. Conclusions drawn in the paper from a review of previous literature and a new stabilised strength database will assist in the selection of an appropriate binder and binder content in pre-contract mixing trails, which are routinely conducted to ascertain the feasibility of soil stabilisation in organic soils. The conclusions are summarised below.

(*a*) The compiled laboratory results show that stabilisation of organic soils is possible and that significant strength increases can be achieved with cement and cement–GGBS binders, even beyond 28 days. Samples stabilised with lime and fly ash binders show lesser strengths gains than those seen with cement and GGBS binders.
(*b*) 28-Day UCS values of between 100 and 1200 kPa are achievable with stabilisation, providing ample strength for many engineering purposes such as foundations for roads, railways and so on.
(*c*) There is no obvious correlation between 28-day UCS and initial moisture content alone.
(*d*) The 28-day UCS shows some correlation with the ratio of the mass of water to the mass of binder in the mix, and therefore is a more suitable basis for estimating expected strengths at design stage. Highest strengths (within the limits of the database) are achieved at water to binder ratios of ≈4.
(*e*) The database has also been used to confirm and quantify (for the first time to this scale) the influence of the degree of humification (as measured by von Post's H classification) on the stabilised UCS value. The difficulties in achieving high stabilised UCS values in highly humified peats emerge; these peats are most likely to have low UCS values to begin with.
(*f*) The trends identified in (*d*) and (*e*) have been confirmed with a statistical analysis of the data, and are encouraging given that it has not been possible to compare mixing energies for the various studies collated. If sufficient care is taken to report the relevant variables in future trials, it may be possible to develop simple design equations to estimate expected stabilised strengths. Other factors are clearly relevant in laboratory testing, such as prestress during curing, host soil temperatures and curing temperatures. Evidence from laboratory and field trials shows strengths achieved in the laboratory will be greater than those obtained in the field owing to factors such as the amount and quality of mixing and uniformity of the soil profile.

Acknowledgements

The authors acknowledge the financial support provided by the Irish Research Council for Science, Engineering and Technology under the Embark Initiative, as well as the technical help

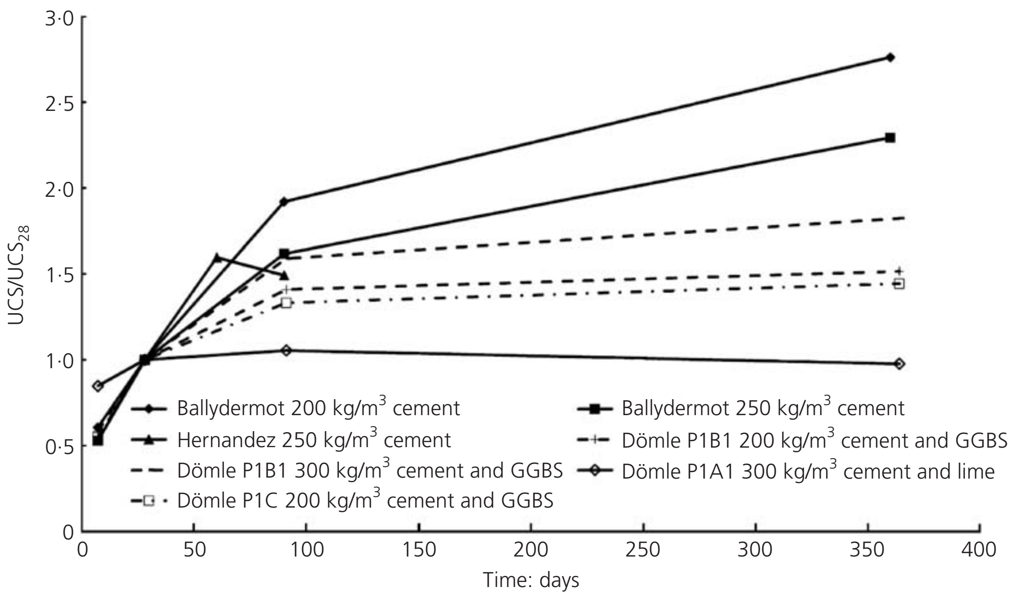


Figure 4. Graph of unconfined compressive strength against time for a number of test data

provided by Dr Dan Adams of Keller Geotechnique in the compilation of this paper.

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Volume 167 Issue GI1

Award-winning paper in 2012

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Award-winning paper in 2012

Papers published in *Ground Improvement* are eligible for awards from the Institution of Civil Engineers. Papers from any of the ICE journals can be nominated for several awards. In addition, each journal has awards dedicated to their specific subject area.

On Friday 18 October 2013, ICE president Barry Clarke presented an award to the following paper published in *Ground Improvement* in 2012. The editorial panel nominated their best papers and an awards committee chaired by David Balmforth allocated the awards.

Telford Premium Prize

The Telford Premium Prize, awarded for the best paper on ground improvement, was awarded to Timoney *et al.* (2012).

Abstract

Soil mixing, or soil stabilisation, is a method of enhancing the geotechnical properties of suitable host soil through the addition of cementitious and/or pozzolanic binders in either dry or slurry forms. In dry soil mixing, the binder is injected into the soil in powder form using compressed air. Published laboratory experiences of stabilising highly organic soils in dry soil mixing laboratory trials are collated in this paper. A large database of stabilised strengths is compiled from which it emerges that cement and a cement/ground granulated blast furnace slag combination are the most suitable binders for peat soils, and that the ratio of mass of water to mass of binder and the von Post classification H value are important indicators of stabilised strength. The data provide a useful frame of reference for practitioners wishing to select an appropriate binder type and content for mixing trials in peat. Stabilised strength gain over time is discussed, as are issues such as soil temperature, binder temperature sensitivity and prestressing.

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Bryan McCabe and Martin Timoney, winners of the Telford Premium Prize, with ICE President Barry Clarke

Some Laboratory Soil Mixing Trials of Irish Peats

Some laboratory soil mixing trials of Irish peats

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ABSTRACT

Highly organic soils such as peat can prove problematic due to their high water content and compressibility when encountered in construction projects. Peat is widespread in Ireland, covering about 17.2% of the country. Many secondary roads in Ireland have been constructed on peat, especially in western Ireland. Road widening and improvement schemes are complicated by extensive settlement and stability issues. Dry Soil Mixing (DSM) is envisaged as a potential method of enabling road widening without adversely affecting the adjacent road.

DSM involves the injection of dry cementitious and pozzolanic binders in to the soil which then react with the pore water of the soil resulting in improved strength and stiffness characteristics. The stabilisation of organic soils is more challenging than that of inorganic soils, as humic acids hinder the hydration processes and the reactions required for the development of strength, creating insoluble products that coat the soil particles, preventing them from binding properly.

This paper presents new laboratory test data from a series of stabilisation trials carried out on Irish peats, using different binders, including cement, rapid hardening cement and ground granulated blast furnace slag. The results show that ratio of water to the total binder content is a key determinant of stabilised strength.

An investigation of the Embodied Energy required in three hypothetical projects shows the production of the binders required in the stabilisation to be the significant contributor and not transportation of the binder to the site. The release of gases from the peat during DSM could be a significant contributor to emissions.

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1. INTRODUCTION

Soil stabilisation is a method of improving the characteristics of a soil through the addition of cementitious and/or pozzolanic binders. Outcomes include increased strength, better deformation characteristics and confinement/remediation of contaminated ground. The stabilisation of organic soils is more difficult than that of inorganic soils, requiring greater binder contents to achieve the required strength as organics in the soil react with the binders creating insoluble products that coat the soil particles delaying and inhibiting the strengthening reactions.

Dry Soil Mixing (DSM) involves the injection of dry binders, such as cement, lime, ground granulated blast furnace slag (GGBS), *etc.,* into the soil. Two mixing methods exist: Deep Dry Soil Mixing, where the soil is stabilised in columns; and Mass Stabilisation, where the soil is stabilised in blocks up to 5m deep. The added binder then reacts with the pore water, initiating the strengthening reactions. DSM provides an alternative method of ground improvement to conventional *excavate and replace* methods used where peat is encountered.

Timoney et al. (2012) provide a detailed review of the stabilisation of organic soils including the various parameters which affect the stabilised strength, including binder type, curing temperature and prestress, as well as detailing the reaction characteristics of different binders. The authors compiled a large database of dry soil mixing stabilisation results from European and Japanese published data, investigating relationships between the strengths achieved and the initial moisture content, binder content, curing time and water to binder ratio. The focus of this paper is on Irish peats; new data is presented and interpreted in the context of existing data and the embodied energy associated with DSM in Irish peats is discussed.

2. PEAT

Peat is a highly organic soil type formed from decaying of plants and vegetation rich in carbohydrates to humus, a process known as humification. Peats can be classified into three simple categories in terms of their degree of humification (Hártlen, 1996):

(a) *Fibrous* peat which has a low degree of humification. This form will have a distinct plant structure and will produce a brown to colourless cloudy to clear water when squeezed.
(b) *Pseudo-fibrous* peat has a mid to high degree of humification. The plant structure is now less identifiable and a mushy mass will be extruded when squeezed.
(c) *Amorphous* is the classification used for the most highly humified peat. Very little, if any, of the plant structure remains and on squeezing no free water is released.

Von Post (1922) provides a very detailed system for classifying peats, taking into account degree of humification, moisture content, type of plants and fibres. This was later extended by Hobbs (1986) to include organic content, smell, plasticity, pH and tensile resistance. One of the main classifications in the system is von Posts degree of humification, H classification. H is a scale ranging from 1 (least humified) to 10 (most humified) representing the state of decay and Hártlen's (1996) categories fall as follows: *fibrous* peats lie in the range H1-H4, *pseudo-fibrous* in the range H5-H7 and *amorphous* between H8 and H10.

2.1. Moisture Content, Strength and Compressibility

Peats, due to manner in which they are formed (discussed later) have very high organic content, typically between 80 and 99%, and very high moisture contents ranging up to many hundreds and even thousands of percent. Typically moisture contents are seen to reduce with an increasing degree of humification due to the manner in which water is stored in each degree of humified peat. Fresh peats have high void ratios and water is stored freely in these voids but with increasing degrees of humification the voids reduce and a lesser amount of water is held by capillary action and eventually by physical, chemical and osmotic processes bound to the peat particles. Due to these very high moisture contents the bulk density is typically found to be close to that of water due to the low specific gravity of the organic constituents making up the peat and in partially saturated peats can be below that of water.

From the authors' experience of current literature on dry soil mixing laboratory and field trials in peat, unconfined compression strengths for peat are seldom reported due to the difficulties in sampling and testing. Peat soils have very low strengths, with unconfined compression strengths typically less than 15kPa. Fibrous peats have higher strengths than amorphous peats as the fibres act to reinforce the peat in the vertical direction but their spongy nature, high void ratio and lack of soil structure results in high compressibility and large deformations when stressed. Further details on the strength of Irish peats can be found in Long (2005).

2.2. Irish Peat Bogs

In Europe many countries have significant areas of peat deposits; 10m hectares of Finland, 1.5m hectares of Sweden and 3m hectares of Norway are covered in peat. In Ireland peat covers 17.2% of Ireland's landmass, giving a total of nearly 1.2m hectares (Hobbs, 1986). These peats are found in three main forms: raised bogs, blanket bogs and fen peats. Figure 1 shows the coverage of raised and blanket bogs across Ireland.

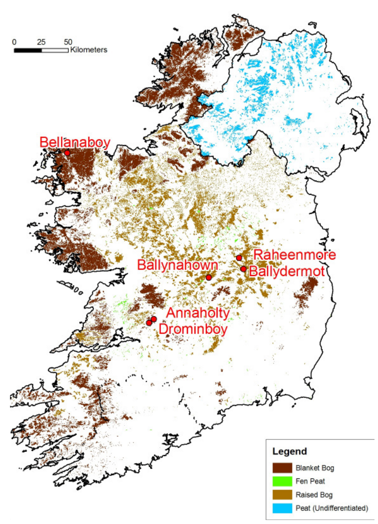

Figure 1: Irish Peatlands Map (courtesy of Geological Survey of Ireland and Geological Survey of Northern Ireland).

2.2.1 Raised Bogs

Raised bogs, normally found in Ireland's midlands, have thicknesses typically between 9 and 12m and make up 0.31m hectares of Irelands peat (Bord na Móna, 2011). They initially began as lakes or hollows, as shown in Figure 2 which were fed by nutrient rich inflows. These nutrients allow plants and vegetation to grow particularly around the edges which results in lake filling and as the bog grows, flow through it becomes impeded resulting in paludification or swamping of the area. As plants and vegetation die off peat is formed and the level of the bog rises above the water table resulting in reliance by the vegetation on precipitation for its nutrient supply. Once the hollow has reached a level surface further growth occurs in an upward dome shape (Hammond, 1981).

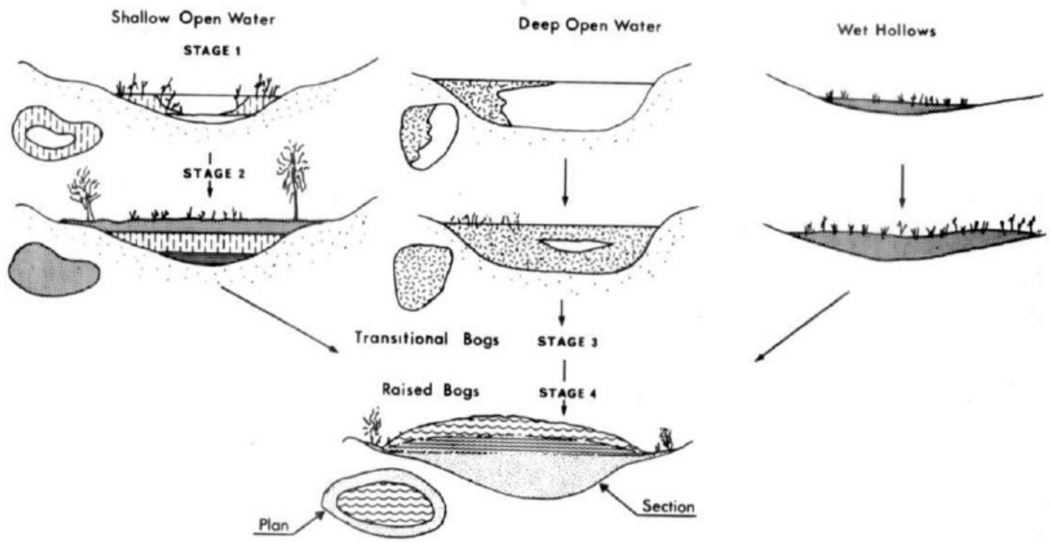

Figure 2: Raised Bog formation stages (Hammond 1981)

2.2.2 Blanket Bogs

Blanket bogs are the main type of bog found in Ireland, particularly in the west of Ireland and in mountainous regions. They are up to 4,000 years old and typically form shallow coverings with depths ranging from 1 to 6m (average of around 2.6m); higher altitude blanket bogs are generally thin with deeper profiles located in depressions and over flat areas (Hobbs, 1986).

The formation of blanket bogs is climate controlled, *i.e.*, cool summers and high precipitation levels on slopes (<20°) where drainage is impeded. In a similar way to raised bogs they initially begin in shallow hollows through water logging caused by the low nutrient precipitation, as shown in Figure 3. As the hollows fill the bog spreads outwards and connects with nearby formations to form a blanket of peat.

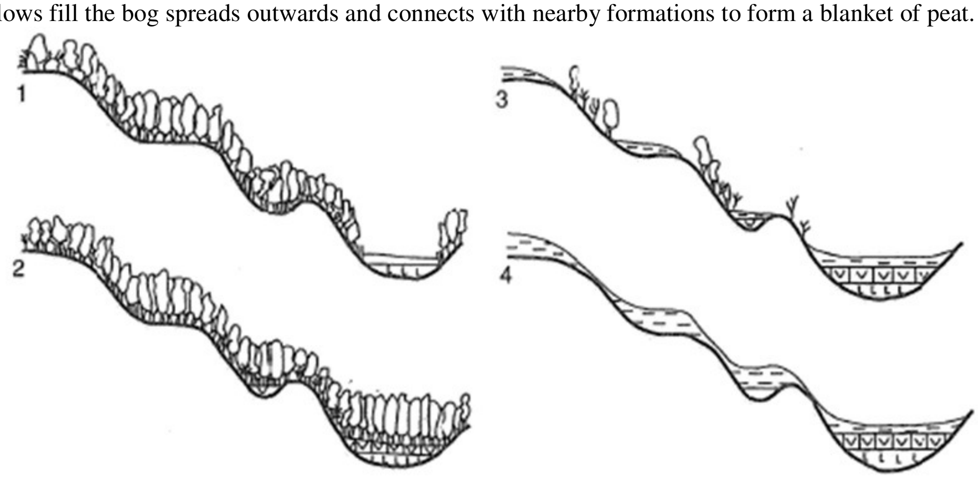

Figure 3: Blanket bog formation (Moore 1987)

2.1.3 *Fen Peat*

Fen peats derive from the decay of vegetation once fed by groundwater rich in calcium and other nutrients. In Ireland they tend to be shallow with depths of around 2.2m and are mainly found in the midlands at the base of raised bogs. These are Ireland's oldest bogs, with formation beginning about 9,000 years ago but many Irish fens have been drained for cultivation purposes but have only provided poor pasture (Hammond, 1981).

3. IRISH STABILISATION TRIALS

A number of laboratory stabilistion trials have been carried out on Irish peast and are collated in Table 1. This paper compares the results across four categories: strength, stiffness, 1-D compression and creep.

Table 1 :Collated Irish peat stabilisation trials

Reference:	Source:	w_i (%)	ρ (kg/m^3)	Organic Content (%)	von Post H	pH	WTBR
Raheenmore	Hebib & Farrell, 2003	1200	1,075	98-99	2	5.3	3.97, 4.96 6.62
Ballydermot	Hebib & Farrell, 2003	850	1,125	94-98	6-9	4.9	4.03, 5.03
Bellanaboy	Quigley & O'Brien, 2010	1019	1,000	98	7-8	4.7	3.64,4.55 6.07
Ballynahown	Timoney *et al*, 2011	800	950	97-98	3	4.8	2.81, 3.38 4.22, 5.63
Annaholty	Ramboll, 2006	991-1664	1,100	88-99	-	5.0	4.06, 5.07 6.77
Druminboy	Ramboll, 2006	861-1580	1,100	88-96	-	5.5	4.05, 5.06 6.74

3.1. Strength

Strength and stiffness measurement were carried out using unconfined compression testing using the methodology in EurosoilStab (2001) and illustrated in Figure 4.

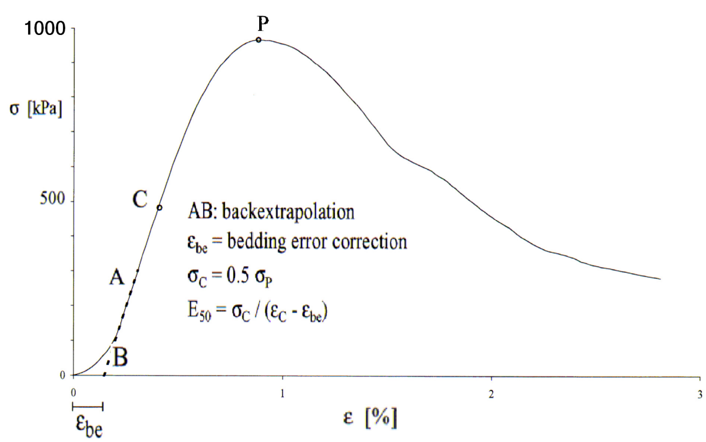

Figure 4 : Methodology for determining strength and stiffness (left) with typical specimen (right)

Timoney et al. (2012) used the Water to Binder Ratio (WTBR, η) defined in equation 1 as a means of combining the influence of water content and binder quantity on the stabilised strength. The WTBR relates the mass per unit volume of water (m_w) in the soil to the mass per unit volume of binder (m_b) added in the stabilisation process. The mass of water is a function of the soil's initial water content (w_i) as no additional water is added during in the DSM process.

$$\eta = \frac{m_w}{m_b} = \frac{\rho}{m_b\left(1+\frac{1}{w_i}\right)} \quad (1)$$

The η value was calculated using the initial water content (w_i), the density of the peat (ρ) and the mass of binder per unit volume (m_b). The relationship between the 28 day unconfined compression strength (UCS_{28}) and η, annotated by binder type, is shown Figure 5. Where two binder constituents were used, the proportions are 50:50 unless otherwise stated. The site location is also annotated beside the data point. Figure 5 highlights a general tendency for increased UCS_{28} values at low η values as might be expected, with some high UCS_{28} values achieved for η <4.5. Research at NUI Galway has shown that these values of η are lower than would be necessary to achieve comparable strength gains in organic clays.

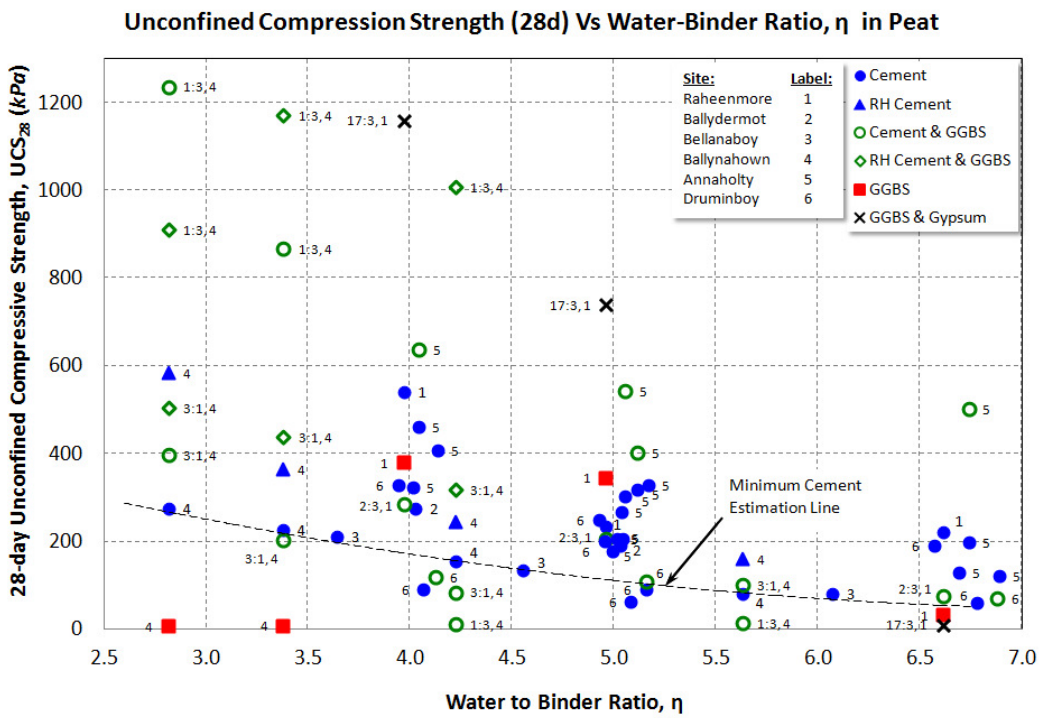

Figure 5 : Unconfined Compression Strength (28d) vs Water-Binder Ratio, η in Irish Peats

The trend of reducing UCS_{28} with η appears clearest for the cement binders, and an approximate lower bound line is shown in Figure 5 to aid designers estimate the minimum likely strength for a given binder dosage. The Rapid Hardening (RH) cements provide greater stabilised strengths at 7 and 28 days than Ordinary Portland Cement. Mixes with 3:1 cement to GGBS gave results similar to the cements alone. However, the 1:3 cement to GGBS mixes, only performed on the Ballynahown peat, showed very high strengths at binder contents of 250 and 300kg/m^3 but poor strengths at 150 and 200kg/m^3. These results may indicate the existence of a binder threshold, particular to the peat in question, which must be exceeded before any strength gain will occur. Axelsson et al. (2002) reports the binder threshold to be the content required to neutralise humic acids present in the soil and allow stabilisation to occur, while Hebib and Farrell (2003) detailed 150kg/m^3 as the minimum content required for stabilisation in their trials. Quigley and O'Brien (2010) also report that a binder concentration of 150kg/m^3 of Ordinary Portland Cement is required to minimise post mixing strains.

GGBS is a latent hydraulic binder and requires activation by calcium hydroxide, provided by the cement in the plotted data or by gypsum in the case of the Raheenmore peat (where very good strength gains are seen with an 85:15 GGBS and gypsum binder). The Ballynahown peat showed that a lack of activation can result in very poor strength gains, but further work is needed to understand why reasonable strengths were seen when GGBS alone was used with the Raheenmore peat.

EuroSoilStab (2001) shows an overall comparison of the results for stabilisation trials in peat across Europe and shows Irish peats to have relatively poor strength gains. The data in Figure 5 suggests high strengths can be achieved when using certain binders and high binder contents (up to 300kg/m^3). It should be noted that these strengths may not be achieved in the field. Parameters such as mixing homogeneity, prestress loading, curing temperature and *insitu* water content at the time of mixing may result in lesser strengths; Hayashi and Nishikawa (1999) detail the factor between field and laboratory results as between 2 and 5, with an average of 3, while experience in Norway by Braaten *et al.*, (1999) showed that field strengths in fact well exceeded strengths achieved in the laboratory.

3.2. Stiffness

The stiffness of stabilised peat (E_{50} – see Figure 1 for definition) was calculated using the methodology outlined in EurosoilStab (2001). Figure 6 shows a pattern of increasing stiffness at 90 days in rough proportion to the cement binder concentration. A review of undrained shear stength at 90 days suggests that a relationship of $E_{50} = 150c_u$ gives a reasonable first estimate of stiffness (Figure 7).

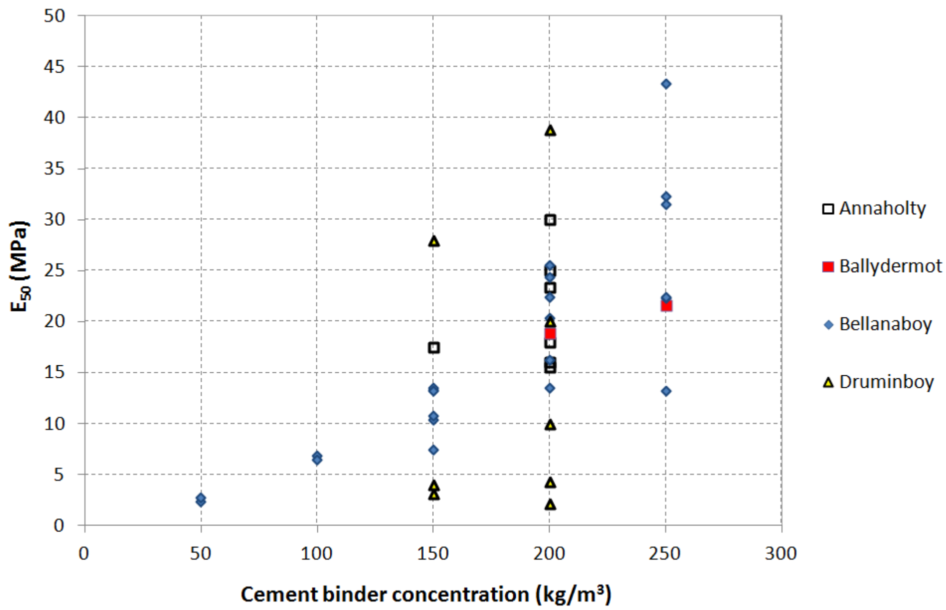

Figure 6 : Compariion of stiffness at 90 days for various cement only binder concentrations.

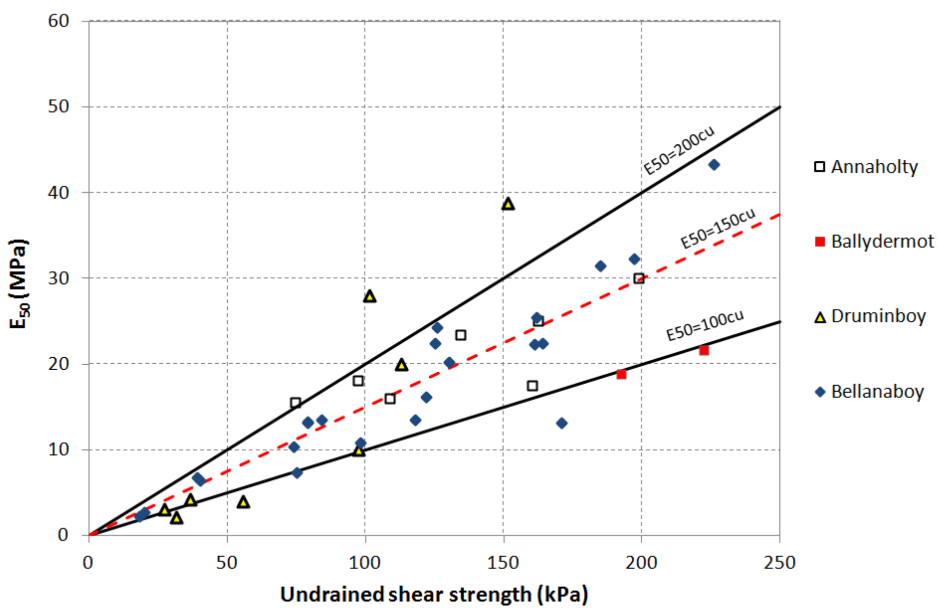

Figure 7 : Correlation between undrained shear strength and stiffness at 90 days for various cement only binder concentrations.

The binder concentratuion was found to have an important role in the early stiffness of the stabilised peat. Following mixing, the stabilised Bellanaboy peat was placed in moulds and a confining stress of 18kPa was placed on top. The axial strain was measureed as the specimens consolidated under the initial stress (Figure 8). At cement concentration of 150kg/m³ and above there was sufficient binder to minimise further compression after Day 1. The lower cement concentrations resulted in increasing the axial strains over the next 5 to 6 days.

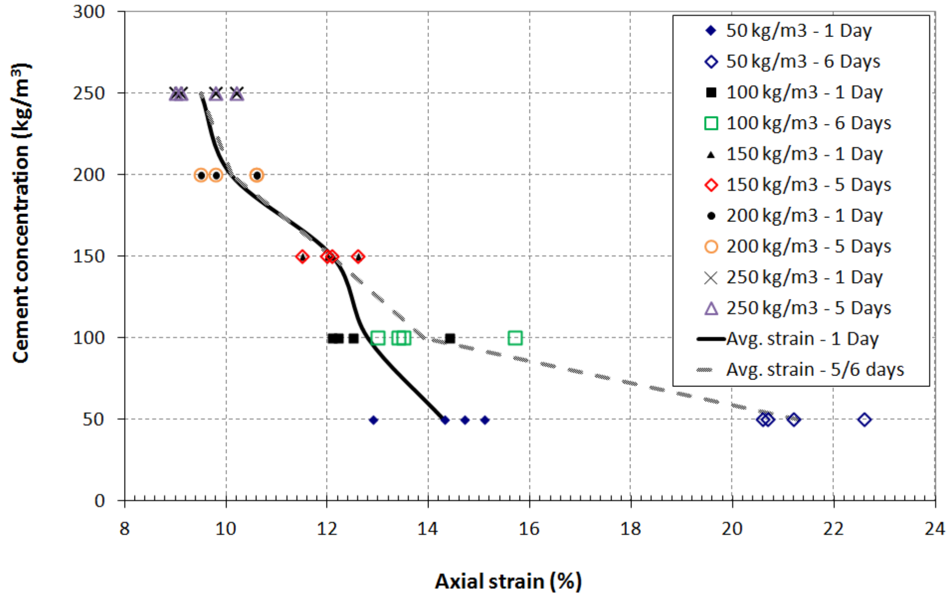

Figure 8 : Axial strains in specimens following mixing

3.3. Compressibility

Oedometer tests using a standard 75mm diameter by 20mm high specimens carried out on peat stabilised with 200kg/m³ of cement from Bellanaboy (Quigley and O'Brien, 2010) and Ballydermot (Hebib, 2001). The results are plotted together on Figure 9 and show a similar stress strain response. The yield stress appeared to vary between 100kPa and 150kPa for both studies.

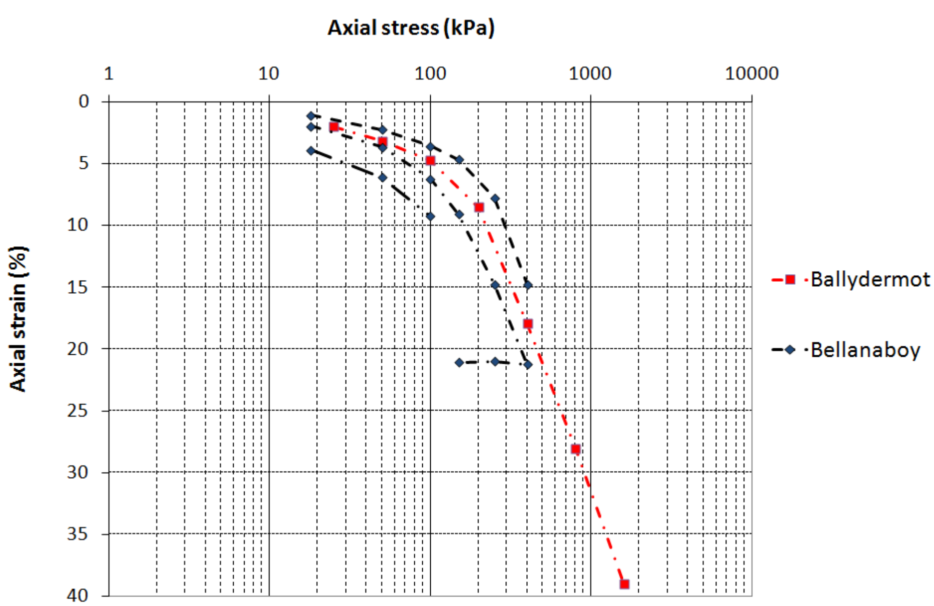

Figure 9 : One dimensional consoldiation testing

3.4. Creep

The secondary consolidation coefficient, C_α, was measured on the linear section of the log time versus deformation plot after each load increment increase. C_α is defined as:

$$C_\alpha = \frac{\left(\Delta H_i / H_{i0}\right)}{\log\left(t_2 / t_1\right)} \qquad 2$$

where H_i is the height of the specimen at the end of primary settlement during each load increment and t_1 and t_2 are the start and end time of the creep measurement. The variation between the blanket bog at Bellanaboy and the raised peat at Ballydermot is shown in Figure 10 and shows a gradual increase up to 100 to 150kPa before increasing more sharply once the yield stress of the stabilised peat is exceeded. Typical C_α values for virgin peat vary between 3% to 6%.

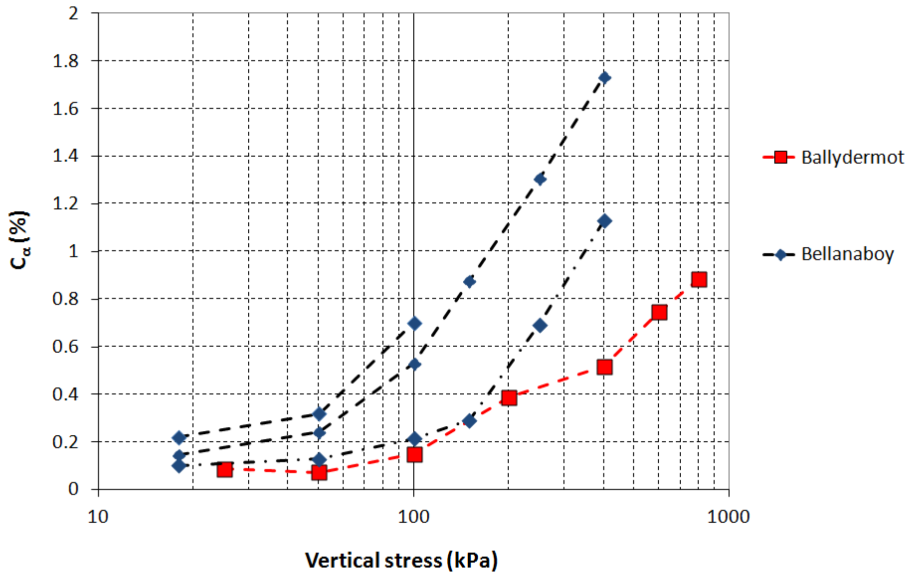

Figure 10 : Comparision creep measurements between blanket bog (Bellanaboy) and raised bog (Ballydermot).

4. EMBODIED ENERGY OF PEAT STABILISATION

There is an increasing awareness of sustainability issues in construction and sustainability is likely to have a greater influence on the choice of construction method. A common comparison tool in evaluating the sustainability of construction methods is the embodied energy (EE). Embodied energy is the energy required to manufacture and supply to the point of use, a product, material or service and is measured in Joules. An EE comparison was carried out for three hypothetical sites in Ireland for treating a 50m long by 5m wide by 5m deep peat block. There is currently a single source of GGBS binder in Ireland while cement production plants are located at various locations across Ireland, shown in Figure 11. The sites A, B and C are located 100km, 200km and 300km away from the GGBS source respectively and are all assumed to be 100km from an OPC production site. The binder concentration is assumed to be 250kg/m^3. Crushed aggregates are readily available across Ireland and the three sites are assumed to be 30km from a suitable quarry.

In this calculation, three types of process are shown, covering materials, installation and transportation energies. Of these, the material energy calculation involves finding the total volume of each material used, calculating its weight, and multiplying this by its Embodied Energy Intensity (EEI) value. The transportation energy is that which is required to move all equipment and materials to and from the site. This is calculated using the litres of fuel consumed by the vehicles multiplied by the respective EEI value for the fuel. The installation energy is calculated by multiplying the amount of fuel used by the machinery with its EEI value. All three values of the material, transportation and installation energy are then summed to give the total embodied energy. The Embodied Energy Intensity values have been adapted from Hammond and Jones (2011) and are provided in Table 2. The results shown in Figure 12 suggest that the material production is responsible for the largest proportion of EE and transport EE is not a significant variable.

Table 2 :Embodied Energy Intensity values

Material	Unit	EEI (MJ/unit):
Ordinary Portland Cement	Kg	5.4
Ground granulaed blast slag	Kg	2.4
Crushed rock	Kg	0.11
Geotextile	Kg	78.1
Diesel fiel	L	45.0

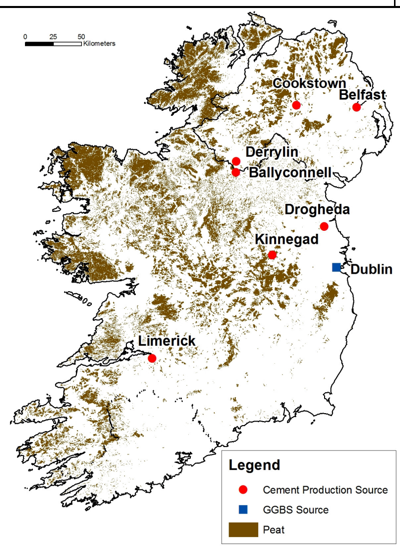

Figure 11 : Cement and GGBS depots in Ireland

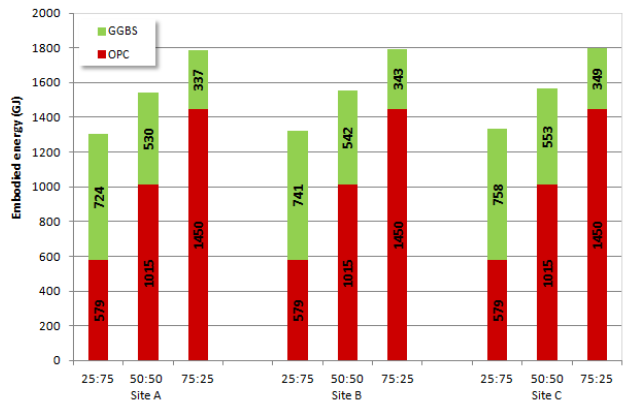

Figure 12 : Embodied Energy calculations for stabilised peat

Typically in construction projects there is a good correlation between embodied energy and CO_2 emissions (e.g. Inui et al., 2011). However, peat bogs are a vast natural reservoir of organic carbon. The invasive nature of soil mixing disturbs a large volume of peat, potentially releasing large volumes of CO_2, methane and other gases. Nayak et al.,(2008) provide some guidance on calculating the carbon losses for excavations and drainage works in peat. It is noteworthy that the excavate and replace approach, often favoured in Ireland when peat is encountered, is also a cause of CO_2 release. However, further research is required to evaluate the carbon loss from peat bogs and the influence of various types of construction.

5. CONCLUSION

Peat is a highly organic soil type unlike other soils, formed from the decay of the dead remains of plant and vegetation. It has a very high moisture content and compressibility. Strengths are very low and in many cases very difficult to quantify due to the fibrous nature and difficulties in undisturbed sampling.

The data in this paper shows that significant strength gains can be obtained by stabilising Irish peats. Unlike stabilisation in other soils, peat requires larger binder concentrations to produce the required strength improvement. The plotted data shows a trend of increasing strength with reducing WTBR. This trend is clearest for cement binders based on the data from the four different sites across a range of degrees of humification. Also visible is the variation in strength that can occur where the same binder is used in two different peats, in particular binders which included a GGBS portion. Cement and GGBS data from the Ballynahown peat show the possible existence of a binder threshold between 200 and 250kg/m^3. The plot may be used as a design guide for future Irish stabilisation projects, although trials are still be required to determine the achievable strengths.

A study of the Embodied Energy required to carry out a peat stabilisation project showed the transportation of the binder to site to be insignificant compared to the amount of embodied energy spent in production binder. It is also noted that carbon stored within the peat body released during mixing can contribute to the carbon emissions of the project but further research is required to quantify this and compare with alternative construction methods such as excavate and replace and piling.

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Appendix B: Preliminary Stabilisation Trial Results

B.1 Ballynahown Peat Stabilisation Trials:

Ordinary Portland Cement Binder:																	
Sample Reference	Binder Type	Binder Content kg/m^3	Binder Proportions	Raw Moisture Content, w_i	Organic Content	Mixed Moisture Content, w_{mix}	Fresh Density ρ_f, kg/m^3	Curing Time, t days	Curing Loading kPa	320*mm* Mould Compression mm	Sample Length mm	Stabilised Density, ρ_s, kg/m^3	Water to Binder Ratio	Stabilised Moisture Content, w_s	UCS, q_t kPa	Secant Stiffness E_{50}, MPa	Failure Strain ε_f
P1-150-C-B	OP Cement	150	1	795%	95%	224%	1,035.0	7	18	29	131	1,093.0	5.63	251%	78.1	4.4	1.79%
P1-150-C-T	OP Cement	150	1	795%	95%	224%	1,035.0	7	18	-	133	1,079.3	5.63	252%	119.4	4.4	4.09%
P1-150-C-B	OP Cement	150	1	795%	95%	224%	1,004.4	28	18	35	127	1,066.8	5.63	273%	100.2	8.0	1.62%
P1-150-C-T	OP Cement	150	1	795%	95%	224%	1,004.4	28	18	-	124	1,103.5	5.63	243%	133.4	4.2	3.27%
P1-150-CB	OP Cement	150	1	795%	95%	224%	998.2	91	18	40.5	129	1,075.1	5.63	259%	162.8	7.1	3.75%
P1-150-CT	OP Cement	150	1	795%	95%	224%	998.2	91	18	-	131	1,099.2	5.63	253%	191.8	10.2	2.72%
P1-200-C-B	OP Cement	200	1	717%	94%	221%	1,051.9	7	18	17	132	1,131.9	4.17	212%	148.1	7.6	3.30%
P1-200-C-T	OP Cement	200	1	717%	94%	221%	1,051.9	7	18	-	132	1,105.6	4.17	211%	146.0	4.9	4.69%
P1-200-C-B	OP Cement	200	1	717%	94%	221%	1,044.4	28	18	24	134	1,138.2	4.17	220%	150.8	11.3	2.76%
P1-200-C-T	OP Cement	200	1	717%	94%	221%	1,044.4	28	18	-	131	1,132.7	4.17	214%	187.3	15.1	3.16%
P1-200-CB	OP Cement	200	1	717%	94%	221%	1,034.0	91	18	43.5	135	1,127.3	4.17	202%	315.7	32.2	2.47%
P1-200-CT	OP Cement	200	1	717%	94%	221%	1,034.0	91	18	-	135	1,127.3	4.17	202%	315.7	32.2	2.47%
P1-250-C-B	OP Cement	250	1	727%	94%	185%	1,064.2	7	18	19	130	1,151.6	3.34	182%	203.3	10.9	3.14%
P1-250-C-T	OP Cement	250	1	727%	94%	185%	1,064.2	7	18	-	130	1,209.3	3.34	177%	228.5	6.7	3.48%
P1-250-C-B	OP Cement	250	1	727%	94%	185%	1,074.5	28	18	26	134	1,148.2	3.34	180%	239.6	17.1	1.87%
P1-250-C-T	OP Cement	250	1	727%	94%	185%	1,074.5	28	18	-	135	1,148.9	3.34	182%	255.8	16.6	1.97%
P1-250-CB	OP Cement	250	1	727%	94%	185%	1,065.1	91	18	28.5	132	1,152.7	3.34	181%	412.4	46.9	1.85%
P1-250-CT	OP Cement	250	1	727%	94%	185%	1,065.1	91	18	-	131	1,183.3	3.34	176%	450.6	52.4	1.83%
P1-300-C-B	OP Cement	300	1	728%	98%	163%	1,093.9	7	18	16	130	1,191.0	2.78	159%	279.6	13.7	3.40%
P1-300-C-T	OP Cement	300	1	728%	98%	163%	1,093.9	7	18	-	130	1,163.5	2.78	158%	225.5	12.0	3.01%
P1-300-C-B	OP Cement	300	1	728%	98%	163%	1,085.9	28	18	13	134	1,166.9	2.78	163%	287.2	25.6	1.88%
P1-300-C-T	OP Cement	300	1	728%	98%	163%	1,085.9	28	18	-	124	1,166.0	2.78	157%	316.7	17.2	2.95%
P1-300-CB	OP Cement	300	1	728%	98%	163%	1,085.5	91	18	25.5	137	1,186.5	2.78	162%	480.5	52.2	1.68%
P1-300-CT	OP Cement	300	1	728%	98%	163%	1,085.5	91	18	-	136	1,192.6	2.78	159%	424.1	58.9	1.29%

B.1 Ballynahown Peat Stabilisation Trials:

Ordinary Portland Cement & GGBS Binder (25:75):																	
Sample Reference	Binder Type	Binder Content kg/m^3	Binder Proportions	Raw Moisture Content, w_i	Organic Content	Mixed Moisture Content, w_{mix}	Fresh Density ρ_f, kg/m^3	Curing Time, t days	Curing Loading kPa	320*mm* Mould Compression mm	Sample Length mm	Stabilised Density, ρ_s, kg/m^3	Water to Binder Ratio	Stabilised Moisture Content, w_s	UCS, q_t kPa	Secant Stiffness E_{50}, MPa	Failure Strain ε_f
P1-150 C+G-B	OPC & GGBS	150	25:75	684%	95%	257%	989.8	7	18	41	133	1,054.0	5.53	273%	9.9	1.3	2.24%
P1-150 C+G-T	OPC & GGBS	150	25:75	684%	95%	257%	989.8	7	18	-	129.5	1,063.2	5.53	252%	15.4	2.0	3.45%
P1-150 C+G-B	OPC & GGBS	150	25:75	684%	95%	257%	1,005.1	28	18	56	132	1,104.5	5.53	265%	8.3	0.2	6.43%
P1-150 C+G-T	OPC & GGBS	150	25:75	684%	95%	257%	1,005.1	28	18	-	115	1,103.9	5.53	231%	21.4	0.6	6.05%
P1-150-C+G B	OPC & GGBS	150	25:75	684%	95%	257%	995.2	91	18	50.5	122	1,097.0	5.53	266%	14.8	0.4	6.94%
P1-150-C+G T	OPC & GGBS	150	25:75	684%	95%	257%	995.2	91	18	-	127.5	1,097.2	5.53	241%	25.0	0.5	6.15%
P1-200 C+G-B	OPC & GGBS	200	25:75	758%	97%	250%	1,016.1	7	18	51	100	1,154.8	4.20	227%	12.8	0.7	2.48%
P1-200 C+G-T	OPC & GGBS	200	25:75	758%	97%	250%	1,016.1	7	18	-	129.5	1,110.8	4.20	218%	11.1	1.7	1.53%
P1-200 C+G-B	OPC & GGBS	200	25:75	758%	97%	250%	1,006.7	28	18	32	130	1,092.5	4.20	229%	12.9	0.9	2.29%
P1-200-C+G-B	OPC & GGBS	200	25:75	758%	97%	250%	1,044.4	91	18	42.5	128	1,124.7	4.20	229%	21.9	0.8	7.92%
P1-200-C+G-T	OPC & GGBS	200	25:75	758%	97%	250%	1,044.4	91	18	-	131	1,157.1	4.20	207%	40.7	2.0	5.28%
P1-250 C+G-B	OPC & GGBS	250	25:75	728%	97%	208%	1,073.6	7	18	32	133	1,145.3	3.34	182%	124.7	4.8	3.56%
P1-250 C+G-T	OPC & GGBS	250	25:75	728%	97%	208%	1,073.6	7	18	-	128	1,147.6	3.34	181%	138.9	7.3	3.68%
P1-250 C+G-B	OPC & GGBS	250	25:75	728%	97%	208%	1,056.6	28	18	40	130	1,201.7	3.34	181%	776.3	40.0	2.02%
P1-250 C+G-T	OPC & GGBS	250	25:75	728%	97%	208%	1,056.6	28	18	-	128	1,147.0	3.34	185%	1146.0	58.5	3.41%
P1-250-C+G-B	OPC & GGBS	250	25:75	728%	97%	208%	1,062.3	91	18	25.5	106	1,179.8	3.34	176%	2015.5	98.8	2.25%
P1-250-C+G-T	OPC & GGBS	250	25:75	728%	97%	208%	1,062.3	91	18	-	130	1,176.2	3.34	174%	1454.8	154.8	0.98%
P1-300 C+G-B	OPC & GGBS	300	25:75	740%	96%	176%	1,083.0	7	18	26	130	1,194.7	2.79	156%	725.9	34.6	3.96%
P1-300 C+G-T	OPC & GGBS	300	25:75	740%	96%	176%	1,083.0	7	18	-	131.5	1,203.8	2.79	152%	660.4	49.3	1.90%
P1-300 C+G-B	OPC & GGBS	300	25:75	740%	96%	176%	1,094.3	28	18	30	136	1,188.5	2.79	158%	1574.5	83.7	1.96%
P1-300 C+G-T	OPC & GGBS	300	25:75	740%	96%	176%	1,094.3	28	18	-	134	1,221.1	2.79	147%	1179.4	68.6	2.48%
P1-300-C+G-B	OPC & GGBS	300	25:75	740%	96%	176%	1,064.2	91	18	31.5	122	1,230.1	2.79	150%	583.8	34.8	3.02%
P1-300-C+G-T	OPC & GGBS	300	25:75	740%	96%	176%	1,064.2	91	18	-	128	1,190.1	2.79	156%	2029.4	140.0	1.51%

B.1 Ballynahown Peat Stabilisation Trials:

Ordinary Portland Cement & GGBS Binder (75:25):																	
Sample Reference	Binder Type	Binder Content kg/m^3	Binder Proportions	Raw Moisture Content, w_i	Organic Content	Mixed Moisture Content, w_{mix}	Fresh Density ρ_f, kg/m^3	Curing Time, t days	Curing Loading kPa	320*mm* Mould Compression mm	Sample Length mm	Stabilised Density, ρ_s, kg/m^3	Water to Binder Ratio	Stabilised Moisture Content, w_s	UCS, q_t kPa	Secant Stiffness E_{50}, MPa	Failure Strain ε_f
P2-150 C+G-B	OPC & GGBS	150	75:25	754%	-	264%	1,003.7	7	18	33	132	1,093.5	5.59	256%	134.04	5.32	3.39%
P2-150 C+G-T	OPC & GGBS	150	75:25	754%	-	264%	1,003.7	7	18	-	135	1,073.4	5.59	247%	110.07	7.86	2.05%
P2-150 C+G-B	OPC & GGBS	150	75:25	754%	-	264%	1,001.6	28	18	33	131	1,090.3	5.59	256%	126.58	10.91	2.09%
P2-150 C+G-T	OPC & GGBS	150	75:25	754%	-	264%	1,001.6	28	18	-	130	1,067.2	5.59	258%	94.15	16.23	1.39%
P2-150-C+G-T	OPC & GGBS	150	75:25	754%	-	264%	1,018.3	91	18	34.5	131	1,114.8	5.59	250%	255.58	12.91	2.44%
P2-150-C+G-B	OPC & GGBS	150	75:25	754%	-	264%	1,018.3	91	18	-	119	1,095.8	5.59	249%	249.73	14.69	3.39%
P2-200 C+G-B	OPC & GGBS	200	75:25	712%	-	234%	1,007.9	7	18	32.5	130	1,121.1	4.17	-	121.67	5.24	4.42%
P2-200 C+G-T	OPC & GGBS	200	75:25	712%	-	234%	1,007.9	7	18	-	120.5	1,052.0	4.17	-	119.66	4.02	4.36%
P2-200 C+G-B	OPC & GGBS	200	75:25	712%	-	234%	1,033.2	28	18	30	135	1,108.4	4.17	-	85.04	7.09	2.28%
P2-200 C+G-T	OPC & GGBS	200	75:25	712%	-	234%	1,033.2	28	18	-	136	1,099.8	4.17	-	98.91	10.30	2.97%
P2-200-C+G-T	OPC & GGBS	200	75:25	712%	-	234%	1,029.6	91	18	23.5	130	1,111.3	4.17	215%	254.60	17.93	1.69%
P2-200-C+G-B	OPC & GGBS	200	75:25	712%	-	234%	1,029.6	91	18	-	126.5	1,124.7	4.17	228%	262.57	29.17	1.54%
P2-250 C+G-B	OPC & GGBS	250	75:25	753%	-	189%	1,070.8	7	18	-	135	1,146.6	3.35	-	173.82	9.15	3.29%
P2-250 C+G-T	OPC & GGBS	250	75:25	753%	-	189%	1,070.8	7	18	-	129.5	1,145.4	3.35	-	177.76	7.47	3.25%
P2-250 C+G-B	OPC & GGBS	250	75:25	753%	-	189%	1,059.5	28	18	15	133	1,106.8	3.35	-	247.92	13.47	2.62%
P2-250 C+G-T	OPC & GGBS	250	75:25	753%	-	189%	1,059.5	28	18	-	134	1,118.5	3.35	-	194.75	15.71	3.06%
P2-250-C+G-T	OPC & GGBS	250	75:25	753%	-	189%	1,069.2	91	18	20.5	130	1,180.9	3.35	177%	615.83	66.94	1.98%
P2-250-C+G-B	OPC & GGBS	250	75:25	753%	-	189%	1,069.2	91	18	-	118	1,180.2	3.35	179%	572.87	51.15	2.12%
P2-300 C+G-B	OPC & GGBS	300	75:25	731%	-	172%	1,083.0	7	18	22	133	1,168.0	2.79	-	184.55	14.88	2.86%
P2-300 C+G-T	OPC & GGBS	300	75:25	731%	-	172%	1,083.0	7	18	-	133	1,171.8	2.79	-	215.43	16.08	2.51%
P2-300 C+G-B	OPC & GGBS	300	75:25	731%	-	172%	1,084.9	28	18	14.5	123	1,200.3	2.79	-	469.95	32.19	3.04%
P2-300 C+G-T	OPC & GGBS	300	75:25	731%	-	172%	1,084.9	28	18	-	133	1,165.8	2.79	-	401.70	35.24	2.01%
P2-300-C+G-T	OPC & GGBS	300	75:25	731%	-	172%	1,100.9	91	18	19	123	1,220.6	2.79	148%	836.40	74.68	2.16%
P2-300-C+G-B	OPC & GGBS	300	75:25	731%	-	172%	1,100.9	91	18	-	127.5	1,197.2	2.79	154%	777.43	60.74	1.91%

B.1 Ballynahown Peat Stabilisation Trials:

GGBS:																		
Sample Reference	Binder Type	Binder Content kg/m^3	Binder Proportions	Raw Moisture Content, w_i	Organic Content	Mixed Moisture Content, w_{mix}	Fresh Density ρ_f, kg/m^3	Curing Time, t days	Curing Loading kPa	320*mm* Mould Compression mm	Sample Length mm	Stabilised Density, ρ_s, kg/m^3	Water to Binder Ratio	Stabilised Moisture Content, w_s	UCS, q_t kPa	Secant Stiffness E_{50}, MPa	Failure Strain ε_f
GG 250	GGBS	250	1	805%	96%	-	-	7	18	45	136	1,123.2	3.38	200%	3.8	0.1	9.19%
GG 250-B	GGBS	250	1	805%	96%	-	-	28	18	50	131	1,121.8	3.38	198%	4.6	0.1	5.72%
GG 250-T	GGBS	250	1	805%	96%	-	-	28	18	-	120	1,173.2	3.38	185%	7.4	0.2	7.49%
GGBS-250-B	GGBS	250	1	805%	96%	-	-	91	18	39.5	127	1,166.7	3.38	193%	32.6	1.2	6.24%
GGBS-250-T	GGBS	250	1	805%	96%	-	-	91	18	-	115	1,188.8	3.38	181%	49.8	2.3	5.56%
GG 300	GGBS	300	1	749%	97%	-	-	7	18	-	136	1,155.0	2.79	198%	4.5	0.1	13.07%
GG 300-B	GGBS	300	1	749%	97%	-	-	28	18	37	132.5	1,173.6	2.79	-	1.6	0.1	3.02%
GG 300-T	GGBS	300	1	749%	97%	-	-	28	18	-	133	1,180.5	2.79	-	11.0	0.4	6.37%
GGBS-300-B	GGBS	300	1	749%	97%	-	-	91	18	-	123	1,188.8	2.79	182%	27.7	1.0	9.71%
GGBS-300-T	GGBS	300	1	749%	97%	-	-	91	18	-	135	1,124.0	2.79	167%	22.5	0.8	8.85%

B.1 Ballynahown Peat Stabilisation Trials:

Rapid Hardening Cement:																	
Sample Reference	Binder Type	Binder Content kg/m^3	Binder Proportions	Raw Moisture Content, w_i	Organic Content	Mixed Moisture Content, w_{mix}	Fresh Density ρ_f, kg/m^3	Curing Time, t days	Curing Loading kPa	320*mm* Mould Compression mm	Sample Length mm	Stabilised Density, ρ_s, kg/m^3	Water to Binder Ratio	Stabilised Moisture Content, w_s	UCS, q_t kPa	Secant Stiffness E_{50}, MPa	Failure Strain ε_f
RH 150-B	RH Cement	150	1	777%	96%	-	-	7	18	-	132	1087.1	5.61	257%	115.1	4.5	5.12%
RH 150-T	RH Cement	150	1	777%	96%	-	-	7	18	-	114	1091.0	5.61	253%	148.7	5.2	4.77%
RH 150-B	RH Cement	150	1	777%	96%	-	-	28	18	26	130	1080.9	5.61	262%	162.7	15.3	2.38%
RH 150-T	RH Cement	150	1	777%	96%	-	-	28	18	-	132	1096.8	5.61	259%	187.1	10.2	3.65%
RH-150-T	RH Cement	150	1	777%	96%	-	-	91	18	28.5	131	1084.2	5.61	245%	212.4	14.4	2.51%
RH-150-B	RH Cement	150	1	777%	96%	-	-	91	18	-	118	1107.0	5.61	260%	211.2	14.7	2.57%
RH 200-B	RH Cement	200	1	756%	97%	-	-	7	18	37	134	1112.8	4.20	208%	186.7	9.9	3.16%
RH 200-T	RH Cement	200	1	756%	97%	-	-	7	18	-	130	1100.9	4.20	207%	219.8	10.5	3.19%
RH 200-B	RH Cement	200	1	756%	97%	-	-	28	18	28	127	1102.0	4.20	-	293.0	14.6	2.86%
RH 200-T	RH Cement	200	1	756%	97%	-	-	28	18	-	131.5	1086.0	4.20	213%	239.2	13.6	3.52%
RH-200-T	RH Cement	200	1	756%	97%	-	-	91	18	22.5	134.5	1138.6	4.20	210%	405.2	33.8	1.99%
RH-200-B	RH Cement	200	1	756%	97%	-	-	91	18	-	128	1128.0	4.20	216%	277.1	27.7	1.50%
RH 250-B	RH Cement	250	1	835%	96%	-	-	7	18	26	100	1154.8	3.39	259%	329.8	8.5	4.75%
RH 250-T	RH Cement	250	1	835%	96%	-	-	7	18	-	80	1125.4	3.39	157%	233.9	7.8	3.69%
RH 250-B	RH Cement	250	1	835%	96%	-	-	28	18	27	131	1141.1	3.39	187%	375.9	31.3	1.78%
RH 250-T	RH Cement	250	1	835%	96%	-	-	28	18	-	130	1152.3	3.39	180%	423.4	36.5	1.82%
RH-250-T	RH Cement	250	1	835%	96%	-	-	91	18	22	132	1184.4	3.39	175%	514.3	38.7	2.28%
RH-250-B	RH Cement	250	1	835%	96%	-	-	91	18	-	127.5	1161.0	3.39	182%	377.2	40.1	4.08%
RH 300-B	RH Cement	300	1	790%	97%	-	-	7	18	15	129.5	1184.4	2.81	150%	505.3	43.6	2.12%
RH 300-T	RH Cement	300	1	790%	97%	-	-	7	18	-	123	1196.0	2.81	147%	607.8	40.0	2.44%
RH 300-B	RH Cement	300	1	790%	97%	-	-	28	18	18	131	1204.5	2.81	185%	635.5	48.1	2.14%
RH 300-T	RH Cement	300	1	790%	97%	-	-	28	18	-	135	1192.0	2.81	155%	651.7	41.2	1.91%
RH-300-T	RH Cement	300	1	790%	97%	-	-	91	18	24.5	131	1206.2	2.81	152%	764.6	64.8	2.22%
RH-300-B	RH Cement	300	1	790%	97%	-	-	91	18	-	115	1208.7	2.81	149%	815.6	63.7	2.07%

B.1 Ballynahown Peat Stabilisation Trials:

Rapid Hardening Cement & GGBS Binder (25:75):																	
Sample Reference	Binder Type	Binder Content kg/m^3	Binder Proportions	Raw Moisture Content, w_i	Organic Content	Mixed Moisture Content, w_{mix}	Fresh Density ρ_f, kg/m^3	Curing Time, t days	Curing Loading kPa	320*mm* Mould Compression mm	Sample Length mm	Stabilised Density, ρ_s, kg/m^3	Water to Binder Ratio	Stabilised Moisture Content, w_s	UCS, q_t kPa	Secant Stiffness E_{50}, MPa	Failure Strain ε_f
RHG 200-B	RHC & GGBS	200	25:75	822%	98%	-	-	7	18	27	131	1,100.0	4.24	217%	355.3	35.5	1.83%
RHG 200-T	RHC & GGBS	200	25:75	822%	98%	-	-	7	18	-	129	1,136.2	4.24	206%	289.6	20.7	3.61%
RHG 200-B	RHC & GGBS	200	25:75	822%	98%	-	-	28	18	24	133	1,115.0	4.24	203%	1129.0	63.4	1.97%
RHG 200-T	RHC & GGBS	200	25:75	822%	98%	-	-	28	18	-	134	1,111.7	4.24	216%	1105.2	70.8	2.05%
RHG-200-T	RHC & GGBS	200	25:75	822%	98%	-	-	91	18	36.5	131	1,131.8	4.24	212%	1853.2	168.5	1.27%
RHG-200-B	RHC & GGBS	200	25:75	822%	98%	-	-	91	18	-	125	1,117.2	4.24	326%	1573.5	145.7	1.38%
RHG 250-B	RHC & GGBS	250	25:75	864%	97%	-	-	7	18	28	91	1,163.0	3.41	185%	589.4	24.2	3.12%
RHG 250-B	RHC & GGBS	250	25:75	864%	97%	-	-	7	18	-	92	1,151.9	3.41	194%	582.8	20.8	4.01%
RHG 250-B	RHC & GGBS	250	25:75	864%	97%	-	-	28	18	36	132	1,179.2	3.41	192%	1540.3	110.0	1.74%
RHG 250-T	RHC & GGBS	250	25:75	864%	97%	-	-	28	18	-	133	1,137.9	3.41	191%	1069.5	67.7	2.13%
RHG-250-T	RHC & GGBS	250	25:75	864%	97%	-	-	91	18	32.5	131	1,130.3	3.41	186%	1131.3	101.0	1.12%
RHG-250-B	RHC & GGBS	250	25:75	864%	97%	-	-	91	18	-	128	1,112.0	3.41	190%	1531.8	193.9	0.93%
RHG 300-B	RHC & GGBS	300	25:75	841%	96%	-	-	7	18	23	127	1,165.5	2.83	168%	509.1	37.9	1.49%
RHG 300-T	RHC & GGBS	300	25:75	841%	96%	-	-	7	18	-	130	1,177.2	2.83	166%	534.6	35.6	2.11%
RHG 300-B	RHC & GGBS	300	25:75	841%	96%	-	-	28	18	32	133	1,142.8	2.83	148%	862.0	114.6	0.75%
RHG 300-T	RHC & GGBS	300	25:75	841%	96%	-	-	28	18	-	134	1,172.6	2.83	176%	1164.5	62.4	1.87%
RHG-300-T	RHC & GGBS	300	25:75	841%	96%	-	-	91	18	24.5	131	1,199.1	2.83	166%	1777.2	277.7	0.74%
RHG-300-B	RHC & GGBS	300	25:75	841%	96%	-	-	91	18	-	128.5	1,203.9	2.83	159%	2467.2	308.4	0.94%

B.1 Ballynahown Peat Stabilisation Trials:

Sample Reference	Binder Type	Binder Content kg/m^3	Binder Proportions	Raw Moisture Content, w_i	Organic Content	Mixed Moisture Content, w_{mix}	Fresh Density ρ_f, kg/m^3	Curing Time, t days	Curing Loading kPa	320*mm* Mould Compression mm	Sample Length mm	Stabilised Density, ρ_s, kg/m^3	Water to Binder Ratio	Stabilised Moisture Content, w_s	UCS, q_t kPa	Secant Stiffness E_{50}, MPa	Failure Strain ε_f
Rapid Hardening Cement & GGBS Binder (75:25):																	
2RHG 200-B	RHC & GGBS	200	75:25	794%	95%	-	-	7	18	27	131.5	1,118.1	4.22	215%	157.8	8.0	2.80%
2RHG 200-T	RHC & GGBS	200	75:25	794%	95%	-	-	7	18	-	130	1,123.4	4.22	207%	182.8	13.9	2.75%
2RHG 200-B	RHC & GGBS	200	75:25	794%	95%	-	-	28	18	24	132	1,117.4	4.22	216%	312.7	23.7	3.46%
2RHG 200-T	RHC & GGBS	200	75:25	794%	95%	-	-	28	18	-	131	1,144.9	4.22	210%	382.3	25.0	2.28%
2RHG-200-T	RHC & GGBS	200	75:25	794%	95%	-	-	91	18	36.5	130.5	1,145.6	4.22	210%	459.8	52.3	1.85%
2RHG-200-B	RHC & GGBS	200	75:25	794%	95%	-	-	91	18	-	129	1,135.6	4.22	205%	422.4	42.2	2.36%
2RHG 250-B	RHC & GGBS	250	75:25	771%	98%	-	-	7	18	28	127	1,146.7	3.36	183%	266.2	26.1	2.10%
2RHG 250-T	RHC & GGBS	250	75:25	771%	98%	-	-	7	18	-	129	1,156.5	3.36	174%	285.8	27.0	2.08%
2RHG 250-B	RHC & GGBS	250	75:25	771%	98%	-	-	28	18	36	109	1,162.5	3.36	185%	441.7	23.2	3.52%
2RHG 250-T	RHC & GGBS	250	75:25	771%	98%	-	-	28	18	-	130	1,151.5	3.36	183%	521.1	46.5	1.71%
2RHG-250-T	RHC & GGBS	250	75:25	771%	98%	-	-	91	18	32.5	128	1,159.5	3.36	179%	726.4	67.9	1.75%
2RHG-250-B	RHC & GGBS	250	75:25	771%	98%	-	-	91	18	-	134	1,176.0	3.36	181%	692.2	84.4	1.58%
2RHG 300-1-B	RHC & GGBS	300	75:25	821%	98%	-	-	7	18	23	130.5	1,168.2	2.82	156%	363.1	34.9	1.83%
2RHG 300-1-T	RHC & GGBS	300	75:25	821%	98%	-	-	7	18	-	131	1,188.0	2.82	153%	365.6	33.2	1.66%
2RHG 300-1-B	RHC & GGBS	300	75:25	821%	98%	-	-	28	18	32	126	1,195.9	2.82	158%	628.0	56.1	1.47%
2RHG 300-1-T	RHC & GGBS	300	75:25	821%	98%	-	-	28	18	-	98	1,156.8	2.82	153%	484.3	22.0	3.47%
2RHG-300-T	RHC & GGBS	300	75:25	821%	98%	-	-	91	18	24.5	134	1,184.9	2.82	156%	747.0	80.3	2.03%
2RHG-300-B	RHC & GGBS	300	75:25	821%	98%	-	-	91	18	-	130.5	1,189.0	2.82	153%	709.3	78.8	1.26%

B.2 Kinnegar *Sleech* Stabilisation Trials:

Ordinary Portland Cement Binder:													
Sample Reference	Binder Type	Binder Content kg/m^3	Binder Proportions	Raw Moisture Content, w_i	Mixed Moisture Content, w_{mix}	Curing Time, t days	Sample Length mm	Stabilised Density ρ_s, kg/m^3	Water to Binder Ratio	Stabilised Moisture Content, w_s	UCS, q_t kPa	Secant Stiffness E_{50}, MPa	Failure Strain ε_f
OPC-25-T	OPC	25	1	48.4%	45.9%	7	134	1,655.4	21.13	47.8%	20.4	0.8	4.10%
OPC-25-B	OPC	25	1	48.4%	45.9%	7	130	1,673.9	21.13	48.8%	20.2	0.4	7.70%
OPC-25-T	OPC	25	1	48.4%	45.9%	28	133	1,660.2	21.13	48.0%	30.2	1.7	3.52%
OPC-25-B	OPC	25	1	48.4%	45.9%	28	132	1,660.9	21.13	47.7%	39.7	2.0	3.91%
OPC-25-T	OPC	25	1	48.4%	45.9%	91	133	1,678.1	21.13	47.9%	30.4	0.6	6.82%
OPC-50-T	OPC	50	1	47.6%	44.9%	7	130	1,679.5	10.44	44.2%	146.7	8.8	3.10%
OPC-50-B	OPC	50	1	47.6%	44.9%	7	130	1,673.9	10.44	44.4%	169.9	13.5	2.30%
OPC-50-T	OPC	50	1	47.6%	44.9%	28	131	1,658.4	10.44	44.2%	224.2	31.1	1.39%
OPC-50-B	OPC	50	1	47.6%	44.9%	28	126	1,659.1	10.44	44.3%	206.5	16.9	3.04%
OPC-50-T	OPC	50	1	47.6%	44.9%	91	129	1,652.1	10.44	44.8%	218.9	30.4	1.43%
OPC-50-B	OPC	50	1	47.6%	44.9%	91	130	1,652.1	10.44	44.5%	250.7	22.8	1.52%
OPC-100-T	OPC	100	1	50.0%	43.5%	7	128	1,654.6	5.40	43.9%	197.8	25.4	1.85%
OPC-100-B	OPC	100	1	50.0%	43.5%	7	130	1,669.1	5.40	43.7%	280.8	33.0	1.70%
OPC-100-T	OPC	100	1	50.0%	43.5%	28	128.5	1,684.6	5.40	45.2%	455.4	65.1	1.48%
OPC-100-B	OPC	100	1	50.0%	43.5%	28	128.5	1,667.5	5.40	40.4%	358.4	77.9	0.99%
OPC-100-T	OPC	100	1	50.0%	43.5%	91	130.5	1,673.5	5.40	43.7%	769.6	67.5	1.37%
OPC-100-B	OPC	100	1	50.0%	43.5%	91	129	1,678.3	5.40	43.7%	789.6	94.0	1.14%
OPC-150-T	OPC	150	1	56.6%	47.7%	7	129	1,670.6	3.91	47.5%	357.6	42.6	1.46%
OPC-150-B	OPC	150	1	56.6%	47.7%	7	128	1,669.5	3.91	47.2%	415.5	41.1	1.99%
OPC-150-T	OPC	150	1	56.6%	47.7%	28	132.5	1,687.2	3.91	45.5%	574.4	46.3	1.74%
OPC-150-B	OPC	150	1	56.6%	47.7%	28	131.5	1,689.0	3.91	44.4%	557.9	67.2	1.32%
OPC-150-T	OPC	150	1	56.6%	47.7%	91	128	1,644.5	3.91	47.2%	823.9	108.4	1.14%
OPC-150-B	OPC	150	1	56.6%	47.7%	91	129	1,656.3	3.91	46.7%	1037.2	92.6	1.54%

B.2 Kinnegar *Sleech* Stabilisation Trials:

Ordinary Portland Cement & GGBS Binder:													
Sample Reference	Binder Type	Binder Content kg/m³	Binder Proportions	Raw Moisture Content, w_i	Mixed Moisture Content, w_{mix}	Curing Time, t days	Sample Length mm	Stabilised Density ρ_s, kg/m³	Water to Binder Ratio	Stabilised Moisture Content, w_s	UCS, q_t kPa	Secant Stiffness E_{50}, MPa	Failure Strain ε_f
OPC+G-50-T	OPC & GGBS	50	50:50	71.2%	64.4%	7	132.5	1,569.1	13.47	63.3%	22.0	1.1	3.50%
OPC+G-50-B	OPC & GGBS	50	50:50	71.2%	64.4%	7	134	1,550.9	13.47	63.5%	23.6	1.0	3.51%
OPC+G-50-T	OPC & GGBS	50	50:50	71.2%	64.4%	28	130	1,538.6	13.47	62.0%	66.0	4.7	1.70%
OPC+G-50-B	OPC & GGBS	50	50:50	71.2%	64.4%	28	132	1,537.0	13.47	62.4%	81.0	2.6	3.60%
OPC+G-50-T	OPC & GGBS	50	50:50	71.2%	64.4%	91	129.5	1,520.5	13.47	62.8%	93.6	5.3	2.19%
OPC+G-50-B	OPC & GGBS	50	50:50	71.2%	64.4%	91	129	1,527.4	13.47	63.6%	116.1	9.8	1.75%
OPC+G-100-T	OPC & GGBS	100	50:50	62.2%	57.1%	7	134	1,602.4	6.21	54.9%	320.4	35.2	1.20%
OPC+G-100-B	OPC & GGBS	100	50:50	62.2%	57.1%	7	131	1,587.3	6.21	56.6%	268.1	30.8	1.37%
OPC+G-100-T	OPC & GGBS	100	50:50	62.2%	57.1%	28	131	1,595.7	6.21	54.4%	440.5	29.8	1.69%
OPC+G-100-B	OPC & GGBS	100	50:50	62.2%	57.1%	28	130	1,597.3	6.21	53.9%	319.6	54.2	1.32%
OPC+G-100-T	OPC & GGBS	100	50:50	62.2%	57.1%	91	130	1,584.7	6.21	56.9%	508.9	63.6	1.28%
OPC+G-100-B	OPC & GGBS	100	50:50	62.2%	57.1%	91	129	1,593.2	6.21	58.6%	614.8	49.6	1.91%
OPC+G-150-T	OPC & GGBS	150	50:50	58.0%	49.1%	7	132	1,635.3	3.96	48.3%	618.0	70.2	1.72%
OPC+G-150-B	OPC & GGBS	150	50:50	58.0%	49.1%	7	131.5	1,656.2	3.96	47.6%	711.9	93.7	1.35%
OPC+G-150-T	OPC & GGBS	150	50:50	58.0%	49.1%	28	130	1,657.7	3.96	45.6%	1488.0	140.4	1.20%
OPC+G-150-T	OPC & GGBS	150	50:50	58.0%	49.1%	28	132.5	1,628.8	3.96	45.6%	1031.3	78.1	1.49%
OPC+G-150-T	OPC & GGBS	150	50:50	58.0%	49.1%	91	131	1,662.3	3.96	-	2117.6	264.7	0.86%
OPC+G-150-B	OPC & GGBS	150	50:50	58.0%	49.1%	91	130.5	1,662.0	3.96	-	2109.2	219.7	1.25%

B.2 Kinnegar *Sleech* Stabilisation Trials:

GGBS:													
Sample Reference	Binder Type	Binder Content kg/m^3	Binder Proportions	Raw Moisture Content, w_i	Mixed Moisture Content, w_{mix}	Curing Time, t days	Sample Length mm	Stabilised Density ρ_s, kg/m^3	Water to Binder Ratio	Stabilised Moisture Content, w_s	UCS, q_t kPa	Secant Stiffness E_{50}, MPa	Failure Strain ε_f
GGBS-50-T	GGBS	50	1	68.0%	51.8%	7	136	1,648.6	13.11	51.2%	14.1	0.6	4.76%
GGBS-50-B	GGBS	50	1	68.0%	51.8%	7	131	1,629.9	13.11	51.1%	14.4	0.6	4.37%
GGBS-50-T	GGBS	50	1	68.0%	51.8%	28	124	1,625.1	13.11	50.5%	17.4	0.9	3.00%
GGBS-50-B	GGBS	50	1	68.0%	51.8%	28	131	1,643.7	13.11	50.7%	19.4	0.6	4.74%
GGBS-50-T	GGBS	50	1	68.0%	51.8%	91	133	1,619.2	13.11	50.9%	40.6	3.4	2.19%
GGBS-50-B	GGBS	50	1	68.0%	51.8%	91	124	1,632.4	13.11	51.4%	26.6	2.2	1.77%
GGBS-100-T	GGBS	100	1	65.0%	50.2%	7	133	1,672.4	6.38	49.6%	11.1	0.7	3.55%
GGBS-100-T	GGBS	100	1	65.0%	50.2%	28	134	1,627.5	6.38	48.7%	23.2	1.8	3.14%
GGBS-100-B	GGBS	100	1	65.0%	50.2%	28	134.5	1,667.4	6.38	48.8%	22.6	0.6	4.11%
GGBS-100-T	GGBS	100	1	65.0%	50.2%	91	131	1,637.2	6.38	59.5%	111.2	12.9	1.93%
GGBS-100-B	GGBS	100	1	65.0%	50.2%	91	116.5	1,656.0	6.38	45.8%	144.3	12.0	2.02%
GGBS-150-T	GGBS	150	1	67.6%	53.1%	7	131	1,609.6	4.35	52.7%	16.6	0.6	3.79%
GGBS-150-B	GGBS	150	1	67.6%	53.1%	7	133	1,636.9	4.35	52.4%	18.9	0.9	3.86%
GGBS-150-T	GGBS	150	1	67.6%	53.1%	28	131.5	1,611.3	4.35	51.5%	25.5	1.7	2.62%
GGBS-150-B	GGBS	150	1	67.6%	53.1%	28	131.5	1,645.6	4.35	51.3%	28.0	1.2	3.37%
GGBS-150-T	GGBS	150	1	67.6%	53.1%	91	131	1,640.7	4.35	45.4%	491.7	41.7	1.46%
GGBS-150-B	GGBS	150	1	67.6%	53.1%	91	125	1,619.4	4.35	47.7%	441.8	47.5	1.13%

B.2 Kinnegar *Sleech* Stabilisation Trials:

Ordinary Portland Cement & Lime Binder:													
Sample Reference	Binder Type	Binder Content kg/m³	Binder Proportions	Raw Moisture Content, w_i	Mixed Moisture Content, w_{mix}	Curing Time, t days	Sample Length mm	Stabilised Density ρ_s, kg/m^3	Water to Binder Ratio	Stabilised Moisture Content, w_s	UCS, q_t kPa	Secant Stiffness E_{50}, MPa	Failure Strain ε_f
OPC+L-50	OPC & Lime	50	50:50	40.0%	37.8%	7	130	1,711.5	9.25	37.0%	82.7	5.2	3.33%
OPC+L-50	OPC & Lime	50	50:50	40.0%	37.8%	7	128	1,720.8	9.25	37.5%	79.7	5.5	3.39%
OPC+L-50-T	OPC & Lime	50	50:50	40.0%	37.8%	28	129.5	1,740.2	9.25	37.5%	160.4	13.8	3.17%
OPC+L-50-B	OPC & Lime	50	50:50	40.0%	37.8%	28	131.5	1,739.6	9.25	37.0%	140.6	9.1	3.39%
OPC+L-50-T	OPC & Lime	50	50:50	40.0%	37.8%	91	130	1,727.9	9.25	36.9%	232.3	17.9	3.17%
OPC+L-50-B	OPC & Lime	50	50:50	40.0%	37.8%	91	131	1,734.1	9.25	37.3%	218.2	11.2	2.86%
OPC+L-100	OPC & Lime	100	50:50	42.0%	37.8%	7	131	1,726.9	4.79	33.4%	120.8	7.3	3.62%
OPC+L-100	OPC & Lime	100	50:50	42.0%	37.8%	7	131	1,707.4	4.79	37.2%	127.5	6.7	3.61%
OPC+L-100-T	OPC & Lime	100	50:50	42.0%	37.8%	28	131.5	1,731.4	4.79	37.4%	207.8	14.4	3.47%
OPC+L-100-B	OPC & Lime	100	50:50	42.0%	37.8%	28	131	1,705.3	4.79	37.3%	159.8	11.3	2.61%
OPC+L-100-T	OPC & Lime	100	50:50	42.0%	37.8%	91	130	1,751.6	4.79	36.9%	321.1	28.2	2.85%
OPC+L-100-B	OPC & Lime	100	50:50	42.0%	37.8%	91	130.5	1,727.6	4.79	36.6%	295.2	23.4	2.18%
OPC+L-150	OPC & Lime	150	50:50	39.9%	34.4%	7	129.5	1,761.6	3.08	33.6%	173.6	11.9	3.00%
OPC+L-150	OPC & Lime	150	50:50	39.9%	34.4%	7	131	1,760.8	3.08	33.8%	158.9	6.5	3.75%
OPC+L-150-T	OPC & Lime	150	50:50	39.9%	34.4%	28	130	1,781.3	3.08	33.5%	254.0	16.7	3.15%
OPC+L-150-B	OPC & Lime	150	50:50	39.9%	34.4%	28	130	1,759.7	3.08	32.6%	274.1	34.3	2.16%
OPC+L-150-T	OPC & Lime	150	50:50	39.9%	34.4%	91	131	1,743.5	3.08	33.4%	379.8	41.3	2.03%
OPC+L-150-B	OPC & Lime	150	50:50	39.9%	34.4%	91	133	1,774.4	3.08	30.9%	337.3	67.5	1.45%

B.2 Kinnegar *Sleech* Stabilisation Trials:

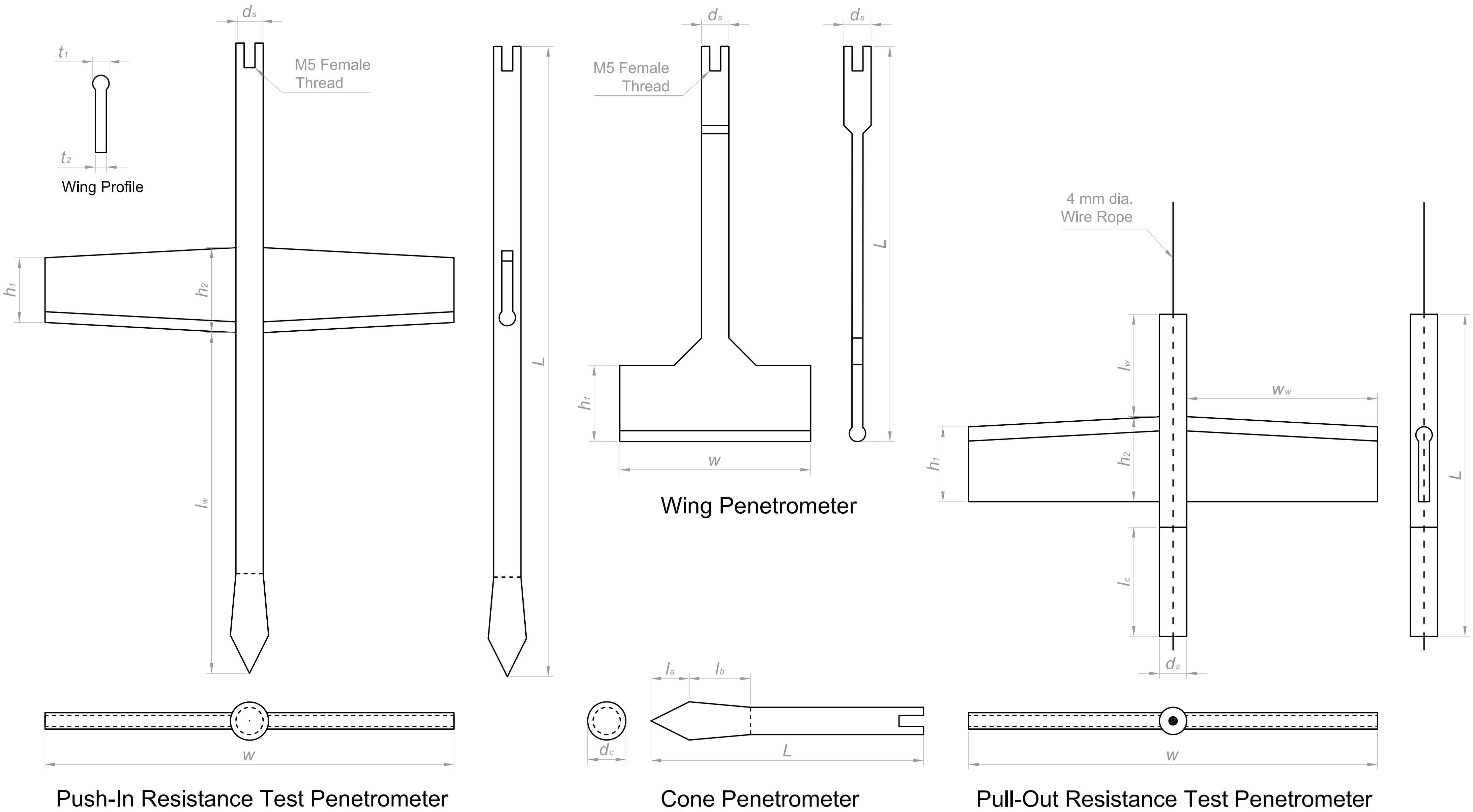
Lime Binder:													
Sample Reference	Binder Type	Binder Content kg/m^3	Binder Proportions	Raw Moisture Content, w_i	Mixed Moisture Content, w_{mix}	Curing Time, t days	Sample Length mm	Stabilised Density ρ_s, kg/m^3	Water to Binder Ratio	Stabilised Moisture Content, w_s	UCS, q_t kPa	Secant Stiffness E_{50}, MPa	Failure Strain ε_f
L-50	Lime	50	1	41.6%	39.6%	7	131	1719.6	9.52	39.2%	26.9	0.6	6.83%
L-50	Lime	50	1	41.6%	39.6%	7	130.5	1721.3	9.52	39.0%	29.5	0.7	6.27%
L-50-T	Lime	50	1	41.6%	39.6%	28	130	1680.7	9.52	38.4%	46.5	2.5	3.58%
L-50-B	Lime	50	1	41.6%	39.6%	28	131	1687.8	9.52	39.3%	48.7	2.6	4.31%
L-50-T	Lime	50	1	41.6%	39.6%	91	131	1672.4	9.52	38.6%	75.6	5.8	3.25%
L-50-B	Lime	50	1	41.6%	39.6%	91	131	1700.0	9.52	38.8%	74.7	4.2	3.89%
L-100	Lime	100	1	39.9%	36.3%	7	122	1667.8	4.62	35.9%	35.3	1.4	5.27%
L-100	Lime	100	1	39.9%	36.3%	7	130	1822.1	4.62	35.9%	35.9	0.9	5.52%
L-100-T	Lime	100	1	39.9%	36.3%	28	129	1725.5	4.62	36.0%	56.6	2.6	5.58%
L-100-B	Lime	100	1	39.9%	36.3%	28	131.5	1738.0	4.62	35.8%	59.5	2.4	5.61%
L-100-T	Lime	100	1	39.9%	36.3%	91	131	1701.6	4.62	35.2%	103.4	8.6	3.46%
L-100-B	Lime	100	1	39.9%	36.3%	91	131	1737.1	4.62	35.3%	93.5	6.2	4.43%
L-150	Lime	150	1	41.3%	36.6%	7	132	1722.8	3.16	35.6%	32.5	0.8	6.77%
L-150	Lime	150	1	41.3%	36.6%	7	131	1725.3	3.16	35.3%	38.0	0.8	6.62%
L-150-T	Lime	150	1	41.3%	36.6%	28	133	1694.2	3.16	36.0%	51.0	2.4	4.24%
L-150-B	Lime	150	1	41.3%	36.6%	28	131	1730.9	3.16	36.3%	42.6	1.0	5.66%
L-150-T	Lime	150	1	41.3%	36.6%	91	130	1680.7	3.16	35.6%	87.5	7.7	3.53%
L-150-B	Lime	150	1	41.3%	36.6%	91	130.5	1736.6	3.16	35.5%	80.3	4.6	4.15%

Appendix C: Fabricated Penetrometer Dimensions & Drawings

C.1 Fabricated Penetrometer Dimensions

Table C-1: Fabricated Penetrometer Dimensions

		PIRT No. 1	PIRT No. 2	PORT No. 1	PORT No. 2	Cone-Only Penetrometer	Wing-Only Penetrometer	
Penetrometer Width	w	150.5	148	149	149.5	-	69.5	mm
Penetrometer Length	L	230	230	126	118.5	100	145	mm
Shaft Diameter	d_s	10	10	10	10	10	10	mm
Wing Leading Edge Thickness	t_1	6	6	6	6	-	6	mm
Wing Plate Thickness	t_2	4	4	4	4	-	4	mm
Wing Height	h_1	25.4	25.5	28	28	-	27	mm
Wing Height at Shaft	h_2	31	31	31	31.5	-	-	mm
Wing Width	w_w	70.3	69.0	69.0	69.8	-	69.5	mm
Front most edge to wing edge:	l_w	125	125	37.5	37.5	-	-	mm
PORT Crimp Length	l_c	-	-	49	40.5	-	-	mm
Pull-Out Rope Diameter	d_r	-	-	4	4	-	-	mm
Cone Tip Diameter	d_c	14	14	-	-	14	-	mm
Length to Cone Apex	l_a	16	16	-	-	16	-	mm
Cone Apex to Shaft	l_b	22	22	-	-	22	-	mm
Penetrometer Mass	m	0.207	0.205	0.254	0.248	0.061	0.108	kg



C.2 Fabricated Penetrometer Drawing

Appendix D: Additional Testing Graphs

D.1 PORT Column Tests

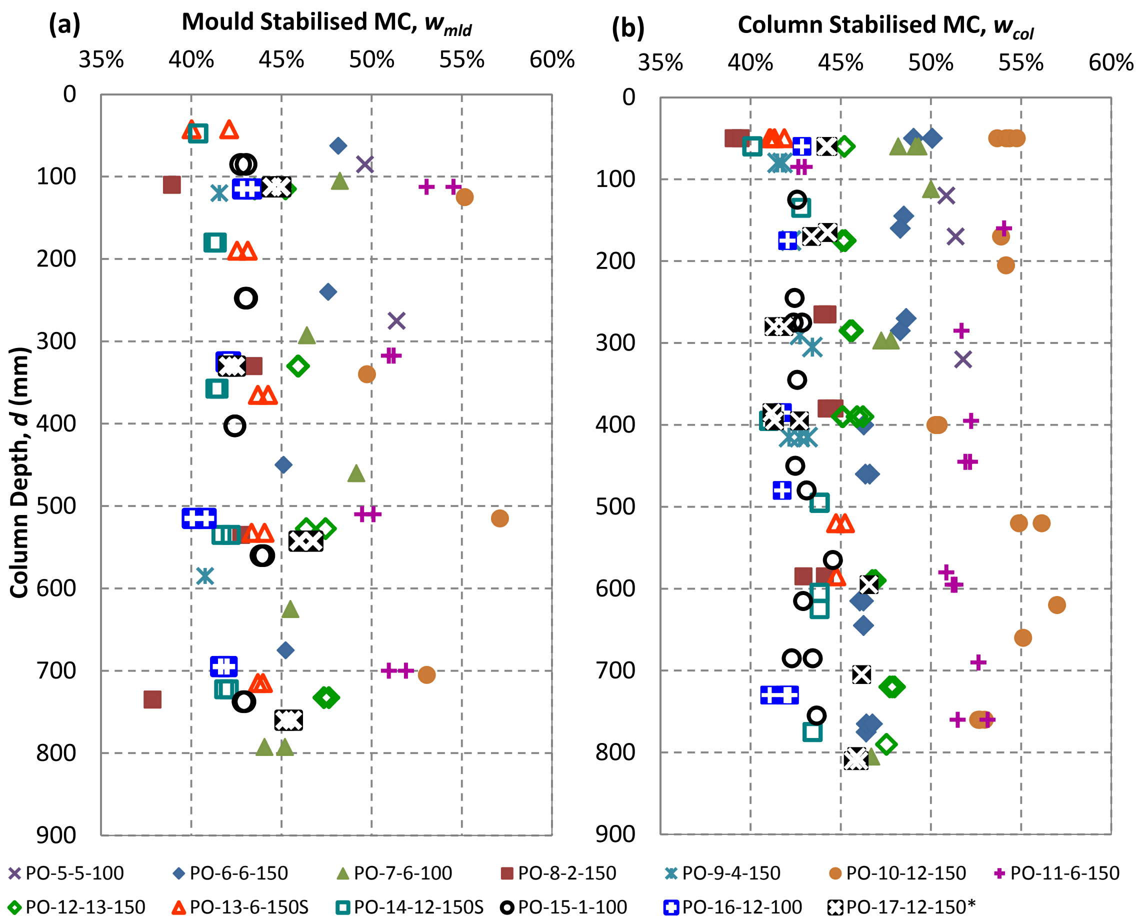


Figure D-1: PORT column tests stabilised moisture content: a) mould samples & b) column samples

D.2 PIRT Column Tests

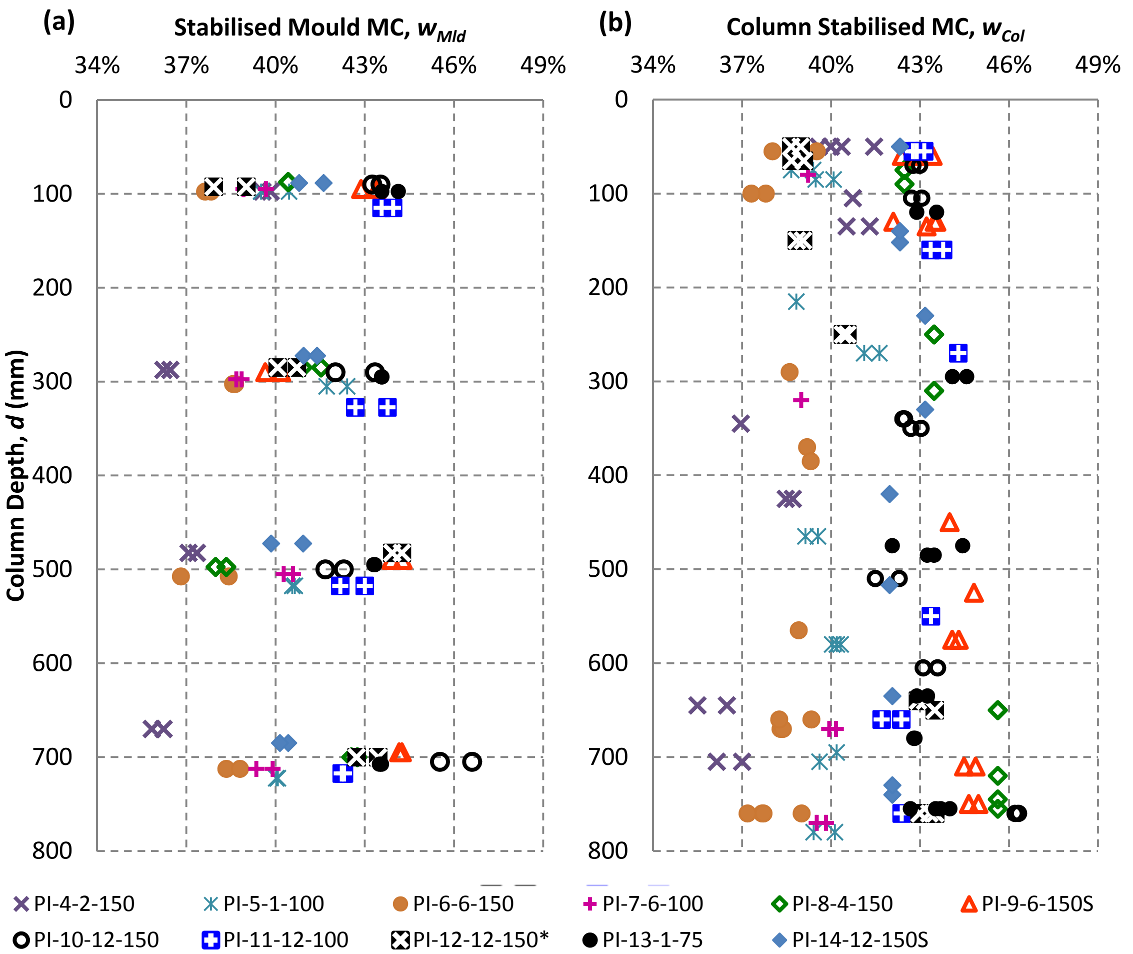


Figure D-2: PIRT column tests stabilised moisture content: a) mould samples & b) column samples

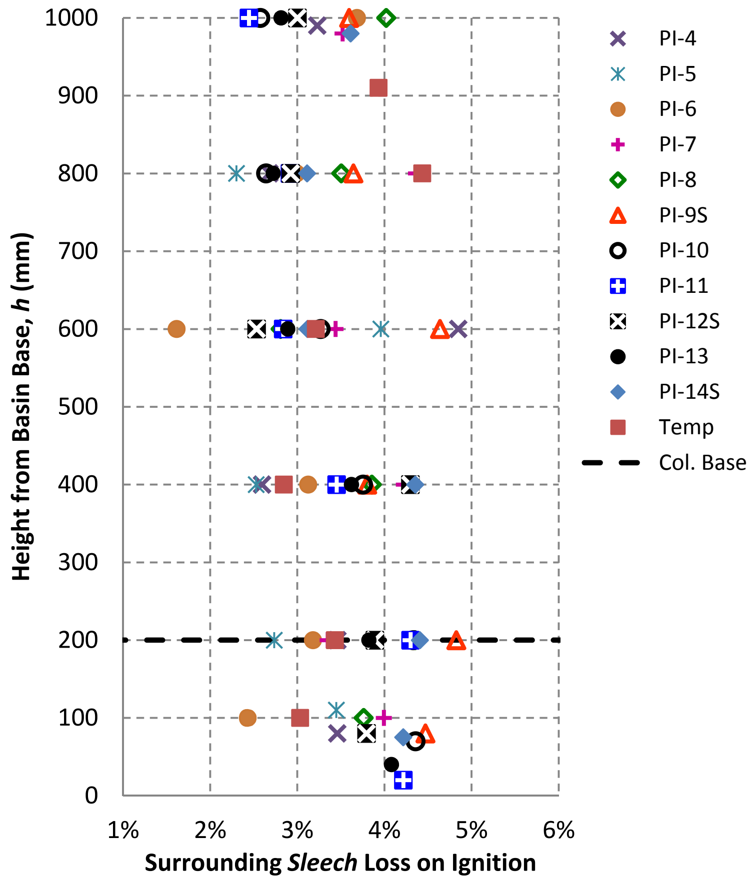


Figure D-3: Loss on ignition of unstabilised surrounding *sleech*

D.3 Wire Friction Tests

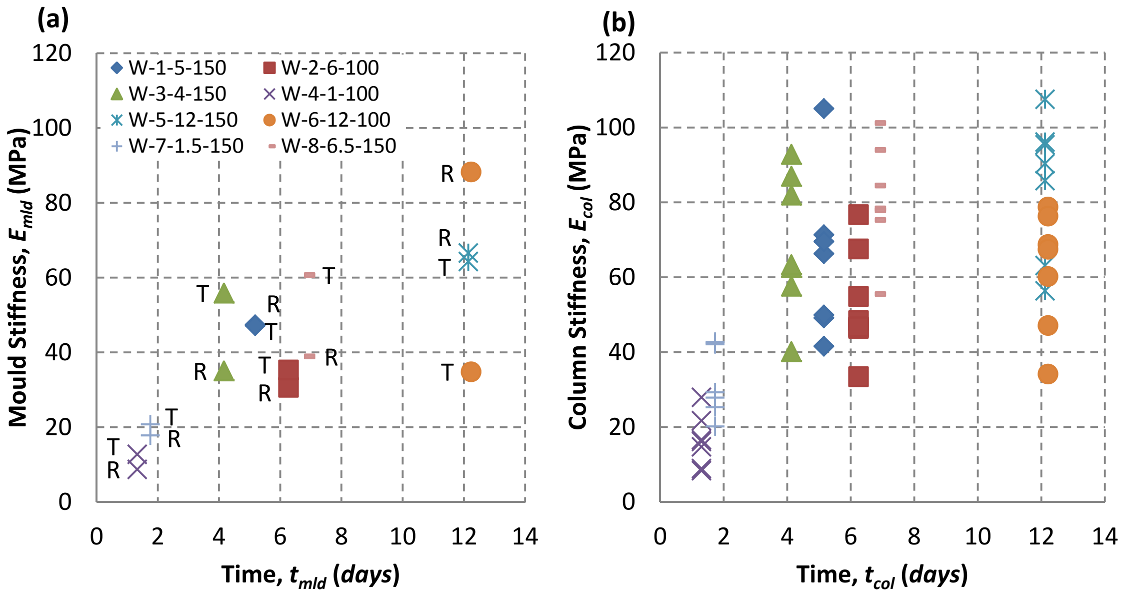


Figure D-4: Wire friction column secant stiffness with curing time: a) mould samples & b) column samples

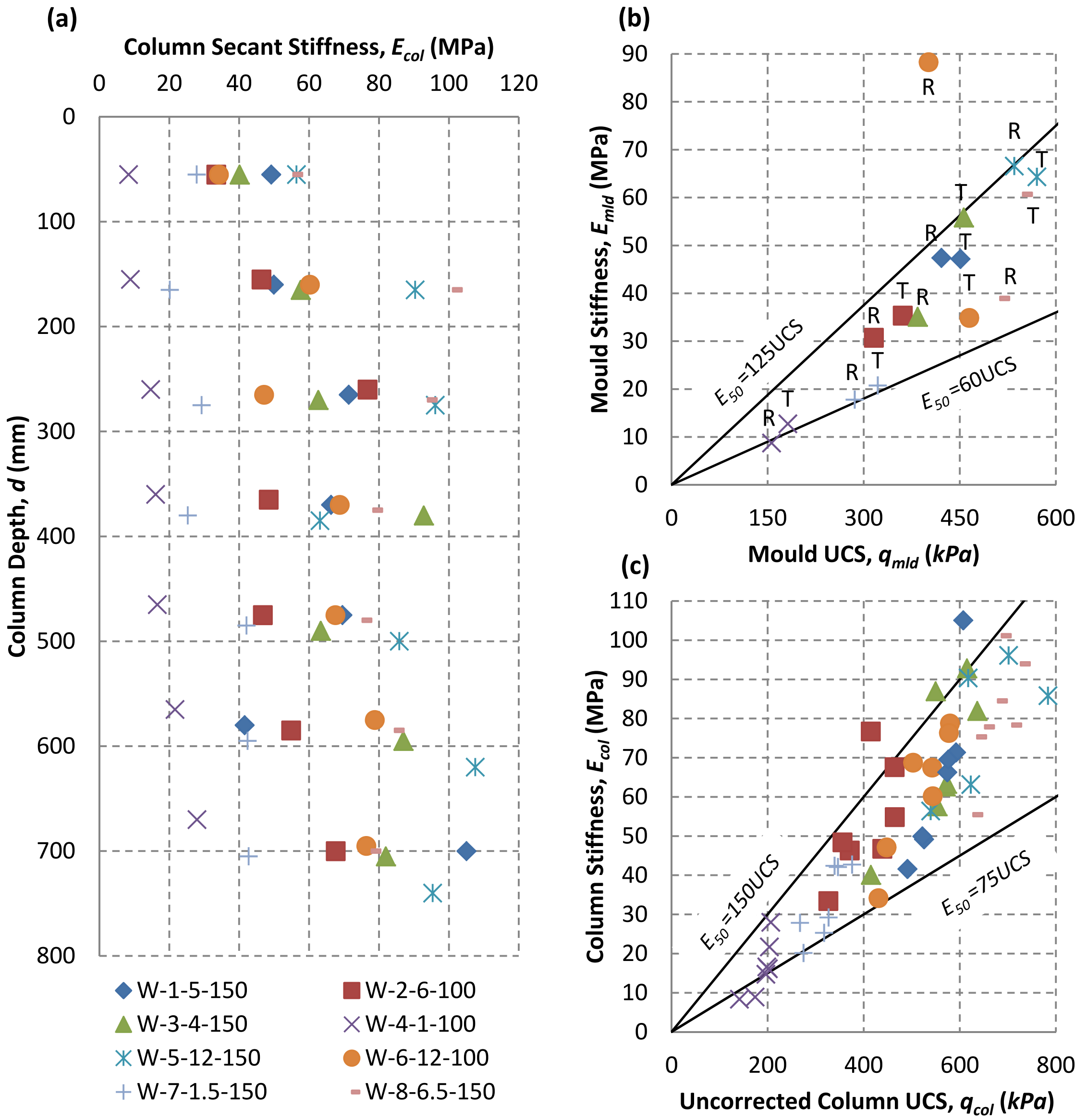


Figure D-5: a) Column secant stiffness with depth; cone penetrometer column E_{50}-UCS: b) mould relationship & c) column relationship

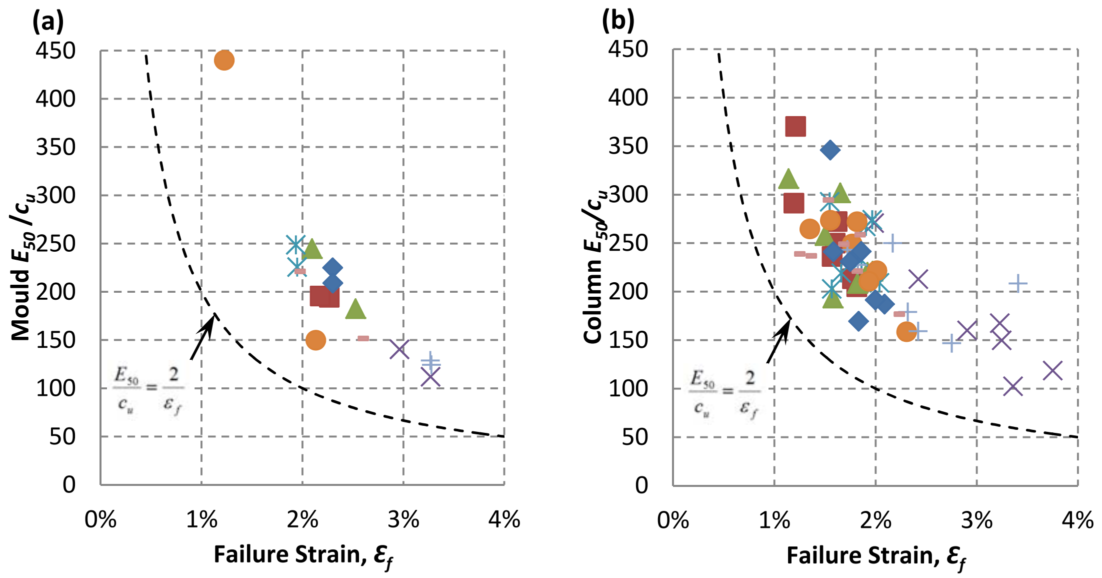


Figure D-6: E_{50}/c_u with failure strain: a) All mould samples & b) column samples

D.4 Cone-Only Penetrometer & Sounding Bar Friction Test

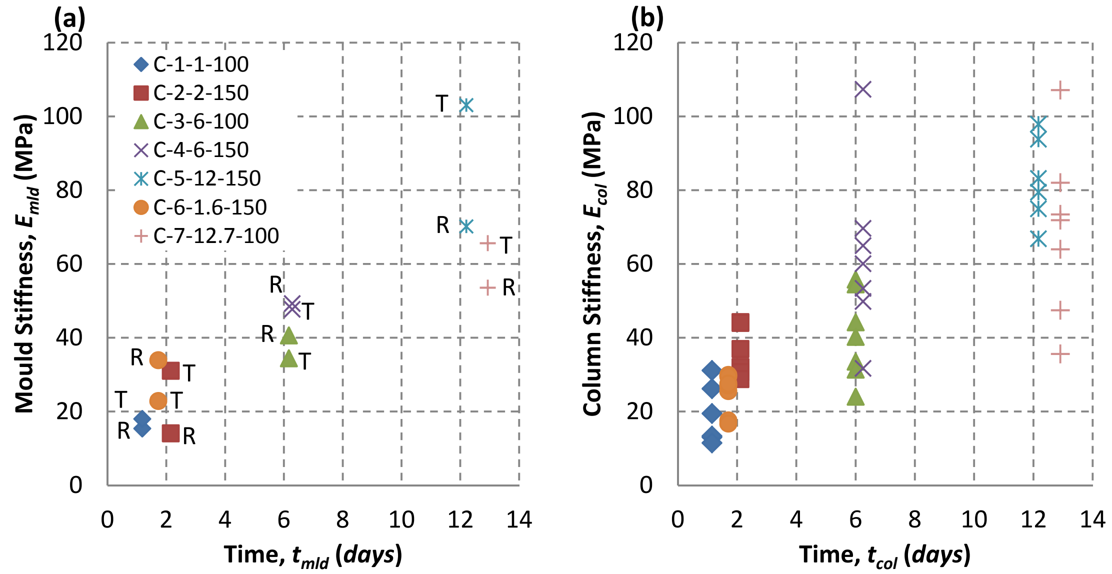


Figure D-7: Secant stiffness with curing time: a) mould samples & b) column samples

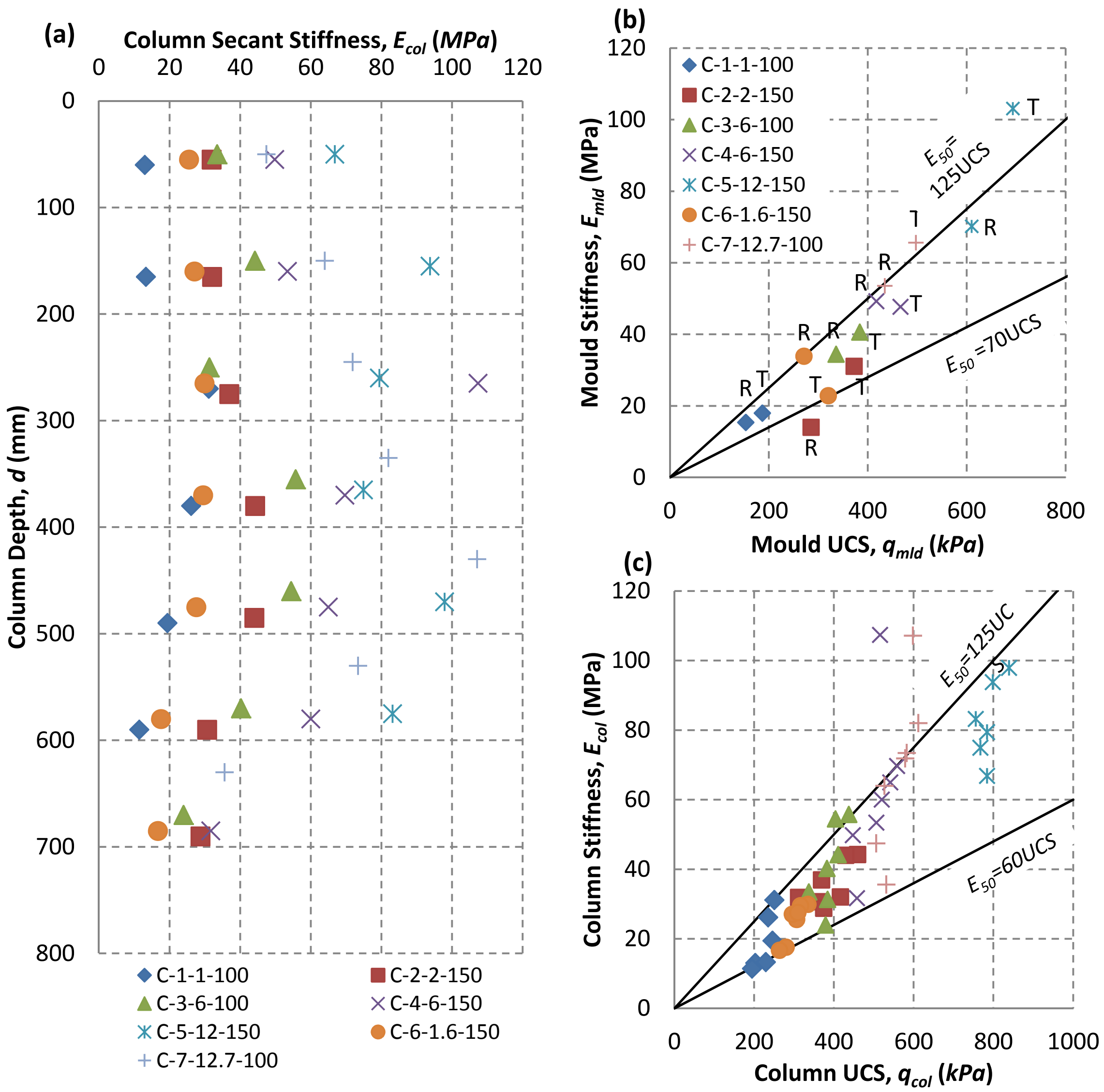


Figure D-8: a) Column secant stiffness with depth; cone penetrometer column E_{50}-UCS: b) mould relationship & c) column relationship

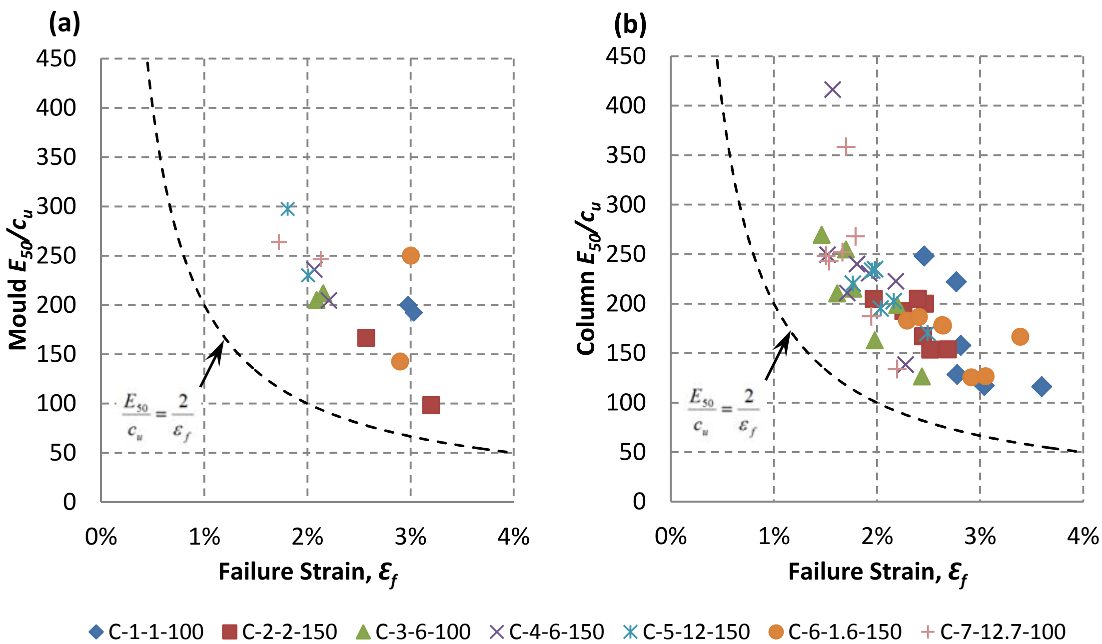


Figure D-9: E_{50}/c_u with failure strain: a) All mould samples & b) column samples

Appendix E: Penetrometer Test Result Summary Sheets

E.1 Summary Sheet Glossary

Average Temp:	Average ambient temperature of the laboratory during curing (T)
Basin dia.:	Diameter of basin in which column cured. Not applicable for friction tests.
Built Height:	Height from the bottom of the basin to the top of the column (h) - PORT: includes 160 mm of raw *sleech* under the column - PIRT: includes 200 mm of raw *sleech* under the column
Column dia.:	Diameter of constructed column
Column Loading:	Column loading during PORT to prevent column pull-out
Column Sample Ref:	Sample reference within the tested column in question
Column Time:	Curing time from average time of mixing to average time of column UCS test (t_{col})
Density:	Stabilised density of UCS sample (ρ_{mld}, ρ_{col})
Depth:	Depth at which the column sample originated (d)
ΔUCSxWTBR:	Correction factor due to UCS testing time delay
Failure Strain:	Strain at maximum UCS ($\mathcal{E}_f$)
Length:	UCS sample height
LHS Column:	Refers to the left side of the column after probing
Mixed MC:	Moisture content of *sleech* after addition of binder and mixing (w_m)
Mould Time:	Curing time from average time of mixing to average time of mould UCS test (t_{mld})
Operator:	Persons who mixed and built columns; column builder listed first
Organic Content:	Organic content of raw *sleech*
Origin Mix:	Mix from which the column sample originated
PIRT/PORT Time:	Curing time from average time of mixing to PIRT or PORT probing of the column (t_{Po} *and* t_{Pi}, respectively)
Probing Force:	Average probing force over the length of the sample, uncorrected for friction
Push-In Rate:	Average PIRT penetrometer push-in rate of each push
Pull-Out Rate:	Average PORT penetrometer pull-out rate
Raw *Sleech* MC:	Moisture content of raw *sleech* (w_i)

Reason to Exclude:	A sample may be excluded from analysis for the following reasons:
	- No issue with sample
	σ-$\mathcal{E}$ Testing issue shown in stress strain graph
	Stone Stone found in the test sample
	ρ Density issue
	UCS UCS issue
RHS Column:	Refers to the right side of the column after probing
Stabilised MC:	Moisture content of stabilised *sleech* at the time of UCS test (w_s)
Stiffness:	Secant stiffness at 50% of the failure strength (E_{mld}, E_{col})
Stress Adjustment:	Stress adjustment factor to account for wire friction with the column on the pull-out force
Surcharge:	Surcharge loading placed across basin top during curing and testing
Uncorrected UCS:	UCS determined from UCS-strain graph and before correction for time delay (q_{mld}, q_{col})
Wire Extension:	Length of wire extending beyond the base of the column
Wire Test:	Wire test paired with the PORT

Graphs:

Surrounding *sleech* properties detail the moisture content (w_{ss}) and bulk density (ρ_{ss}) determined from 50.5 mm long, 50 mm dia. cores taken in the unstabilised *sleech* that surrounded the column during curing and were taken during column extraction. Undrained shear strengths (c_u) were determined using a 33 mm Pilcon pocket shear vane.

Error bars on the *Sample Average* data points on the probing force graph represent the location of the UCS sample in the column; forces are averaged over this location to give the average probing resistance for the sample

E.2 PORT Column Results Summary Sheet

Pull-Out Resistance Test No. 5

Test Type:	PORT	Binder:	OP Cement		Mixing Date:	13/07/2012			
Reference:	PO-5-5-100	OPC Content:	100	kg/m^3	PORT Date:	18/07/2012		Pull-Out Rate:	
Operator:	MT & BC	Built Height:	550	mm	PORT Time:	4.95	days	14.8	mm/sec
Column dia.	200 mm	Average Temp:	18.0	°C	Mould Time:	5.09	days	ΔUCSxWTBR	18.5
Basin dia.	750 mm	Column Loading:	100	kg	Column Time:	5.10	days	Wire Test:	Wire 7

65 mm dia. Mould Sample Properties:

Mould Sample:	Curing Condition:	Raw *Sleech* MC:	Organic Content:	Mixed MC:	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, ε_f
Mix 1R	Room	57.6%	-	52.5%	131	1598.8	292.7	51.4%	17.6	2.12%
Mix 2R	Room	56.2%	-	51.1%	131	1609.3	391.2	49.6%	21.4	2.56%

50 mm dia. Column Sample Properties:

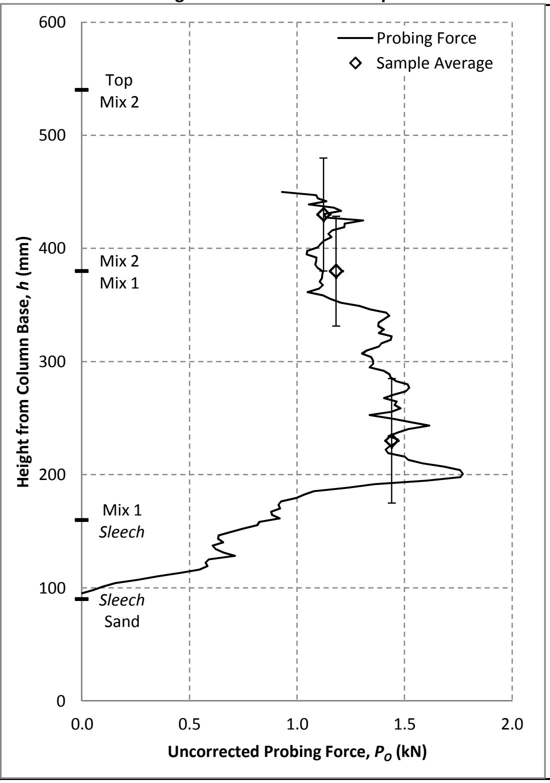
Column Sample Ref:	Origin Mix:	Height from Basin Base, mm	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, ε_f	Reason to Exclude:	Probing Force, kN
Column A	1	430	100	1618.4	288.6	50.9%	14.1	2.48%	-	1.12
Column B	1	380	97	1616.6	172.3	51.4%	9.2	2.30%	UCS	1.18
Column C	2	230	110	1682.8	236.9	51.8%	19.3	1.67%	-	1.44

Comments:

Issues encountered during column construction, form pipe was noted to damage the column when raised after the compaction of each layer.

Displacement rates of the penetrometer estimated from initial and final locations; better displacement monitoring required to track the location of the penetrometer during the test.

Column Probing Force with Column Sample Locations:



Pull-Out Resistance Test No. 6

Test Type:	PORT	Binder:	OP Cement		Mixing Date:	26/07/2012			
Reference:	PO-6-6-150	OPC Content:	150	kg/m^3	PORT Date:	01/08/2012		Pull-Out Rate:	
Operator:	MT & BC	Built Height:	965	mm	PORT Time:	5.88	days	15.3	mm/sec
Column dia.	200 mm	Average Temp:	19.2	°C	Mould Time:	6.03	days	ΔUCSxWTBR	20.6
Basin dia.	750 mm	Column Loading:	150	kg	Column Time:	6.07	days	Wire Test:	Wire 1

65 mm dia. Mould Sample Properties:

Mould Sample:	Curing Condition:	Raw *Sleech* MC:	Organic Content:	Mixed MC:	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, ε_f
Mix 1R	Room	54.1%	-	47.7%	130	1668.8	657.9	45.2%	50.8	1.77%
Mix 2R	Room	55.5%	-	42.0%	130	1726.3	686.8	45.1%	47.0	2.19%
Mix 3R	Room	58.1%	-	49.0%	129	1638.5	630.7	47.6%	53.8	2.11%
Mix 4R	Room	59.2%	-	50.0%	129	1636.7	538.0	48.1%	44.9	1.99%
Mix 4R	In Basin	59.2%	-	50.0%	125	1717.3	422.4	49.3%	57.1	1.58%

50 mm dia. Column Sample Properties:

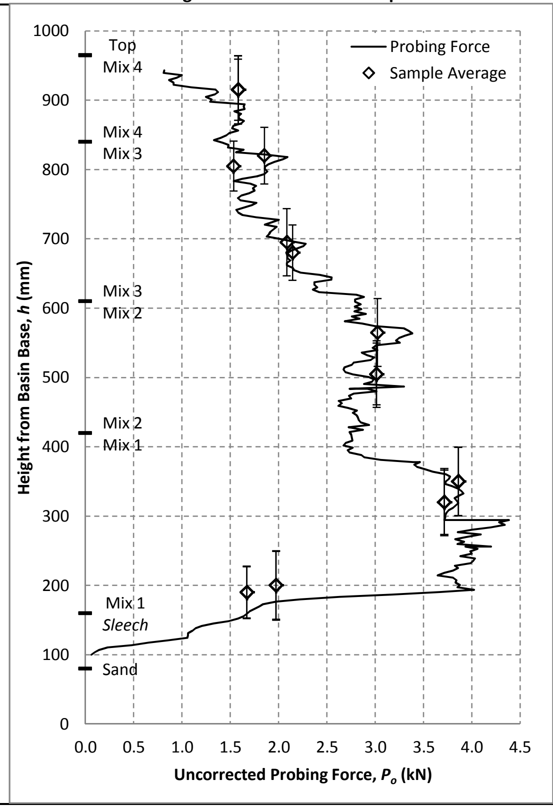
Column Sample Ref:	Origin Mix:	Height from Basin Base, mm	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, ε_f	Reason to Exclude:	Probing Force, kN
Column A	1	190	74	1761.9	460.7	46.6%	13.7	3.93%	σ-ε	3.90
Column B	1	190	76	1786.6	654.8	46.4%	51.8	2.19%	-	3.90
Column C	1	200	98	1696.3	623.0	46.4%	33.0	2.11%	-	3.83
Column D	1	200	100	1705.1	692.0	46.8%	36.5	2.10%	-	3.83
Column E	1	320	97	1692.8	789.3	46.3%	71.8	1.35%	-	3.93
Column F	1	320	93	1754.6	619.3	46.3%	70.9	1.27%	-	3.93
Column G	1	350	98	1772.7	724.5	46.1%	28.3	2.44%	-	3.82
Column H	1	350	99	1728.5	661.4	46.3%	47.7	1.66%	-	3.82
Column I	2	565	98	1598.6	619.6	46.3%	65.4	1.34%	-	2.97
Column J	2	505	96	1592.6	613.5	46.6%	32.1	2.10%	-	2.81
Column K	2	505	89	1721.9	696.0	46.4%	65.2	1.58%	-	2.82
Column L	3	680	80	1700.4	563.9	48.3%	37.6	1.92%	-	2.28
Column M	3	695	97	1652.3	464.0	48.6%	33.2	1.78%	-	2.17
Column N	3	820	82	1687.5	494.2	48.5%	88.8	0.86%	-	1.73
Column O	3	805	72	1687.5	451.5	48.3%	21.5	1.80%	-	1.78
Column P	4	915	99	1661.6	417.9	50.1%	30.6	2.30%	-	1.34
Column Q	4	915	98	1651.9	430.1	50.1%	88.8	0.99%	-	1.34
Column R	4	915	88	1696.8	457.9	49.0%	37.4	2.05%	-	1.38

Comments:

New column construction method trialled; all stabilised material from a single mix was compacted into the form pipe before pealing it from the column and raising it to a higher level. This prevented damage to the column during raising of the form pipe and allowed voids in the face to filled.

Draw wire gauge used to monitor displacement of the PORT penetrometer during the test. Twisting of the crane hook occurred, requiring the test to be momentarily paused at 295 mm.

Column Probing Force with Column Sample Locations:



Pull-Out Resistance Test No. 7

Test Type:	PORT	Binder:	OP Cement		Mixing Date:	09/08/2012			
Reference:	PO-7-6-100	OPC Content:	100	kg/m³	PORT Date:	15/08/2012		Pull-Out Rate:	
Operator:	MT BC & JLP	Built Height:	1,040	mm	PORT Time:	5.96	days	16.9	mm/sec
Column dia.	200 mm	Average Temp:	20.5	°C	Mould Time:	6.11	days	ΔUCSxWTBR	18.3
Basin dia.	750 mm	Column Loading:	150	kg	Column Time:	6.14	days	Wire Test:	Wire 7

65mm dia. Mould Sample Properties:

Mould Sample:	Curing Condition:	Raw *Sleech* MC:	Organic Content:	Mixed MC:	Length: mm	Density: kg/m³	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, ε_f
Mix 1R	Room	53.8%	-	48.2%	129	1646.9	371.0	44.1%	32.6	2.21%
Mix 2R	Room	54.1%	-	48.9%	129	1637.3	434.0	45.5%	37.8	1.98%
Mix 3R	Room	59.6%	-	52.6%	129	1617.0	485.7	49.1%	35.3	1.89%
Mix 4R	Room	54.7%	-	49.0%	130	1638.7	430.6	46.4%	23.0	2.50%
Mix 5R	Room	58.0%	-	51.4%	130	1633.9	498.5	48.2%	33.1	1.97%

50mm dia. Column Sample Properties:

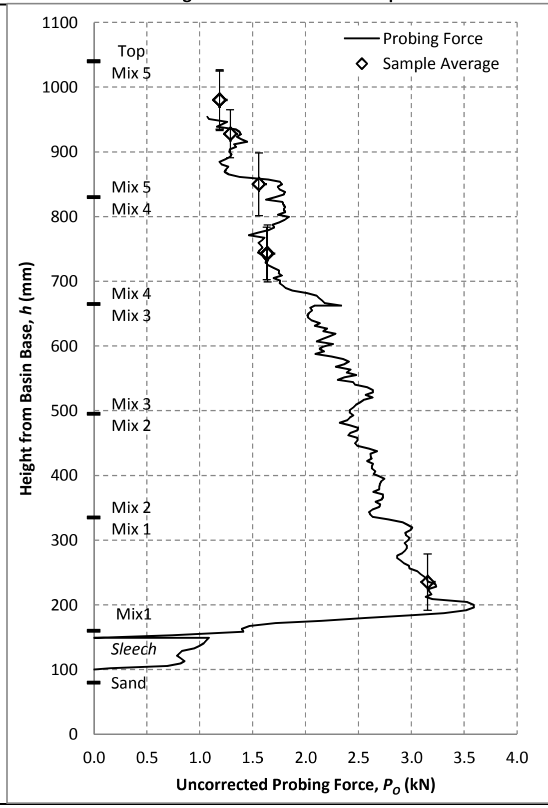
Column Sample Ref:	Origin Mix:	Height from Basin Base, mm	Length: mm	Density: kg/m³	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, ε_f	Reason to Exclude:	Probing Force, kN
Column A	1	235	87	1697.2	286.1	46.7%	16.5	2.65%	-	3.15
Column B	4	743	88	1768.8	233.8	47.8%	7.6	3.91%	-	1.64
Column C	4	743	81	1720.0	328.2	47.2%	29.7	1.93%	-	1.63
Column D	5	980	90	1603.4	412.4	49.3%	47.2	1.65%	-	1.19
Column E	5	850	97	1647.5	306.7	47.7%	13.9	3.08%	See comments	1.56
Column F	5	928	74	1669.0	308.6	50.0%	22.2	2.55%	-	1.29
Column G	5	980	94	1637.7	416.3	48.2%	19.6	2.47%	-	1.19
Column H	5	980	90	1787.2	451.8	49.1%	35.0	2.12%	-	1.19

Comments:

Penetrometer raised 47 mm on 13/08/2012 to replicated breaking of bond between the pull-out wire and the column that happens in testing of field columns.

Column E sample damaged before UCS testing but shows similar strength to other samples near it.

Column Probing Force with Column Sample Locations:



Pull-Out Resistance Test No. 8

Test Type:	PORT	Binder:	OP Cement		Mixing Date:	21/08/2012			
Reference:	PO-8-2-150	OPC Content:	150	kg/m^3	PORT Date:	23/08/2012		Pull-Out Rate:	
Operator:	MT & JLP	Built Height:	1,000	mm	PORT Time:	1.95	days	16.5	mm/sec
Column dia.	200 mm	Average Temp:	20.1	°C	Mould Time:	2.20	days	ΔUCSxWTBR	81.1
Basin dia.	750 mm	Column Loading:	150	kg	Column Time:	2.22	days	Wire Test:	Wire 2

65 mm dia. Mould Sample Properties:

Mould Sample:	Curing Condition:	Raw *Sleech* MC:	Organic Content:	Mixed MC:	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, ε_f
Mix 1R	Room	51.3%	-	44.4%	131	1721.9	469.0	37.8%	32.6	2.39%
Mix 2R	Room	51.4%	-	44.9%	129	1684.1	486.9	42.8%	18.3	3.30%
Mix 3R	Room	53.9%	-	45.1%	129	1676.2	435.5	43.4%	19.0	3.37%
Mix 4R	Room	47.6%	-	41.2%	130	1739.8	435.3	38.9%	14.3	4.09%

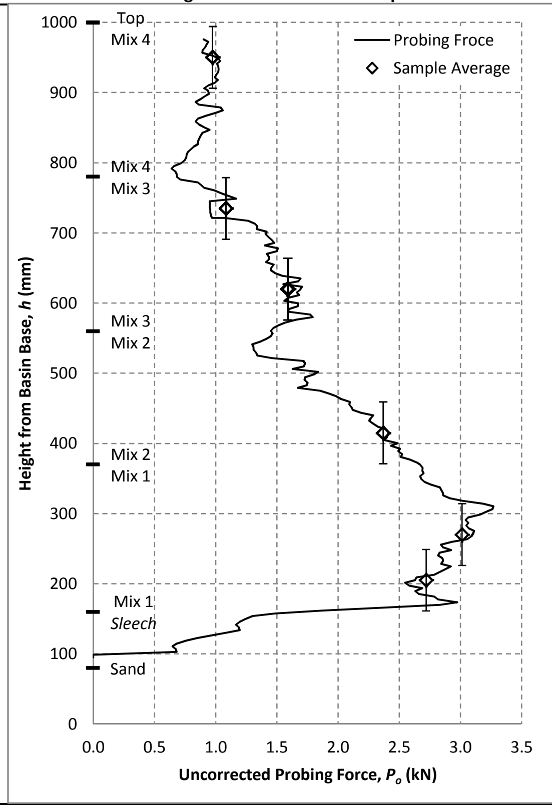
50 mm dia. Column Sample Properties:

Column Sample Ref:	Origin Mix:	Height from Basin Base, mm	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, ε_f	Reason to Exclude:	Probing Force, kN
Column A	4	950	76	1775.2	372.4	39.1%	17.4	2.93%	-	0.98
Column B	4	950	76	1726.9	374.6	39.4%	18.3	2.58%	-	0.98
Column C	3	735	91	1729.9	424.5	44.3%	24.3	2.73%	-	1.08
Column D	3	735	91	1685.7	389.1	44.0%	32.4	1.99%	-	1.08
Column E	3	620	90	1706.1	396.0	44.2%	23.5	2.04%	-	1.60
Column F	3	620	96	1667.4	369.9	44.7%	35.7	1.47%	-	1.59
Column G	3	620	96	1621.3	400.2	44.3%	27.6	1.97%	-	1.59
Column H	2	415	90	1718.0	482.0	44.1%	31.5	1.91%	-	2.37
Column I	2	415	89	1768.8	495.6	42.9%	36.7	2.26%	-	2.37
Column J	1	205	83	1704.6	192.7	43.6%	13.2	2.95%	LS	2.72
Column K	1	270	85	1659.1	240.5	44.0%	23.5	1.73%	LS	3.01

Comments:

Samples J & K found to have very low strengths compared to other samples recovered.

Column Probing Force with Column Sample Locations:



Pull-Out Resistance Test No. 9

Test Type:	PORT	Binder:	OP Cement		Mixing Date:	31/08/2012			
Reference:	PO-9-4-150	OPC Content:	150	kg/m^3	PORT Date:	04/09/2012		Pull-Out Rate:	
Operator:	MT	Built Height:	860	mm	PORT Time:	3.95	days	16.5	mm/sec
Column dia.	200 mm	Average Temp:	19.6	°C	Mould Time:	4.14	days	ΔUCSxWTBR	31.0
Basin dia.	750 mm	Column Loading:	150	kg	Column Time:	4.15	days	Wire Test:	Wire 6

65 mm dia. Mould Sample Properties:

Mould Sample:	Curing Condition:	Raw *Sleech* MC:	Organic Content:	Mixed MC:	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, ε_f
Mix 1R	Room	49.1%	-	42.0%	130	1752.0	599.4	40.8%	41.9	2.35%
Mix 2R	Room	49.4%	-	41.0%	-	-	-	-	-	-
Mix 3R	Room	48.4%	-	43.0%	129	1710.1	548.7	41.6%	52.8	2.17%

50 mm dia. Column Sample Properties:

Column Sample Ref:	Origin Mix:	Height from Basin Base, mm	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, ε_f	Reason to Exclude:	Probing Force, kN
Column A	3	780	105	1809.3	469.5	41.5%	58.1	1.12%	-	1.35
Column B	3	780	101	1708.0	380.5	41.8%	36.1	1.85%	-	1.35
Column C	3	685	102	1728.3	533.7	42.2%	38.3	2.16%	-	1.48
Column D	3	685	107	1739.6	509.2	42.2%	41.6	1.82%	-	1.53
Column E	2	555	106	1657.4	328.5	43.4%	79.8	0.69%	LS	1.83
Column F	2	445	103.5	1677.3	536.3	43.2%	47.3	1.74%	-	2.20
Column G	2	570	80	1715.8	486.9	42.7%	26.4	2.11%	-	1.73
Column H	2	445	96.5	1715.8	476.1	42.1%	48.9	1.52%	-	2.19
Column I	2	445	95.5	1767.1	515.6	42.7%	56.2	1.34%	-	2.19
Column J	1	325	88	1645.7	284.7	42.4%	32.0	1.19%	LS	2.31
Column K	1	255	78	1596.3	261.9	42.8%	23.8	1.26%	LS	2.75

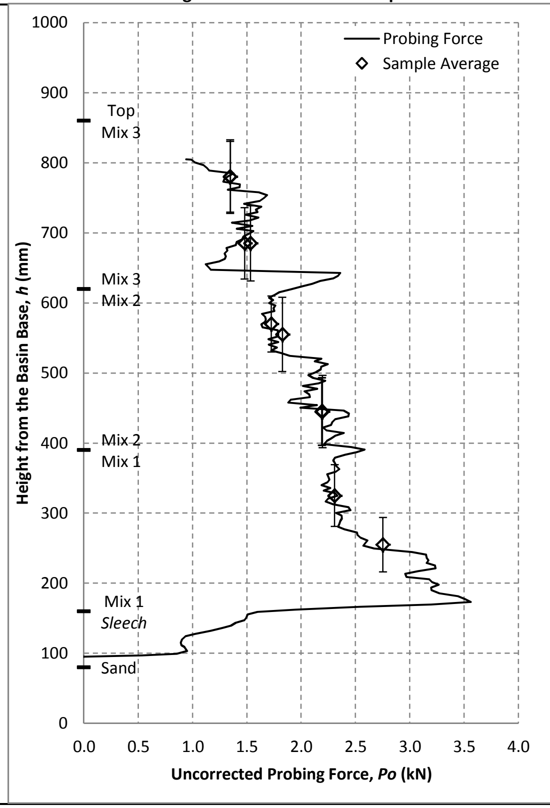
Comments:

No mould samples created for Mix 2.

Significant cracking in the lower section of the column.

Column samples J & K removed as strengths significantly lower than other samples obtained

Column Probing Force with Column Sample Locations:



Pull-Out Resistance Test No. 10

Test Type:	PORT	Binder:	OP Cement		Mixing Date:	21/11/2012			
Reference:	PO-10-12-150	OPC Content:	150	kg/m^3	PORT Date:	03/12/2012		Pull-Out Rate:	
Operator:	MT & FYs	Built Height:	970	mm	PORT Time:	11.97	days	16.8	mm/sec
Column dia.	200 mm	Average Temp:	14.6	°C	Mould Time:	13.03	days	ΔUCSxWTBR	14.5
Basin dia.	750 mm	Column Loading:	150	kg	Column Time:	12.25	days	Wire Test:	Wire 2

65 mm dia. Mould Sample Properties:

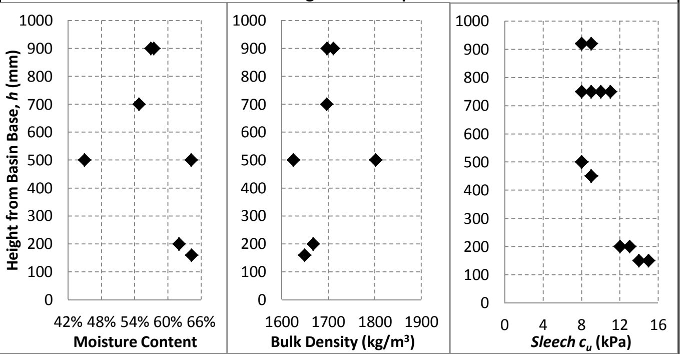
Mould Sample:	Curing Condition:	Raw *Sleech* MC:	Organic Content:	Mixed MC:	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, ε_f
Mix 1R	Room	65.3%	-	55.6%	128	1609.8	448.0	53.1%	25.0	2.38%
Mix 2R	Room	69.4%	-	59.0%	130	1582.5	448.1	57.1%	43.1	1.80%
Mix 3R	Room	54.7%	-	52.0%	129	1617.0	438.9	49.7%	42.8	1.86%
Mix 4R	Room	67.4%	-	55.8%	128	1574.7	425.8	55.2%	34.9	2.05%

50 mm dia. Column Sample Properties:

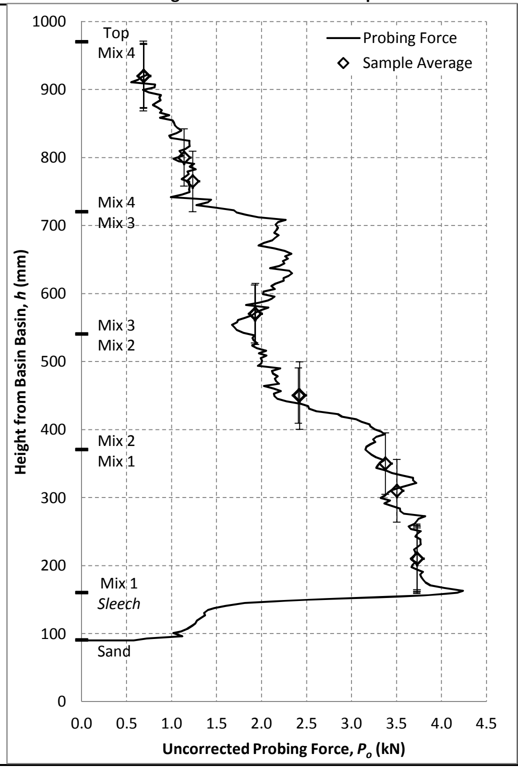
Column Sample Ref:	Origin Mix:	Height from Basin Base, mm	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50}, MPa	Failure Strain, ε_f	Reason to Exclude:	Probing Force, kN
Column A	4	920	93	1640.2	373.1	53.7%	34.9	1.55%	-	0.69
Column B	4	920	93	1670.3	493.3	54.2%	47.6	1.93%	-	0.69
Column C	4	800	84.5	1635.7	495.2	53.9%	57.8	1.40%	-	1.14
Column D	4	920	95.5	1674.4	453.2	54.4%	31.8	2.12%	-	0.69
Column E	4	920	102.5	1638.2	430.2	54.8%	27.6	1.97%	-	0.69
Column F	4	765	89	1695.5	513.6	54.2%	41.5	1.45%	-	1.24
Column G	3	570	90	1711.8	390.4	50.2%	31.7	1.88%	-	1.93
Column H	3	570	85	1731.5	373.2	50.4%	23.0	1.84%	-	1.92
Column I	2	450	81.5	1648.9	489.1	56.1%	39.7	1.72%	-	2.41
Column J	2	450	99	1646.7	394.7	54.9%	33.9	1.44%	-	2.42
Column K	1	350	90.5	1680.3	506.1	57.0%	51.4	1.31%	-	3.38
Column L	1	310	92	1643.6	461.5	55.1%	43.4	1.57%	-	3.51
Column M	1	210	98	1637.3	383.4	52.6%	36.4	1.42%	-	3.73
Column N	1	210	91	1619.5	418.3	52.7%	51.2	1.26%	-	3.73
Column O	1	210	102	1734.3	442.4	53.0%	46.4	1.47%	-	3.73
Column P	1	210	95.5	1644.9	423.2	52.7%	44.0	1.33%	-	3.73

Comments:

Surrounding *Sleech* Properties:



Column Probing Force with Column Sample Locations:



Pull-Out Resistance Test No. 11

Test Type:	PORT	Binder:	OP Cement		Mixing Date:	12/12/2012				
Reference:	PO-11-6-150	OPC Content:	150	kg/m^3	PORT Date:	18/12/2012		Pull-Out Rate:		
Operator:	MT	Built Height:	960	mm	PORT Time:	5.89	days	16.8	mm/sec	
Column dia.	200 mm	Average Temp:	14.1	°C	Mould Time:	6.24	days	ΔUCSxWTBR	40.6	
Basin dia.	750 mm	Column Loading:	150	kg	Column Time:	6.28	days	Wire Test:	Wire 2	

65 mm dia. Mould Sample Properties:

Mould Sample:	Curing Condition:	Raw *Sleech* MC:	Organic Content:	Mixed MC:	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, ε_f
Mix 1R	Room	60.6%	-	53.4%	128	1605.0	521.4	51.0%	39.2	2.13%
Mix 2R	Room	62.8%	-	54.1%	130	1615.9	432.3	50.1%	33.8	1.97%
Mix 3R	Room	62.5%	-	53.0%	127	1585.3	404.5	50.9%	30.2	2.19%
Mix 4R	Room	65.3%	-	55.7%	130	1593.8	448.5	53.0%	45.8	1.92%
Mix 1T	20°*C*	60.6%	-	53.4%	125.5	1608.6	563.2	51.9%	70.4	1.94%
Mix 2T	20°*C*	62.8%	-	54.1%	130	1615.9	554.5	49.5%	33.8	2.41%
Mix 3T	20°*C*	62.5%	-	53.0%	129	1612.2	466.5	51.2%	41.8	1.74%
Mix 4T	20°*C*	65.3%	-	55.7%	129	1599.7	482.2	54.5%	42.5	2.08%

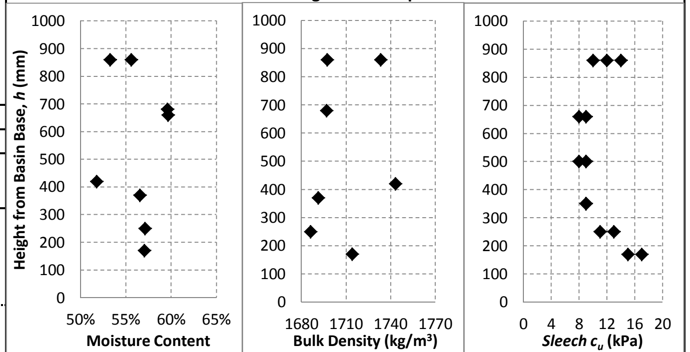
50 mm dia. Column Sample Properties:

Column Sample Ref:	Origin Mix:	Height from Basin Base, mm	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, ε_f	Reason to Exclude:	Probing Force, kN
Column A	4	875	97.5	1682.4	465.6	73.9%	21.2	105.17%	-	2.68%
Column B	4	875	102	1739.7	428.8	42.6%	38.0	108.75%	-	1.65%
Column C	4	800	84	1673.0	440.6	54.1%	31.9	104.59%	-	2.30%
Column D	3	675	80.5	1742.6	399.3	51.7%	18.1	108.09%	-	2.48%
Column E	3	565	94	1750.4	482.8	52.2%	30.1	108.58%	-	2.16%
Column F	2	380	90	1724.5	391.3	50.9%	51.2	106.72%	-	1.21%
Column G	2	515	106	1760.7	333.0	52.2%	23.8	108.96%	-	1.74%
Column H	2	515	102	1744.2	334.9	51.9%	19.5	107.94%	-	2.02%
Column I	2	365	93.5	1800.0	540.3	51.4%	47.7	111.39%	-	1.71%
Column J	2	365	99	1780.9	514.5	51.2%	31.6	110.21%	-	1.88%
Column K	1	270	70	1741.6	462.4	52.6%	29.9	108.27%	-	1.93%
Column L	1	200	77	1722.9	393.2	53.1%	27.8	107.10%	-	1.64%
Column M	1	200	79.5	1714.4	527.7	51.5%	44.3	106.57%	-	1.52%

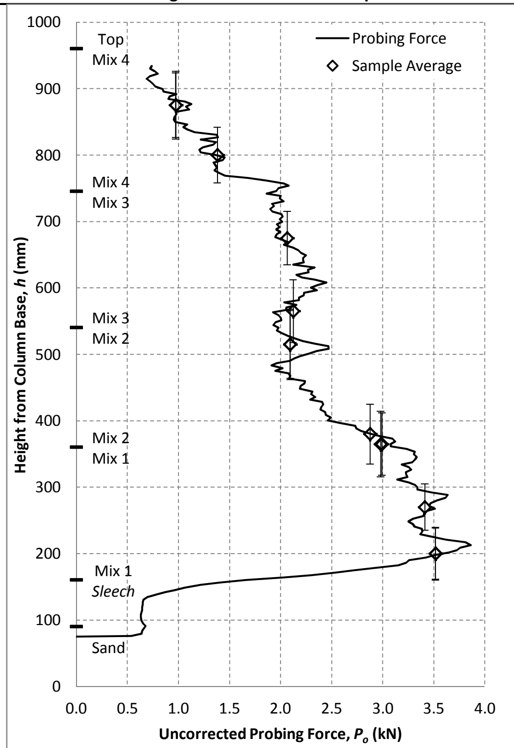
Comments:

Cracking and crumbling of the column effect sampling.

Surrounding *Sleech* Properties:



Column Probing Force with Column Sample Locations:



Pull-Out Resistance Test No. 12

Test Type:	PORT	Binder:	OP Cement		Mixing Date:	09/01/2013			
Reference:	PO-12-13-150	OPC Content:	150	kg/m^3	PORT Date:	22/01/2013		Pull-Out Rate:	
Operator:	MT & FYs	Built Height:	1,000	mm	PORT Time:	12.95	days	16.6	mm/sec
Column dia.	200 mm	Average Temp:	15.5	°C	Mould Time:	13.30	days	ΔUCSxWTBR	19.2
Basin dia.	750 mm	Column Loading:	200	kg	Column Time:	13.36	days	Wire Test:	Wire 5

65 mm dia. Mould Sample Properties:

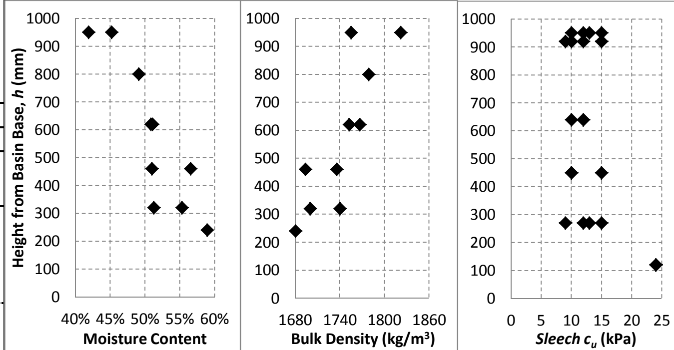
Mould Sample:	Curing Condition:	Raw *Sleech* MC:	Organic Content:	Mixed MC:	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, $\mathcal{E}_f$
Mix 1R	Room	57.9%	-	49.0%	130	1652.2	612.2	47.3%	40.2	2.55%
Mix 2R	Room	57.7%	-	49.0%	124.5	1627.3	569.3	46.4%	29.7	2.42%
Mix 3R	Room	55.1%	-	49.4%	125	1638.5	593.9	45.9%	37.6	2.63%
Mix 4R	Room	56.4%	-	49.1%	125	1636.4	591.4	43.5%	41.7	2.33%
Mix 1T	20°C	57.9%	-	49.0%	128	1627.6	722.9	47.6%	58.3	2.08%
Mix 2T	20°C	57.7%	-	49.0%	129	1651.6	666.5	47.4%	61.0	1.88%
Mix 3T	20°C	55.1%	-	49.4%	129	1656.0	633.1	45.9%	51.3	1.81%
Mix 4T	20°C	56.4%	-	49.1%	128.5	1651.8	606.0	45.2%	44.6	2.14%

50 mm dia. Column Sample Properties:

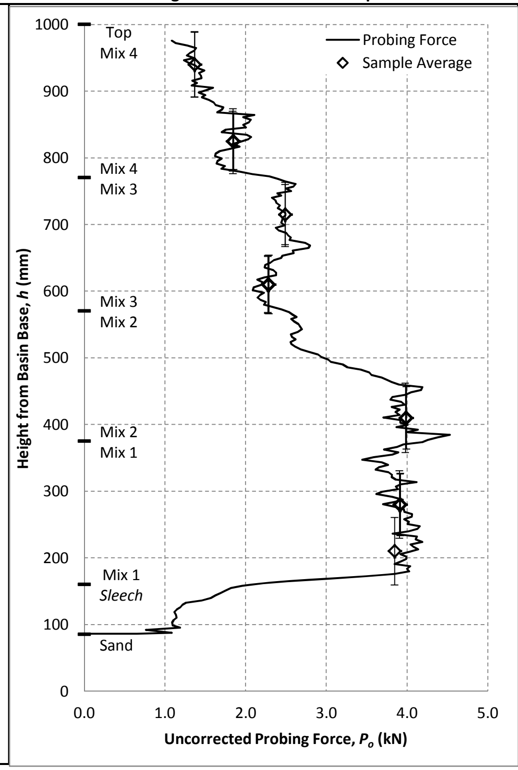
Column Sample Ref:	Origin Mix:	Height from Basin Base, mm	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, $\mathcal{E}_f$	Reason to Exclude:	Probing Force, kN
Column A	1	210	101	1718.3	621.7	47.5%	38.9	1.77%	-	3.85
Column B	1	280	92	1813.8	690.7	48.0%	57.6	1.62%	-	3.92
Column C	1	280	101	1755.0	680.6	47.7%	65.0	1.43%	-	3.91
Column D	1	280	94	1753.7	708.5	47.9%	59.4	1.64%	-	3.92
Column E	2	410	104	1707.8	733.6	46.7%	52.6	1.92%	-	3.98
Column F	2	410	94	1729.2	838.9	46.9%	53.2	2.19%	-	3.99
Column G	3	610	86.5	1691.9	660.7	45.1%	40.3	2.30%	-	2.28
Column H	3	610	88	1713.7	618.4	46.2%	34.0	2.57%	-	2.29
Column I	3	610	88	1688.7	637.6	45.9%	38.8	2.16%	-	2.29
Column J	3	610	84	1764.6	812.2	45.1%	41.8	2.56%	-	2.28
Column K	3	715	96.5	1655.1	625.8	45.5%	38.2	2.00%	-	2.49
Column L	3	715	90	1730.4	544.1	45.6%	30.4	1.94%	-	2.49
Column M	4	825	84.5	1798.5	750.9	45.1%	41.0	2.40%	-	1.85
Column O	4	825	97	1666.1	660.1	45.2%	53.6	1.92%	-	1.85
Column P	4	825	90	1729.4	637.6	45.2%	29.4	2.76%	-	1.84
Column Q	4	940	97	1723.3	517.1	45.3%	37.6	1.90%	Stone	1.37
Column R	4	940	98.5	1711.9	623.6	45.2%	45.0	2.09%	-	1.37

Comments:

Surrounding *Sleech* Properties:



Column Probing Force with Column Sample Locations:



Pull-Out Resistance Test No. 13

Test Type:	PORT	Binder:	OP Cement		Mixing Date:	13/02/2013			
Reference:	PO-13-6-150S	OPC Content:	150	kg/m^3	PORT Date:	25/02/2013		Pull-Out Rate:	
Operator:	MT & FYs	Built Height:	975	mm	PORT Time:	5.96	days	16.5	mm/sec
Column dia.	200 mm	Average Temp:	14.9	°C	Mould Time:	6.20	days	ΔUCSxWTBR	29.0
Basin dia.	750 mm	Surcharge	13.6	kPa	Column Time:	6.24	days	Wire Test:	Wire 1

65 mm dia. Mould Sample Properties:

Mould Sample:	Curing Condition:	Raw *Sleech* MC:	Organic Content:	Mixed MC:	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, ε_f
Mix 1R	Room	54.4%	-	46.8%	113	1644.4	534.8	43.7%	32.3	2.82%
Mix 2R	Room	53.9%	-	46.3%	114	1655.9	530.7	44.1%	24.9	3.26%
Mix 3R	Room	53.1%	-	45.2%	115	1641.0	456.6	43.7%	29.3	2.91%
Mix 4R	Room	51.6%	-	43.6%	117	1661.3	407.7	42.5%	19.1	3.43%
Mix 5R	Room	48.8%	-	43.6%	113	1672.0	455.3	40.0%	27.7	3.16%
Mix 1T	20°C	54.4%	-	46.8%	109	1602.4	603.3	44.0%	53.1	2.42%
Mix 2T	20°C	53.9%	-	46.3%	118	1650.0	473.5	43.3%	25.3	2.90%
Mix 3T	20°C	53.1%	-	45.2%	115	1662.8	545.4	44.3%	68.1	2.58%
Mix 4T	20°C	51.6%	-	43.6%	117	1670.2	486.3	43.1%	38.2	2.11%
Mix 5T	20°C	48.8%	-	43.6%	115	1690.6	530.9	42.1%	40.1	2.52%

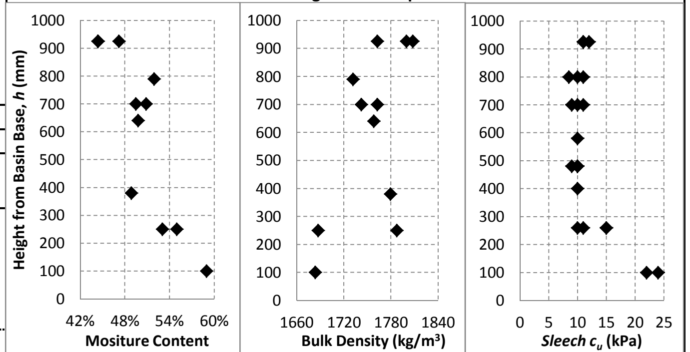
50 mm dia. Column Sample Properties:

Column Sample Ref:	Origin Mix:	Height from Basin Base, mm	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, ε_f	Reason to Exclude:	Probing Force, kN
Column A	5	925	80	1732.4	495.7	41.3%	42.7	2.24%	-	1.72
Column B	5	925	91	1742.6	445.8	41.1%	63.0	1.61%	-	1.73
Column C	5	925	104	1620.5	435.1	41.9%	34.8	1.69%	-	1.75
Column D	5	925	95	1738.8	437.1	41.0%	47.2	1.96%	-	1.73
Column E	2	455	83	1796.2	533.7	45.2%	29.2	2.58%	-	3.00
Column F	2	455	87	1722.9	513.0	44.7%	32.8	1.90%	-	3.01
Column G	2	390	75	1700.7	431.8	44.8%	23.5	2.24%	-	3.37

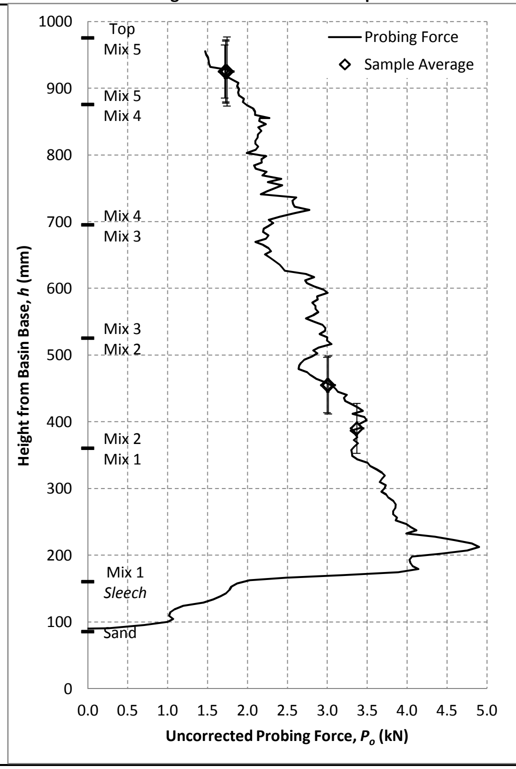
<u>Comments:</u>

Maximum settlement recorded due to the surcharge was 10mm but includes settlement of the hand-compacted sand layer over the column.
Mould samples over cut.
Column extracted in semi-circular sections but significant cracking found on trimming of sampleas with only 7 samples recovered.

Surrounding *Sleech* Properties:



Column Probing Force with Column Sample Locations:



Pull-Out Resistance Test No. 14

Test Type:	PORT	Binder:	OP Cement		Mixing Date:	13/02/2013			
Reference:	PO-14-12-150S	OPC Content:	150	kg/m^3	PORT Date:	25/02/2013		Pull-Out Rate:	
Operator:	MT & FYs	Built Height:	975	mm	PORT Time:	11.98	days	16.5	mm/sec
Column dia.	200 mm	Average Temp:	13.5	°C	Mould Time:	12.22	days	ΔUCSxWTBR	14.9
Basin dia.	750 mm	Surcharge:	13.7	kPa	Column Time:	12.28	days	Wire Test:	Wire 5

65 mm dia. Mould Sample Properties:

Mould Sample:	Curing Condition:	Raw *Sleech* MC:	Organic Content:	Mixed MC:	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, ε_f
Mix 1R	Room	51.1%	-	43.4%	130	1705.5	511.3	41.8%	34.6	2.29%
Mix 2R	Room	50.5%	-	43.8%	128.5	1670.6	651.7	41.7%	67.8	2.00%
Mix 3R	Room	51.5%	-	42.9%	128.5	1687.7	580.9	41.5%	32.1	2.30%
Mix 4R	Room	50.6%	-	42.8%	130.5	1675.8	599.5	41.2%	52.4	2.37%
Mix 5R	Room	50.0%	-	40.7%	129	1692.0	615.5	40.4%	52.2	2.35%
Mix 1T	20°C	51.1%	-	43.4%	127	1691.0	678.2	42.1%	85.8	1.69%
Mix 2T	20°C	50.5%	-	43.8%	129	1697.8	743.2	42.2%	67.8	2.41%
Mix 3T	20°C	51.5%	-	42.9%	126	1683.2	695.3	41.3%	84.9	1.92%
Mix 4T	20°C	50.6%	-	42.8%	130	1711.6	668.6	41.4%	52.4	2.22%
Mix 5T	20°C	50.0%	-	40.7%	127.5	1699.1	670.9	40.4%	44.6	2.35%

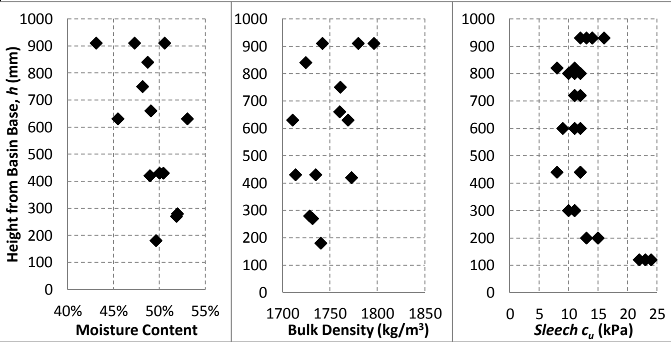
50 mm dia. Column Sample Properties:

Column Sample Ref:	Origin Mix:	Height from Basin Base, mm	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, ε_f	Reason to Exclude:	Probing Force, kN
Column A	5	925	102	1765.5	742.8	39.9%	64.4	1.95%	-	2.27
Column B	5	925	100	1788.6	578.3	40.0%	29.4	2.30%	-	2.27
Column C	5	925	96	1787.7	740.1	39.4%	73.2	1.70%	-	2.27
Column D	5	925	85	1739.5	571.5	39.4%	31.8	2.57%	-	2.28
Column E	4	850	95	1744.0	465.8	40.8%	32.0	2.07%	-	2.34
Column F	3	590	76	1761.9	501.8	41.7%	31.8	1.98%	-	3.12
Column G	3	590	94.5	1680.6	496.4	41.9%	54.1	1.10%	-	3.16
Column H	3	590	90	1737.6	545.8	41.2%	32.1	2.01%	-	3.14
Column I	2	490	91	1721.6	692.5	41.9%	40.2	2.13%	-	3.50
Column J	2	490	102	1734.5	747.3	42.5%	66.4	1.49%	-	3.51
Column L	2	360	83	1764.9	623.0	42.7%	42.2	2.58%	-	4.12
Column M	2	360	97	1749.3	672.2	42.3%	60.9	1.60%	-	3.51
Column N	2	490	97	1848.6	845.4	40.8%	52.0	1.94%	-	3.51
Column O	2	490	90	1733.3	731.0	42.9%	36.5	2.16%	-	4.05
Column P	2	380	88	1796.7	600.6	42.1%	77.2	1.40%	-	4.05
Column Q	1	380	95	1796.7	622.2	42.5%	57.7	1.39%	-	4.96
Column R	1	210	87	1691.6	646.2	42.7%	44.9	1.89%	-	5.07
Column S	1	210	91	1663.2	570.3	41.6%	35.4	2.04%	-	4.97

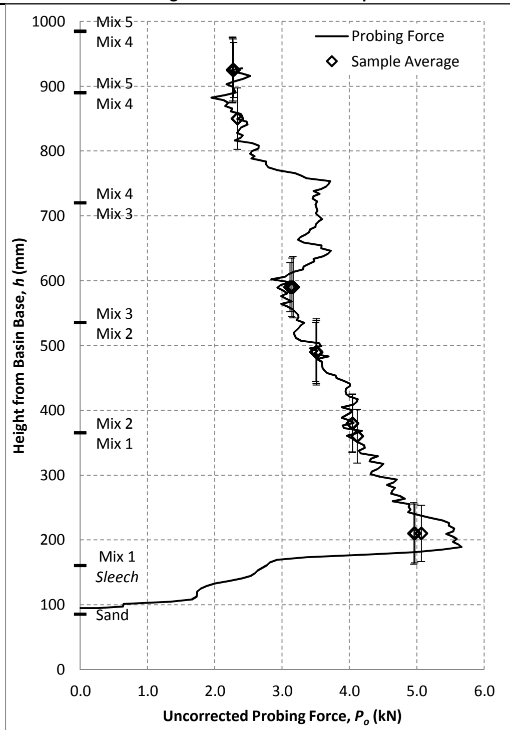
Comments:

Maximum settlement recorded due to the surcharge was 10 mm but includes settlement of the hand-compacted sand layer over the column.

Surrounding *Sleech* Properties:



Column Probing Force with Column Sample Locations:



Pull-Out Resistance Test No. 15

Test Type:	PORT	Binder:	OP Cement		Mixing Date:	04/03/2013			
Reference:	PO-15-1-100	OPC Content:	100	kg/m^3	PORT Date:	05/03/2013		Pull-Out Rate:	
Operator:	MT & FYs	Built Height:	995	mm	PORT Time:	0.95	days	16.7	mm/sec
Column dia.	200 mm	Average Temp:	14.1	°C	Mould Time:	1.29	days	ΔUCSxWTBR	160.0
Basin dia.	750 mm	Column Loading:	150	kg	Column Time:	1.23	days	Wire Test:	Wire 4

65 mm dia. Mould Sample Properties:

Mould Sample:	Curing Condition:	Raw *Sleech* MC:	Organic Content:	Mixed MC:	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, ε_f
Mix 1R	Room	48.5%	-	45.3%	125.5	1692.0	173.4	43.0%	8.9	3.73%
Mix 2R	Room	48.4%	-	44.5%	129.5	1690.5	143.3	44.0%	4.7	4.33%
Mix 3R	Room	49.6%	-	44.5%	129	1692.5	191.0	42.4%	10.1	3.52%
Mix 4R	Room	48.6%	-	43.3%	125.5	1692.5	150.4	43.0%	5.7	3.83%
Mix 5R	Room	47.5%	-	44.0%	129	1705.7	194.8	42.7%	7.9	4.13%
Mix 1T	20°C	48.5%	-	45.3%	129	1698.4	208.5	42.9%	15.8	2.79%
Mix 2T	20°C	48.4%	-	44.5%	130	1695.5	161.5	43.9%	8.3	3.17%
Mix 3T	20°C	49.6%	-	44.5%	127.5	1687.6	208.7	42.4%	10.1	3.50%
Mix 4T	20°C	48.6%	-	43.3%	130.5	1706.8	188.6	43.1%	9.7	3.57%
Mix 5T	20°C	47.5%	-	44.0%	129.5	1683.0	237.6	43.0%	14.6	3.28%

50 mm dia. Column Sample Properties:

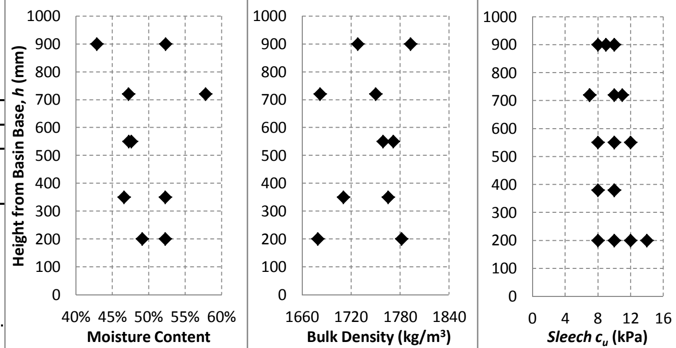
Column Sample Ref:	Origin Mix:	Height from Basin Base, mm	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, ε_f	Reason to Exclude:	Probing Force, kN
Column A	5	960	Vane	-	72.0	43.9%	-	0.00%	Vane	0.77
Column B	5	960	Vane	-	112.0	42.7%	-	0.00%	Vane	0.77
Column C	5	880	Vane	-	68.0	42.9%	-	0.00%	Vane	0.83
Column D	4	790	Vane	-	100.0	0.0%	-	0.00%	Vane	0.88
Column E	5	870	94.5	1820.6	151.4	42.6%	8.1	2.86%	-	0.87
Column F	4	720	108.5	1798.8	145.0	42.4%	7.4	3.35%	-	0.90
Column G	4	720	99.5	1716.1	133.0	42.9%	4.2	4.31%	-	0.90
Column H	2	515	102	1745.5	161.8	43.1%	6.5	3.21%	-	1.19
Column I	2	380	99	1681.9	161.4	42.9%	7.6	3.34%	-	1.34
Column J	1	240	88.5	1761.2	115.9	43.7%	5.3	2.72%	LS	1.57
Column K	4	750	97	1738.2	127.1	42.4%	5.6	3.45%	-	0.88
Column L	3	650	86	1692.4	154.6	42.6%	6.9	3.53%	-	0.97
Column M	3	545	101.5	1695.9	151.5	42.5%	7.3	2.61%	-	1.14
Column N	2	430	103	1787.5	119.8	44.6%	8.5	2.33%	LS	1.30
Column O	1	310	87.5	1676.9	191.8	42.3%	11.0	2.78%	-	1.45
Column P	1	310	94	1693.1	155.3	43.4%	9.3	2.33%	-	1.45

Comments:

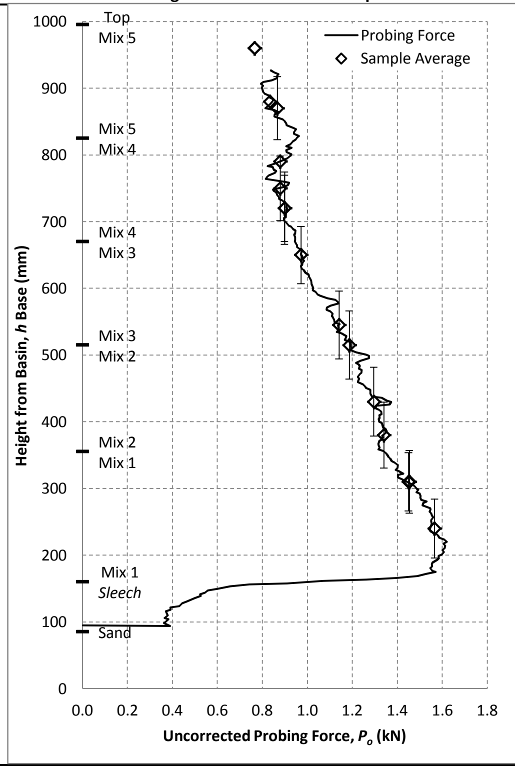
Column samples A, B, C & D were carried out with a shear vane; samples are excluded as the vane cracked the stabilised soil on insertion.

Column samples J and N show lower strengths than compared to other samples near them.

Surrounding *Sleech* Properties:



Column Probing Force with Column Sample Locations:



Pull-Out Resistance Test No. 16

Test Type:	PORT	Binder:	OP Cement		Mixing Date:	17/04/2013			
Reference:	PO-16-12-100	OPC Content:	100	kg/m^3	PORT Date:	29/04/2013		Pull-Out Rate:	
Operator:	MT	Built Height:	950	mm	PORT Time:	11.92	days	17.3	mm/sec
Column dia.	200 mm	Average Temp:	14.6	°C	Mould Time:	12.27	days	ΔUCSxWTBR	15.8
Basin dia.	750 mm	Column Loading:	150	kg	Column Time:	12.23	days	Wire Test:	Wire 6

65 mm dia. Mould Sample Properties:

Mould Sample:	Curing Condition:	Raw *Sleech* MC:	Organic Content:	Mixed MC:	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, ε_f
Mix 1R	Room	47.7%	-	43.2%	129	1705.7	477.9	42.0%	30.8	2.43%
Mix 2R	Room	46.2%	-	41.6%	130	1695.1	417.1	40.8%	65.2	2.04%
Mix 3R	Room	48.3%	-	42.7%	126	1691.2	436.1	41.9%	42.8	1.94%
Mix 4R	Room	49.8%	-	44.8%	129	1680.1	356.6	43.4%	29.8	2.29%
Mix 1T	20°C	47.7%	-	43.2%	130.5	1711.9	522.9	41.6%	65.0	1.61%
Mix 2T	20°C	46.2%	-	41.6%	130	1719.5	550.3	40.1%	52.3	1.95%
Mix 3T	20°C	48.3%	-	42.7%	130.5	1689.9	524.7	42.2%	55.4	1.87%
Mix 4T	20°C	49.8%	-	44.8%	129	1679.9	420.2	42.8%	100.1	1.39%

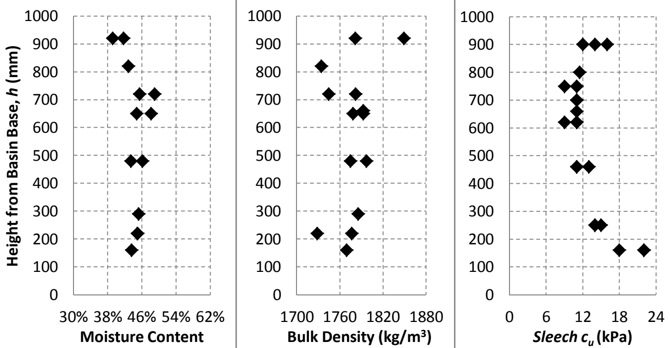
50 mm dia. Column Sample Properties:

Column Sample Ref:	Origin Mix:	Height from Basin Base, mm	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, ε_f	Reason to Exclude:	Probing Force, kN
Column A	4	890	85	1743.8	343.0	42.8%	19.7	2.43%	-	1.53
Column B	4	775	98	1781.9	461.4	42.0%	29.7	2.04%	-	1.57
Column D	3	565	93	1774.6	467.6	41.8%	52.0	1.94%	-	1.98
Column E	3	565	96	1848.6	511.5	41.8%	46.2	2.29%	-	2.00
Column F	2	470	80	1749.7	518.0	41.7%	48.6	1.61%	-	2.47
Column G	1	220	102	1760.4	495.2	41.9%	82.5	1.95%	-	2.94
Column H	1	220	89	1823.5	522.7	41.1%	41.2	1.87%	-	2.95
Column I	1	220	102	1729.4	602.5	42.2%	60.9	1.39%	-	2.94
Column J	1	220	100.5	1749.5	600.3	42.1%	66.6	0.00%	-	2.94

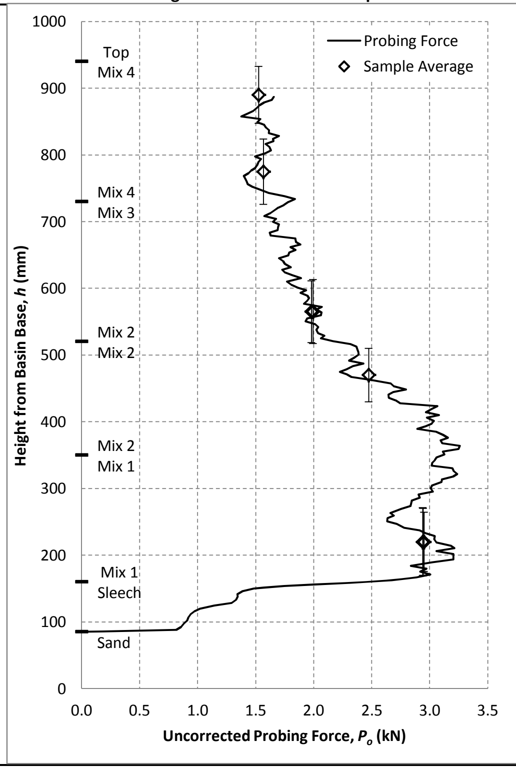
Comments:

Significant cracking and crumbling of the column in the top LHS. Lower portions of the column extracted in sections but no samples obtained from many section due to cracking.

Surrounding *Sleech* Properties:



Column Probing Force with Column Sample Locations:



Pull-Out Resistance Test No. 17

Test Type:	PORT	Binder:	OP Cement		Mixing Date:	21/06/2013			
Reference:	PO-17-12-150*	OPC Content:	100/150*	kg/m³	PORT Date:	03/07/2013		Pull-Out Rate:	
Operator:	MT &..	Built Height:	1040	mm	PORT Time:	11.81	days	16.2	mm/sec
Column dia.	200 mm	Average Temp:	18.0	°C	Mould Time:	12.00	days	ΔUCSxWTBR	12.7
Basin dia.	750 mm	Column Loading:	150	kg	Column Time:	12.05	days	Wire Test:	Wire 6

65 mm dia. Mould Sample Properties:

Mould Sample:	Curing Condition:	Raw *Sleech* MC:	Organic Content:	Mixed MC:	Length: mm	Density: kg/m³	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, $\mathcal{E}_f$
Mix 1R	Room	56.4%	-	47.8%	130	1646.4	451.8	45.6%	46.5	1.39%
Mix 2R*	Room	53.3%	-	47.7%	129	1642.4	411.8	46.7%	42.7	1.55%
Mix 3R	Room	52.1%	-	44.4%	130	1672.7	518.6	42.1%	70.5	1.87%
Mix 4R	Room	54.9%	-	46.8%	130	1655.3	516.9	45.0%	63.9	1.69%
Mix 1T	20°C	56.4%	-	47.8%	125	1651.1	654.1	45.2%	63.5	1.83%
Mix 2T*	20°C	53.3%	-	47.7%	131	1658.4	465.0	46.0%	51.2	1.85%
Mix 3T	20°C	52.1%	-	44.4%	131	1685.7	554.7	42.4%	56.2	2.04%
Mix 4T	20°C	54.9%	-	46.8%	130	1660.3	598.0	44.5%	42.2	2.51%

50 mm dia. Column Sample Properties:

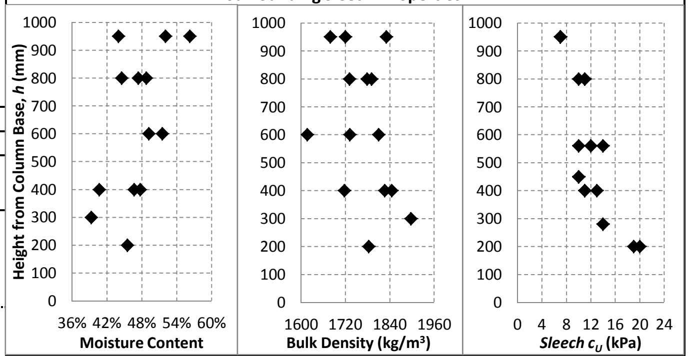
Column Sample Ref:	Origin Mix:	Height from Basin Base, mm	Length: mm	Density: kg/m³	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, $\mathcal{E}_f$	Reason to Exclude:	Probing Force, *kN*
Column A	4	970	101	1677.5	528.9	44.2%	35.3	2.04%	-	0.71
Column B	4	860	85	1659.6	459.2	43.4%	20.3	2.57%	-	1.09
Column C	4	865	102	1743.0	575.4	44.2%	46.5	1.59%	-	1.05
Column D	4	970	104	1690.8	532.1	44.3%	60.4	1.55%	-	0.71
Column E	4	865	100	1732.7	584.6	44.3%	82.1	1.30%	-	1.05
Column F	3	645	88	1728.4	486.8	41.2%	43.2	1.78%	-	2.10
Column G	3	635	91	1725.3	544.8	41.3%	42.2	1.74%	-	2.11
Column H	3	750	105	1742.2	432.0	41.3%	31.7	1.98%	-	1.87
Column I	3	750	99	1726.8	427.4	41.8%	33.9	1.54%	-	1.87
Column J	3	635	86	1692.3	415.7	42.7%	46.9	1.92%	-	2.09
Column K*	2	525	97	1723.4	247.4	45.6%	42.6	0.67%	σ-Ɛ	1.99
Column L*	2	435	90	1666.1	421.4	46.6%	34.1	1.39%	-	1.94
Column M	1	325	90	1651.1	377.6	46.2%	23.8	1.97%	-	2.32
Column N	1	220	101	1692.7	635.3	46.0%	66.9	1.14%	-	3.12
Column O	1	210	85	1661.9	103.0	46.0%	19.8	0.71%	σ-Ɛ	3.21
Column P	1	225	116	1612.0	534.8	45.9%	42.0	1.76%	-	3.04
Column Q	1	220	97	1630.5	438.9	45.7%	40.4	1.65%	-	3.12

Comments:

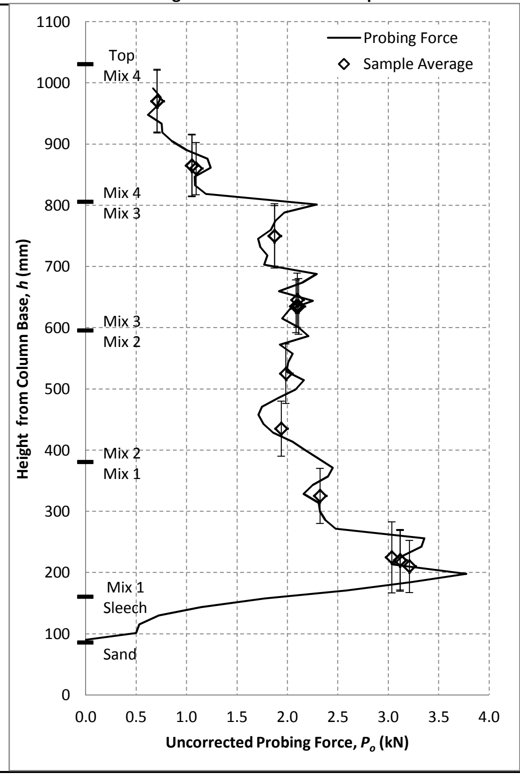
Mixes 1, 3 & 4 stabilised at a binder content of 150 kg/m³; Mix 2 stabilised at a binder content of 100 kg/m³

*Column samples K & L originate from Mix 2, stabilised with 100 kg/m³, but the strength of sample K is significantly lower than expected.

Surrounding *Sleech* Properties:



Column Probing Force with Column Sample Locations:



E.3 PORT Column Summary Statistics

PORT Mould Sample Summary Statistics:															
PIRT Reference:		PO-5	PO-6	PO-7	PO-8	PO-9	PO-10	PO-11	PO-12	PO-13S	PO-14S	PO-15	PO-16	PO-17*	
No. of Samples:		2	4	6	4	2	4	4	4	5	5	5	4	3	1
Binder Content (kg/m^3):		100	150	100	150	150	150	150	150	150	150	100	100	150	100
		Initial Sleech Moisture Content:													
Raw *Sleech* Moisture Content, w_i	Maximum:	0.58	0.59	0.60	0.54	0.49	0.69	0.65	0.58	0.54	0.52	0.50	0.50	0.56	-
	Minimum:	0.56	0.54	0.54	0.48	0.48	0.55	0.61	0.55	0.49	0.50	0.47	0.46	0.52	-
	Range:	0.01	0.05	0.06	0.06	0.01	0.15	0.05	0.03	0.06	0.02	0.02	0.04	0.04	-
	Average:	0.57	0.57	0.56	0.51	0.49	0.64	0.63	0.57	0.52	0.51	0.49	0.48	0.54	-
	St Dev:	0.01	0.02	0.03	0.03	0.01	0.07	0.02	0.01	0.02	0.01	0.01	0.01	0.02	-
	CoV:	1.7%	4.1%	4.5%	5.1%	1.1%	10.2%	3.1%	2.3%	4.3%	1.2%	1.5%	3.1%	3.5%	-
		Mould Sample Density:													
Room-Cured Density ρ_{mldRr} kg/m^3	Maximum:	1609.3	1726.3	1648.5	1739.8	1752.0	1617.0	1615.9	1652.2	1672.0	1705.5	1705.7	1705.7	1672.7	1642.4
	Minimum:	1598.8	1636.7	1617.0	1676.2	1710.1	1574.7	1585.3	1627.3	1641.0	1670.6	1690.5	1680.1	1646.4	-
	Range:	10.4	89.6	31.5	63.6	41.9	42.3	30.7	24.9	31.1	34.9	15.2	25.6	26.3	-
	Average:	1604.0	1667.6	1637.0	1705.5	1731.1	1596.0	1600.0	1638.6	1654.9	1686.3	1694.6	1693.1	1658.1	-
	St Dev:	7.4	41.8	11.3	30.3	29.6	20.6	13.3	10.3	12.7	13.8	6.2	10.6	13.4	-
	CoV:	0.5%	2.5%	0.7%	1.8%	1.7%	1.3%	0.8%	0.6%	0.8%	0.8%	0.4%	0.6%	0.8%	-
20°C Cured Density ρ_{mldTr} kg/m^3	Maximum:	-	-	-	-	-	-	1615.9	1656.0	1690.6	1711.6	1706.8	1719.5	1685.7	1658.4
	Minimum:	-	-	-	-	-	-	1599.7	1627.6	1602.4	1683.2	1683.0	1679.9	1651.1	-
	Range:	-	-	-	-	-	-	16.3	28.4	88.2	28.4	23.9	39.6	34.6	-
	Average:	-	-	-	-	-	-	1609.1	1646.7	1655.2	1696.6	1694.3	1700.3	1665.7	-
	St Dev:	-	-	-	-	-	-	7.0	12.9	33.0	10.5	9.3	18.5	17.9	-
	CoV:	-	-	-	-	-	-	0.4%	0.8%	2.0%	0.6%	0.6%	1.1%	1.1%	-
		Mould Sample UCS:													
Room-Cured UCS q_{mldRr} kPa	Maximum:	391.2	686.8	498.5	486.9	599.4	448.1	521.4	612.2	534.8	651.7	194.8	477.9	518.6	411.8
	Minimum:	292.7	538.0	371.0	435.3	548.7	425.8	404.5	569.3	407.7	511.3	143.3	356.6	451.8	-
	Range:	98.5	148.7	127.5	51.6	50.7	22.3	116.9	42.9	127.1	140.4	51.5	121.3	66.8	-
	Average:	341.9	628.3	436.7	456.7	574.1	440.2	451.7	591.7	477.0	591.8	170.6	421.9	495.8	-
	St Dev:	69.7	64.4	48.8	25.6	35.9	10.5	49.9	17.6	54.6	52.0	23.2	50.4	38.1	-
	COV:	20.4%	10.3%	11.2%	5.6%	6.2%	2.4%	11.1%	3.0%	11.4%	8.8%	13.6%	12.0%	7.7%	-
20°C Cured UCS q_{mldTr} kPa	Maximum:	-	-	-	-	-	-	563.2	722.9	603.3	743.2	237.6	550.3	654.1	465.0
	Minimum:	-	-	-	-	-	-	466.5	606.0	473.5	668.6	161.5	420.2	554.7	-
	Range:	-	-	-	-	-	-	96.7	117.0	129.8	74.7	76.1	130.0	99.4	-
	Average:	-	-	-	-	-	-	516.6	657.1	527.9	691.2	201.0	504.5	602.3	-
	St Dev:	-	-	-	-	-	-	49.3	50.4	51.7	30.9	28.1	57.6	49.9	-
	CoV:	-	-	-	-	-	-	9.5%	7.7%	9.8%	4.5%	14.0%	11.4%	8.3%	-
		Mould Sample Stiffness:													
Room-Cured Stiffness, E_{mldRr} MPa	Maximum:	21.4	52.1	37.8	32.6	52.8	43.1	45.8	41.7	32.3	67.8	10.1	65.2	70.5	42.7
	Minimum:	17.6	45.4	23.0	14.3	41.9	25.0	30.2	29.7	19.1	32.1	4.7	29.8	46.5	-
	Range:	3.8	6.7	14.8	18.4	10.8	18.1	15.6	12.0	13.2	35.7	5.4	35.4	24.0	-
	Average:	19.5	49.2	32.4	21.0	47.4	36.4	37.2	37.3	26.7	47.8	7.4	42.1	60.3	-
	St Dev:	2.7	2.8	5.0	8.0	7.6	8.5	6.8	5.3	5.0	14.7	2.2	16.4	12.4	-
	CoV:	13.7%	5.7%	15.5%	38.0%	16.1%	23.4%	18.3%	14.3%	18.7%	30.7%	30.2%	39.0%	20.6%	-
20°C Cured Stiffness, E_{mldTr} MPa	Maximum:	-	-	-	-	-	-	70.4	61.0	68.1	85.8	15.8	100.1	63.5	51.2
	Minimum:	-	-	-	-	-	-	33.8	44.6	25.3	44.6	8.3	52.3	42.2	-
	Range:	-	-	-	-	-	-	36.6	16.3	42.8	41.2	7.5	47.7	21.3	-
	Average:	-	-	-	-	-	-	47.1	53.8	45.0	67.1	11.7	68.2	54.0	-
	St Dev:	-	-	-	-	-	-	16.0	7.3	16.3	18.6	3.3	21.9	10.8	-
	CoV:	-	-	-	-	-	-	34.0%	13.6%	36.2%	27.8%	28.0%	32.1%	20.1%	-

Note: Summary statistics for PI-17* are seperately shown for the 100kg/m^3 and 150kg/m^3 binder contents.

PORT Column Sample Summary Statistics:															
PIRT Reference:		PO-5	PO-6	PO-7	PO-8	PO-9	PO-10	PO-11	PO-12	PO-13S	PO-14S	PO-15	PO-16	PO-17*	
No. of Samples:		3	17	7	9	9	16	13	16	7	18	12	9	14	1
Binder Content (kg/m3):		100	150	100	150	150	150	150	150	150	150	100	100	150	100
		Column Sample Density:													
Column Density ρ_{col}, kg/m^3	Maximum:	1682.8	1786.6	1787.2	1775.2	1809.3	1734.3	1800.0	1813.8	1796.2	1848.6	1820.6	1848.6	1743.0	1666.1
	Minimum:	1616.6	1592.6	1603.4	1621.3	1657.4	1619.5	1673.0	1655.1	1620.5	1663.2	1676.9	1729.4	1612.0	-
	Range:	66.1	193.9	183.9	153.8	151.9	114.7	127.0	158.7	175.6	185.4	143.7	119.2	131.0	-
	Average:	1639.3	1693.4	1697.6	1711.0	1724.3	1665.8	1736.7	1726.8	1722.0	1750.3	1734.0	1773.5	1693.2	-
	St Dev:	37.7	52.8	67.0	48.4	45.3	35.8	35.0	43.2	53.3	45.4	49.2	39.3	42.5	-
	CoV:	2.3%	3.1%	3.9%	2.8%	2.6%	2.1%	2.0%	2.5%	3.1%	2.6%	2.8%	2.2%	2.5%	-
		Column Sample Strength:													
Column UCS q_{mol}, kPa	Maximum:	288.6	789.3	451.8	495.6	536.3	513.6	540.3	838.9	533.7	845.4	191.8	602.5	635.3	421.4
	Minimum:	172.3	417.9	233.8	369.9	328.5	373.1	333.0	544.1	431.8	465.8	115.9	343.0	377.6	-
	Range:	116.4	371.4	218.0	125.7	207.8	140.5	207.3	294.9	101.9	379.7	75.9	259.6	257.7	-
	Average:	232.6	586.6	348.2	411.6	470.7	440.1	439.6	677.8	470.3	633.0	147.4	502.5	498.1	-
	St Dev:	58.3	114.4	80.0	47.0	71.1	49.1	67.8	76.4	42.6	102.9	21.1	78.0	75.3	-
	CoV:	25.1%	19.5%	23.0%	11.4%	15.1%	11.2%	15.4%	11.3%	9.1%	16.3%	14.3%	15.5%	15.1%	-
		Column Sample Stiffness:													
Column Stiffness, E_{col}, MPa	Maximum:	19.3	89.2	47.2	36.7	79.8	57.8	51.2	65.0	63.0	77.2	11.0	82.5	82.1	34.1
	Minimum:	9.2	32.2	7.6	17.4	26.4	23.0	18.1	29.4	23.5	29.4	4.2	19.7	20.3	-
	Range:	10.1	57.0	39.6	19.3	53.4	34.8	33.1	35.6	39.5	47.8	6.8	62.8	61.8	-
	Average:	14.2	52.9	25.4	27.5	48.1	40.1	31.9	45.0	39.0	47.9	7.3	49.7	44.0	-
	St Dev:	5.1	19.8	13.1	7.1	15.5	9.5	10.6	10.7	13.2	15.7	1.8	19.0	16.6	-
	CoV:	35.6%	37.3%	51.5%	25.8%	32.3%	23.7%	33.3%	23.8%	33.9%	32.8%	25.2%	38.2%	37.7%	-

Note: No samples were recovered from the 100kg/m^3 binder contetn section of column PI-17*.

E.4 PIRT Column Results Summary Sheet

Push-In Resistance Test No. 1

Test Type:	PIRT	Binder:	OP Cement		Mixing Date:	22/02/2013		Push-In Rate:	
Reference:	PI-1-3-100	OPC Content:	100	kg/m^3	PIRT Date:	25/02/2013		29.5	mm/sec
Operator:	(MT), McG & O'M	Built Height:	650	mm	PIRT Time:	3.09	days	-	mm/sec
Column dia.	200 mm	Average Temp:	11.2	°C	Mould Time:	3.15	days	ΔUCSxWTBR	15.0
Basin dia.	750 mm	Surcharge:	NA	kPa	Column Time:	3.18	days		

65 mm dia. Mould Sample Properties:

Mould Sample:	Curing Condition:	Raw *Sleech* MC, w_i	Organic Content:	Mixed MC, w_m	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC, w_s	Stiffness E_{50} MPa	Failure Strain, ε_f
Mix 1R	Room	46.1%	NA	41.3%	131	1764.8	428.5	NA	27.0	3.32%
Mix 2R	Room	45.3%	NA	41.3%	130.5	1742.1	308.8	NA	20.6	3.21%

50 mm dia. Column Sample Properties:

Column Sample Ref:	Origin Mix:	Height from Basin Base, mm	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC, w_s	Stiffness E_{50} MPa	Failure Strain, ε_f	Reason to Exclude:	Probing Force, kN
Column A	1	260	102	1856.8	232.1	NA	15.9	1.74%	Test exluded from PIRT analysis, see comments below.	1.34
Column B	1	260	82	1868.6	219.6	NA	20.6	2.06%		1.34
Column C	2	520	101.5	1801.3	199.1	NA	10.3	2.84%		0.97
Column D	2	520	109.5	1853.3	245.7	NA	12.9	2.59%		0.97
Column E	1	340	101	2010.5	216.4	NA	15.7	1.80%		1.13
Column F	2	520	97	1523.5	203.4	NA	15.1	1.89%		0.97

Comments:

Trial test to ensure that replication of pre-drilling would prevent deviation of the PIRT penetrometer in long columns.

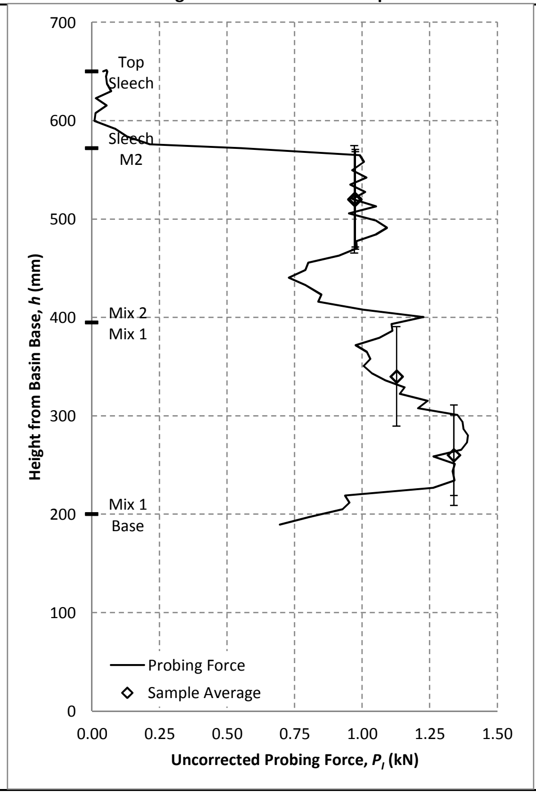
Column built to 570 mm and capped with sleech to 650 mm by final year students. Sleech used was discarded from previous tests due to its low moisture content and as it was contaminated with sand. Mechanical issues with the mixer resulted in only two mixes been created.

CPT rig mounted to the top of the basin and secured with cross members and strapping using the basins weight as a reaction.

Surrounding *Sleech* Properties:

No properties determined in the surrounding sleech.

Column Probing Force with Column Sample Locations:



Push-In Resistance Test No. 2

Test Type:	PIRT	Binder:	OP Cement		Mixing Date:	01/03/2013		Push-In Rate:	
Reference:	PI-2-11-150	OPC Content:	150	kg/m^3	PIRT Date:	12/03/2013		12.4	mm/sec
Operator:	MT, McG & O'M	Built Height:	890	mm	PIRT Time:	10.99	days	11.1	mm/sec
Column dia.	200 mm	Average Temp:	13.7	°C	Mould Time:	11.21	days	ΔUCSxWTBR	8.7
Basin dia.	750 mm	Surcharge:	NA	kPa	Column Time:	11.17	days		

65 mm dia. Mould Sample Properties:

Mould Sample:	Curing Condition:	Raw *Sleech* MC, w_i	Organic Content:	Mixed MC, w_m	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC, w_s	Stiffness E_{50} MPa	Failure Strain, ε_f
Mix 1R	Room	40.5%	-	35.9%	132	1798.6	1068.2	34.3%	87.8	2.99%
Mix 2R	Room	40.5%	-	36.1%	129	1839.7	1356.5	32.7%	137.3	2.34%
Mix 3R	Room	38.3%	-	34.2%	131.5	1791.8	1187.8	32.3%	97.1	1.90%
Mix 4R	Room	43.7%	-	39.3%	128.5	1736.4	1226.3	37.6%	100.1	2.51%

50 mm dia. Column Sample Properties:

Column Sample Ref:	Origin Mix:	Height from Basin Base, mm	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC, w_s	Stiffness E_{50} MPa	Failure Strain, ε_f	Reason to Exclude:	Probing Force, kN
Column A	4	840	88	1823.6	582.7	37.8%	38.5	2.78%	Test data exluded from PIRT analysis, see comments below.	1.60
Column B	4	840	98	1787.1	526.8	37.8%	25.3	2.64%		1.71
Column C	4	840	90	1793.3	520.0	37.3%	32.1	2.75%		1.60
Column D	3	650	84	1861.5	581.5	33.0%	42.8	1.90%		2.02
Column E	3	652	88	1879.8	542.8	33.1%	30.1	2.09%		2.02
Column F	3	595	89	1882.7	768.1	32.9%	49.9	2.45%		2.04
Column G	3	595	90	1836.9	527.0	32.3%	41.5	2.14%		2.04
Column H	2	485	100	1900.3	736.4	16.5%	61.0	2.09%		2.01
Column I	2	485	99.5	1839.0	755.7	37.0%	66.8	2.15%		2.01
Column J	2	400	100.5	1851.7	626.2	16.7%	52.8	1.80%		2.19
Column K	2	400	96	1865.3	611.3	18.4%	39.4	2.55%		2.18
Column L	1	240	88	1752.2	405.6	74.3%	33.0	1.99%		2.19
Column M	1	240	94.5	1931.1	436.2	30.6%	44.2	1.44%		2.20
Column N	1	240	104	1818.4	376.5	34.8%	75.3	1.31%		2.20
Column O	1	240	95	1777.9	441.2	35.4%	44.9	1.76%		2.20

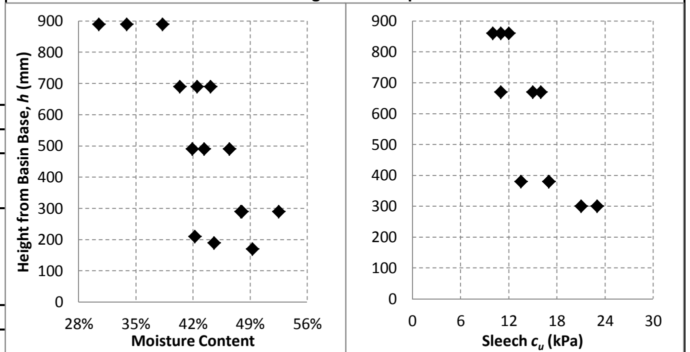
Comments:

Trial test to ensure replication of pre-drilling would prevent deviation of the PIRT penetrometer in high strength, long columns.

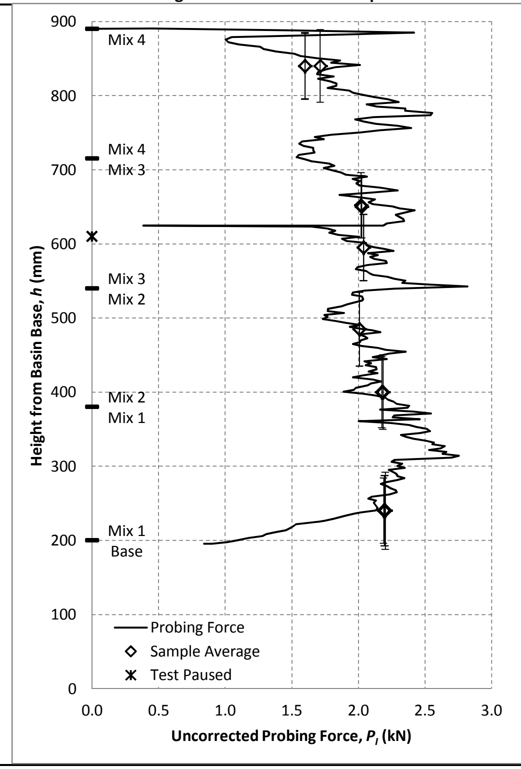
Sleech used was discarded from previous tests due to its low moisture content and as it was contaminated with sand.

CPT rig mounted to the top of the basin and secured with cross members and strapping using the basins weight as a reaction.

Surrounding *Sleech* Properties:



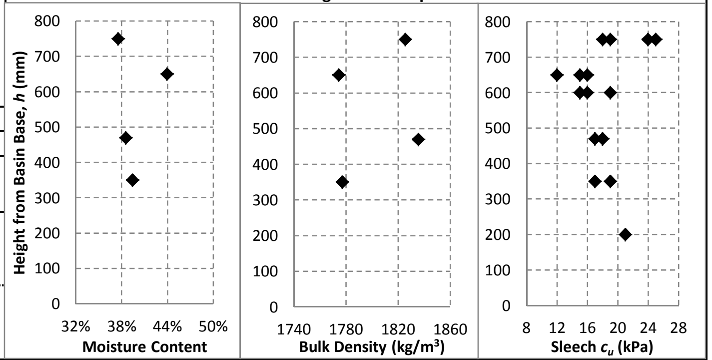
Column Probing Force with Column Sample Locations:



Push-In Resistance Test No. 3

Test Type:	PIRT	Binder:	OP Cement		Mixing Date:	11/07/2013		Push-In Rate:	
Reference:	PI-3-13-150	OPC Content:	150	kg/m^3	PIRT Date:	24/07/2013		32.3	mm/sec
Operator:	MT & AB	Built Height:	785	mm	PIRT Time:	12.88	days	32.7	mm/sec
Column dia.	200 mm	Average Temp:	21.3	°C	Mould Time:	12.99	days	ΔUCSxWTBR	6.3
Basin dia.	750 mm	Surcharge:	NA	kPa	Column Time:	13.04	days		

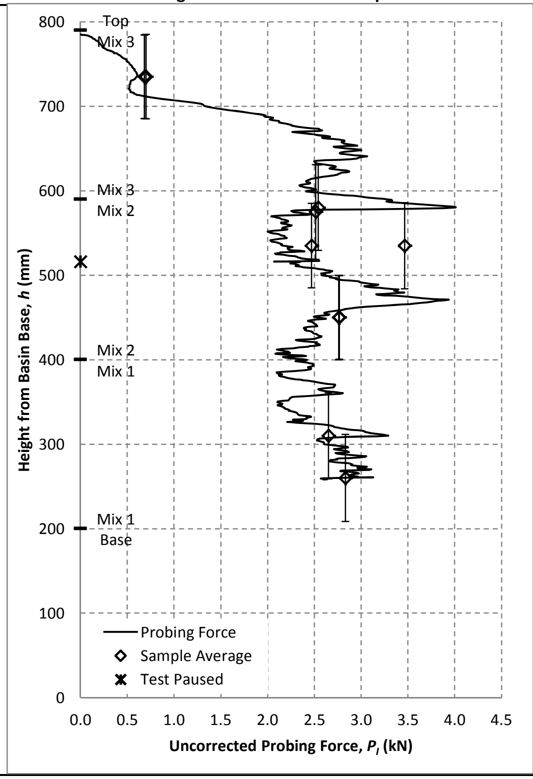
Surrounding *Sleech* Properties:



65 mm dia. Mould Sample Properties:

Mould Sample:	Curing Condition:	Raw *Sleech* MC, w_i	Organic Content:	Mixed MC, w_m	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC, w_s	Stiffness E_{50} MPa	Failure Strain, ε_f
Mix 1R	Room	45.7%	3.9%	39.0%	99	1736.9	640.5	38.3%	56.6	1.93%
Mix 2R	Room	47.5%	3.5%	40.6%	100	1722.2	678.6	38.2%	70.2	1.63%
Mix 3R	Room	47.9%	3.2%	41.4%	99	1694.5	653.5	39.0%	58.1	1.63%
Mix 1T	20°C	45.7%	3.9%	39.0%	112	1726.4	771.0	35.4%	94.1	1.03%
Mix 2T	20°C	47.5%	3.5%	40.6%	101	1723.8	814.2	38.0%	105.1	0.95%
Mix 3T	20°C	47.9%	3.5%	41.4%	102	1706.4	883.0	39.7%	106.6	1.15%

Column Probing Force with Column Sample Locations:



50 mm dia. Column Sample Properties:

Column Sample Ref:	Origin Mix:	Height from Basin Base, mm	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC, w_s	Stiffness E_{50} MPa	Failure Strain, ε_f	Reason to Exclude:	Probing Force, kN
Column A	3	735	99	1746.2	640.5	39.6%	56.6	1.93%	Test data exluded from PIRT analysis. see comments below.	0.68
Column B	3	735	100	1743.0	678.6	39.8%	70.2	1.63%		0.70
Column C	3	735	99	1818.1	653.5	38.9%	58.1	1.63%		0.68
Column E	2	575	112	1685.1	771.0	38.6%	94.1	1.03%		2.51
Column F	2	580	101	1837.0	814.2	38.6%	105.1	0.95%		2.54
Column G	2	535	102	1742.7	883.0	38.1%	106.6	1.15%		3.46
Column H	2	535	100	1776.1	828.3	38.6%	96.4	1.19%		2.47
Column I	1	450	99	1735.6	855.3	37.7%	84.2	1.11%		2.77
Column J	1	450	100	1745.7	854.6	38.9%	48.9	1.57%		2.76
Column K	1	260	103	1720.5	889.0	38.7%	100.3	1.05%		2.83
Column L	1	310	102	1680.2	914.3	37.7%	111.1	1.16%		2.65

Comments:

Test not included in PIRT analysis as *sleech* used was contaminated in places by foreign material such as sand.

First test carried out with CPT rig mounted on a specific reaction frame. Initial PIRT on 21/06/2013 stopped after 70 mm due to bending of sounding bars. Sounding bar guide installed on CPT rig and test re-run on 24/07/2013 with the PIRT turned 90° to first test attempt.

Push-In Resistance Test No. 4

Test Type:	PIRT	Binder:	OP Cement		Mixing Date:	29/07/2013		Push-In Rate:	
Reference:	PI-4-2-150	OPC Content:	150	kg/m^3	PIRT Date:	31/07/2013		18.3	mm/sec
Operator:	MT & AB	Built Height:	1000	mm	PIRT Time:	1.85	days	21.1	mm/sec
Column dia.	200 mm	Average Temp:	19.2	°C	Mould Time:	2.05	days	ΔUCSxWTBR	66.5
Basin dia.	750 mm	Surcharge:	NA	kPa	Column Time:	2.10	days		

65 mm dia. Mould Sample Properties:

Mould Sample:	Curing Condition:	Raw *Sleech* MC, w_i	Organic Content:	Mixed MC, w_m	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC, w_s	Stiffness E_{50} MPa	Failure Strain, ε_f
Mix 1R	Room	43.1%	306.0%	37.5%	130	1710.9	393.4	36.2%	22.8	2.76%
Mix 2R	Room	41.6%	336.9%	38.9%	130	1716.0	349.5	37.4%	17.5	2.40%
Mix 3R	Room	43.8%	262.8%	38.0%	129	1724.9	382.1	36.2%	28.8	2.44%
Mix 4R	Room	48.0%	301.1%	41.3%	128	1694.3	361.1	39.6%	21.1	2.64%
Mix 1T	20°C	43.1%	306.0%	37.5%	128	1759.7	392.9	35.8%	29.5	2.40%
Mix 2T	20°C	41.6%	336.9%	38.9%	129	1734.7	382.8	37.1%	19.3	2.79%
Mix 3T	20°C	43.8%	262.8%	38.0%	126	1736.2	387.8	36.5%	23.6	2.34%
Mix 4T	20°C	48.0%	301.1%	41.3%	131	1699.9	333.5	39.8%	19.6	2.30%

50 mm dia. Column Sample Properties:

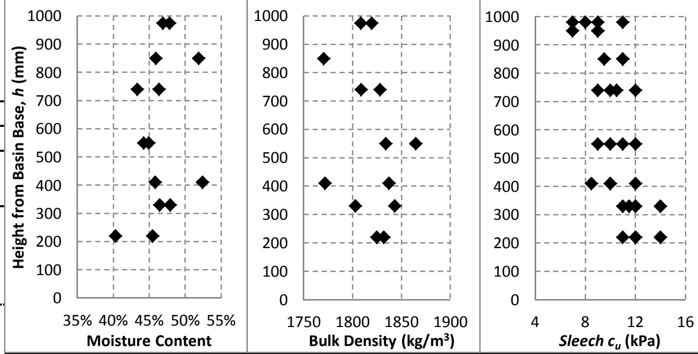
Column Sample Ref:	Origin Mix:	Height from Basin Base, mm	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC, w_s	Stiffness E_{50} MPa	Failure Strain, ε_f	Reason to Exclude:	Probing Force, kN
Column A	4	905	104	1720.9	263.2	39.6%	17.1	3.16%	-	1.07
Column B	4	905	100	1828.6	270.7	40.4%	15.7	1.98%	-	1.07
Column C	4	850	89	1743.0	311.1	40.7%	16.9	3.05%	-	1.25
Column D	4	905	98	1733.8	317.9	40.0%	25.7	2.16%	-	1.06
Column E	4	905	98	1830.2	325.9	41.5%	21.0	2.14%	-	1.06
Column F	4	820	93	1788.0	284.1	41.3%	17.6	1.66%	-	1.32
Column G	4	820	95	1803.3	302.6	40.5%	12.9	2.64%	-	1.32
Column H	3	610	102	1806.7	359.2	37.0%	16.9	2.38%	-	1.63
Column I	2	530	103	1903.9	389.9	38.5%	25.9	1.55%	-	1.55
Column J	2	530	100	1777.8	442.8	38.7%	50.8	1.35%	-	1.54
Column K	1	310	106	1882.4	449.4	35.5%	28.2	1.76%	-	1.61
Column L	1	310	108	1937.8	381.4	36.5%	26.3	1.93%	-	1.61
Column M	1	250	100	1824.6	410.1	36.2%	32.3	1.53%	-	1.63
Column N	1	250	105	1786.8	357.3	37.0%	29.6	1.51%	-	1.64

Comments:

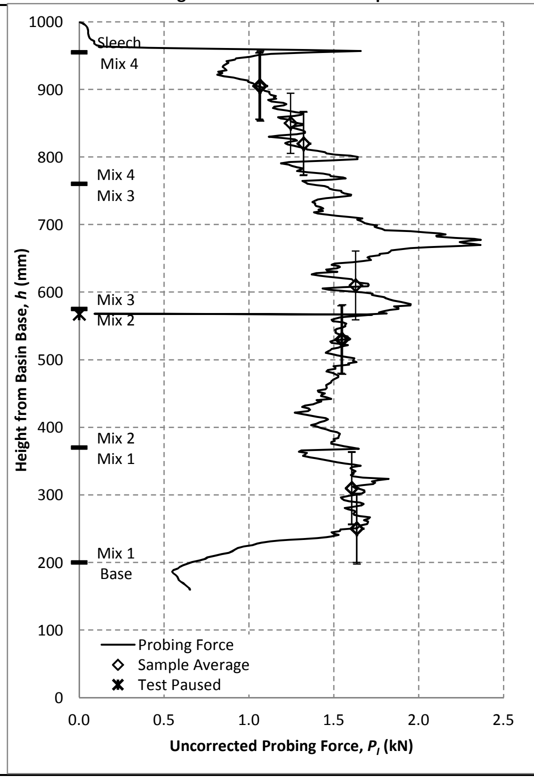
45 mm sleech cap placed on column to fill basin to 1,000 mm.

Much of the column extracted in semi-circular sections but cracks found when obtaining strength samples.

Surrounding *Sleech* Properties:



Column Probing Force with Column Sample Locations:



Push-In Resistance Test No. 5

Test Type:	PIRT	Binder:	OP Cement		Mixing Date:	06/08/2013		Push-In Rate:		
Reference:	PI-5-1-100	OPC Content:	100	kg/m^3	PIRT Date:	07/08/2013		31.2	mm/sec	
Operator:	MT & AB	Built Height:	1025	mm	PIRT Time:	0.93	days	21.3	mm/sec	
Column dia.	200 mm	Average Temp:	18.5	°C	Mould Time:	1.11	days	16.1	mm/sec	
Basin dia.	750 mm	Surcharge:	NA	kPa	Column Time:	1.16	days			

65 mm dia. Mould Sample Properties:

Mould Sample:	Curing Condition:	Raw *Sleech* MC, w_i	Organic Content:	Mixed MC, w_m	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC, w_s	Stiffness E_{50} MPa	Failure Strain, ε_f
Mix 1R	Room	46.0%	3.3%	41.5%	131	1698.3	201.9	40.1%	13.4	2.93%
Mix 2R	Room	45.2%	4.6%	40.8%	130	1687.3	191.5	40.6%	15.7	2.68%
Mix 3R	Room	47.0%	2.4%	42.5%	129	1684.5	180.1	41.7%	14.8	2.83%
Mix 4R	Room	45.4%	2.6%	40.7%	129	1683.4	211.7	39.5%	12.2	3.55%
Mix 1T	20°C	46.0%	3.3%	41.5%	130	1694.2	197.7	40.0%	12.8	3.06%
Mix 2T	20°C	45.2%	4.6%	40.8%	130	1699.5	224.2	40.7%	17.2	2.99%
Mix 3T	20°C	47.0%	2.4%	42.5%	126	1688.3	195.6	42.4%	9.8	3.05%
Mix 4T	20°C	45.4%	2.6%	40.7%	131	1708.2	218.3	40.5%	17.7	2.90%

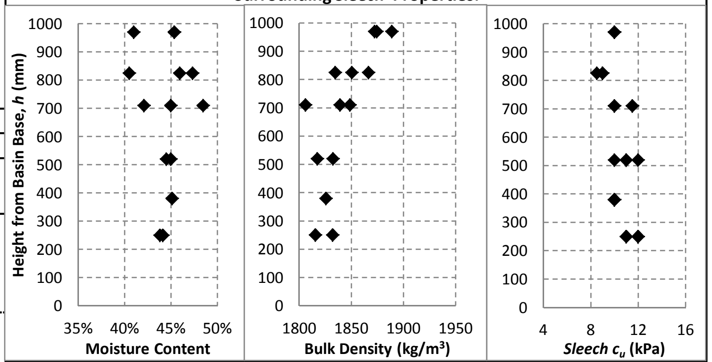
50 mm dia. Column Sample Properties:

Column Sample Ref:	Origin Mix:	Height from Basin Base, mm	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC, w_s	Stiffness E_{50} MPa	Failure Strain, ε_f	Reason to Exclude:	Probing Force, kN
Column A	4	950	105	1801.8	208.3	38.7%	9.9	3.93%	-	0.69
Column B	4	950	100	1808.6	210.6	39.4%	10.0	3.34%	-	0.70
Column C	4	940	105	1783.5	215.9	40.1%	18.4	2.12%	-	0.71
Column D	4	940	105	1793.1	236.7	39.5%	14.6	2.81%	-	0.71
Column E	3	810	88	1806.0	218.2	38.8%	13.6	3.00%	-	0.85
Column F	3	755	91	1765.1	226.9	41.1%	11.9	2.82%	-	0.90
Column G	3	755	91	1767.0	208.2	41.6%	10.8	2.88%	-	0.90
Column H	2	560	99	1791.6	244.4	39.6%	18.7	2.07%	-	0.93
Column I	2	560	92	1848.8	264.9	39.1%	15.2	2.71%	-	0.93
Column J	2	445	85	1750.2	252.7	40.2%	13.8	2.82%	-	1.05
Column K	2	445	90	1843.3	243.0	40.0%	19.6	2.38%	-	1.05
Column L	2	445	89	1810.1	247.8	40.3%	18.9	2.12%	-	1.05
Column M	1	320	107	1867.6	177.9	39.6%	8.7	2.75%	-	0.97
Column N	1	330	89	1773.3	187.0	40.2%	7.6	3.40%	-	0.97
Column O	1	245	91	1772.6	201.0	40.1%	7.5	3.22%	-	0.96
Column P	1	245	90	1782.9	201.4	39.4%	9.1	3.27%	-	0.96

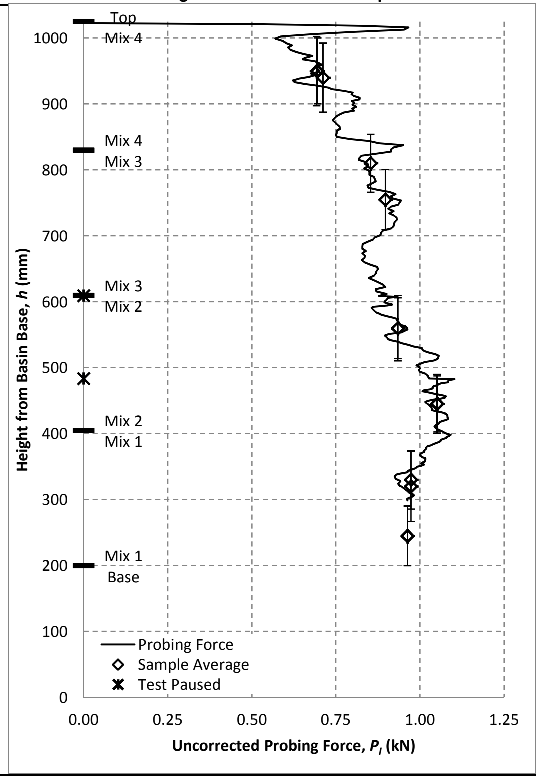
Comments:

Penetrometer did not fully probe the column due to issue with addition of sounding bars during the test.

Surrounding *Sleech* Properties:



Column Probing Force with Column Sample Locations:



Push-In Resistance Test No. 6

Test Type:	PIRT	Binder:	OP Cement		Mixing Date:	06/08/2013		Push-In Rate:		
Reference:	PI-6-6-150	OPC Content:	150	kg/m^3	PIRT Date:	07/08/2013		24.9	mm/sec	
Operator:	MT & AB	Built Height:	1020	mm	PIRT Time:	5.93	days	26.1	mm/sec	
Column dia.	200 mm	Average Temp:	18.4	°C	Mould Time:	6.07	days	ΔUCSxWTBR	16.0	
Basin dia.	750 mm	Surcharge:	NA	kPa	Column Time:	6.11	days			

65 mm dia. Mould Sample Properties:

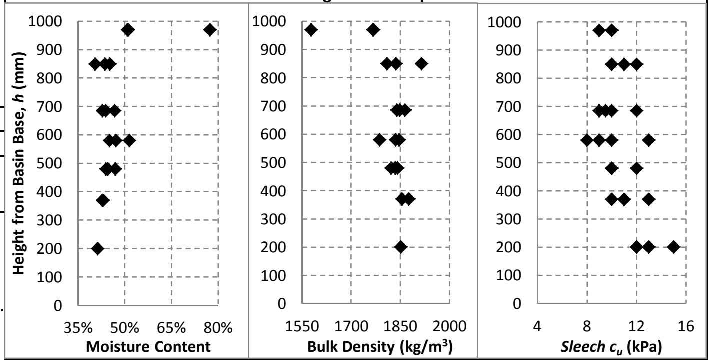
Mould Sample:	Curing Condition:	Raw *Sleech* MC, w_i	Organic Content:	Mixed MC, w_m	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC, w_s	Stiffness E_{50} MPa	Failure Strain, ε_f
Mix 1R	Room	45.9%	3.4%	39.4%	131	1707.9	463.0	39.4%	28.7	2.43%
Mix 2R	Room	46.4%	3.3%	39.8%	131	1719.0	456.7	39.8%	33.5	2.23%
Mix 3R	Room	45.9%	2.5%	39.7%	131	1719.0	423.0	39.7%	31.5	1.99%
Mix 4R	Room	45.9%	2.3%	39.4%	126	1702.9	396.2	39.4%	27.8	2.29%
Mix 1T	20°C	45.9%	3.4%	39.4%	127	1714.9	528.5	39.4%	46.8	2.12%
Mix 2T	20°C	46.4%	3.3%	39.8%	129	1701.6	535.9	39.8%	38.1	2.29%
Mix 3T	20°C	45.9%	2.5%	39.7%	130	1720.5	518.9	39.7%	32.4	2.44%
Mix 4T	20°C	45.9%	2.3%	39.4%	130	1716.5	522.9	39.4%	34.2	2.39%

50 mm dia. Column Sample Properties:

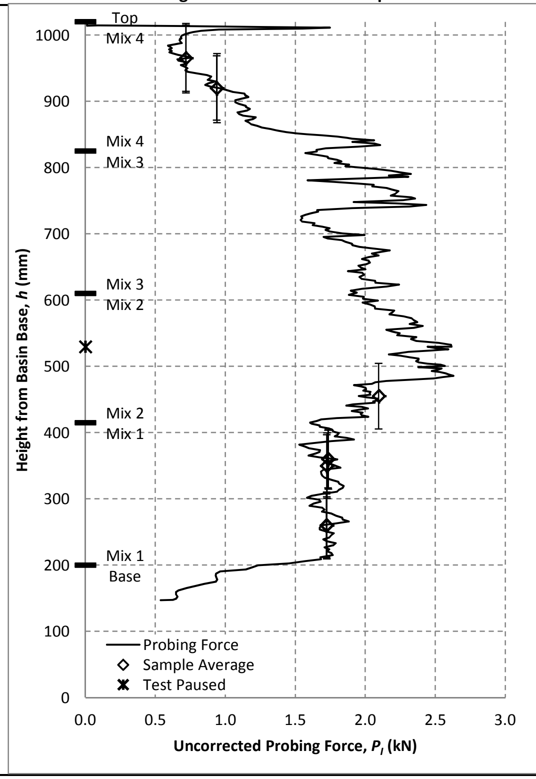
Column Sample Ref:	Origin Mix:	Height from Basin Base, mm	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC, w_s	Stiffness E_{50} MPa	Failure Strain, ε_f	Reason to Exclude:	Probing Force, kN
Column A	4	965	100	1913.8	392.1	39.5%	36.0	1.58%	-	0.72
Column B	4	965	105	1805.7	500.6	38.0%	30.3	1.93%	-	0.72
Column C	4	920	97	1780.3	415.7	37.8%	42.6	1.59%	-	0.94
Column D	4	920	104	1842.2	543.7	37.3%	49.0	1.69%	-	0.94
Column E	2	455	99	1799.9	561.2	38.9%	53.9	1.92%	-	2.10
Column F	2	350	94	1817.2	403.9	38.3%	24.9	2.82%	-	1.72
Column G	2	350	99	1811.1	487.9	38.4%	58.2	1.71%	-	1.73
Column H	2	360	91	1806.6	511.2	38.3%	60.8	1.28%	-	1.74
Column I	2	360	87	1807.2	432.6	39.3%	32.4	1.34%	-	1.73
Column J	1	260	101	1828.3	443.0	37.7%	32.4	1.60%	-	1.72
Column K	1	260	100	1813.5	506.9	39.0%	29.3	1.95%	-	1.72
Column L	1	260	96	1768.4	420.9	37.7%	35.8	2.27%	-	1.72
Column M	1	260	95	1859.3	547.2	37.2%	41.8	1.73%	-	1.72

Comments:

Surrounding *Sleech* Properties:



Column Probing Force with Column Sample Locations:



Push-In Resistance Test No. 7

Test Type:	PIRT	Binder:	OP Cement		Mixing Date:	15/08/2013		Push-In Rate:	
Reference:	PI-7-6-100	OPC Content:	100	kg/m^3	PIRT Date:	21/08/2013		23.5	mm/sec
Operator:	MT & AB	Built Height:	1020	mm	PIRT Time:	5.93	days	29.9	mm/sec
Column dia.	200 mm	Average Temp:	18.7	°C	Mould Time:	6.07	days	ΔUCSxWTBR	18.1
Basin dia.	750 mm	Surcharge:	NA	kPa	Column Time:	6.13	days		

65 mm dia. Mould Sample Properties:

Mould Sample:	Curing Condition:	Raw *Sleech* MC, w_i	Organic Content:	Mixed MC, w_m	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC, w_s	Stiffness E_{50} MPa	Failure Strain, ε_f
Mix 1R	Room	46.6%	2.9%	42.2%	129	1696.3	382.3	39.9%	40.2	1.85%
Mix 2R	Room	46.4%	2.8%	42.2%	130	1680.1	416.5	40.3%	31.1	2.29%
Mix 3R	Room	46.0%	2.9%	39.8%	130	1708.3	389.1	38.9%	37.0	2.25%
Mix 4R	Room	43.6%	2.9%	41.5%	129	1698.1	338.9	38.9%	39.9	1.84%
Mix 1T	20°C	46.6%	2.9%	42.2%	131	1691.5	410.9	39.4%	19.9	2.85%
Mix 2T	20°C	46.4%	2.8%	42.2%	128	1693.9	455.1	40.6%	46.9	1.95%
Mix 3T	20°C	46.0%	2.9%	39.8%	127	1705.4	406.2	38.7%	37.3	1.96%
Mix 4T	20°C	43.6%	2.9%	41.5%	128	1666.8	340.0	39.7%	28.0	2.23%

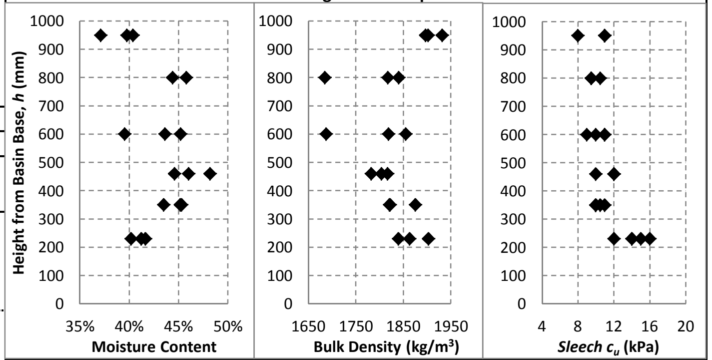
50 mm dia. Column Sample Properties:

Column Sample Ref:	Origin Mix:	Height from Basin Base, mm	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC, w_s	Stiffness E_{50} MPa	Failure Strain, ε_f	Reason to Exclude:	Probing Force, kN
Column A	4	960	99	1783.6	352.9	38.9%	22.7	2.04%	-	1.07
Column B	4	940	102	1799.0	349.5	39.2%	27.6	1.73%	-	1.10
Column C	3	700	85	1776.3	327.0	39.0%	14.2	2.60%	-	1.72
Column D	1	350	86	1775.5	394.6	40.2%	23.9	2.35%	-	1.94
Column E	1	350	89	1798.1	447.2	39.9%	28.8	2.15%	-	1.88
Column F	1	250	91	1820.2	448.6	39.5%	33.6	1.63%	-	1.96
Column G	1	250	88	1841.9	462.0	39.8%	32.3	1.65%	-	1.96

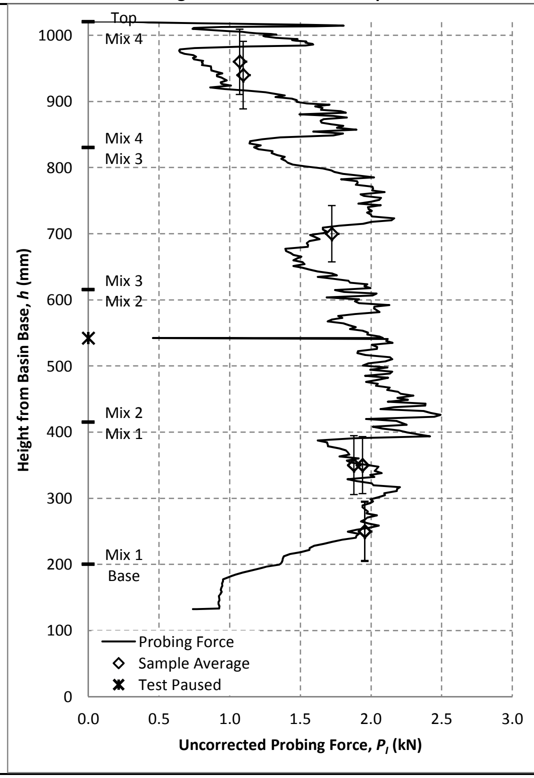
Comments:

Significant cracking and crumbing throughout the column caused by the test.

Surrounding *Sleech* Properties:



Column Probing Force with Column Sample Locations:



Push-In Resistance Test No. 8

Test Type:	PIRT	Binder:	OP Cement		Mixing Date:	23/08/2013		Push-In Rate:	
Reference:	PI-8-4-150	OPC Content:	150	kg/m^3	PIRT Date:	27/08/2013		27.4	mm/sec
Operator:	MT & AB	Built Height:	1000	mm	PIRT Time:	3.94	days	25.3	mm/sec
Column dia.	200 mm	Average Temp:	17.9	°C	Mould Time:	4.10	days	ΔUCSxWTBR	26.0
Basin dia.	750 mm	Surcharge:	NA	kPa	Column Time:	4.13	days		

65 mm dia. Mould Sample Properties:

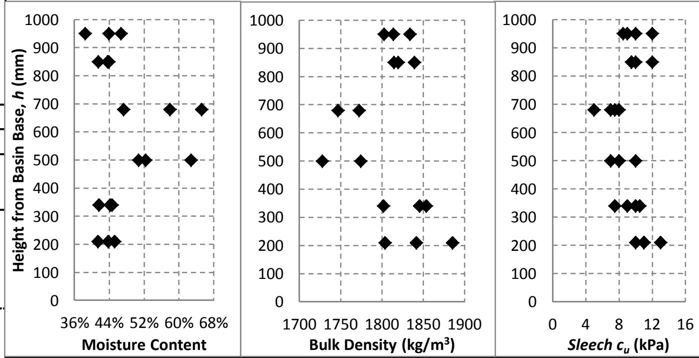
Mould Sample:	Curing Condition:	Raw *Sleech* MC, w_i	Organic Content:	Mixed MC, w_m	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC, w_s	Stiffness E_{50} MPa	Failure Strain, ε_f
Mix 1R	Room	52.2%	3.6%	45.6%	128	1652.1	433.1	42.8%	31.8	1.91%
Mix 2R	Room	47.9%	2.6%	40.9%	126	1683.0	402.7	38.0%	31.0	2.35%
Mix 3R	Room	50.4%	2.5%	43.5%	131	1678.7	385.5	40.9%	35.6	1.99%
Mix 4R	Room	50.0%	2.6%	42.5%	129	1667.7	414.9	40.4%	41.1	1.66%
Mix 1T	20°C	52.2%	3.6%	45.6%	130	1665.7	459.0	42.6%	38.8	1.87%
Mix 2T	20°C	47.9%	2.6%	40.9%	131	1699.6	470.0	38.3%	32.4	2.23%
Mix 3T	20°C	50.4%	2.5%	43.5%	130	1680.5	435.0	41.5%	30.1	2.45%
Mix 4T	20°C	50.0%	2.6%	42.5%	126	1707.5	511.9	40.4%	47.8	2.14%

50 mm dia. Column Sample Properties:

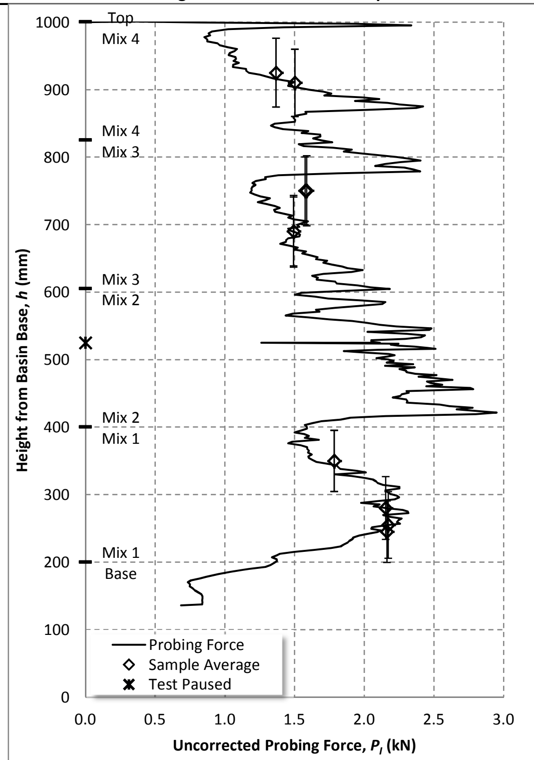
Column Sample Ref:	Origin Mix:	Height from Basin Base, mm	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC, w_s	Stiffness E_{50} MPa	Failure Strain, ε_f	Reason to Exclude:	Probing Force, kN
Column A	4	925	102	1815.1	522.3	39.9%	42.6	1.84%	-	1.37
Column B	4	925	102	1773.2	517.0	40.3%	52.5	2.03%	-	1.37
Column C	4	910	100	1834.0	461.1	40.5%	44.5	2.09%	-	1.50
Column D	4	910	99	1795.1	516.4	40.3%	33.7	2.04%	-	1.50
Column E	3	750	100	1714.8	469.7	37.6%	38.7	2.57%	-	1.58
Column F	3	750	104	1731.9	454.0	41.1%	48.3	1.95%	-	1.59
Column G	3	690	102	1791.7	456.5	41.4%	25.0	2.89%	-	1.49
Column H	3	690	106	1726.5	457.5	41.4%	36.2	2.34%	-	1.49
Column I	1	350	90	1829.1	401.9	42.5%	33.1	1.76%	-	1.79
Column J	1	350	91	1788.9	416.0	41.4%	34.1	1.68%	-	1.79
Column K	1	245	91	1850.2	351.4	42.5%	32.6	2.67%	σ-ε	2.16
Column L	1	255	99	1780.6	486.5	42.5%	41.5	1.89%	-	2.17
Column M	1	280	93	1853.6	461.5	42.8%	33.2	1.86%	-	2.16

Comments:

Surrounding *Sleech* Properties:



Column Probing Force with Column Sample Locations:



Push-In Resistance Test No. 9

Test Type:	PIRT	Binder:	OP Cement		Mixing Date:	29/08/2013		Push-In Rate:		
Reference:	PI-9-6-150S	OPC Content:	150	kg/m^3	PIRT Date:	04/09/2013		22.0	mm/sec	
Operator:	MT & AB	Built Height:	1000	mm	PIRT Time:	5.91	days	30.7	mm/sec	
Column dia.	200 mm	Average Temp:	18.3	°C	Mould Time:	6.07	days	ΔUCSxWTBR	17.7	
Basin dia.	750 mm	Surcharge:	13.5	kPa	Column Time:	6.11	days			

65 mm dia. Mould Sample Properties:

Mould Sample:	Curing Condition:	Raw *Sleech* MC, w_i	Organic Content:	Mixed MC, w_m	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC, w_s	Stiffness E_{50} MPa	Failure Strain, ε_f
Mix 1R*	Room	54.3%	3.4%	46.8%	127	1659.7	355.0	44.2%	26.3	2.15%
Mix 2R	Room	53.4%	3.1%	45.9%	131	1654.5	482.0	43.9%	37.8	1.85%
Mix 3R	Room	48.0%	2.6%	42.5%	125	1671.4	450.4	40.2%	39.5	2.33%
Mix 4R	Room	51.7%	3.0%	44.2%	129	1660.3	435.9	43.4%	42.5	1.93%
Mix 1T	20°C	54.3%	3.4%	46.8%	129	1677.8	469.5	44.3%	43.8	1.92%
Mix 2T	20°C	53.4%	3.1%	45.9%	130	1658.9	503.0	44.3%	51.7	1.78%
Mix 3T	20°C	48.0%	2.6%	42.5%	130	1696.7	509.9	39.7%	44.6	2.02%
Mix 4T	20°C	51.7%	3.0%	44.2%	131	1673.9	481.7	42.9%	36.8	1.99%

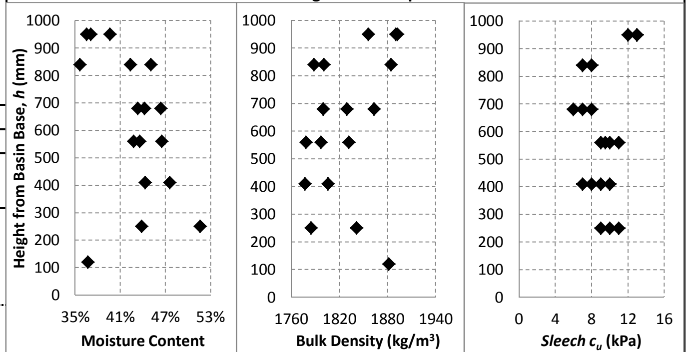
50 mm dia. Column Sample Properties:

Column Sample Ref:	Origin Mix:	Height from Basin Base, mm	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC, w_s	Stiffness E_{50} MPa	Failure Strain, ε_f	Reason to Exclude:	Probing Force, kN
Column A	4	940	92	1786.8	559.7	42.9%	39.2	2.04%	-	2.04
Column B	4	940	88	1777.8	531.0	42.4%	42.0	1.60%	-	2.05
Column C	4	870	96	1708.6	492.1	43.5%	57.9	1.60%	-	2.04
Column D	4	870	95	1700.9	499.9	42.1%	42.7	1.82%	-	2.04
Column E	4	940	94	1792.9	542.5	42.9%	65.6	1.74%	-	2.05
Column F	4	940	96	1746.1	534.1	43.4%	59.2	1.64%	-	2.05
Column G	4	870	100	1762.0	446.1	43.6%	33.5	1.71%	-	2.06
Column H	4	865	82	1704.5	479.7	43.2%	40.5	1.76%	-	2.00
Column I	2	550	89	1674.4	415.1	44.0%	33.5	1.44%	-	2.61
Column J	2	475	86	1756.4	520.1	44.8%	43.0	1.65%	-	2.23
Column K	2	425	101	1699.1	459.3	44.3%	27.9	2.21%	-	2.22
Column L	2	425	104	1665.3	532.4	44.1%	39.9	1.95%	-	2.22
Column M	1	290	94	1738.3	350.4	44.5%	33.7	1.49%	-	2.30
Column N	1	290	101	1704.0	391.9	44.9%	46.4	1.15%	-	2.30
Column O	1	250	96	1701.9	340.6	45.0%	45.9	1.11%	-	2.33
Column P	1	250	90	1756.7	316.0	44.6%	23.8	1.66%	-	2.34

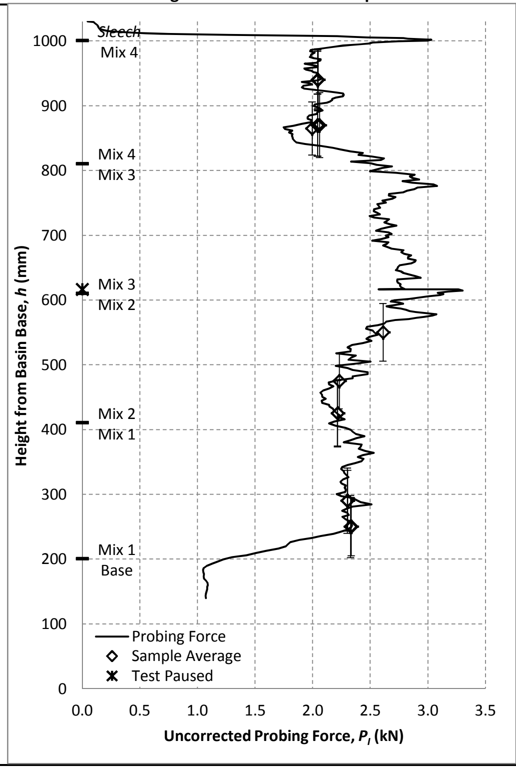
Comments:

*Mould sample M1R shows a significantly lower strength than the other room samples in this test which have similar moisture contents.
The stress-strain graph shows an earlier failure occuring at a strength of 100 kPa, before the sample contiues to a strength of 355 kPa.
Maximum settlement recorded due to the surcharge was 8 mm but includes settlement of the hand-compacted sand layer over the column.
Penetrometer passed through 30 mm of unstabilised sleech before entering the column.

Surrounding *Sleech* Properties:



Column Probing Force with Column Sample Locations:



Push-In Resistance Test No. 10

Test Type:	PIRT	Binder:	OP Cement		Mixing Date:	06/09/2013		Push-In Rate:		
Reference:	PI-10-12-150	OPC Content:	150	kg/m^3	PIRT Date:	18/09/2013		34.5	mm/sec	
Operator:	MT (& AB)	Built Height:	1010	mm	PIRT Time:	11.86	days	26.3	mm/sec	
Column dia.	200 mm	Average Temp:	17.8	°C	Mould Time:	12.24	days	ΔUCSxWTBR	14.8	
Basin dia.	750 mm	Surcharge:	NA	kPa	Column Time:	12.19	days			

65 mm dia. Mould Sample Properties:

Mould Sample:	Curing Condition:	Raw *Sleech* MC, w_i	Organic Content:	Mixed MC, w_m	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC, w_s	Stiffness E_{50} MPa	Failure Strain, ε_f
Mix 1R	Room	56.3%	4.0%	47.4%	127.5	1645.7	482.8	46.6%	44.7	1.57%
Mix 2R	Room	54.9%	4.0%	45.4%	129.5	1683.1	549.2	42.3%	124.8	1.26%
Mix 3R	Room	53.0%	2.7%	46.4%	127	1675.5	530.6	43.3%	44.6	1.77%
Mix 4R	Room	52.7%	2.6%	46.3%	129	1676.8	586.2	43.3%	122.5	1.34%
Mix 1T	20°C	56.3%	4.0%	47.4%	126	1645.5	597.6	45.5%	49.6	2.15%
Mix 2T	20°C	54.9%	4.0%	45.4%	128	1687.0	575.8	41.7%	59.3	1.82%
Mix 3T	20°C	53.0%	2.7%	46.4%	128	1676.4	609.7	42.0%	47.2	2.05%
Mix 4T	20°C	52.7%	2.6%	46.3%	129	1676.9	582.0	43.5%	59.8	1.70%

50 mm dia. Column Sample Properties:

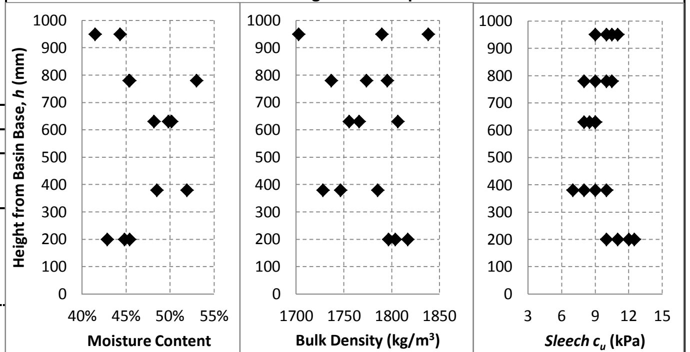
Column Sample Ref:	Origin Mix:	Height from Basin Base, mm	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC, w_s	Stiffness E_{50} MPa	Failure Strain, ε_f	Reason to Exclude:	Probing Force, kN
Column A	4	940	100	1693.9	719.7	42.8%	86.3	1.37%	-	1.12
Column B	4	940	100	1764.6	746.7	43.0%	61.5	1.86%	-	1.12
Column C	4	905	98	1781.4	606.1	43.1%	51.6	1.92%	-	1.47
Column D	4	905	98	1722.6	695.1	42.7%	70.0	1.71%	-	1.47
Column E	3	660	94	1784.6	816.2	42.7%	100.9	1.60%	-	1.54
Column F	3	660	96	1782.1	702.9	43.0%	109.9	1.10%	-	1.55
Column G	3	670	98	1783.2	698.3	42.4%	61.6	1.64%	-	1.50
Column H	3	670	98	1789.7	777.1	42.5%	70.8	1.62%	-	1.50
Column I	2	500	93	1764.3	705.5	42.3%	60.2	1.62%	-	2.72
Column J	2	500	93.5	1763.1	659.0	41.5%	69.2	1.45%	-	2.72
Column K	2	405	86	1769.2	707.5	43.6%	77.1	1.30%	-	2.52
Column L	2	405	89	1792.9	762.6	43.1%	55.8	1.75%	-	2.52
Column M	1	250	102	1749.1	701.3	46.3%	84.5	1.30%	-	2.15
Column N	1	250	95	1759.4	676.4	46.2%	66.6	1.31%	-	2.16

Comments:

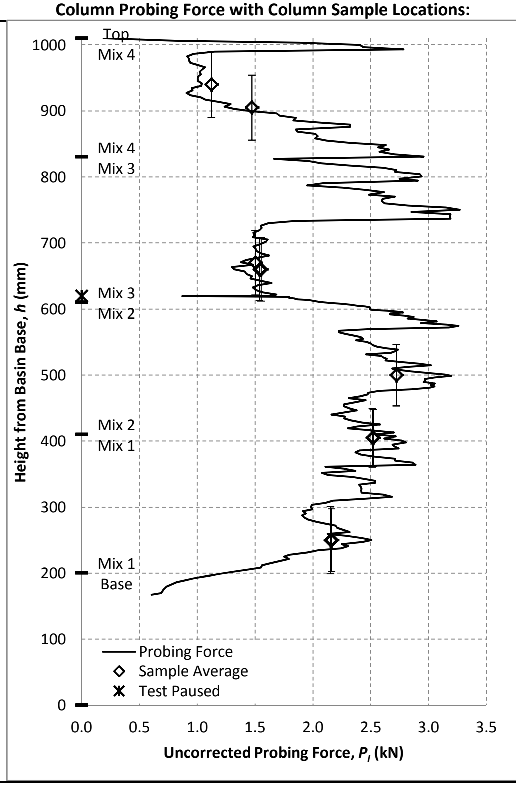
Significant cracking and crumbling noted throughout the column but 14 samples recovered.

Drop in force between h = 620 mm and 720 mm thought to a result of cracking in the column.

Surrounding *Sleech* Properties:



Column Probing Force with Column Sample Locations:



Push-In Resistance Test No. 11

Test Type:	PIRT	Binder:	OP Cement		Mixing Date:	20/09/2013		Push-In Rate:	
Reference:	PI-11-12-100	OPC Content:	100	kg/m^3	PIRT Date:	02/10/2013		19.0	mm/sec
Operator:	MT	Built Height:	1010	mm	PIRT Time:	11.88	days	28.9	mm/sec
Column dia.	200 mm	Average Temp:	18.7	°C	Mould Time:	12.23	days	ΔUCSxWTBR	13.3
Basin dia.	750 mm	Surcharge:	NA	kPa	Column Time:	12.18	days		

65 mm dia. Mould Sample Properties:

Mould Sample:	Curing Condition:	Raw *Sleech* MC, w_i	Organic Content:	Mixed MC, w_m	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC, w_s	Stiffness E_{50} MPa	Failure Strain, ε_f
Mix 1R	Room	47.6%	4.1%	43.6%	130	1679.4	430.4	42.2%	31.8	2.00%
Mix 2R	Room	49.9%	4.3%	44.1%	129.5	1673.9	469.5	43.0%	35.3	2.09%
Mix 3R	Room	52.8%	3.1%	45.4%	130.5	1650.5	466.4	42.7%	43.5	1.74%
Mix 4R	Room	52.3%	3.3%	45.0%	129	1663.2	449.0	43.6%	50.9	1.80%
Mix 1T	20°C	47.6%	4.1%	43.6%	127	1690.4	449.3	42.3%	55.5	1.61%
Mix 2T	20°C	49.9%	4.3%	44.1%	126	1663.3	496.5	42.2%	46.0	1.69%
Mix 3T	20°C	52.8%	3.1%	45.4%	126	1659.3	442.6	43.8%	45.2	1.41%
Mix 4T	20°C	52.3%	3.3%	45.0%	128.5	1684.2	451.8	44.0%	45.0	1.73%

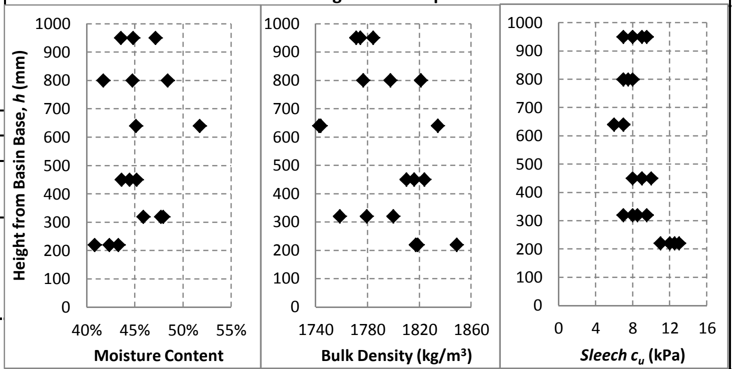
50 mm dia. Column Sample Properties:

Column Sample Ref:	Origin Mix:	Height from Basin Base, mm	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC, w_s	Stiffness E_{50} MPa	Failure Strain, ε_f	Reason to Exclude:	Probing Force, kN
Column A	4	955	93	1814.3	451.3	42.8%	451.3	1.40%	-	1.56
Column B	4	955	84.5	1746.6	445.1	43.1%	445.1	2.34%	-	1.54
Column C	4	955	85	1807.9	387.6	42.9%	387.6	1.34%	-	1.54
Column D	4	850	95	1753.1	476.4	43.4%	476.4	1.53%	-	1.53
Column E	4	850	94	1787.9	500.9	43.8%	500.9	2.45%	-	1.53
Column F	3	740	79	1775.3	418.4	44.3%	418.4	1.82%	-	1.83
Column G	2	460	83.5	1810.7	543.3	43.4%	543.3	1.95%	-	2.19
Column H	1	350	99.5	1858.3	505.7	42.4%	505.7	1.08%	-	2.05
Column I	1	350	90.5	1867.1	505.1	41.7%	505.1	1.34%	-	2.06
Column J	1	250	92.5	1796.3	559.9	42.4%	559.9	1.48%	-	1.93

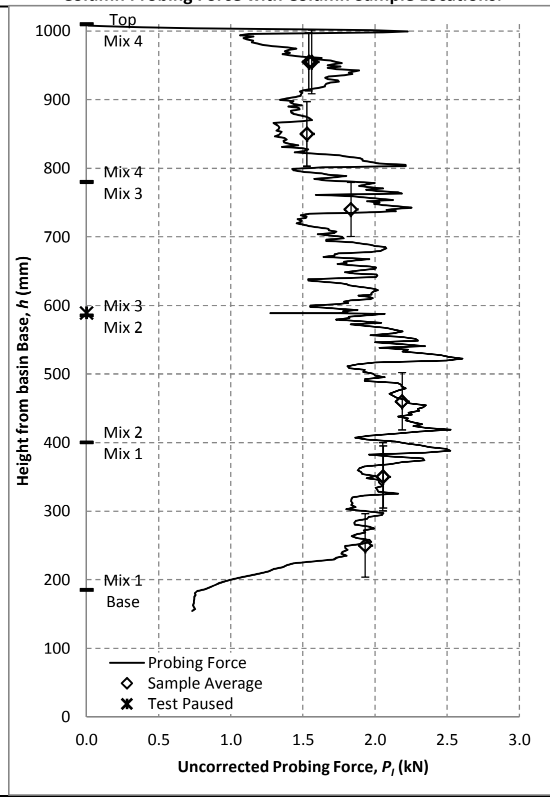
Comments:

Significant cracking and crumbling in the mid sections of the column.

Surrounding *Sleech* Properties:



Column Probing Force with Column Sample Locations:



Push-In Resistance Test No. 12

Test Type:	PIRT	Binder:	OP Cement		Mixing Date:	04/10/2013		Push-In Rate:
Reference:	PI-12-12-150*	OPC Content:	100/150*	kg/m^3	PIRT Date:	16/10/2013		19.8 mm/sec
Operator:	MT	Built Height:	1000	mm	PIRT Time:	11.90	days	19.9 mm/sec
Column dia.	200 mm	Average Temp:	17.6	°C	Mould Time:	12.28	days	ΔUCSxWTBR 14.4
Basin dia.	750 mm	Surcharge:	NA	kPa	Column Time:	12.22	days	

65 mm dia. Mould Sample Properties:

Mould Sample:	Curing Condition:	Raw *Sleech* MC, w_i	Organic Content:	Mixed MC, w_m	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC, w_s	Stiffness E_{50} MPa	Failure Strain, ε_f
Mix 1R	Room	52.9%	4.0%	46.4%	129	1678.7	478.5	42.7%	36.5	2.29%
Mix 2R*	Room	51.4%	3.7%	45.1%	125.5	1659.6	394.7	44.3%	35.9	1.99%
Mix 3R	Room	50.2%	2.6%	42.7%	129	1706.7	473.6	40.1%	39.0	2.21%
Mix 4R	Room	47.3%	2.3%	41.4%	127	1719.0	495.7	39.0%	50.6	1.83%
Mix 1T	20°C	52.9%	4.0%	46.4%	127	1687.8	457.9	43.5%	40.7	2.09%
Mix 2T*	20°C	51.4%	3.7%	45.1%	129	1658.8	357.5	43.9%	29.1	2.00%
Mix 3T	20°C	50.2%	2.6%	42.7%	129	1700.5	503.5	40.7%	51.1	1.92%
Mix 4T	20°C	47.3%	2.3%	41.4%	128	1716.5	469.2	37.9%	32.5	2.16%

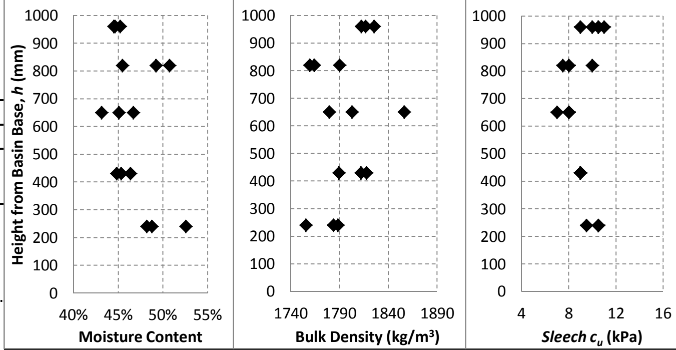
50 mm dia. Column Sample Properties:

Column Sample Ref:	Origin Mix:	Height from Basin Base, mm	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC, w_s	Stiffness E_{50} MPa	Failure Strain, ε_f	Reason to Exclude:	Probing Force, kN
Column A	4	950	88.5	1884.3	555.2	39.0%	36.7	2.21%	-	1.43
Column B	4	950	86	1844.5	492.8	38.7%	24.0	2.41%	-	1.41
Column C	4	850	93.5	1880.1	617.3	38.9%	39.8	2.14%	-	2.08
Column D	4	850	77	1905.2	622.0	39.1%	43.5	2.05%	-	2.09
Column E	4	935	96	1862.5	505.1	39.1%	51.8	2.26%	-	1.56
Column F	4	935	99	1913.8	479.6	38.7%	83.5	1.39%	-	1.55
Column G	3	750	82	1833.3	556.7	40.4%	42.8	2.10%	-	1.63
Column H	3	750	95.5	1827.0	654.5	40.6%	73.9	2.15%	-	1.66
Column I	1	350	73	1862.5	491.9	43.5%	22.3	2.41%	-	1.81
Column J	1	360	97	1850.9	535.9	42.9%	61.4	1.44%	-	1.72
Column K	1	360	101	1756.1	484.4	43.2%	51.0	1.55%	-	1.72
Column L	1	240	88	1749.7	511.4	43.5%	41.3	1.76%	-	1.87
Column M	1	240	92	1797.5	552.0	43.0%	53.9	1.56%	-	1.87
Column N	1	240	98.5	1783.4	537.3	43.0%	60.7	1.44%	-	1.87
Column O	1	240	95	1780.2	500.5	43.3%	51.7	1.39%	-	1.87

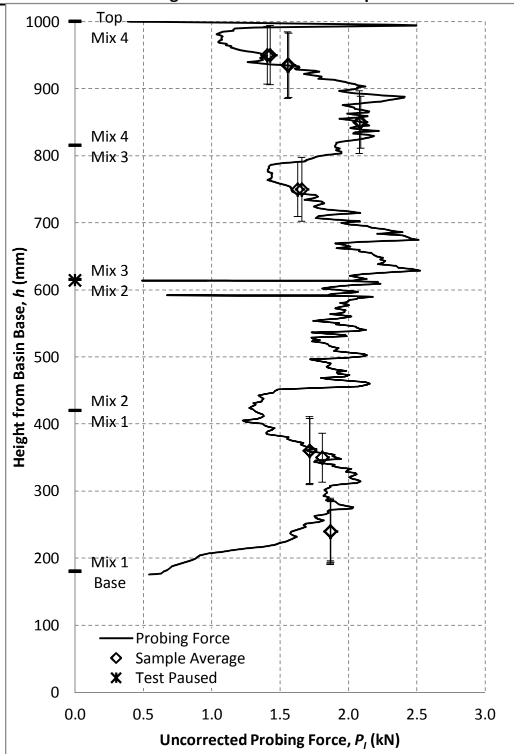
Comments:

*Mix 1, 3 & 4 stabilised at a binder content of 150 kg/m^3; Mix 2 stabilised at a binder content of 100 kg/m^3.
Significant cracking in the mid sections of the column, no samples recovered from Mix 2.

Surrounding *Sleech* Properties:



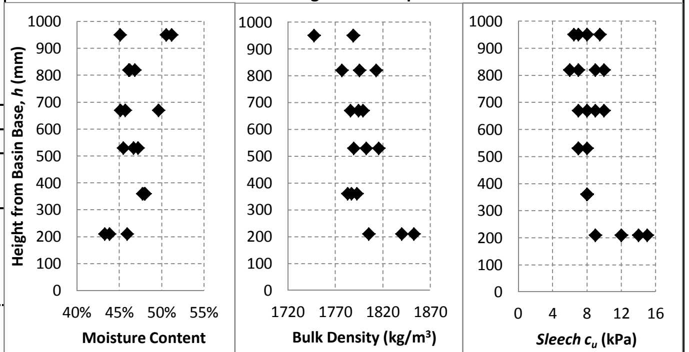
Column Probing Force with Column Sample Locations:



Push-In Resistance Test No. 13

Test Type:	PIRT	Binder:	OP Cement		Mixing Date:	22/10/2013		Push-In Rate:		
Reference:	PI-13-1-75	OPC Content:	75	kg/m^3	PIRT Date:	23/10/2013		20.1	mm/sec	
Operator:	MT	Built Height:	1005	mm	PIRT Time:	0.88	days	20.2	mm/sec	
Column dia.	200 mm	Average Temp:	17.5	°C	Mould Time:	1.28	days	ΔUCSxWTBR	175.6	
Basin dia.	750 mm	Surcharge:	NA	kPa	Column Time:	1.22	days			

Surrounding *Sleech* Properties:



65 mm dia. Mould Sample Properties:

Mould Sample:	Curing Condition:	Raw *Sleech* MC, w_i	Organic Content:	Mixed MC, w_m	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC, w_s	Stiffness E_{50} MPa	Failure Strain, ε_f
Mix 1R	Room	48.4%	3.8%	44.3%	129	1682.3	161.8	43.5%	11.2	2.78%
Mix 2R	Room	48.9%	3.9%	44.9%	126	1663.0	162.2	43.3%	8.8	3.26%
Mix 3R	Room	49.1%	2.8%	44.8%	125	1675.4	138.2	43.6%	7.2	3.22%
Mix 4R	Room	48.7%	2.6%	44.4%	126.5	1666.0	142.7	44.1%	7.3	3.32%
Mix 1T	20°C	48.4%	3.8%	44.3%	130	1665.7	177.3	43.6%	12.0	2.91%
Mix 2T	20°C	48.9%	3.9%	44.9%	128	1673.8	165.0	43.3%	9.2	3.47%
Mix 3T	20°C	49.1%	2.8%	44.8%	127.5	1663.9	168.1	43.6%	7.4	3.68%
Mix 4T	20°C	48.7%	2.6%	44.4%	129	1667.1	163.0	43.6%	9.2	3.54%

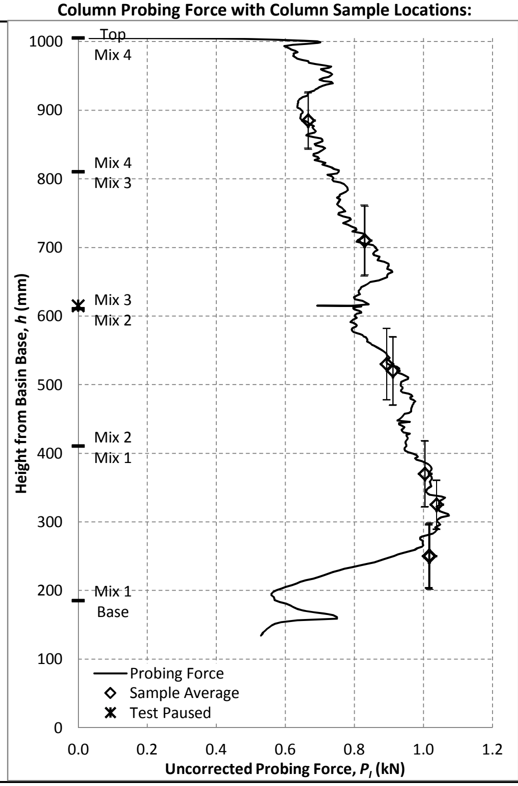
50 mm dia. Column Sample Properties:

Column Sample Ref:	Origin Mix:	Height from Basin Base, mm	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC, w_s	Stiffness E_{50} MPa	Failure Strain, ε_f	Reason to Exclude:	Probing Force, kN
Column A	4	885	84	1845.0	159.8	43.6%	7.3	3.64%	-	0.67
Column B	4	885	80	1836.3	147.7	42.9%	5.0	3.82%	-	0.67
Column C	3	710	100	1933.0	184.1	44.1%	8.0	3.21%	-	0.83
Column D	3	710	103.5	1848.6	177.6	44.6%	9.8	2.95%	-	0.83
Column E	2	530	104.5	1809.3	149.4	44.4%	11.8	2.44%	-	0.89
Column F	2	530	103.5	1870.9	210.3	42.1%	17.6	2.41%	-	0.89
Column G	1	250	97	1808.2	208.2	42.7%	17.1	2.45%	-	1.02
Column H	1	250	94	1813.6	166.7	43.7%	11.3	2.34%	-	1.02
Column I	1	325	70.5	1794.0	194.6	42.8%	5.4	3.90%	-	1.04
Column J	1	325	72	1844.9	203.7	42.8%	6.7	3.62%	-	1.04
Column K	2	520	100	1772.0	174.7	43.2%	12.5	2.60%	-	0.91
Column L	2	520	98.5	1768.2	152.5	43.5%	11.4	2.20%	-	0.91
Column M	1	370	97	1733.6	162.8	42.9%	12.9	2.25%	-	1.00
Column N	1	370	95	1816.9	212.2	43.3%	11.7	2.44%	-	1.01
Column O	1	250	92	1829.5	184.1	44.0%	10.3	2.59%	-	1.02
Column P	1	250	91	1862.7	199.6	43.5%	11.8	2.30%	-	1.02

<u>Comments:</u>

No issues with the test.

Column Probing Force with Column Sample Locations:



Push-In Resistance Test No. 14

Test Type:	PIRT	Binder:	OP Cement		Mixing Date:	30/10/2013		Push-In Rate:	
Reference:	PI-14-12-150S	OPC Content:	150	kg/m³	PIRT Date:	11/11/2013		18.2	mm/sec
Operator:	MT	Built Height:	980	mm	PIRT Time:	11.86	days	21.6	mm/sec
Column dia.	200 mm	Average Temp:	16.9	°C	Mould Time:	12.40	days	ΔUCSxWTBR	20.5
Basin dia.	750 mm	Surcharge:	13.8	kPa	Column Time:	12.33	days		

65 mm dia. Mould Sample Properties:

Mould Sample:	Curing Condition:	Raw *Sleech* MC, w_i	Organic Content:	Mixed MC, w_m	Length: mm	Density: kg/m³	Uncorrected UCS, kPa	Stabilised MC, w_s	Stiffness E_{50} MPa	Failure Strain, ε_f
Mix 1R	Room	48.9%	4.6%	42.1%	125	1718.9	482.2	40.4%	33.5	1.92%
Mix 2R	Room	49.0%	4.6%	42.0%	124.5	1704.7	494.6	39.9%	39.7	2.20%
Mix 3R	Room	48.1%	3.3%	43.2%	127	1696.8	458.8	40.9%	37.4	1.77%
Mix 4R	Room	50.6%	2.9%	42.3%	128	1703.9	485.3	40.8%	53.8	1.84%
Mix 1T	20°C	48.9%	4.6%	42.1%	126	1712.1	489.8	40.1%	55.4	1.95%
Mix 2T	20°C	49.0%	4.6%	42.0%	130	1716.1	523.8	40.9%	39.4	2.07%
Mix 3T	20°C	48.1%	3.3%	43.2%	130	1702.1	505.2	41.4%	44.2	1.97%
Mix 4T	20°C	50.6%	2.9%	42.3%	129	1705.7	432.8	41.6%	67.8	1.28%

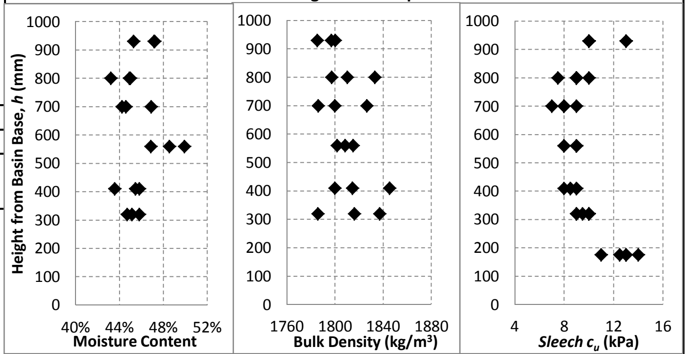
50 mm dia. Column Sample Properties:

Column Sample Ref:	Origin Mix:	Height from Basin Base, mm	Length: mm	Density: kg/m³	Uncorrected UCS, kPa	Stabilised MC, w_s	Stiffness E_{50} MPa	Failure Strain, ε_f	Reason to Exclude:	Probing Force, kN
Column A	4	930	75	1806.9	548.4	40.2%	26.8	3.06%	-	2.12
Column B	4	930	77	1852.5	660.5	39.6%	35.8	2.59%	-	2.14
Column C	4	828	91	1750.5	611.7	40.3%	55.8	1.87%	-	2.10
Column D	4	828	93	1874.9	707.0	40.0%	72.5	2.13%	-	2.10
Column E	4	930	81	1837.4	663.3	39.9%	58.9	1.67%	-	2.15
Column F	4	930	82	1854.1	649.9	40.0%	60.9	1.75%	-	2.15
Column G	4	840	84	1733.1	640.8	41.0%	40.3	2.49%	-	2.04
Column H	4	840	84	1787.8	651.2	40.3%	42.6	2.00%	-	2.04
Column I	3	750	86.5	1754.2	636.5	41.9%	52.7	1.65%	-	2.57
Column J	3	750	89	1755.0	634.5	40.9%	41.4	2.30%	-	2.57
Column K	3	650	80	1789.3	622.6	41.6%	36.1	2.33%	-	2.64
Column L	3	650	88.5	1770.7	647.7	41.3%	56.5	1.67%	-	2.64
Column M	2	560	78	1821.1	573.4	39.2%	45.9	1.60%	-	2.81
Column N	2	560	76.5	1823.7	629.3	40.4%	60.7	1.71%	-	2.81
Column O	2	463	98.5	1835.6	643.4	40.6%	55.1	1.85%	-	2.55
Column P	*1*	380	*87.5*	*1751.0*	*495.0*	*40.8%*	*66.4*	*1.26%*	*Stone*	*2.57*
Column R	1	345	95	1865.4	663.0	41.3%	50.3	1.91%	-	2.52
Column S	1	345	97	1798.9	660.3	40.9%	52.5	1.71%	-	2.52
Column T	1	240	95	1731.8	627.7	40.5%	69.7	1.53%	-	2.51
Column U	1	240	95	1785.1	638.0	40.8%	59.4	1.73%	-	2.51
Column V	1	250	86.5	1737.1	586.2	41.3%	76.2	1.41%	-	2.50
Column W	1	250	89	1773.3	591.0	41.0%	63.7	1.46%	-	2.50

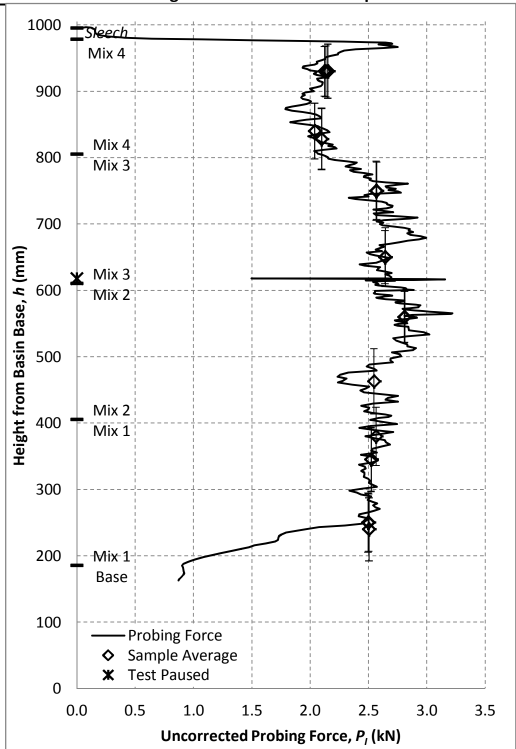
Comments:

Maximum settlement recorded due to the surcharge was 12 mm but includes settlement of the hand-compacted sand layer over the column.
Penetrometer passed through 15*mm* thick *sleech* layer before entering the column.
Column P found to have a stone within it, which effected the UCS test.

Surrounding *Sleech* Properties:



Column Probing Force with Column Sample Locations:



E.5 PIRT Column Summary Statistics

PIRT Mould Sample Summary Statistics:													
PIRT Reference:		PI-4	PI-5	PI-6	PI-7	PI-8	PI-9S	PI-10	PI-11	PI-12*		PI-13	PI-14S
No. of Samples:		4	4	4	4	4	3	4	4	3	1	4	4
Binder Content (kg/m^3):		150	100	150	100	150	150	150	100	150	100	75	150
		Initial Sleech Moisture and Organic Content:											
Raw *Sleech* Moisture Content, w_i	Maximum:	0.48	0.47	0.46	0.47	0.52	0.54	0.56	0.53	0.53	-	0.49	0.51
	Minimum:	0.42	0.45	0.46	0.44	0.48	0.48	0.53	0.48	0.47	-	0.48	0.48
	Range:	0.06	0.02	0.00	0.03	0.04	0.06	0.04	0.05	0.06	-	0.01	0.03
	Average:	0.44	0.46	0.46	0.46	0.50	0.52	0.54	0.51	0.50	-	0.49	0.49
	St Dev:	0.03	0.01	0.00	0.01	0.02	0.03	0.02	0.02	0.02	-	0.00	0.01
	CoV:	6.2%	1.7%	0.5%	3.0%	3.5%	5.3%	3.1%	4.8%	4.7%	-	0.6%	2.1%
Loss on Ignition	Maximum:	3.4	4.6	3.4	2.9	3.6	3.1	4.0	4.3	4.0	-	3.9	4.6
	Minimum:	2.6	2.4	2.3	2.8	2.5	2.6	2.6	3.1	2.3	-	2.6	2.9
	Range:	0.7	2.2	1.1	0.1	1.0	0.5	1.4	1.2	1.8	-	1.3	1.7
	Average:	3.0	3.2	2.9	2.9	2.8	2.9	3.3	3.7	3.2	-	3.3	3.8
	St Dev:	0.3	1.0	0.6	0.0	0.5	0.3	0.8	0.6	0.8	-	0.7	0.9
	CoV:	10.1%	30.6%	19.4%	1.2%	18.1%	9.5%	22.7%	16.0%	26.5%	-	20.2%	22.9%
		Mould Sample Density:											
Room-Cured Density ρ_{mldR}, kg/m^3	Maximum:	1724.9	1698.3	1719.0	1708.3	1683.0	1671.4	1683.1	1679.4	1719.0	1659.6	1682.3	1718.9
	Minimum:	1694.3	1683.4	1702.9	1680.1	1652.1	1654.5	1645.7	1650.5	1678.7	-	1663.0	1696.8
	Range:	30.6	14.9	16.1	28.3	31.0	16.9	37.4	29.0	40.3	-	19.2	22.0
	Average:	1711.5	1688.4	1712.2	1695.7	1670.4	1662.1	1670.2	1666.8	1701.5	-	1671.7	1706.1
	St Dev:	12.8	6.8	8.1	11.7	13.8	8.6	16.7	12.8	20.6	-	8.8	9.2
	CoV:	0.8%	0.4%	0.5%	0.7%	0.8%	0.5%	1.0%	0.8%	1.2%	-	0.5%	0.5%
20°C Cured Density ρ_{mldT}, kg/m^3	Maximum:	1759.7	1708.2	1720.5	1705.4	1707.5	1696.7	1687.0	1690.4	1716.5	1658.8	1673.8	1716.1
	Minimum:	1699.9	1688.3	1701.6	1666.8	1665.7	1658.9	1645.5	1659.3	1687.8	-	1663.9	1702.1
	Range:	59.9	19.8	18.9	38.6	41.9	37.8	41.5	31.1	28.7	-	10.0	14.0
	Average:	1732.6	1697.6	1713.4	1689.4	1688.3	1676.8	1671.4	1674.3	1701.6	-	1667.6	1709.0
	St Dev:	24.7	8.4	8.2	16.2	18.9	15.6	18.0	15.3	14.4	-	4.4	6.3
	CoV:	1.4%	0.5%	0.5%	1.0%	1.1%	0.9%	1.1%	0.9%	0.8%	-	0.3%	0.4%
		Mould Sample UCS:											
Room-Cured UCS q_{mldR}, kPa	Maximum:	393.4	211.7	463.0	416.5	433.1	482.0	586.2	469.5	495.7	394.7	162.2	494.6
	Minimum:	349.5	180.1	396.2	338.9	385.5	435.9	482.8	430.4	473.6	-	138.2	458.8
	Range:	44.0	31.6	66.8	77.7	47.5	46.1	103.3	39.1	22.1	-	24.0	35.8
	Average:	371.5	196.3	434.7	381.7	409.0	456.1	537.2	453.8	482.6	-	151.2	480.2
	St Dev:	19.9	13.6	31.1	32.2	20.0	23.6	43.0	18.0	11.6	-	12.6	15.2
	COV:	5.4%	6.9%	7.2%	8.4%	4.9%	5.2%	8.0%	4.0%	2.4%	-	8.3%	3.2%
20°C Cured UCS q_{mldT}, kPa	Maximum:	392.9	224.2	535.9	455.1	511.9	509.9	609.7	496.5	503.5	357.5	177.3	523.8
	Minimum:	333.5	195.6	518.9	340.0	435.0	469.5	575.8	442.6	457.9	-	163.0	432.8
	Range:	59.4	28.6	17.0	115.2	76.8	40.4	33.9	54.0	45.6	-	14.2	91.0
	Average:	374.3	209.0	526.5	403.1	469.0	491.0	591.3	460.0	476.9	-	168.3	487.9
	St Dev:	27.5	14.4	7.4	47.5	32.1	18.7	15.3	24.6	23.8	-	6.3	39.3
	CoV:	7.3%	6.9%	1.4%	11.8%	6.8%	3.8%	2.6%	5.4%	5.0%	-	3.7%	8.1%
		Mould Sample Stiffness:											
Room-Cured Stiffness, E_{mldR} MPa	Maximum:	28.8	15.7	33.5	40.2	41.1	42.5	124.8	50.9	50.6	35.9	11.2	53.8
	Minimum:	17.5	12.2	27.8	31.1	31.0	37.8	44.6	31.8	36.5	-	7.2	33.5
	Range:	11.3	3.5	5.7	9.2	10.1	4.7	80.2	19.1	14.1	-	4.0	20.3
	Average:	22.5	14.0	30.4	37.0	34.9	39.9	84.1	40.4	42.0	-	8.6	41.1
	St Dev:	4.7	1.6	2.6	4.2	4.6	2.4	45.6	8.6	7.5	-	1.9	8.9
	CoV:	20.9%	11.1%	8.6%	11.4%	13.2%	6.0%	54.2%	21.2%	17.8%	-	21.9%	21.6%
20°C Cured Stiffness, E_{mldT}, MPa	Maximum:	29.5	17.7	46.8	46.9	47.8	51.7	59.8	55.5	51.1	29.1	12.0	67.8
	Minimum:	19.3	9.8	32.4	19.9	30.1	36.8	47.2	45.0	32.5	-	7.4	39.4
	Range:	10.2	8.0	14.4	27.0	17.6	14.9	12.7	10.4	18.6	-	4.6	28.4
	Average:	23.0	14.4	37.9	33.0	37.3	44.2	54.0	47.9	41.4	-	9.4	51.7
	St Dev:	4.7	3.8	6.4	11.7	7.9	6.1	6.6	5.1	9.3	-	1.9	12.7
	CoV:	20.6%	26.2%	16.9%	35.3%	21.2%	13.8%	12.1%	10.6%	22.5%	-	20.2%	24.5%

Note: Summary statistics for PI-12* are seperately shown of the 100kg/m^3 and 150kg/m^3 binder contents.

PIRT Column Sample Summary Statistics:													
PIRT Reference:		PI-4	PI-5	PI-6	PI-7	PI-8	PI-9S	PI-10	PI-11	PI-12*		PI-13	PI-14S
No. of Samples:		14	16	13	7	12	16	14	10	15	0	16	21
Binder Content (kg/m^3):		150	100	150	100	150	150	150	100	150	100	75	150
		Column Sample Density:											
Column Density ρ_{col}, kg/m^3	Maximum:	1937.8	1867.6	1913.8	1841.9	1853.6	1792.9	1792.9	1867.1	1913.8	-	1933.0	1874.9
	Minimum:	1720.9	1750.2	1768.4	1775.5	1714.8	1665.3	1693.9	1746.6	1749.7	-	1733.6	1731.8
	Range:	216.9	117.4	145.5	66.4	138.8	127.5	99.0	120.6	164.2	-	199.4	143.1
	Average:	1812.0	1797.8	1819.5	1799.2	1791.1	1729.7	1764.3	1801.8	1835.4	-	1824.2	1797.1
	St Dev:	63.0	32.6	36.8	24.5	45.8	39.9	27.5	39.6	52.2	-	46.7	45.2
	CoV:	3.5%	1.8%	2.0%	1.4%	2.6%	2.3%	1.6%	2.2%	2.8%	-	2.6%	2.5%
		Column Sample Density:											
Column UCS q_{mol}, kPa	Maximum:	449.4	264.9	561.2	462.0	522.3	559.7	816.2	559.9	654.5	-	212.2	707.0
	Minimum:	263.2	177.9	392.1	327.0	401.9	316.0	606.1	387.6	479.6	-	147.7	548.4
	Range:	186.1	87.0	169.1	135.0	120.4	243.7	210.1	172.3	175.0	-	64.5	158.6
	Average:	347.5	221.6	474.4	397.4	468.4	463.2	712.5	479.4	539.8	-	180.5	632.7
	St Dev:	60.9	24.8	59.0	55.5	37.7	78.7	51.8	54.3	54.4	-	22.5	35.4
	CoV:	17.5%	11.2%	12.4%	14.0%	8.1%	17.0%	7.3%	11.3%	10.1%	-	12.5%	5.6%
		Column Sample Density:											
Column Stiffness, E_{col}, MPa	Maximum:	50.8	19.6	60.8	33.6	52.5	65.6	109.9	62.6	83.5	-	17.6	76.2
	Minimum:	12.9	7.5	24.9	14.2	25.0	23.8	51.6	30.7	22.3	-	5.0	26.8
	Range:	37.9	12.1	36.0	19.4	27.5	41.8	58.3	31.9	61.3	-	12.6	49.5
	Average:	24.1	13.0	40.6	26.2	38.1	42.2	73.3	43.3	49.2	-	10.7	53.0
	St Dev:	9.8	4.2	11.7	6.6	7.5	11.2	16.9	12.3	16.6	-	3.6	12.8
	CoV:	40.5%	32.3%	28.8%	25.3%	19.7%	26.7%	23.1%	28.4%	33.7%	-	34.0%	24.1%

Note: No samples were recovered from the 100kg/m^3 binder content section of column PI-12*.

E.6 PIRT and Cone-Only Penetrometer & Sounding Bar in Sleech

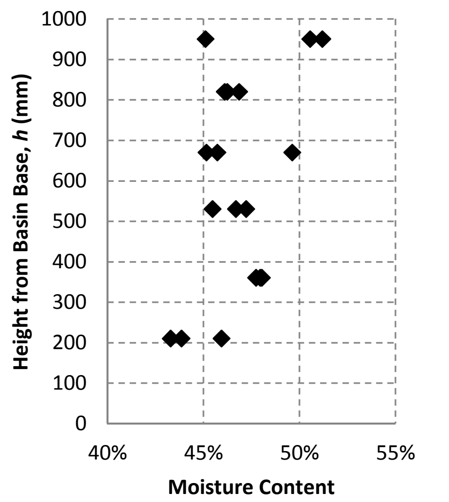
Push-In Resistance Test No. *Sleech-13*

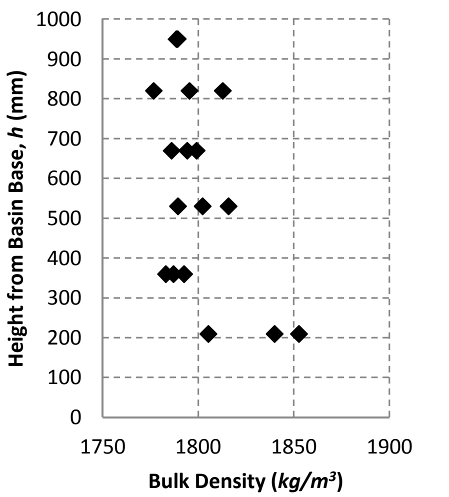
Test Type:	PIRT	Material Tested:	Raw Sleech		Push-In Rate:	
Reference:	PI-*Sleech* -13	Built Height:	1000	mm	22.1	mm/sec
Operator:	MT	PIRT Date:	23/10/2013		20.5	mm/sec
Column dia.	200 mm	Predrilled:	Yes			
Basin dia.	750 mm	Penetrometer No:	2			

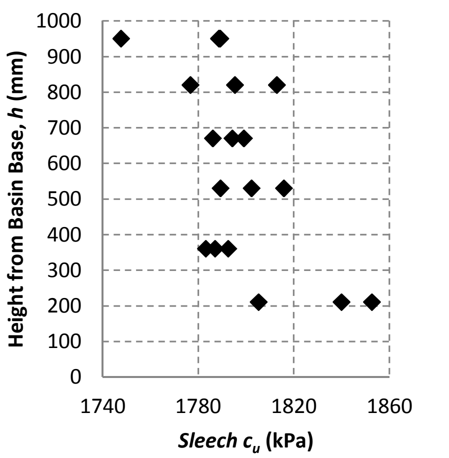
Strength Properties at PIRT Location:

Reference:	Height from Basin Base, mm	Undrained Shear Strength, c_u, kPa
A	950	8
B	950	8
C	820	6
D	820	7
E	670	9
F	670	7
G	530	7
H	530	7
I	360	8
J	360	8
K	210	9
L	210	12

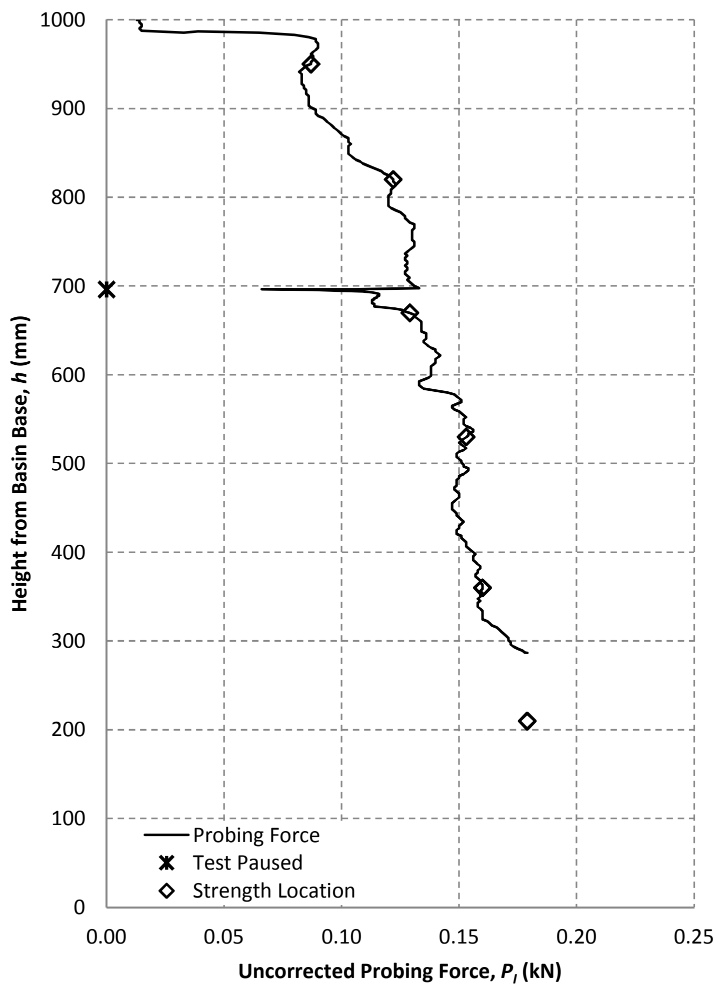
Basin *Sleech* Properties:







***Sleech* Probing Force with Column Sample Locations:**



Comments:

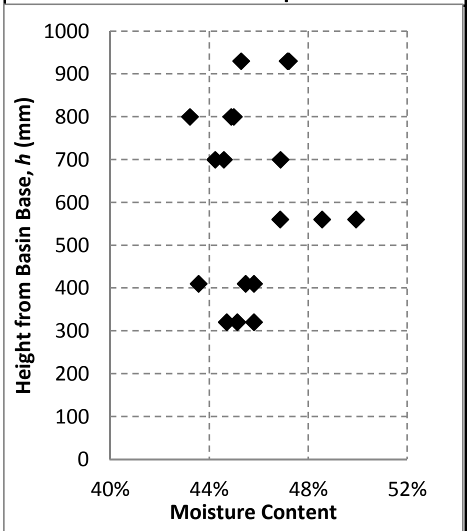
Push-In Resistance Test No. *Sleech* PIRT-14

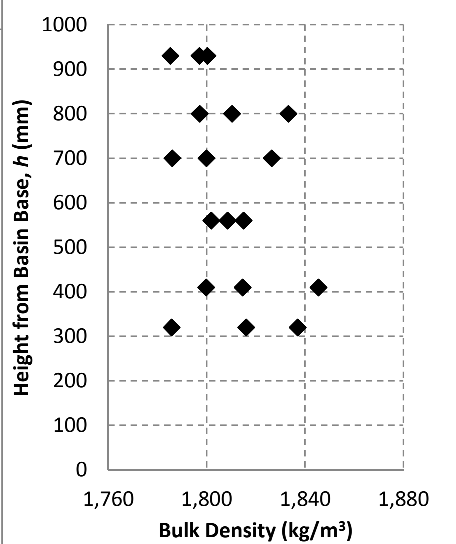
Test Type:	PIRT	Material Tested:	Raw *Sleech*		Push-In Rate:	
Reference:	PI-*Sleech* -14	Built Height:	978	mm	20.4	mm/sec
Operator:	MT	PIRT Date:	11/11/2013		17.9	mm/sec
Column dia.	200 mm	Predrilled:	Yes			
Basin dia.	750 mm	Penetrometer No:	2			

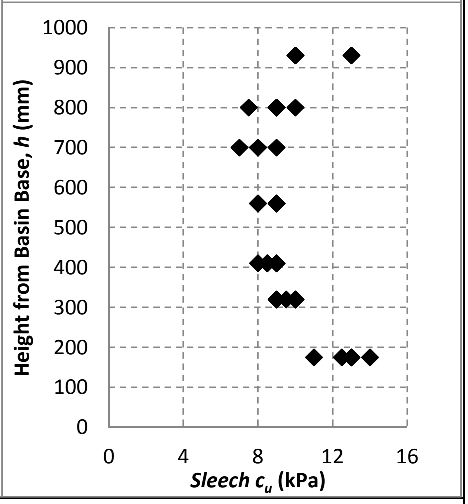
Strength Properties at PIRT Location:

Reference:	Height from Basin Base, mm	Undrained Shear Strength, c_u, kPa
A	930	10
B	930	10
C	800	9
D	800	9
E	700	7
G	700	8
H	560	8
I	560	9
J	410	9
K	410	8
L	320	9
M	310	9
N	175	14
O	175	11

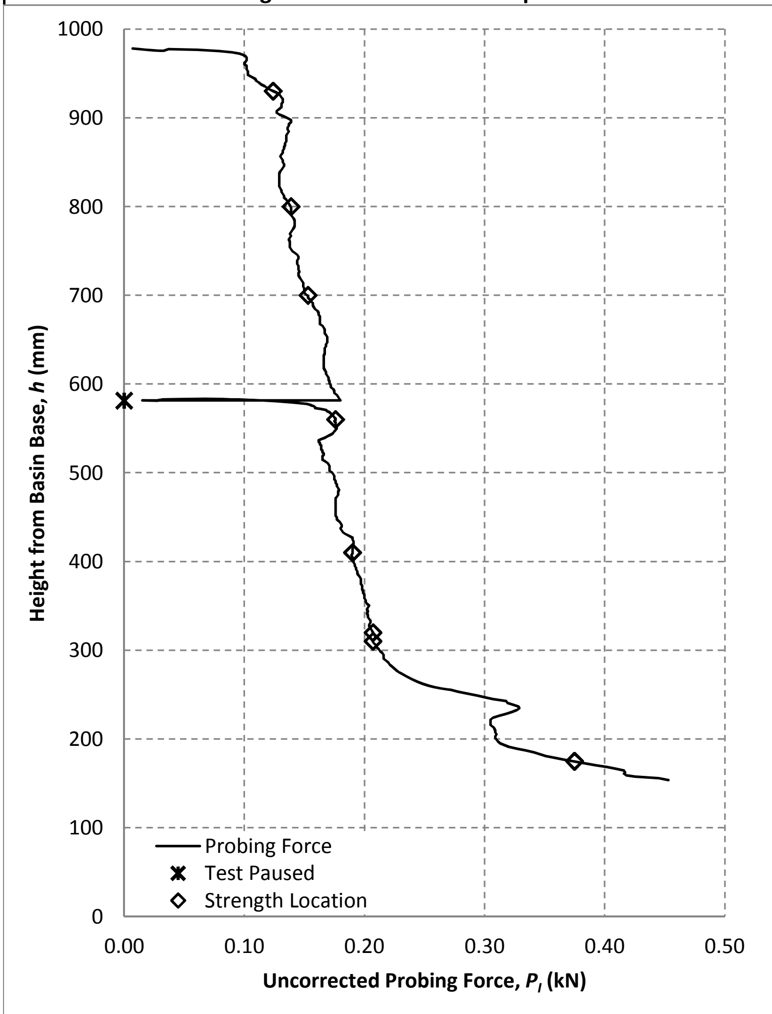
Basin *Sleech* Properties:







***Sleech* Probing Force with Column Sample Locations:**



Comments:

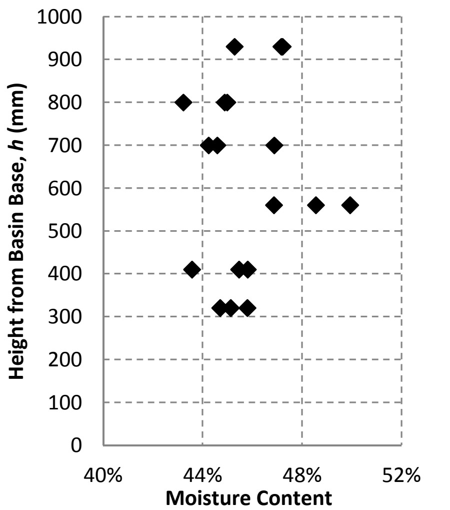
Push-In Resistance Test No. *Sleech* Cone-14

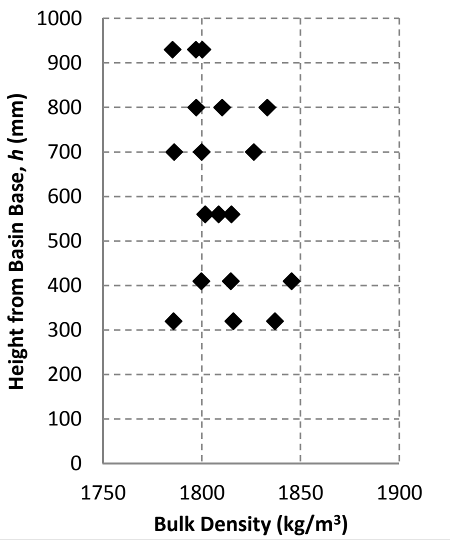
Test Type:	Cone	Material Tested:	Raw *Sleech*		Push-In Rate:	
Reference:	PI-C-*Sleech* -14	Built Height:	978	mm	16.9	mm/sec
Operator:	MT	PIRT Date:	11/11/2013		15.8	mm/sec
Column dia.	200 mm	Predrilled:	Yes			
Basin dia.	750 mm	Penetrometer No:	2			

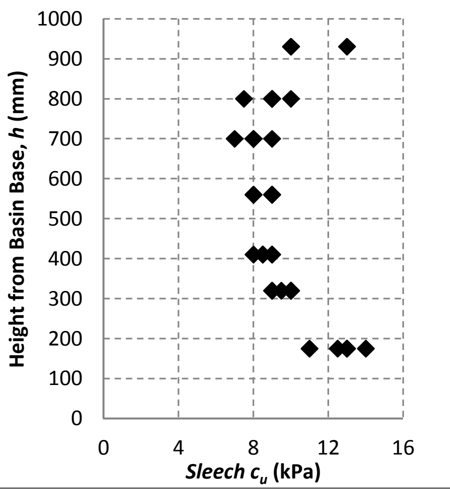
Strength Properties at PIRT Location:

Reference:	Height from Basin Base, mm	Undrained Shear Strength, c_u, kPa
A	930	10
B	930	10
C	800	9
D	800	9
E	700	7
G	700	8
H	560	8
I	560	9
J	410	9
K	410	8
L	320	9
M	310	9
N	175	14
O	175	11

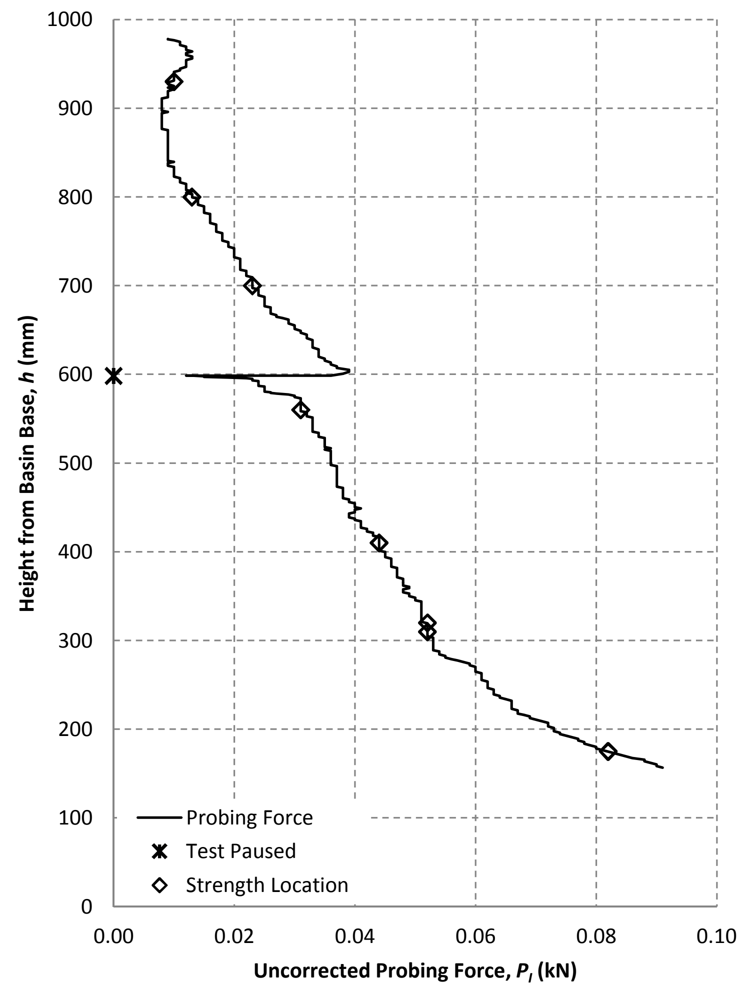
Basin *Sleech* Properties:







***Sleech* Probing Force with Column Sample Locations:**



Comments:

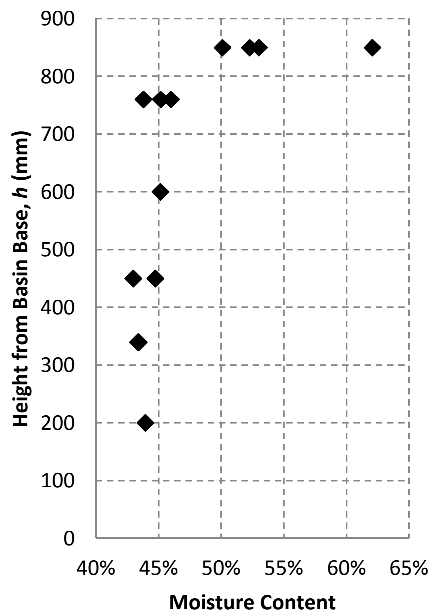
Push-In Resistance Test No. *Sleech* Temp-1

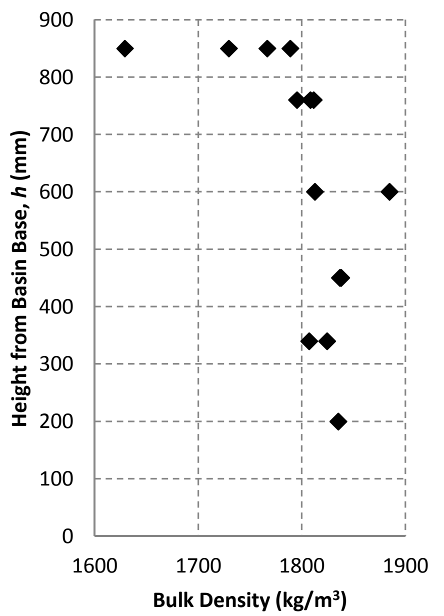
Test Type:	PIRT	Material Tested:	Raw *Sleech*		Push-In Rate:	
Reference:	PI-*Sleech* -T-1	Built Height:	910	mm	15.1	mm/sec
Operator:	MT	PIRT Date:	17/12/2013		14.2	mm/sec
Column dia.	200 mm	Predrilled:	No			
Basin dia.	750 mm	Penetrometer No:	2			

Strength Properties at PIRT Location:

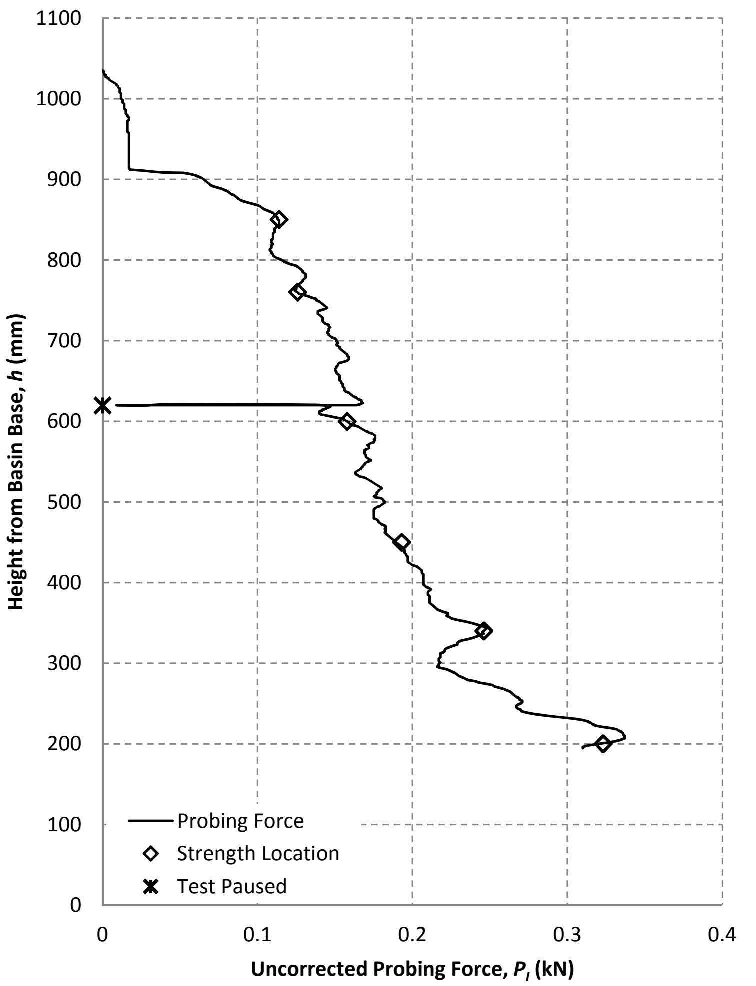
Reference:	Height from Basin Base, mm	Undrained Shear Strength, c_u, kPa
A	850	9
B	850	8
C	760	9
D	760	9.5
E	600	11.5
F	600	11.5
G	450	10
H	450	12
I	340	13
J	340	13
K	200	15
L	200	16

Basin *Sleech* Properties:





***Sleech* Probing Force with Column Sample Locations:**



Comments:
Probing force is plotted relative to the location of the leading edge of the wing and not the cone tip.

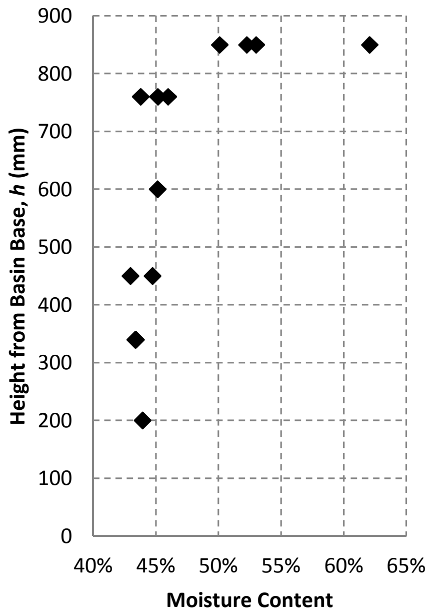
Push-In Resistance Test No. *Sleech* Temp-2

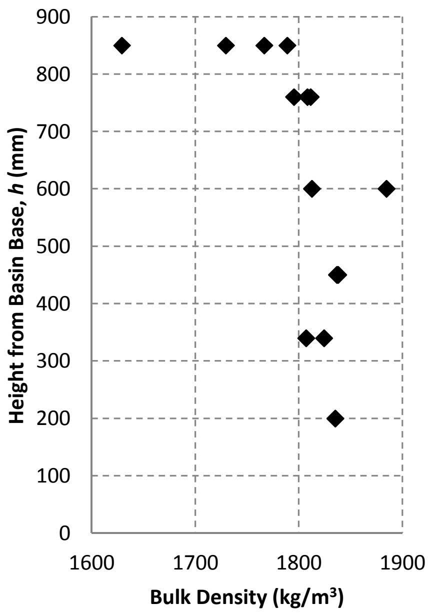
Test Type:	PIRT	Material Tested:	Raw *Sleech*		Push-In Rate:
Reference:	PI-*Sleech* -T-2	Built Height:	910	mm	15.1 mm/sec
Operator:	MT	PIRT Date:	17/12/2013		18.7 mm/sec
Column dia.	200 mm	Predrilled:	No		
Basin dia.	750 mm	Penetrometer No:	2		

Strength Properties at PIRT Location:

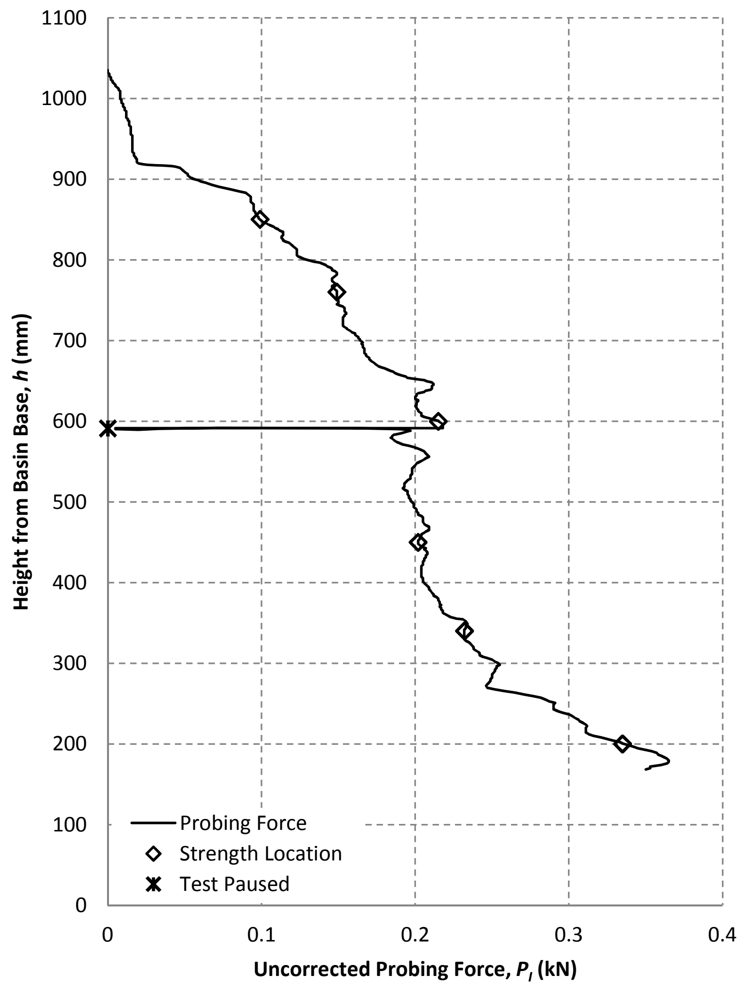
Reference:	Height from Basin Base, mm	Undrained Shear Strength, c_u, kPa
A	850	8.5
B	850	11
C	760	9
D	760	13
E	600	10
F	600	10
G	450	9.5
H	450	10.5
I	340	12
J	340	11
K	200	12
L	200	13

Basin *Sleech* Properties:





***Sleech* Probing Force with Column Sample Locations:**



Comments:
Probing force is plotted relative to the location of the leading edge of the wing and not the cone tip.

E.7 Wire Friction Test Summary Sheet

PORT Wire Friction Test No. 1

Test Type:	Wire	Binder:	OP Cement		Mixing Date:	22/11/2013		Pull-Out Rate:	
Reference:	W-1-5-150	OPC Content:	150	kg/m^3	Wire Date:	27/11/2013		16.6	mm/sec
Operator:	MT	Built Height:	800	mm	Wire Time:	4.99	days	ΔUCSxWTBR	23.2
Column dia.	104 mm	Average Temp:	15.8	°C	Mould Time:	5.18	days	Wire Friction Correction:	
Basin Height:	800 mm	Wire Extension:	51	mm	Column Time:	5.15	days	0.451	kN/m

65 mm dia. Mould Sample Properties:

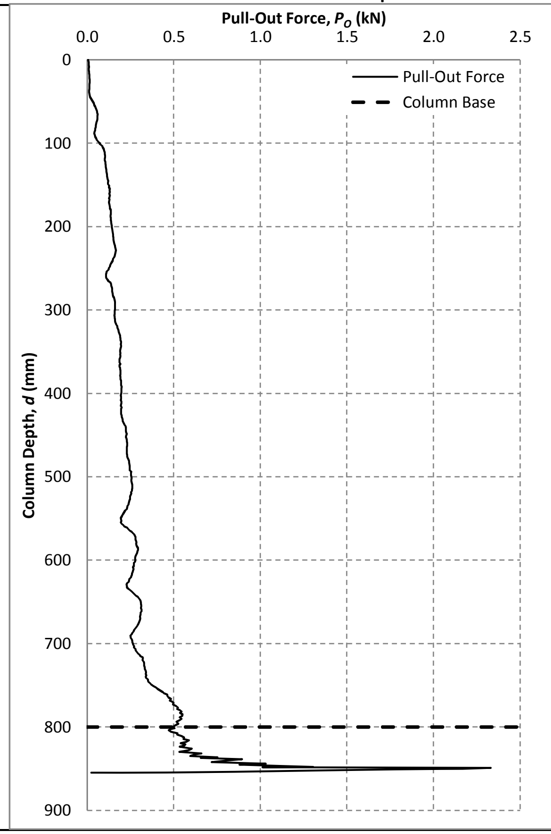
Mould Sample:	Curing Condition:	Raw *Sleech* MC:	Organic Content:	Mixed MC:	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, ε_f
Mix 1R	Room	45.5%	3.3%	40.4%	129.5	1734.4	421.3	38.7%	47.4	2.30%
Mix 1T	20°C	45.5%	3.3%	40.4%	129.5	1729.7	451.1	38.7%	47.2	2.30%

50 mm dia. Column Sample Properties:

Column Sample Ref:	Sample dia. mm	Depth: mm	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, ε_f	Reason to Exclude:	-
Column A	50	55	88	1801.7	525.8	38.1%	49.2	2.09%	-	
Column B	50	160	86.5	1798.0	522.0	38.3%	49.9	2.00%	-	
Column C	50	265	98	1833.7	592.1	38.0%	71.4	1.58%	-	
Column D	50	370	92	1777.8	573.9	38.4%	66.3	1.75%	-	
Column E	50	475	96.5	1779.2	576.2	38.2%	69.5	1.86%	-	
Column F	50	580	86	1669.5	491.1	38.7%	41.6	1.83%	-	
Column G	50	700	98	1802.2	607.3	37.5%	105.1	1.55%	-	
Column H	*38*	*55*	*72.5*	*1746.2*	*498.1*	*37.7%*	*38.5*	*2.63%*	Sample trimming issues	
Column I	*38*	*160*	*73*	*1715.4*	*534.5*	*38.2%*	*57.0*	*1.78%*		
Column J	*38*	*265*	*78*	*1677.5*	*561.6*	*38.0%*	*73.7*	*1.64%*		
Column K	*38*	*370*	*74.5*	*1762.1*	*617.5*	*37.8%*	*109.1*	*1.68%*		
Column L	*38*	*475*	*76*	*1694.5*	*553.1*	*37.8%*	*64.3*	*2.23%*		
Column M	*38*	*580*	*78*	*1724.7*	*611.9*	*37.7%*	*61.4*	*1.88%*		
Column N	*38*	*700*	*74*	*1741.9*	*550.8*	*37.8%*	*52.8*	*1.79%*		

Comments:
Wire was clean of any adheared pieces of column. Good column construction noted and no cracking found in the extracted column.
Sample F found to have lower than expected strength compared to other 50 mm dia. samples around it. The 38 mm dia. sample at the same level has a higher strength indicating an issue with Column F.

Wire Pull-Out Force with Depth:



PORT Wire Friction Test No. 2

Test Type:	Wire	Binder:	OP Cement		Mixing Date:	22/11/2013		Pull-Out Rate:	
Reference:	W-2-6-100	OPC Content:	100	kg/m^3	Wire Date:	28/11/2013		17.0	mm/sec
Operator:	MT	Built Height:	800	mm	Wire Time:	6.08	days	ΔUCSxWTBR	18.3
Column dia.	104 mm	Average Temp:	16.0	°C	Mould Time:	6.27	days	Wire Friction Correction:	
Basin Height:	800 mm	Wire Extension:	51	mm	Column Time:	6.24	days	0.208	kN/m

65 mm dia. Mould Sample Properties:

Mould Sample:	Curing Condition:	Raw *Sleech* MC:	Organic Content:	Mixed MC:	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, ε_f
Mix 1R	Room	51.5%	2.6%	46.1%	129	1689.6	315.8	44.8%	30.7	2.26%
Mix 1T	20°C	51.5%	2.6%	46.1%	128.5	1674.8	360.9	44.2%	35.3	2.17%

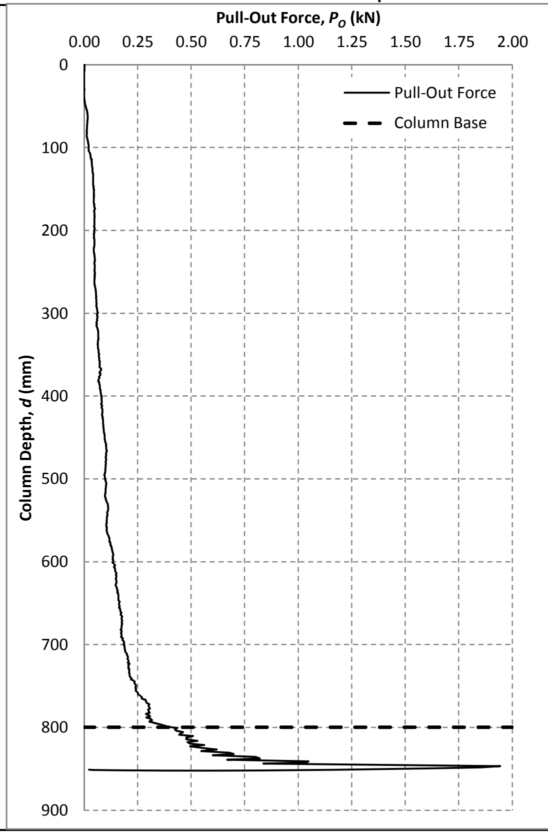
50 mm dia. Column Sample Properties:

Column Sample Ref:	Sample dia. mm	Depth: mm	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, ε_f	Reason to Exclude:	-
Column A	50	55	103	1758.4	326.3	43.7%	33.4	1.81%	-	
Column B	50	155	202	1681.0	370.9	44.4%	46.4	1.60%	-	
Column C	50	260	308	1672.2	414.6	44.1%	76.7	1.21%	-	
Column D	50	365	415	1702.9	355.7	44.0%	48.4	1.62%	-	
Column E	50	475	518	1917.6	438.5	44.6%	46.8	1.77%	-	
Column F	50	585	629	1776.6	464.5	43.9%	54.9	1.57%	-	
Column G	50	700	745	1699.6	464.3	43.5%	67.6	1.19%	-	
Column H	*38*	*55*	*90*	*1654.2*	*316.2*	*44.3%*	*52.7*	*1.55%*	*Sample trimming issues*	
Column I	*38*	*155*	*192*	*1717.7*	*404.7*	*44.6%*	*41.3*	*1.91%*		
Column J	*38*	*260*	*296*	*1586.9*	*377.2*	*44.0%*	*48.9*	*1.51%*		
Column K	*38*	*475*	*514*	*1677.3*	*416.3*	*41.7%*	*46.3*	*1.62%*		
Column L	*38*	*585*	*621*	*1625.8*	*395.4*	*43.6%*	*48.3*	*1.61%*		
Column M	*38*	*700*	*737*	*1653.8*	*475.2*	*43.1%*	*51.6*	*1.44%*		

Comments:

No pieces of column noted on the wire and good column construction found with minor voids in the column face and no cracking.
Route of the wire in the column noted to be straight with a small curve near the base of the column.

Wire Pull-Out Force with Depth:



PORT Wire Friction Test No. 3

Test Type:	Wire	Binder:	OP Cement		Mixing Date:	28/11/2013		Pull-Out Rate:		
Reference:	W-3-4-150	OPC Content:	150	kg/m^3	Wire Date:	02/12/2013		16.8	mm/sec	
Operator:	MT	Built Height:	800	mm	Wire Time:	3.95	days	ΔUCSxWTBR	32.5	
Column dia.	104 mm	Average Temp:	16.6	°C	Mould Time:	4.16	days	Wire Friction Correction:		
Basin Height:	800 mm	Wire Extension:	51	mm	Column Time:	4.13	days	0.440	kN/m	

65 mm dia. Mould Sample Properties#:

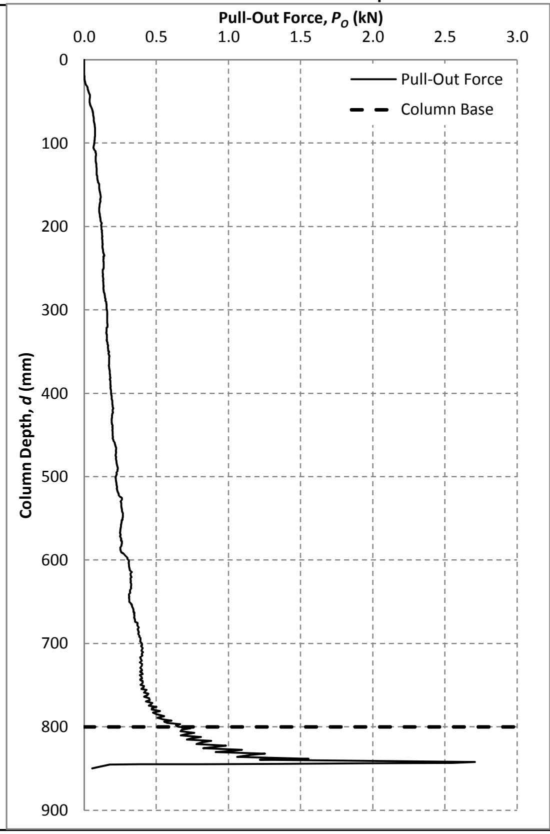
Mould Sample:	Curing Condition:	Raw *Sleech* MC:	Organic Content:	Mixed MC:	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, ε_f
Mix 1R	Room	48.8%	3.9%	41.5%	129	1710.2	384.2	40.3%	35.1	2.53%
Mix 1T	20°C	48.8%	3.9%	41.5%	129	1708.4	456.1	40.0%	55.9	2.09%

50 mm dia. Column Sample Properties:

Column Sample Ref:	Sample dia. mm	Depth: mm	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, ε_f	Reason to Exclude:	-
Column A	50	55	95	1763.1	415.0	40.1%	40.1	1.58%	-	
Column B	50	165	99	1779.4	553.2	40.1%	57.6	1.82%	-	
Column C	50	270	92	1829.5	570.1	39.8%	62.7	1.92%	-	
Column D	50	380	100	1807.6	614.9	40.2%	92.8	1.65%	-	
Column E	50	490	97	1787.5	573.1	39.5%	63.4	1.97%	-	
Column F	50	595	94	1800.4	549.6	39.4%	87.0	1.14%	-	
Column G	50	705	92.5	1810.5	636.2	39.3%	82.0	1.50%	-	
Column H	*38*	*55*	*68*	*1618.0*	*501.3*	*39.3%*	*35.8*	*2.47%*	*Sample trimming issues*	
Column I	*38*	*165*	*76*	*1716.9*	*591.3*	*39.0%*	*57.7*	*1.92%*		
Column J	*38*	*270*	*73.5*	*1695.2*	*618.6*	*39.3%*	*53.8*	*2.28%*		
Column K	*38*	*380*	*71.5*	*1718.0*	*617.5*	*39.5%*	*55.3*	*2.29%*		
Column L	*38*	*490*	*77*	*1623.9*	*613.6*	*39.1%*	*65.4*	*2.41%*		
Column M	*38*	*595*	*77*	*1602.8*	*509.8*	*38.6%*	*59.5*	*1.38%*		
Column N	*38*	*705*	*78*	*1578.1*	*563.2*	*38.7%*	*63.5*	*1.95%*		

Comments:
One small piece of adhered material found on the middle of the wire.
Good column construction noted and no cracking found in the extracted column.
Route of the wire noted to fluctuate in the mid to lower section of the column.

Wire Pull-Out Force with Depth:



PORT Wire Friction Test No. 4

Test Type:	Wire	Binder:	OP Cement		Mixing Date:	01/12/2013		Pull-Out Rate:		
Reference:	W-4-1-100	OPC Content:	100	kg/m^3	Wire Date:	02/12/2013		16.8	mm/sec	
Operator:	MT	Built Height:	770	mm	Wire Time:	1.15	days	ΔUCSxWTBR	84.9	
Column dia.	104 mm	Average Temp:	16.7	°C	Mould Time:	1.33	days	Wire Friction Correction:		
Basin Height:	800 mm	Wire Extension:	48	mm	Column Time:	1.30	days	0.095	kN/m	

65 mm dia. Mould Sample Properties:

Mould Sample:	Curing Condition:	Raw *Sleech* MC:	Organic Content:	Mixed MC:	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, ε_f
Mix 1R	Room	46.9%	2.8%	42.2%	127.5	1706.6	156.3	41.3%	8.8	3.27%
Mix 1T	20°C	46.9%	2.8%	42.2%	129	1712.7	181.7	41.5%	12.8	2.96%

50 mm dia. Column Sample Properties:

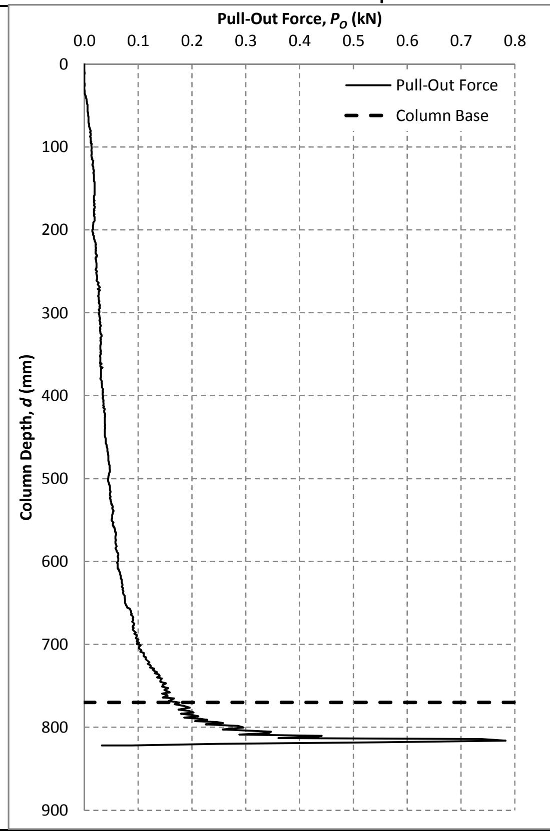
Column Sample Ref:	Sample dia. mm	Depth: mm	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, ε_f	Reason to Exclude:	-
Column A	50	55	96	1755.7	141.3	40.4%	0.4	3.75%	-	
Column B	50	155	90.5	1740.4	173.9	41.4%	0.4	3.36%	-	
Column C	50	260	97	1742.0	196.5	41.1%	0.4	3.25%	-	
Column D	50	360	84	1791.5	201.7	40.5%	0.4	2.90%	-	
Column E	50	465	100	1760.4	198.5	41.2%	0.4	3.23%	-	
Column F	50	565	86	1738.4	203.9	41.1%	0.4	2.42%	-	
Column G	50	670	92	1760.8	206.7	40.6%	0.4	1.99%	-	
Column H	*38*	*155*	*76.5*	*1703.0*	*148.2*	*41.8%*	*0.4*	*2.58%*	*Sample trimming issues*	
Column I	*38*	*260*	*78.5*	*1703.1*	*203.4*	*40.4%*	*0.4*	*3.81%*		
Column J	*38*	*360*	*77.5*	*1748.4*	*202.3*	*40.6%*	*0.4*	*2.82%*		
Column K	*38*	*465*	*72*	*1618.7*	*197.4*	*39.8%*	*0.4*	*2.75%*		
Column L	*38*	*565*	*74.5*	*1700.9*	*188.3*	*41.0%*	*0.4*	*2.48%*		

Comments:

No material adhered to the wire and route taken by the wire was straight.

Extracted column found to be well constructed with only minor voids on the column face.

Wire Pull-Out Force with Depth:



PORT Wire Friction Test No. 5

Test Type:	Wire	Binder:	OP Cement		Mixing Date:	04/12/2013		Pull-Out Rate:	
Reference:	W-5-12-150	OPC Content:	150	kg/m^3	Wire Date:	16/12/2013		17.4	mm/sec
Operator:	MT	Built Height:	800	mm	Wire Time:	11.96	days	ΔUCSxWTBR	9.4
Column dia.	104 mm	Average Temp:	17.2	°C	Mould Time:	12.15	days	Wire Friction Correction:	
Basin Height:	800 mm	Wire Extension:	48	mm	Column Time:	12.12	days	0.400	kN/m

65 mm dia. Mould Sample Properties:

Mould Sample:	Curing Condition:	Raw *Sleech* MC:	Organic Content:	Mixed MC:	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, ε_f
Mix 1R	Room	46.6%	4.1%	39.9%	129	1725.4	535.2	38.9%	66.6	1.94%
Mix 1T	20°C	46.6%	4.1%	39.9%	130.5	1728.9	570.3	38.6%	64.3	1.95%

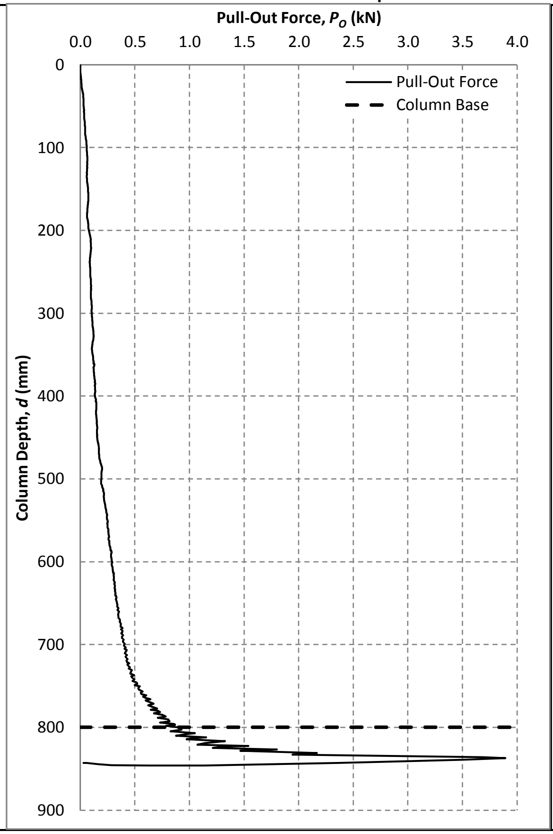
50 mm dia. Column Sample Properties:

Column Sample Ref:	Sample dia. mm	Depth: mm	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, ε_f	Reason to Exclude:	-
Column A	50	55	97	1817.1	539.5	38.3%	56.4	2.04%	-	
Column B	50	165	99	1861.8	617.6	38.6%	90.4	1.55%	-	
Column C	50	275	103.5	1815.8	701.5	37.9%	96.1	1.97%	-	
Column D	50	385	98.5	1864.2	622.9	38.0%	63.2	1.57%	-	
Column E	50	500	99	1888.6	783.7	37.3%	85.8	1.66%	-	
Column F	50	620	99	1864.4	805.3	37.9%	107.5	1.90%	-	
Column G	50	740	95	1735.5	821.1	37.2%	95.4	1.86%	-	
Column H	*38*	*55*	*74*	*1719.6*	*456.4*	*37.6%*	*33.8*	*2.41%*	*Sample trimming issues*	
Column I	*38*	*165*	*76*	*1681.7*	*630.9*	*37.6%*	*65.6*	*1.81%*		
Column J	*38*	*275*	*76*	*1615.9*	*597.0*	*37.8%*	*49.4*	*2.08%*		
Column K	*38*	*385*	*74.5*	*1667.7*	*574.0*	*36.5%*	*62.0*	*2.11%*		
Column L	*38*	*500*	*75.5*	*1595.8*	*668.7*	*37.1%*	*79.5*	*1.98%*		
Column M	*38*	*740*	*72.5*	*1753.0*	*833.8*	*37.0%*	*99.4*	*2.05%*		

Comments:

No material adhered to the wire and route taken by the wire found to be very good.
Extracted column found to be well constructed with only minor voids on the column face.

Wire Pull-Out Force with Depth:



PORT Wire Friction Test No. 6

Test Type:	Wire	Binder:	OP Cement		Mixing Date:	04/12/2013		Pull-Out Rate:		
Reference:	W-6-12-100	OPC Content:	100	kg/m^3	Wire Date:	16/12/2013		17.4	mm/sec	
Operator:	MT	Built Height:	800	mm	Wire Time:	12.07	days	ΔUCSxWTBR	8.3	
Column dia.	104 mm	Average Temp:	17.4	°C	Mould Time:	12.24	days	Wire Friction Correction:		
Basin Height:	800 mm	Wire Extension:	48	mm	Column Time:	12.21	days	0.218	kN/m	

65 mm dia. Mould Sample Properties:

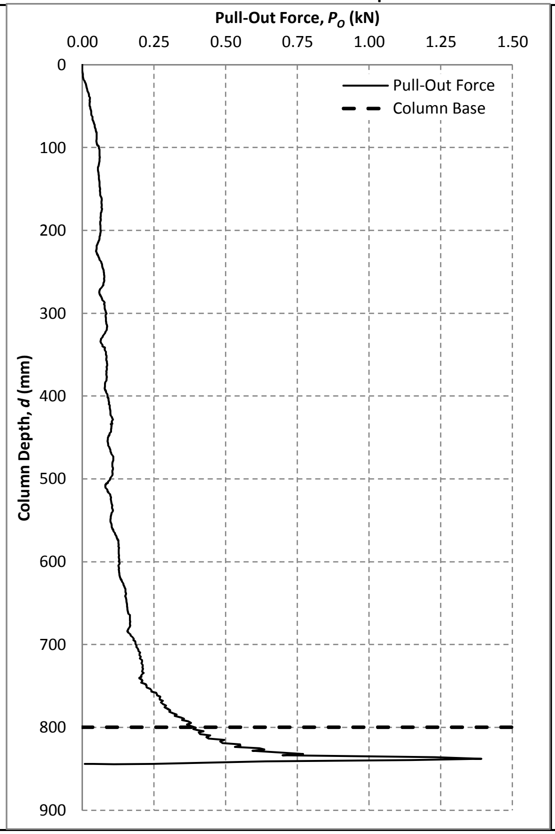
Mould Sample:	Curing Condition:	Raw *Sleech* MC:	Organic Content:	Mixed MC:	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, ε_f
Mix 1R	Room	46.9%	3.3%	41.3%	128	1715.1	401.2	40.2%	88.3	1.22%
Mix 1T	20°C	46.9%	3.3%	41.3%	130.5	1705.9	464.7	40.4%	34.9	2.13%

50 mm dia. Column Sample Properties:

Column Sample Ref:	Sample dia. mm	Depth: mm	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, ε_f	Reason to Exclude:	-
Column A	50	55	99.5	1789.4	430.7	40.4%	34.2	2.31%	-	
Column B	50	160	100	1816.2	543.6	40.5%	60.2	2.01%	-	
Column C	50	265	92	1743.7	447.5	40.2%	47.1	1.93%	-	
Column D	50	370	95	1785.4	502.7	40.2%	68.8	1.55%	-	
Column E	50	475	96.5	1830.4	542.2	40.3%	67.5	1.77%	-	
Column F	50	575	104.5	1838.5	579.3	40.4%	78.8	1.82%	-	
Column G	50	695	93.5	1830.4	577.0	39.7%	76.4	1.35%	-	
Column H	*38*	*55*	*75*	*1619.7*	*441.2*	*40.1%*	*31.0*	*2.57%*	*Sample trimming issues*	
Column I	*38*	*160*	*77*	*1717.9*	*493.8*	*40.3%*	*54.4*	*1.99%*		
Column J	*38*	*265*	*74*	*1667.9*	*536.3*	*39.7%*	*53.4*	*2.15%*		
Column K	*38*	*370*	*76*	*1712.8*	*546.7*	*40.0%*	*44.2*	*2.09%*		
Column L	*38*	*475*	*78*	*1714.4*	*564.3*	*40.5%*	*67.3*	*1.98%*		
Column M	*38*	*695*	*74*	*1762.2*	*524.0*	*39.9%*	*127.8*	*1.13%*		

Comments:
No material adhered to the wire and route taken by the wire found to be very good.
Extracted column found to be well constructed with only minor voids on the column face.

Wire Pull-Out Force with Depth:



PORT Wire Friction Test No. 7

Test Type:	Wire	Binder:	OP Cement		Mixing Date:	20/12/2013		Pull-Out Rate:	
Reference:	W-7-1.5-150	OPC Content:	150	kg/m^3	Wire Date:	22/12/2013		17.2	mm/sec
Operator:	MT	Built Height:	800	mm	Wire Time:	1.59	days	ΔUCSxWTBR	57.4
Column dia.	104 mm	Average Temp:	15.7	°C	Mould Time:	1.76	days	Wire Friction Correction:	
Basin Height:	800 mm	Wire Extension:	48	mm	Column Time:	1.73	days	0.177	kN/m

65 mm dia. Mould Sample Properties:

Mould Sample:	Curing Condition:	Raw *Sleech* MC:	Organic Content:	Mixed MC:	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, ε_f
Mix 1R	Room	47.1%	3.5%	40.1%	127	1731.9	285.9	39.4%	17.8	3.28%
Mix 1T	20°C	47.1%	3.5%	40.1%	130	1721.8	322.0	39.0%	20.8	3.27%

50 mm dia. Column Sample Properties:

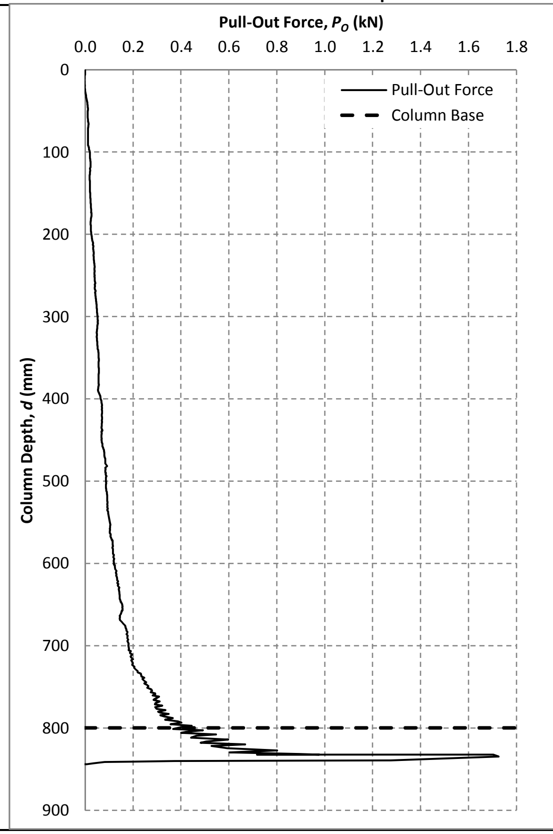
Column Sample Ref:	Sample dia. mm	Depth: mm	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, ε_f	Reason to Exclude:	-
Column A	50	55	95.5	1867.5	267.4	39.2%	27.9	3.41%	-	
Column B	50	165	96	1795.4	274.8	38.8%	20.2	2.75%	-	
Column C	50	275	102.5	1804.9	326.8	38.3%	29.3	2.32%	-	
Column D	50	380	90.5	1822.2	317.8	38.6%	25.3	2.42%	-	
Column E	50	485	99	1799.4	346.5	38.8%	42.1	1.72%	-	
Column F	50	595	89.5	1828.8	339.4	38.7%	42.4	2.17%	-	
Column G	50	705	96	1838.1	375.8	38.4%	42.7	1.82%	-	
Column H	38	165	75.5	1810.0	322.9	39.1%	42.5	2.86%	Sample trimming issues	
Column I	38	275	77	1781.5	355.4	38.7%	26.2	2.83%		
Column J	38	485	73.5	1767.3	373.0	38.5%	31.8	2.53%		
Column K	38	705	70.5	1738.4	378.6	38.3%	31.3	2.41%		

Comments:

No material adhered to the wire and straight route taken by the wire.

Extracted column found to be well constructed with only minor voids on the column face.

Wire Pull-Out Force with Depth:



PORT Wire Friction Test No. 8

Test Type:	Wire	Binder:	OP Cement		Mixing Date:	21/12/2013		Pull-Out Rate:		
Reference:	W-8-6.5-150	OPC Content:	150	kg/m^3	Wire Date:	28/12/2013		17.0	mm/sec	
Operator:	MT	Built Height:	800	mm	Wire Time:	6.63	days	ΔUCSxWTBR	17.2	
Column dia.	104 mm	Average Temp:	15.1	°C	Mould Time:	6.81	days	Wire Friction Correction:		
Basin Height:	800 mm	Wire Extension:	48	mm	Column Time:	6.79	days	0.405	kN/m	

65 mm dia. Mould Sample Properties:

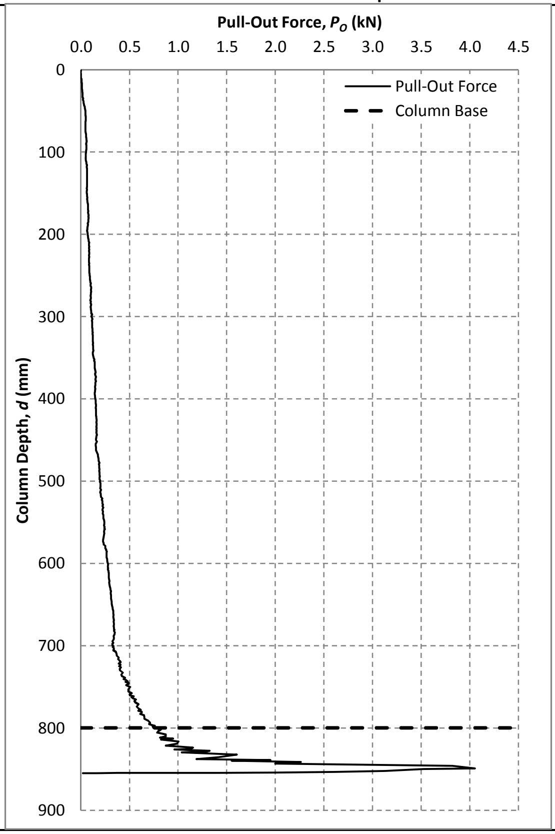
Mould Sample:	Curing Condition:	Raw *Sleech* MC:	Organic Content:	Mixed MC:	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, ε_f
Mix 1R	Room	45.9%	2.7%	38.9%	130	1744.8	513.1	37.2%	38.9	2.56%
Mix 1T	20°C	45.9%	2.7%	38.9%	129.5	1744.7	548.6	37.5%	60.7	1.93%

50 mm dia. Column Sample Properties:

Column Sample Ref:	Sample dia. mm	Depth: mm	Length: mm	Density: kg/m^3	Uncorrected UCS, kPa	Stabilised MC:	Stiffness E_{50} MPa	Failure Strain, ε_f	Reason to Exclude:	-
Column A	50	55	99.5	1911.4	628.0	37.1%	55.5	2.19%	-	
Column B	50	165	93.5	1887.8	687.1	36.9%	101.2	1.49%	-	
Column C	50	270	98	1906.5	726.9	36.9%	94.0	1.80%	-	
Column D	50	375	97	1904.2	709.0	37.6%	78.4	1.77%	-	
Column E	50	480	95.5	1876.4	636.1	37.3%	75.3	1.32%	-	
Column F	50	585	91.5	1837.0	679.1	36.7%	84.5	1.64%	-	
Column G	50	700	94.5	1879.4	652.3	36.8%	77.9	1.20%	-	
Column H	*38*	*55*	*77*	*1816.4*	*613.9*	*37.6%*	*58.0*	*2.15%*	*Sample trimming issues*	
Column I	*38*	*165*	*75*	*1803.8*	*682.7*	*37.2%*	*81.8*	*1.82%*		
Column J	*38*	*375*	*74.5*	*1746.1*	*635.2*	*36.6%*	*53.7*	*2.17%*		
Column K	*38*	*480*	*73.5*	*1755.2*	*635.4*	*37.0%*	*84.7*	*1.21%*		
Column L	*38*	*585*	*76.5*	*1773.4*	*699.2*	*36.9%*	*80.9*	*1.58%*		
Column M (Shc	*38*	*700*	*78*	*1614.2*	*554.5*	*36.3%*	*87.8*	*1.16%*		

Comments:
No material adhered to the wire and straight route taken by the wire.
Extracted column found to be well constructed with only minor voids on the column face.

Wire Pull-Out Force with Depth:



E.8 Wire Column Summary Statistics

PORT Wire Column Sample Summary Statistics:									
PIRT Reference:		W1	W2	W3	W4	W5	W6	W7	W8
No. of Samples:		7	7	7	7	7	7	7	7
Binder Content (kg/m^3):		150	100	150	100	150	100	150	150
		Column Sample Density:							
Column Density ρ_{col}, kg/m^3	Maximum:	1833.7	1917.6	1829.5	1791.5	1888.6	1838.5	1867.5	1911.4
	Minimum:	1669.5	1672.2	1763.1	1738.4	1735.5	1743.7	1795.4	1837.0
	Range:	164.2	245.3	66.4	53.1	153.1	94.8	72.1	74.4
	Average:	1780.3	1744.0	1796.9	1755.6	1835.3	1804.9	1822.3	1886.1
	St Dev:	52.2	85.8	22.0	18.5	51.5	34.0	25.4	25.6
	CoV:	2.9%	4.9%	1.2%	1.1%	2.8%	1.9%	1.4%	1.4%
		Column Sample Strength:							
Column UCS q_{mol}, kPa	Maximum:	607.3	464.5	636.2	206.7	821.1	579.3	375.8	726.9
	Minimum:	491.1	326.3	415.0	141.3	539.5	430.7	267.4	628.0
	Range:	116.2	138.3	221.2	65.4	281.6	148.6	108.4	98.9
	Average:	555.5	405.0	558.9	188.9	698.8	517.6	321.2	674.1
	St Dev:	42.7	54.9	71.0	23.6	109.0	59.6	38.8	37.1
	CoV:	7.7%	13.5%	12.7%	12.5%	15.6%	11.5%	12.1%	5.5%
		Column Sample Stiffness:							
Column Stiffness, E_{col}, MPa	Maximum:	105.1	76.7	92.8	28.0	107.5	78.8	42.7	101.2
	Minimum:	41.6	33.4	40.1	8.4	56.4	34.2	20.2	55.5
	Range:	63.4	43.3	52.7	19.6	51.2	44.6	22.6	45.7
	Average:	64.7	53.5	69.4	16.3	85.0	61.9	32.8	80.9
	St Dev:	21.2	14.5	18.7	6.9	18.6	16.1	9.4	14.6
	CoV:	32.7%	27.2%	26.9%	42.2%	21.8%	26.1%	28.6%	18.1%

E.9 Cone-Only Penetrometer & Sounding Bar Experiment Summary Sheet

Cone-Only & Sounding Bar Friction Test-Trial Test

Test Type:	S. Bar	Binder:	OP Cement		Mixing Date:	16/11/2013		Push-In Rate:	
Reference:	C-Trial	OPC Content:	180	*kg/m^3*	Test Date:	18/11/2013		19.4	*mm/sec*
Operator:	MT	Column Length:	800	*mm*	Test Time:	2.08	*days*	15.8	*mm/sec*
Column dia.	104*mm*	Sleech Layer:	-	*mm*	Mould Time:	2.18	*days*	ΔUCSxWTBR	42.1
Basin Height.	800*mm*	Average Temp:	17.4	*°C*	Column Time:	2.20	*days*	Wire Test:	NA

65*mm* dia. Mould Sample Properties:

Mould Sample:	Curing Condition:	Raw *Sleech* MC:	Organic Content:	Mixed MC:	Length: *mm*	Density: *kg/m^3*	Uncorrected UCS, *kPa*	Stabilised MC:	Stiffness E_{50} *MPa*	Failure Strain, ε_f:
Mix 1R	Room	43.7%	-	37.4%	130.5	1748.5	417.8	36.9%	26.4	3.16%

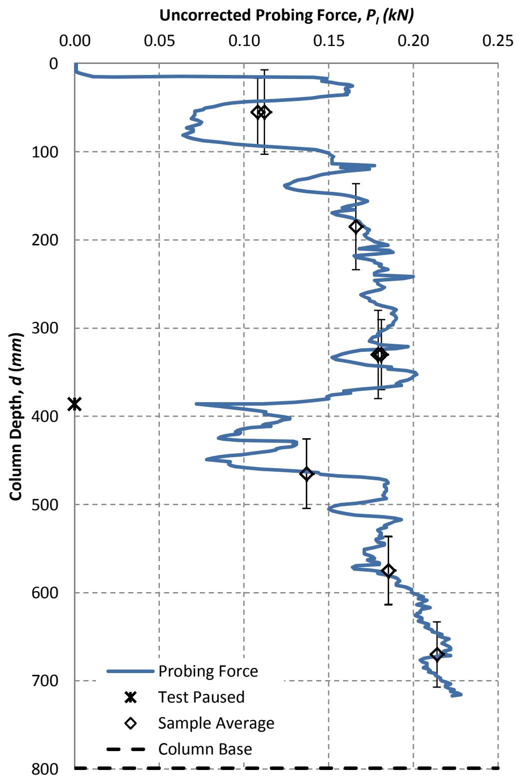
50*mm* dia. Column Sample Properties:

Column Sample Ref:	Sample dia. *mm*	Depth: *mm*	Length: *mm*	Density: *kg/m^3*	Uncorrected UCS, *kPa*	Stabilised MC:	Stiffness E_{50} *MPa*	Failure Strain, ε_f:	Reason to Exclude:	Probing Force, *kN*
Column A	50	55	96	1825.2	453.2	30.0%	45.1	2.03%		0.11
Column B	50	185	97.5	1858.0	513.5	40.2%	38.8	2.32%		0.17
Column C	50	330	100	1799.0	554.1	36.1%	79.1	1.57%		0.18
Column D	38	330	79.5	1822.8	502.5	35.4%	55.9	1.61%		0.18
Column E	38	465	78.5	1731.8	388.7	36.2%	52.5	1.47%		0.14
Column F	38	465	78.5	1828.0	570.0	35.6%	48.0	2.63%		0.14
Column G	38	575	78	1760.3	511.2	36.4%	37.6	2.24%		0.19
Column H	38	575	76.5	1652.1	492.9	36.0%	43.7	2.20%		0.19
Column I	38	670	74	1568.3	412.4	35.4%	21.3	2.75%		0.21
Column J	38	55	76.5	1651.5	482.6	35.7%	33.5	2.76%		0.11

Comments:

180*kg/m^3* of cement used to get significant strength gain at an early age. No sleech placed under the column during curing and testing.
During raising of load cell after push 1, the cone was pulled up by 70*mm* due to friction with the sounding bar sleeve.
Column intact when removed from curing pipe. Plug of stabilised soil noted ahead of the cone at the end of the test.

Column Probing Force with Column Sample Locations:



Cone-Only & Sounding Bar Friction Test No. 1

Test Type:	S. Bar	Binder:	OP Cement	Mixing Date:	19/11/2013	Push-In Rate:	
Reference:	C-1-1-100	OPC Content:	180 *kg/m³*	Test Date:	20/11/2013	17.8	*mm/sec*
Operator:	MT	Column Length:	800 *mm*	Test Time:	1.01 *days*	19.3	*mm/sec*
Column dia.	104*mm*	Sleech Layer:	100 *mm*	Mould Time:	1.19 *days*	ΔUCSxWTBR	94.8
Basin Height:	900*mm*	Average Temp:	- *°C*	Column Time:	1.15 *days*		

65*mm* dia. Mould Sample Properties:

Mould Sample:	Curing Condition:	Raw *Sleech* MC, w_i	Organic Content:	Mixed MC, w_m	Length: *mm*	Density: kg/m^3	Uncorrected UCS, *kPa*	Stabilised MC, w_s	Stiffness E_{50} *MPa*	Failure Strain, ε_f
Mix 1R	Room	45.8%	4.1%	40.3%	129.5	1713.2	153.7	38.8%	15.4	2.98%
Mix 1T	20°C	45.8%	4.1%	40.3%	130.5	1716.0	187.0	40.0%	18.0	3.03%

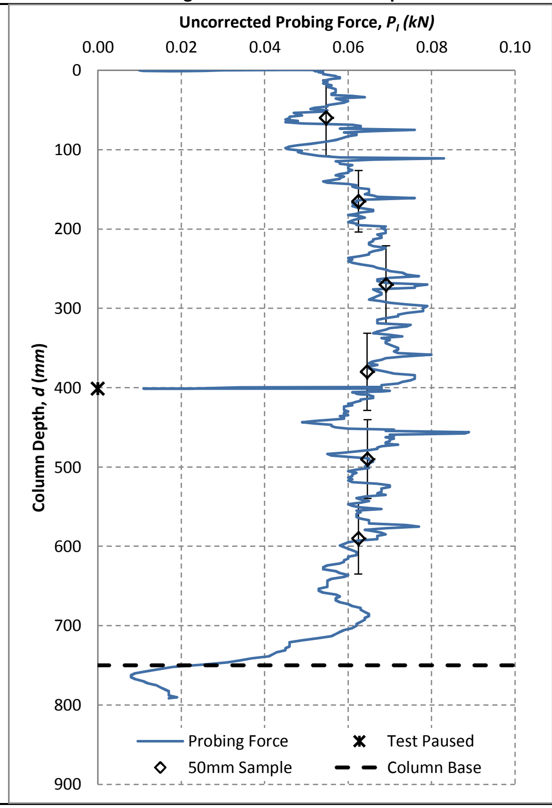
Column Sample Properties:

Column Sample Ref:	Sample dia. *mm*	Depth: *mm*	Length: *mm*	Density: kg/m^3	Uncorrected UCS, *kPa*	Stabilised MC, w_s	Stiffness E_{50} *MPa*	Failure Strain, ε_f	Reason to Exclude:	Probing Force, *kN*
Column A	50	60	95.5	1794.2	202.9	39.9%	101.4	2.78%	-	0.05
Column B	50	165	77.5	1727.8	229.3	39.9%	114.6	3.60%	-	0.06
Column C	50	270	98	1796.4	250.8	38.9%	125.4	2.46%	-	0.07
Column D	50	380	97.5	1771.8	235.4	37.6%	117.7	2.77%	-	0.06
Column E	50	490	99	1666.4	246.2	39.6%	123.1	2.81%	-	0.06
Column F	50	590	89.5	1773.4	195.0	39.7%	97.5	3.04%	-	0.06
Column a	*38*	*60*	*78*	*1708.7*	*187.4*	*38.9%*	*93.7*	*2.67%*	Sample trimming issues	*0.06*
Column b	*38*	*165*	*73.5*	*1752.0*	*215.8*	*37.6%*	*107.9*	*2.77%*		*0.06*
Column c	*38*	*270*	*73.5*	*1710.8*	*269.4*	*38.8%*	*134.7*	*3.23%*		*0.07*
Column d	*38*	*380*	*73.5*	*1700.1*	*235.8*	*38.9%*	*117.9*	*2.84%*		*0.06*
Column e	*38*	*490*	*72*	*1750.5*	*277.3*	*40.7%*	*138.7*	*2.98%*		*0.07*
Column f	*38*	*590*	*74*	*1808.2*	*259.9*	*38.8%*	*129.9*	*3.52%*		*0.06*
Column g	*38*	*690*	*75*	*1732.9*	*232.3*	*38.9%*	*116.1*	*4.14%*		*0.06*

<u>Comments:</u>

Column was intact with no cracking on removal from curing pipe. 50*mm* sample at 690*mm* broke during trimming.

Column Probing Force with Column Sample Locations:



Cone-Only & Sounding Bar Friction Test No. 2

Test Type:	S. Bar	Binder:	OP Cement		Mixing Date:	20/11/2013		Push-In Rate:		
Reference:	C-2-2-150	OPC Content:	100	*kg/m^3*	Test Date:	22/11/2013		19.6	*mm/sec*	
Operator:	MT	Column Length:	750	*mm*	Test Time:	1.97	*days*	22.6	*mm/sec*	
Column dia.	104*mm*	Sleech Layer:	150	*mm*	Mould Time:	2.15	*days*	ΔUCSxWTBR	54.6	
Basin Height:	900*mm*	Average Temp:	208.0	°C	Column Time:	2.12	*days*			

65*mm* dia. Mould Sample Properties:

Mould Sample:	Curing Condition:	Raw *Sleech* MC, w_i	Organic Content:	Mixed MC, w_m	Length: *mm*	Density: *kg/m^3*	Uncorrected UCS, *kPa*	Stabilised MC, w_s	Stiffness E_{50} *MPa*	Failure Strain, ε_f
Mix 1R	Room	46.0%	3.2%	38.9%	129	1727.8	285.5	38.6%	14.1	3.20%
Mix 1T	20°C	46.0%	2.6%	38.9%	129	1738.6	372.7	37.5%	31.1	2.57%

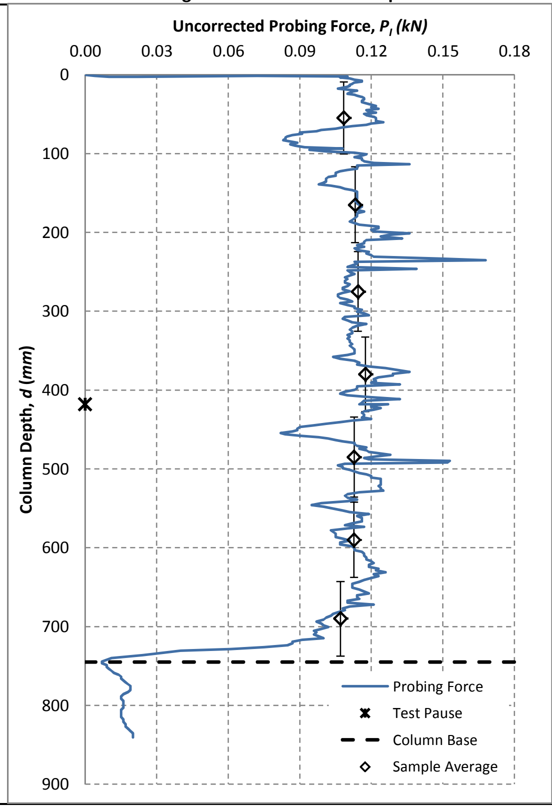
50*mm* dia. Column Sample Properties:

Column Sample Ref:	Sample dia. *mm*	Depth: *mm*	Length: *mm*	Density: *kg/m^3*	Uncorrected UCS, *kPa*	Stabilised MC, w_s	Stiffness E_{50} *MPa*	Failure Strain, ε_f	Reason to Exclude:	Probing Force, *kN*
Column A	50	55	91.5	1743.5	311.7	37.2%	31.9	1.97%	-	0.11
Column B	50	165	96	1808.9	416.6	37.4%	32.0	2.69%	-	0.11
Column C	50	275	101	1768.4	369.2	37.7%	36.9	2.46%	-	0.11
Column D	50	380	94.5	1846.1	459.7	37.4%	44.2	2.26%	-	0.12
Column E	50	485	101.5	1803.9	429.5	37.2%	44.0	2.40%	-	0.11
Column F	50	590	95.5	1724.3	367.2	37.3%	30.7	2.45%	-	0.11
Column G	50	690	94.5	1787.9	374.6	37.5%	28.8	2.52%	-	0.11
Column H	*38*	*55*	*74*	*1688.3*	*378.2*	*37.1%*	*22.1*	*3.51%*	Sample trimming issues	*0.11*
Column I	*38*	*165*	*78*	*1619.7*	*345.8*	*37.1%*	*30.4*	*2.63%*		*0.11*
Column J	*38*	*275*	*74.5*	*1812.4*	*407.7*	*36.9%*	*28.2*	*2.79%*		*0.11*
Column K	*38*	*380*	*74*	*1657.0*	*416.2*	*37.1%*	*43.4*	*2.33%*		*0.12*
Column L	*38*	*485*	*71.5*	*1795.3*	*450.2*	*36.7%*	*34.5*	*2.84%*		*0.11*
Column M	*38*	*590*	*76*	*1719.5*	*403.2*	*35.6%*	*24.6*	*3.19%*		*0.11*
Column N	*38*	*690*	*80*	*1659.7*	*369.5*	*37.2%*	*30.6*	*2.21%*		*0.11*

Comments:

Column was intact with no cracking on removal from curing pipe. No foreign material noted in the column to be the result of the spikes in the force at 235*mm* and 490*mm*.

Column Probing Force with Column Sample Locations:



Cone-Only & Sounding Bar Friction Test No. 3

Test Type:	S. Bar	Binder:	OP Cement		Mixing Date:	23/11/2013		Push-In Rate:		
Reference:	C-3-6-100	OPC Content:	150	*kg/m*^{3}	Test Date:	29/11/2013		12.9	*mm/sec*	
Operator:	MT	Column Length:	740	*mm*	Test Time:	6.01	*days*	15.0	*mm/sec*	
Column dia.	104*mm*	Sleech Layer:	160	*mm*	Mould Time:	6.17	*days*	ΔUCSxWTBR	16.9	
Basin Height:	900*mm*	Average Temp:	373.7	*°C*	Column Time:	6.15	*days*			

65*mm* dia. Mould Sample Properties:

Mould Sample:	Curing Condition:	Raw *Sleech* MC, w_i	Organic Content:	Mixed MC, w_m	Length: *mm*	Density: *kg/m*^{3}	Uncorrected UCS, *kPa*	Stabilised MC, w_s	Stiffness E_{50} *MPa*	Failure Strain, ε_f
Mix 1R	Room	49.1%	4.4%	43.7%	128.5	1680.8	335.9	41.8%	34.4	2.09%
Mix 1T	20°C	49.1%	4.4%	43.7%	128	1688.4	383.8	42.2%	40.6	2.15%

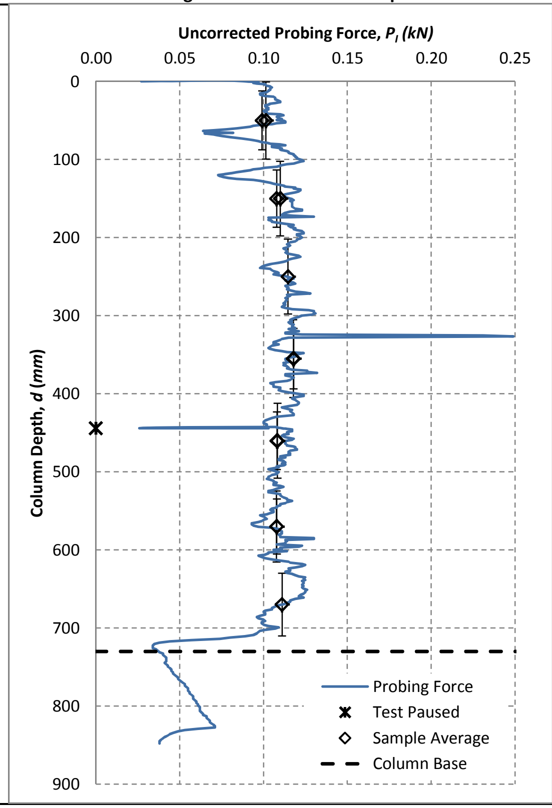
Column Sample Properties:

Column Sample Ref:	Sample dia. *mm*	Depth: *mm*	Length: *mm*	Density: *kg/m*^{3}	Uncorrected UCS, *kPa*	Stabilised MC, w_s	Stiffness E_{50} *MPa*	Failure Strain, ε_f	Reason to Exclude:	Probing Force, *kN*
Column A	50	50	99	1704.8	337.3	41.9%	33.5	2.19%	-	0.10
Column B	50	150	95.5	1691.2	410.9	40.2%	44.2	1.77%	-	0.11
Column C	50	250	96	1748.7	384.2	42.6%	31.3	1.98%	-	0.11
Column D	50	355	99.5	1762.2	437.6	42.5%	55.8	1.70%	-	0.12
Column E	50	460	96	1747.5	404.0	41.9%	54.5	1.46%	-	0.11
Column F	50	570	91	1706.7	382.7	42.6%	40.2	1.61%	-	0.11
Column G	50	670	80.5	1697.8	379.3	42.6%	24.0	2.44%	-	0.11
Column H	*38*	*50*	*75.5*	*1710.4*	*356.2*	*40.8%*	*27.9*	*2.47%*	Sample trimming issues	*0.10*
Column I	*38*	*150*	*73.5*	*1709.9*	*415.0*	*42.0%*	*40.4*	*1.67%*		*0.11*
Column J	*38*	*355*	*77.5*	*1712.6*	*432.1*	*41.9%*	*33.4*	*2.44%*		*0.12*
Column K	*38*	*460*	*74*	*1708.2*	*453.0*	*42.0%*	*51.3*	*2.09%*		*0.11*
Column L	*38*	*570*	*70.5*	*1616.9*	*428.7*	*42.0%*	*42.7*	*1.95%*		*0.11*

Comments:

Column was intact with no cracking on removal from curing pipe. No foreign material noted in the column to be the result of the spike in the force at 327*mm.*

Column Probing Force with Column Sample Locations:



Cone-Only & Sounding Bar Friction Test No. 4

Test Type:	S. Bar	Binder:	OP Cement		Mixing Date:	30/11/2013		Push-In Rate:		
Reference:	C-4-6-150	OPC Content:	100	*kg/m³*	Test Date:	06/12/2013		13.1	*mm/sec*	
Operator:	MT	Column Length:	747	*mm*	Test Time:	6.08	*days*	15.0	*mm/sec*	
Column dia.	104*mm*	Sleech Layer:	153	*mm*	Mould Time:	6.28	*days*	ΔUCSxWTBR	20.1	
Basin Height:	900*mm*	Average Temp:	387.7	*°C*	Column Time:	6.25	*days*			

65*mm* dia. Mould Sample Properties:

Mould Sample:	Curing Condition:	Raw *Sleech* MC, w_i	Organic Content:	Mixed MC, w_m	Length: *mm*	Density: kg/m^3	Uncorrected UCS, *kPa*	Stabilised MC, w_s	Stiffness E_{50} *MPa*	Failure Strain, ε_f
Mix 1R	Room	49.2%	4.8%	41.8%	128	1721.6	417.5	40.3%	49.3	2.07%
Mix 1T	20°C	49.2%	4.8%	41.8%	128	1720.6	466.2	39.7%	47.7	2.21%
Mix 1R (Tri)	Room	49.2%	4.8%	41.8%	123	1727.4	455.7	39.6%	38.6	2.48%

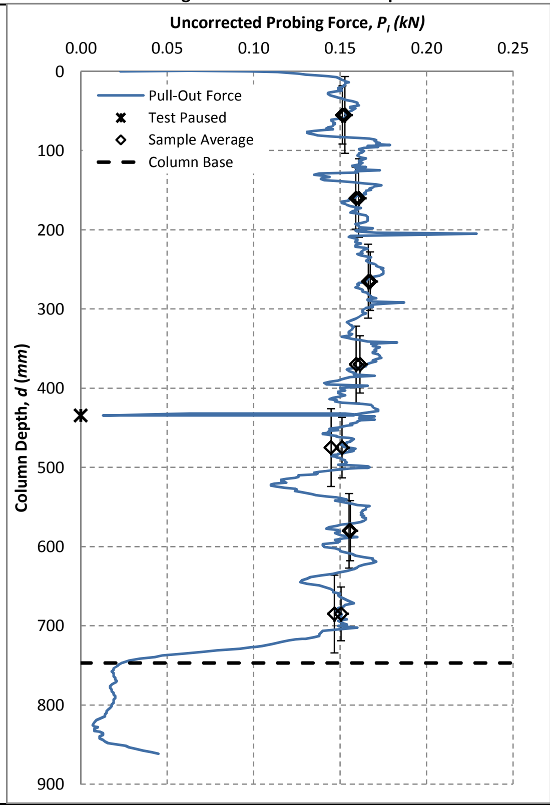
Column Sample Properties:

Column Sample Ref:	Sample dia. *mm*	Depth: *mm*	Length: *mm*	Density: kg/m^3	Uncorrected UCS, *kPa*	Stabilised MC, w_s	Stiffness E_{50} *MPa*	Failure Strain, ε_f	Reason to Exclude:	Probing Force, *kN*
Column A	50	55	97	1807.5	447.5	40.0%	49.8	2.18%	-	0.15
Column B	50	160	99	1799.2	506.6	39.6%	53.4	1.71%	-	0.16
Column C	50	265	93.5	1866.7	515.8	40.4%	107.4	1.57%	-	0.17
Column D	50	370	97	1839.5	558.8	40.4%	69.7	1.52%	-	0.16
Column E	50	475	98.5	1780.2	541.4	40.0%	65.0	1.81%	-	0.14
Column F	50	580	94	1789.7	520.4	40.0%	60.0	1.92%	-	0.16
Column G	50	685	98	1821.0	457.9	39.8%	31.7	2.28%	-	0.15
Column H	*38*	*55*	*73.5*	*1713.1*	*452.4*	*39.2%*	*30.8*	*2.72%*	Sample trimming issues	*0.15*
Column I	*38*	*160*	*78.5*	*1750.7*	*527.1*	*39.1%*	*80.3*	*1.61%*		*0.16*
Column J	*38*	*265*	*74*	*1792.3*	*533.5*	*39.4%*	*54.9*	*2.04%*		*0.17*
Column K	*38*	*370*	*72.5*	*1784.4*	*603.5*	*39.4%*	*63.6*	*1.89%*		*0.16*
Column L	*38*	*475*	*76.5*	*1842.7*	*496.6*	*39.8%*	*53.5*	*1.47%*		*0.15*
Column M	*38*	*580*	*76*	*1746.6*	*459.6*	*39.6%*	*31.9*	*1.98%*		*0.16*
Column N	*38*	*685*	*68*	*1770.0*	*323.4*	*39.4%*	*23.3*	*1.94%*		*0.15*

Comments:

Column was intact with no cracking on removal from curing pipe. Stabilised material noted on the cone tip on extraction of the column.

Column Probing Force with Column Sample Locations:



Cone-Only & Sounding Bar Friction Test No. 5

Test Type:	S. Bar	Binder:	OP Cement		Mixing Date:	07/12/2013		Push-In Rate:	
Reference:	C-5-12-150	OPC Content:	150	*kg/m³*	Test Date:	19/12/2013		16.5	*mm/sec*
Operator:	MT	Column Length:	755	*mm*	Test Time:	12.01	*days*	19.4	*mm/sec*
Column dia.	104*mm*	Sleech Layer:	145	*mm*	Mould Time:	12.20	*days*	18.0	*mm/sec*
Basin Height:	900*mm*	Average Temp:	501.3	*°C*	Column Time:	12.17	*days*	ΔUCSxWTBR	9.4

65*mm* dia. Mould Sample Properties:

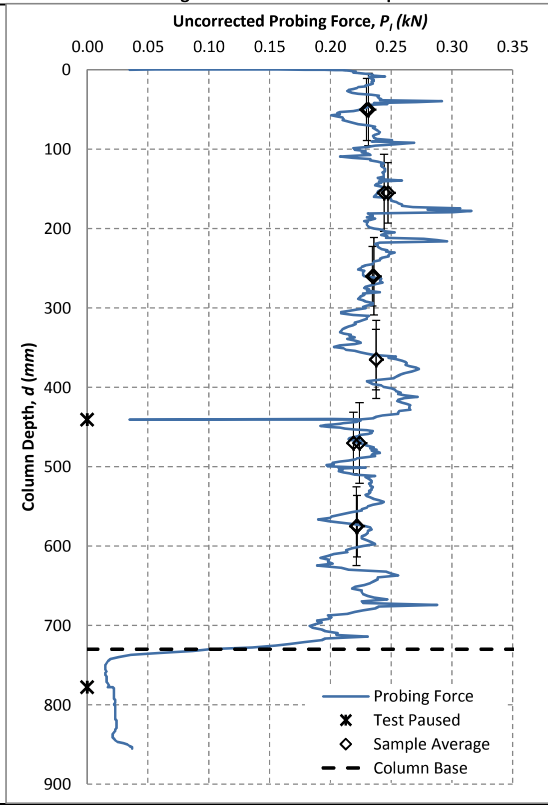
Mould Sample:	Curing Condition:	Raw *Sleech* MC, w_i	Organic Content:	Mixed MC, w_m	Length: *mm*	Density: kg/m^3	Uncorrected UCS, *kPa*	Stabilised MC, w_s	Stiffness E_{50} *MPa*	Failure Strain, ε_f
Mix 1R	Room	47.0%	4.3%	38.0%	128	1735.1	610.1	37.0%	70.2	2.01%
Mix 1T	20°*C*	47.0%	4.3%	0.38	127.5	1741.3	693.3	36.9%	103.1	1.81%
Mix 1R (Tri)	Room	47.0%	4.3%	38.0%	128.5	1743.1	745.9	37.2%	60.2	2.27%

Column Sample Properties:

Column Sample Ref:	Sample dia. *mm*	Depth: *mm*	Length: *mm*	Density: kg/m^3	Uncorrected UCS, *kPa*	Stabilised MC, w_s	Stiffness E_{50} *MPa*	Failure Strain, ε_f	Reason to Exclude:	Probing Force, *kN*
Column A	50	50	91	1902.1	784.3	36.5%	66.8	2.49%	-	0.23
Column B	50	155	97	1894.3	798.6	37.0%	93.8	1.98%	-	0.24
Column C	50	260	97.5	1915.9	784.1	36.6%	79.4	2.16%	-	0.24
Column D	50	365	98.5	1849.4	767.6	37.4%	74.9	2.04%	-	0.24
Column E	50	470	101.5	1896.1	839.1	37.0%	97.9	1.95%	-	0.22
Column F	50	575	99	1860.2	755.8	36.7%	83.2	1.77%	-	0.22
Column G	*38*	*50*	*78*	*1814.7*	*736.4*	*36.3%*	*68.4*	*2.19%*	Sample trimming issues	*0.23*
Column H	*38*	*155*	*76*	*1867.9*	*835.5*	*36.4%*	*108.7*	*1.92%*		*0.25*
Column I	*38*	*260*	*75*	*1804.2*	*895.0*	*37.1%*	*76.4*	*2.41%*		*0.23*
Column J	*38*	*365*	*76*	*1780.4*	*821.5*	*38.8%*	*116.1*	*2.01%*		*0.24*
Column K	*38*	*470*	*77.5*	*1826.0*	*842.1*	*36.5%*	*67.9*	*2.21%*		*0.22*
Column L	*38*	*575*	*77.5*	*1760.4*	*764.1*	*36.4%*	*105.2*	*1.83%*		*0.22*

Comments:
Column crack running from 625*mm* to 730*mm*, column otherwise extracted in good condition.

Column Probing Force with Column Sample Locations:



Cone-Only & Sounding Bar Friction Test No. 6

Test Type:	S. Bar	Binder:	OP Cement		Mixing Date:	19/12/2013		Push-In Rate:	
Reference:	C-6-1.6-150	OPC Content:	150	kg/m^3	Test Date:	21/12/2013		14.2	*mm/sec*
Operator:	MT	Column Length:	740	*mm*	Test Time:	1.59	*days*	19.1	*mm/sec*
Column dia.	104*mm*	Sleech Layer:	160	*mm*	Mould Time:	1.73	*days*	ΔUCSxWTBR	52.4
Basin Height:	900*mm*	Average Temp:	785.5	°*C*	Column Time:	1.70	*days*		

65*mm* dia. Mould Sample Properties:

Mould Sample:	Curing Condition:	Raw *Sleech* MC, w_i	Organic Content:	Mixed MC, w_m	Length: *mm*	Density: kg/m^3	Uncorrected UCS, *kPa*	Stabilised MC, w_s	Stiffness E_{50} *MPa*	Failure Strain, ε_f
Mix 1R	Room	47.2%	4.1%	40.1%	128	1729.2	271.2	39.4%	33.9	3.00%
Mix 1T	20°*C*	47.2%	4.1%	40.1%	128	1731.4	320.3	39.4%	22.9	2.90%
Mix 1R (Tri)	Room	47.2%	4.1%	40.1%	129	1745.4	300.5	38.7%	20.3	2.91%

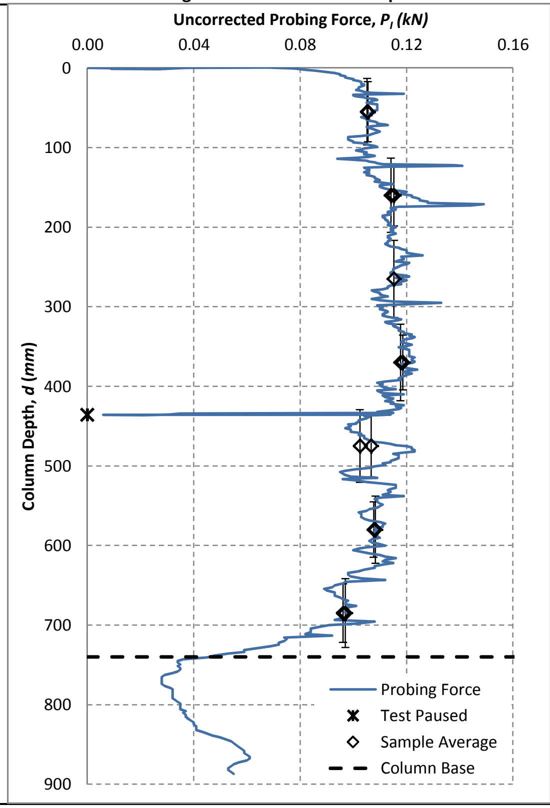
Column Sample Properties:

Column Sample Ref:	Sample dia. *mm*	Depth: *mm*	Length: *mm*	Density: kg/m^3	Uncorrected UCS, *kPa*	Stabilised MC, w_s	Stiffness E_{50} *MPa*	Failure Strain, ε_f	Reason to Exclude:	Probing Force, *kN*
Column A	50	55	83.5	1849.9	306.5	38.0%	25.5	3.39%	-	0.11
Column B	50	160	93	1862.1	295.8	38.8%	27.1	2.29%	-	0.11
Column C	50	265	97	1832.3	335.0	38.9%	29.9	2.63%	-	0.12
Column D	50	370	96	1864.8	316.2	38.0%	29.5	2.41%	-	0.12
Column E	50	475	91	1831.0	309.9	39.0%	27.6	2.64%	-	0.10
Column F	50	580	84.5	1803.1	280.1	38.5%	17.6	2.92%	-	0.11
Column G	50	685	86.5	1796.8	263.5	38.8%	16.7	3.05%	-	0.10
Column H	*38*	*55*	*75.5*	*1723.7*	*289.1*	*38.6%*	*19.4*	*3.10%*	Sample trimming issues	*0.11*
Column I	*38*	*160*	*77.5*	*1798.5*	*317.2*	*37.2%*	*21.8*	*2.71%*		*0.12*
Column J	*38*	*370*	*69*	*1760.8*	*345.4*	*38.1%*	*22.6*	*3.12%*		*0.12*
Column K	*38*	*475*	*77.5*	*1858.1*	*343.9*	*38.2%*	*19.5*	*2.91%*		*0.11*
Column L	*38*	*580*	*69.5*	*1711.1*	*316.3*	*38.6%*	*23.2*	*3.29%*		*0.11*
Column M	*38*	*685*	*73.5*	*1690.0*	*298.2*	*38.2%*	*15.4*	*3.50%*		*0.10*

Comments:

Column was intact with no cracking on removal from curing pipe.

Column Probing Force with Column Sample Locations:



Cone-Only & Sounding Bar Friction Test No. 7

Test Type:	S. Bar	Binder:	OP Cement		Mixing Date:	22/12/2013		Push-In Rate:	
Reference:	C-7-12.7-100	OPC Content:	150	*kg/m*^{3}	Test Date:	04/01/2014		15.7	*mm/sec*
Operator:	MT	Column Length:	740	*mm*	Test Time:	12.75	*days*	18.1	*mm/sec*
Column dia.	104*mm*	Sleech Layer:	160	*mm*	Mould Time:	12.93	*days*	ΔUCSxWTBR	8.9
Basin Height:	900*mm*	Average Temp:	285.9	°*C*	Column Time:	12.91	*days*		

65*mm* dia. Mould Sample Properties:

Mould Sample:	Curing Condition:	Raw *Sleech* MC, w_i	Organic Content:	Mixed MC, w_m	Length: *mm*	Density: *kg/m*^{3}	Uncorrected UCS, *kPa*	Stabilised MC, w_s	Stiffness E_{50} *MPa*	Failure Strain, ε_f
Mix 1R	Room	45.5%	3.1%	40.8%	128.5	1703.8	434.6	39.6%	53.6	2.13%
Mix 1T	20°C	45.5%	3.1%	40.8%	127.5	1712.6	497.5	39.5%	65.6	1.72%
Mix 1R (Tri)	Room	45.5%	3.1%	40.8%	129	1722.3	366.4	39.2%	45.8	1.67%

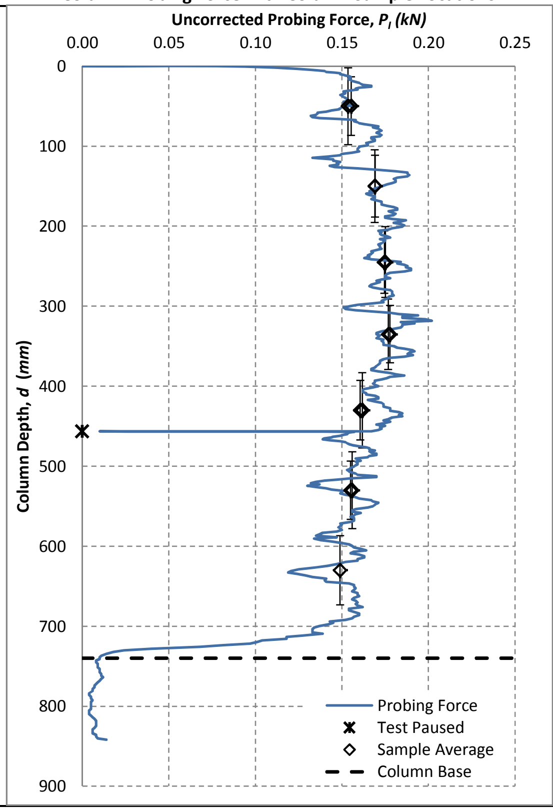
Column Sample Properties:

Column Sample Ref:	Sample dia. *mm*	Depth: *mm*	Length: *mm*	Density: *kg/m*^{3}	Uncorrected UCS, *kPa*	Stabilised MC, w_s	Stiffness E_{50} *MPa*	Failure Strain, ε_f	Reason to Exclude:	Probing Force, *kN*
Column A	50	50	96	1820.3	506.3	39.5%	47.4	1.94%	-	0.15
Column B	50	150	90.5	1860.6	526.6	39.5%	64.0	1.54%	-	0.17
Column C	50	245	88.5	1857.5	578.9	39.5%	71.9	1.51%	-	0.18
Column D	50	335	88	1870.3	611.9	38.9%	82.0	1.79%	-	0.18
Column E	50	430	94	1900.2	598.1	39.6%	107.1	1.70%	-	0.16
Column F	50	530	96	1853.6	582.7	39.5%	73.4	1.66%	-	0.16
Column G	50	630	86.5	1863.8	531.4	38.7%	35.6	2.20%	-	0.15
Column H	*38*	*50*	*73*	*1771.2*	*487.1*	*39.2%*	*45.9*	*1.68%*	Sample trimming issues	*0.16*
Column I	*38*	*150*	*77.5*	*1749.4*	*518.0*	*39.2%*	*68.7*	*1.44%*		*0.17*
Column J	*38*	*245*	*78*	*1798.0*	*568.6*	*39.4%*	*63.9*	*1.65%*		*0.17*
Column K	*38*	*335*	*71.5*	*1715.3*	*541.3*	*39.1%*	*68.1*	*1.57%*		*0.18*
Column L	*38*	*430*	*74.5*	*1714.6*	*523.1*	*38.7%*	*58.9*	*1.84%*		*0.16*
Column M	*38*	*530*	*73*	*1712.2*	*595.4*	*38.7%*	*66.3*	*1.98%*		*0.16*

Comments:

Column crack running near horizontally from 680mm to 700mm and no samples recovered from the base; column otherwise extracted in good condition. Stabilised material noted on the cone tip on extraction of the column.

Column Probing Force with Column Sample Locations:



E.10 Cone-Only Penetrometer & Sounding Bar Column Summary Statistics

PORT Wire Column Sample Summary Statistics:								
PIRT Reference:		C1	C2	C3	C4	C5	C6	C7
No. of Samples:		6	7	7	7	6	7	7
Binder Content (kg/m^3):		100	150	100	150	150	150	100
		Column Sample Density:						
Column Density ρ_{col}, kg/m^3	Maximum:	1796.4	1846.1	1762.2	1866.7	1915.9	1864.8	1900.2
	Minimum:	1666.4	1724.3	1691.2	1780.2	1849.4	1796.8	1820.3
	Range:	130.0	121.8	71.0	86.6	66.5	67.9	79.9
	Average:	1755.0	1783.3	1722.7	1814.8	1886.3	1834.3	1860.9
	St Dev:	49.9	41.5	29.0	30.2	25.8	26.9	23.6
	CoV:	2.8%	2.3%	1.7%	1.7%	1.4%	1.5%	1.3%
		Column Sample Strength:						
Column UCS q_{mol}, kPa	Maximum:	250.8	459.7	437.6	558.8	839.1	335.0	611.9
	Minimum:	195.0	311.7	337.3	447.5	755.8	263.5	506.3
	Range:	55.8	148.0	100.3	111.2	83.4	71.5	105.5
	Average:	226.6	389.8	390.9	506.9	788.2	301.0	562.3
	St Dev:	22.9	49.1	31.3	41.0	29.0	23.7	40.4
	CoV:	10.1%	12.6%	8.0%	8.1%	3.7%	7.9%	7.2%
		Column Sample Stiffness:						
Column Stiffness, E_{col}, MPa	Maximum:	31.1	44.2	55.8	107.4	97.9	29.9	107.1
	Minimum:	11.4	28.8	24.0	31.7	66.8	16.7	35.6
	Range:	19.7	15.4	31.7	75.7	31.1	13.2	71.5
	Average:	19.1	35.5	40.5	62.4	82.7	24.8	68.8
	St Dev:	8.0	6.4	11.9	23.3	11.6	5.5	23.3
	CoV:	42.1%	18.0%	29.3%	37.4%	14.1%	22.0%	33.9%

Appendix F: Exhumed Column Photographs & Cracking Diagrams

F.1 Exhumed PORT Column Photographs

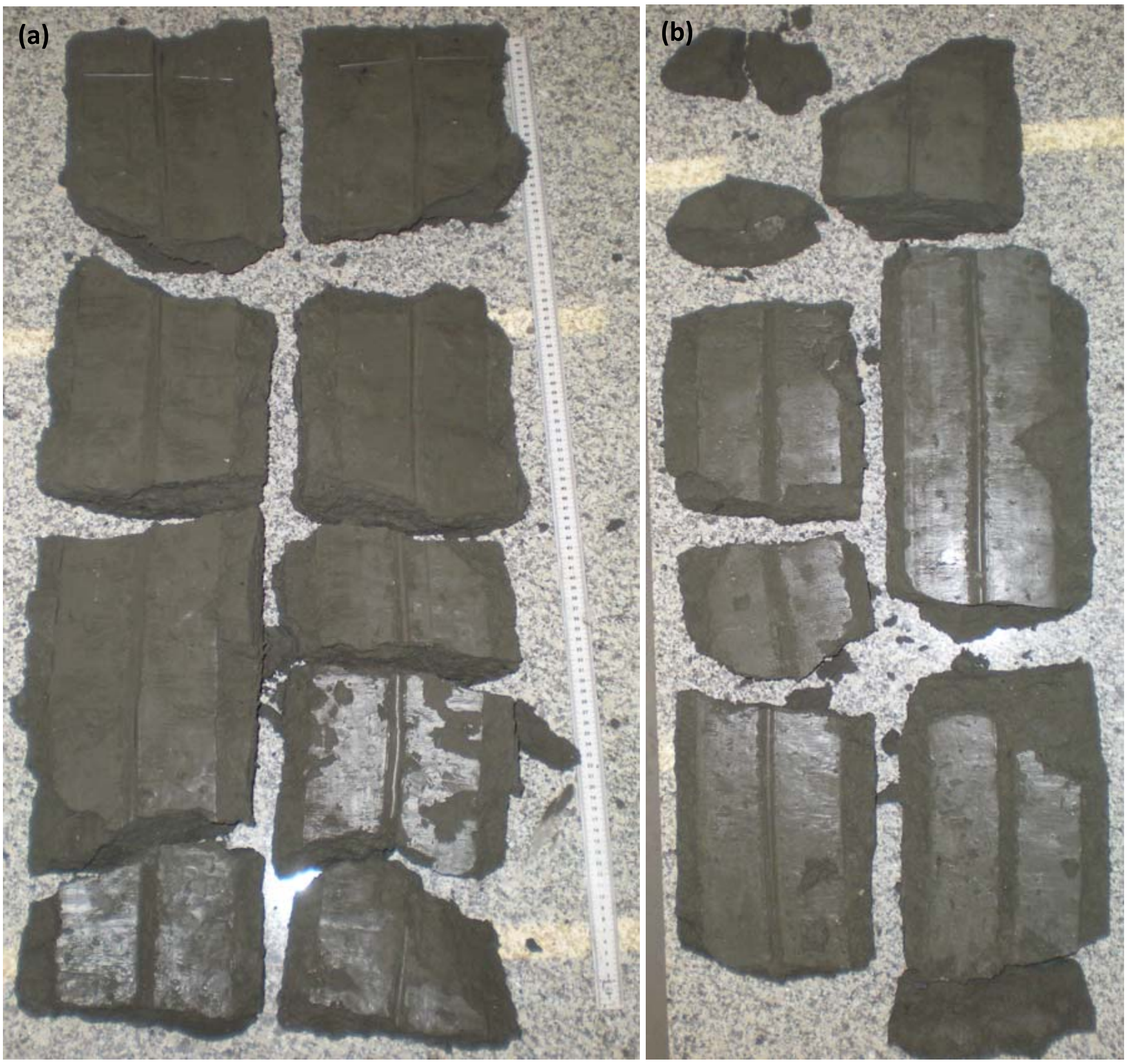


Figure F-1: PORT columns where good sampling numbers were achieved; a) PO-14S & b) PO-15

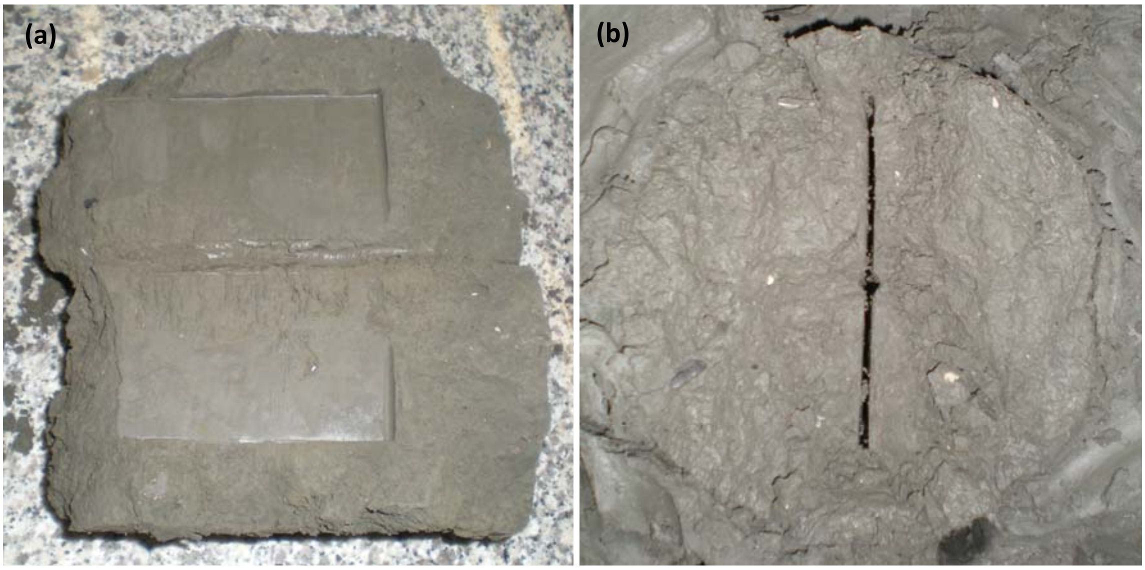


Figure F-2: a) Track of PORT penetrometer at the top of PO-9 & b) void left in the lower section of PO-14S following pull-out of the PORT penetrometer

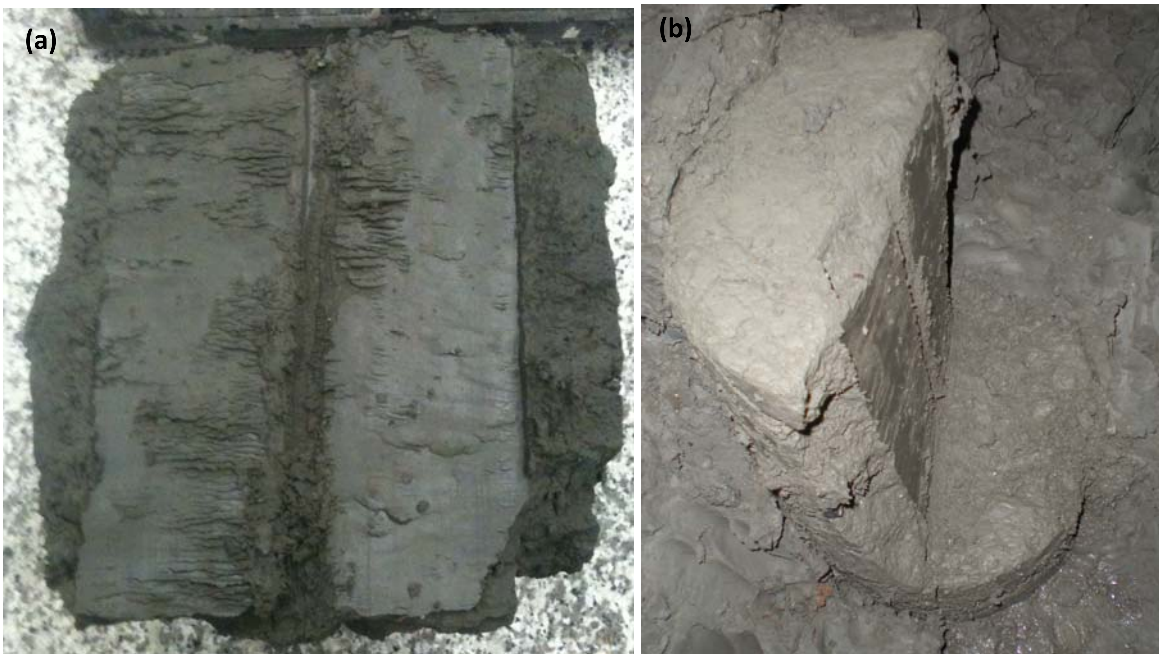


Figure F-3: a) Track of the PORT penetrometer in PO-4 & b) twisted path of PORT penetrometer in the upper section of PO-8

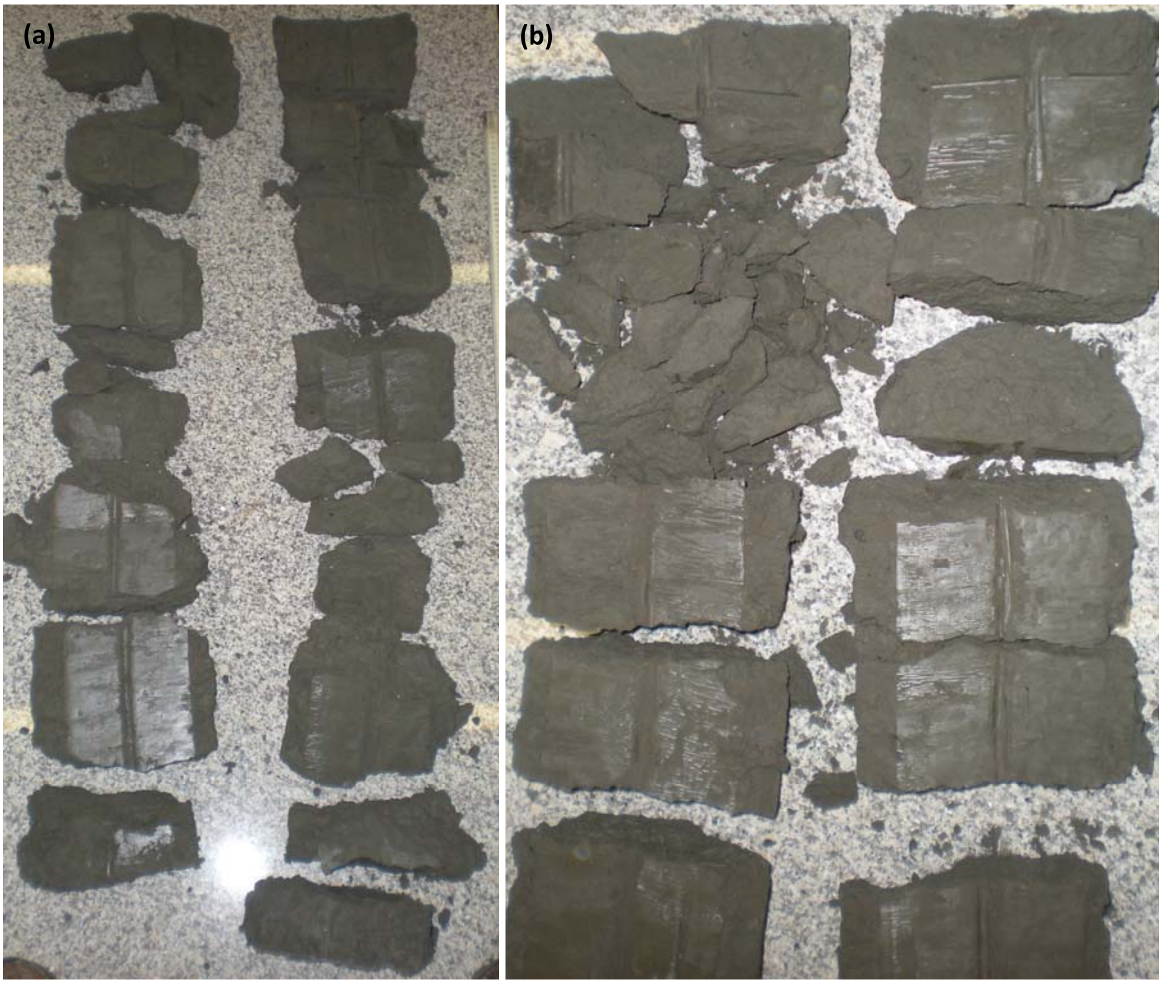


Figure F-4: Significant cracking in PO-7 (a) and in the upper section of PO-16 (b)


Figure F-5: Stone pulled up by the PORT penetrometer in PO-16

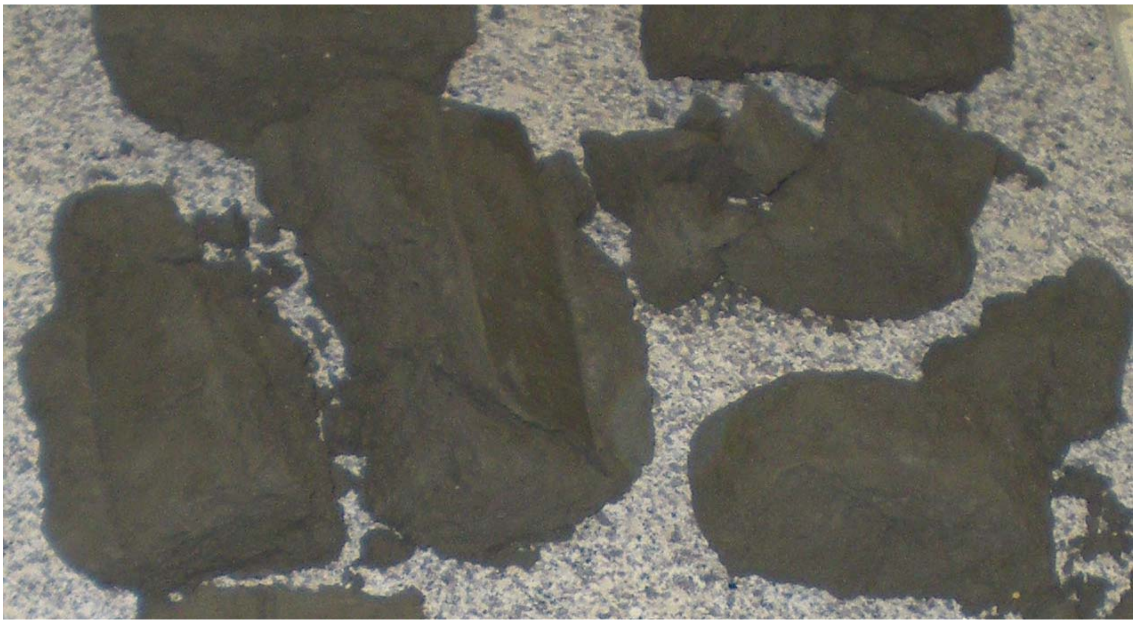
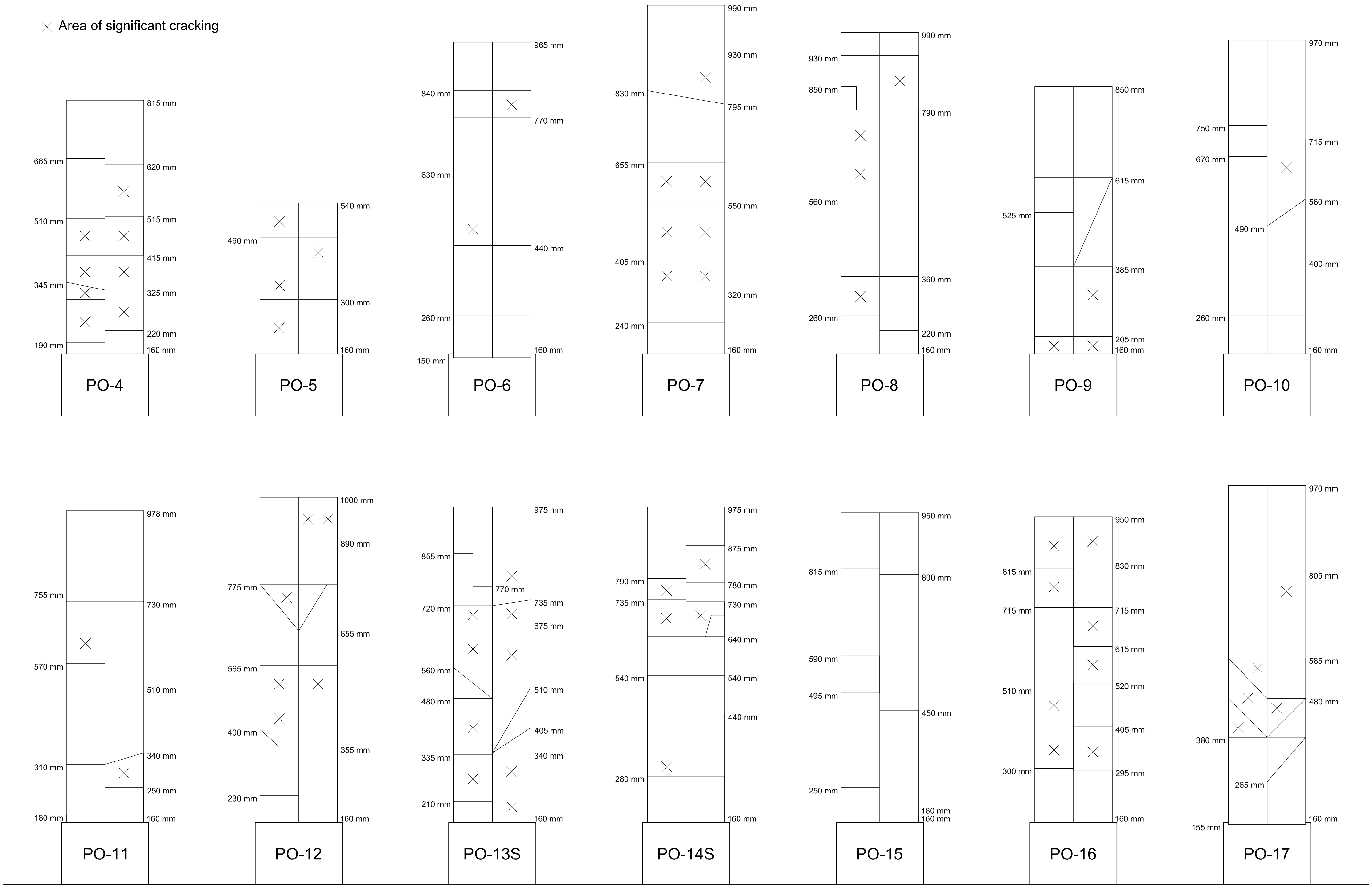


Figure F-6: Diagonal cracking in PO-9



F.2 Pull-Out Resistance Test Column Cracking Diagrams

F.3 PORT Wire Column Photographs

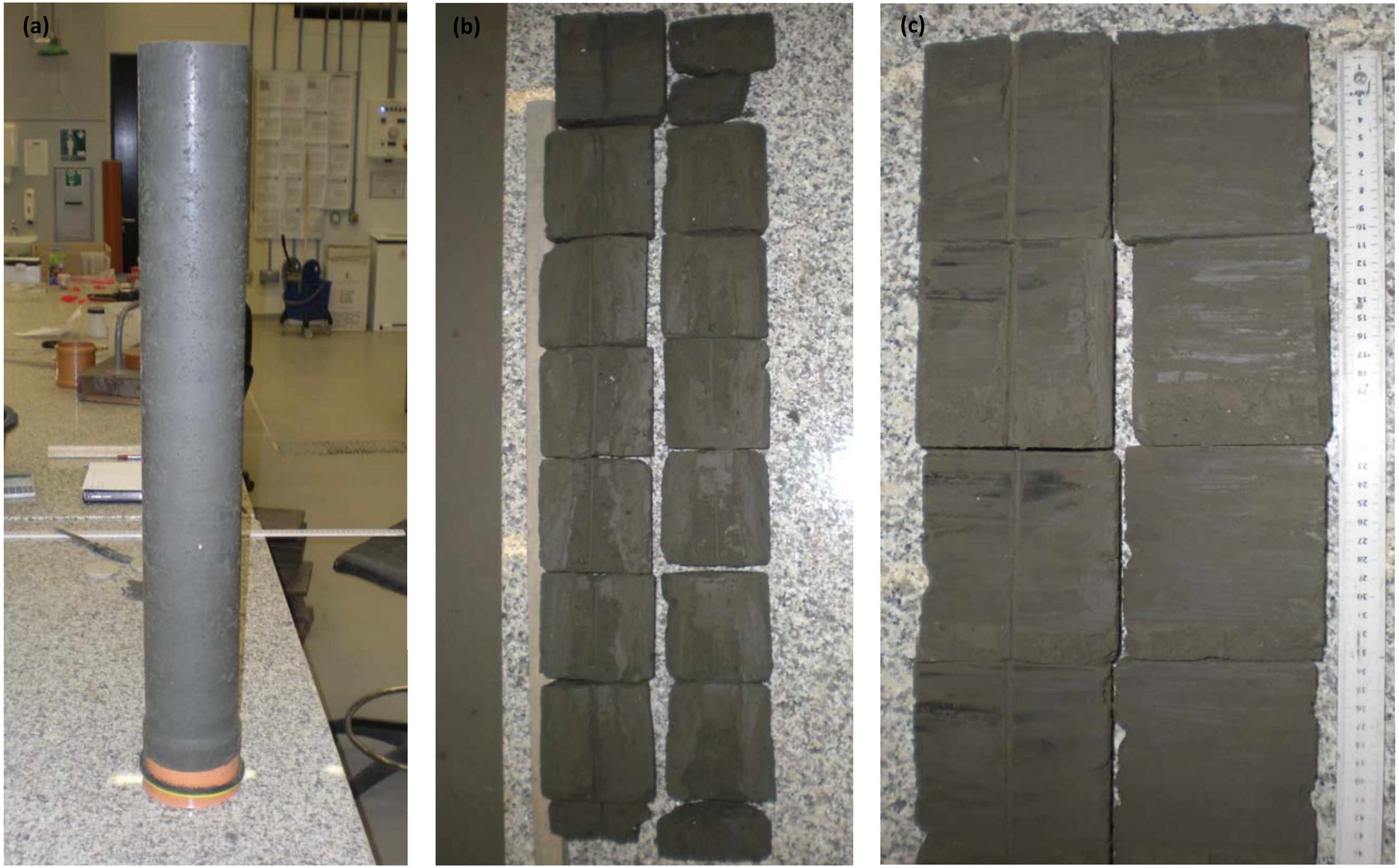


Figure F-7: PORT wire column; a) exhumed column W-3 following wire pull-out, b) column W-4 cut into sections for sampling & c) column W-5 showing the track of pull-out wire

F.4 Exhumed PIRT Column Photographs

Figure F-8: Extracted columns from which high sampling numbers were achieved; a) PI-13 & b) PI-14S

Figure F-9: Extracted PI-4 column before sampling. Diagonal cracking and bulging at the column base can be seen

Figure F-10: PIRT penetrometer at final location in PI-5 with stabilised *sleech* adhered to the penetrometer's wings

Figure F-11: Route taken by PIRT penetrometer in a soft column (PI-13). Track of a small stone can be seen on the right of the photograph

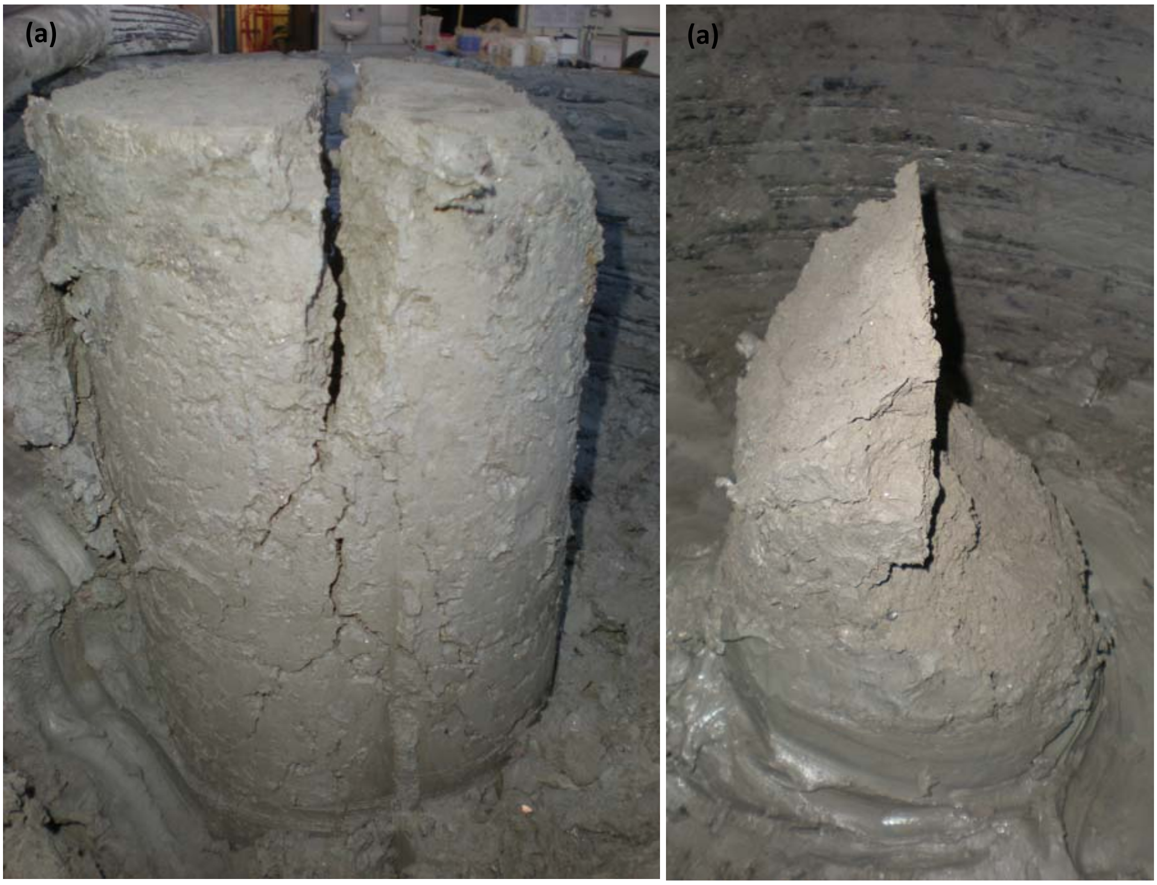


Figure F-12: Diagonal cracking noted during column extraction; a) in the upper section of PI-5 & b) in the mid-section of PI-10

Figure F-13: Left to right, diagonal crack, intentional cut made in the column (for extraction purposes) and horizontal crack at Mix 3-4 interface in PI-13

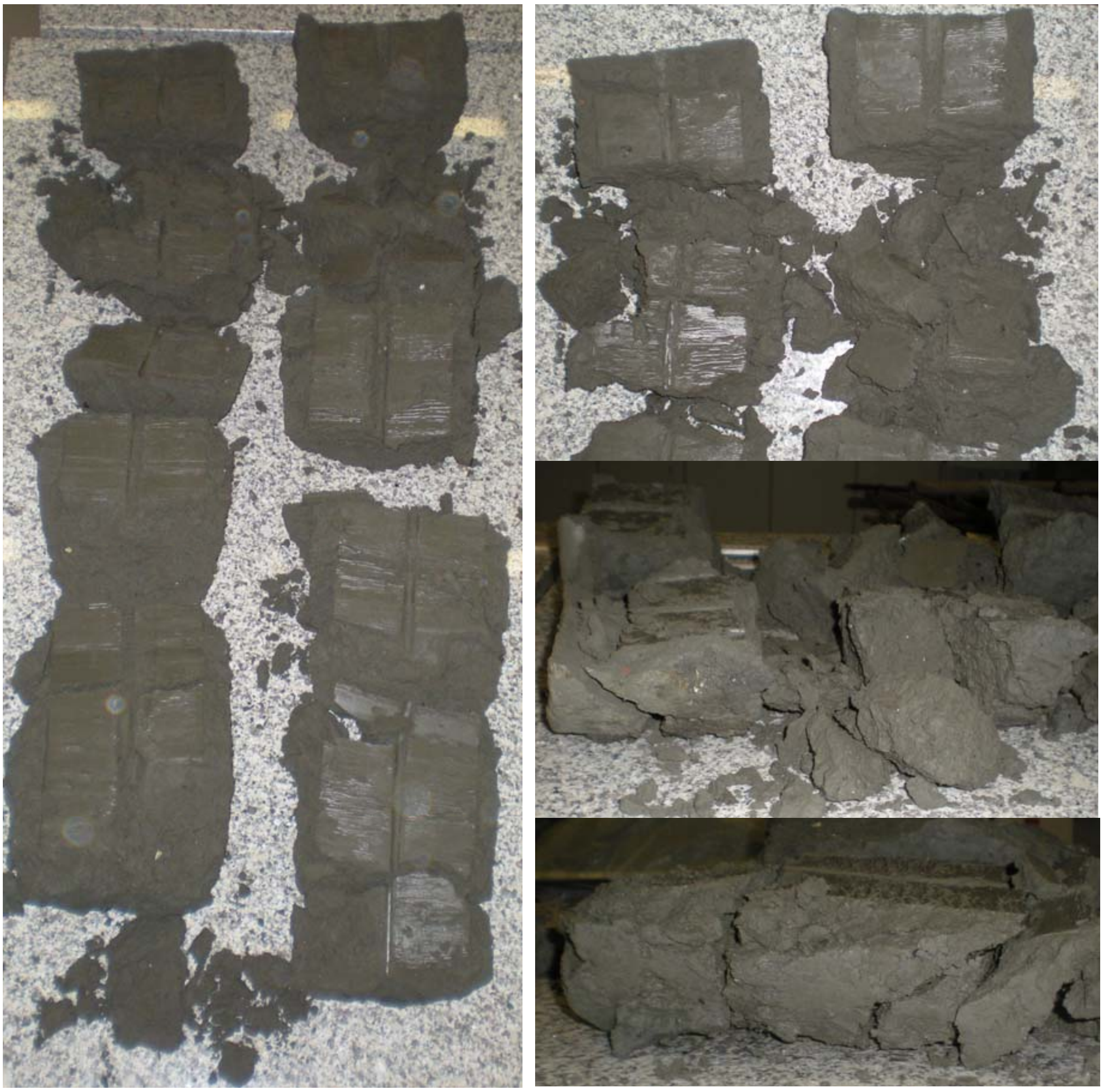
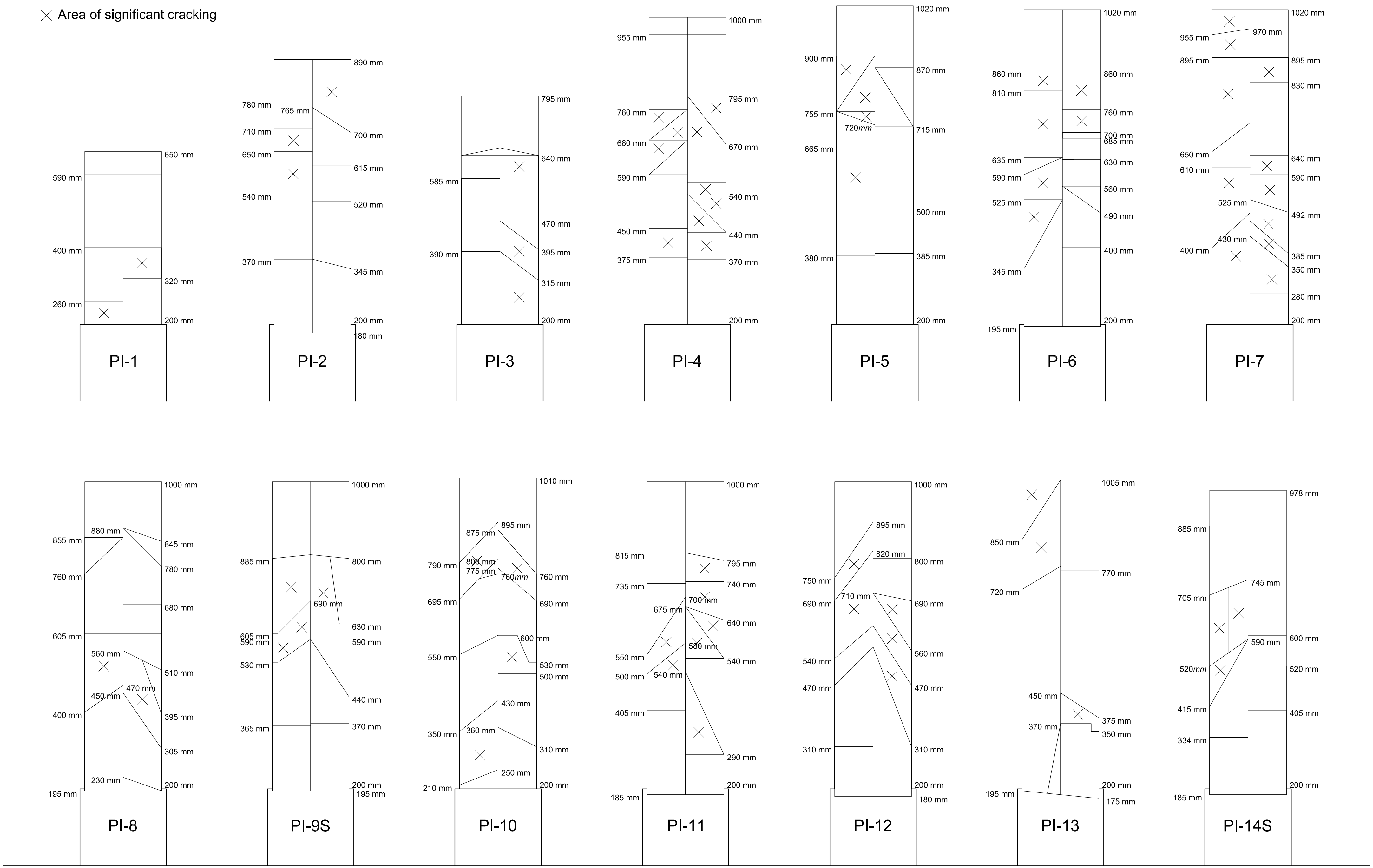


Figure F-14: Significant cracking resulting in poor sample numbers in PI-7



F.5 Push-In Resistance Test Column Cracking Diagrams

F.6 Cone-Only Penetrometer & Sounding Bar Column Photographs

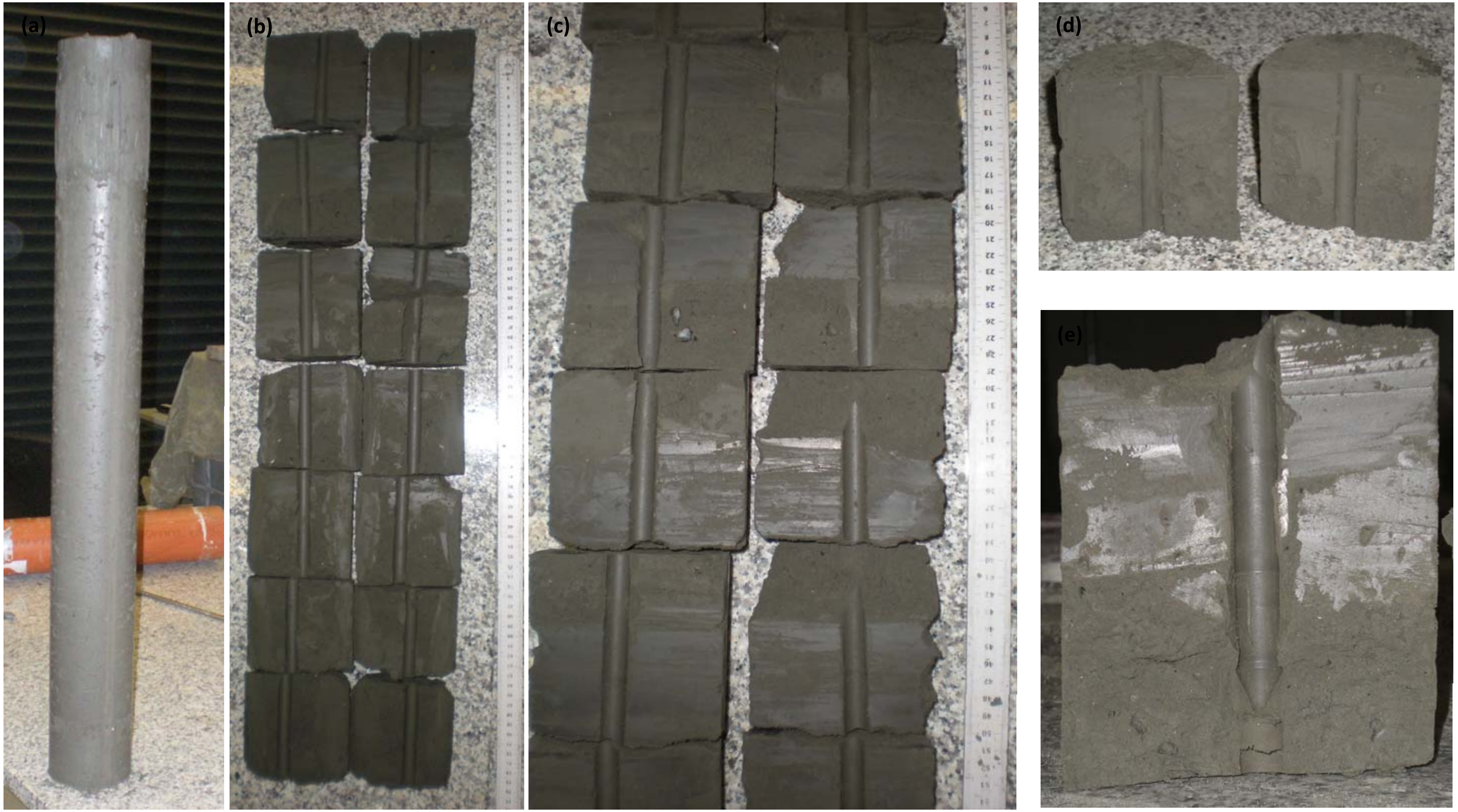


Figure F-15: Cone-only & sounding bar friction column: a) column C-2 following extraction from curing pipe, b) column C-6 cut into sections for sampling, c) column C-7 showing the guide hole and route taken by cone, d) 110 mm high sections from column C-1 & e) plug of stabilised soil noted in an initial test column

Appendix G: SPSS Statistical Analysis Outputs

G.1 SPSS Bivariate Correlation Tables

PORT Room Cured Mould Sample Correlations:

Correlations

		UCS	Time	Binder	Density	RawMC	Temp
UCS	Pearson Correlation	1	.490**	.659**	.000	.185	.201
	Sig. (2-tailed)		.000	.000	.999	.193	.158
	N	51	51	51	51	51	51
Time	Pearson Correlation	.490**	1	.282*	-.286*	.250	-.371**
	Sig. (2-tailed)	.000		.045	.042	.077	.007
	N	51	51	51	51	51	51
Binder	Pearson Correlation	.659**	.282*	1	-.069	.314*	-.082
	Sig. (2-tailed)	.000	.045		.630	.025	.569
	N	51	51	51	51	51	51
Density	Pearson Correlation	.000	-.286*	-.069	1	-.858**	.098
	Sig. (2-tailed)	.999	.042	.630		.000	.494
	N	51	51	51	51	51	51
RawMC	Pearson Correlation	.185	.250	.314*	-.858**	1	.011
	Sig. (2-tailed)	.193	.077	.025	.000		.937
	N	51	51	51	51	51	51
Temp	Pearson Correlation	.201	-.371**	-.082	.098	.011	1
	Sig. (2-tailed)	.158	.007	.569	.494	.937	
	N	51	51	51	51	51	51

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

PORT Column Correlations

Correlations

		UCS	Time	Binder	RawMC	Temp	Density	Depth
UCS	Pearson Correlation	1	.603**	.577**	.042	-.029	.187*	.167*
	Sig. (2-tailed)		.000	.000	.607	.722	.022	.040
	N	151	151	151	151	151	151	151
Time	Pearson Correlation	.603**	1	.297**	.246**	-.387**	.015	.113
	Sig. (2-tailed)	.000		.000	.002	.000	.859	.167
	N	151	151	151	151	151	151	151
Binder	Pearson Correlation	.577**	.297**	1	.338**	.040	-.102	-.010
	Sig. (2-tailed)	.000	.000		.000	.624	.212	.907
	N	151	151	151	151	151	151	151
RawMC	Pearson Correlation	.042	.246**	.338**	1	-.089	-.402**	.010
	Sig. (2-tailed)	.607	.002	.000		.275	.000	.907
	N	151	151	151	151	151	151	151
Temp	Pearson Correlation	-.029	-.387**	.040	-.089	1	-.259**	-.180*
	Sig. (2-tailed)	.722	.000	.624	.275		.001	.027
	N	151	151	151	151	151	151	151
Density	Pearson Correlation	.187*	.015	-.102	-.402**	-.259**	1	.069
	Sig. (2-tailed)	.022	.859	.212	.000	.001		.397
	N	151	151	151	151	151	151	151
Depth	Pearson Correlation	.167*	.113	-.010	.010	-.180*	.069	1
	Sig. (2-tailed)	.040	.167	.907	.907	.027	.397	
	N	151	151	151	151	151	151	151

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

PIRT 20C Cured Mould Sample Correlations

Correlations

		UCS	Time	Binder	Raw	Density	Organics
UCS	Pearson Correlation	1	.722**	.755**	.408**	.067	.020
	Sig. (2-tailed)		.000	.000	.007	.669	.899
	N	43	43	43	43	43	43
Time	Pearson Correlation	.722**	1	.347*	.534**	-.124	.260
	Sig. (2-tailed)	.000		.023	.000	.428	.092
	N	43	43	43	43	43	43
Binder	Pearson Correlation	.755**	.347*	1	.200	.339*	-.100
	Sig. (2-tailed)	.000	.023		.199	.026	.523
	N	43	43	43	43	43	43
Raw	Pearson Correlation	.408**	.534**	.200	1	-.590**	.204
	Sig. (2-tailed)	.007	.000	.199		.000	.190
	N	43	43	43	43	43	43
Density	Pearson Correlation	.067	-.124	.339*	-.590**	1	-.101
	Sig. (2-tailed)	.669	.428	.026	.000		.520
	N	43	43	43	43	43	43
Organics	Pearson Correlation	.020	.260	-.100	.204	-.101	1
	Sig. (2-tailed)	.899	.092	.523	.190	.520	
	N	43	43	43	43	43	43

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

PIRT Column Correlations

Correlations

		UCS	Time	Binder	RawMC	Temp	Density	Depth	Organic
UCS	Pearson Correlation	1	.857**	.732**	.511**	-.380**	-.137	-.087	.086
	Sig. (2-tailed)		.000	.000	.000	.000	.096	.293	.296
	N	149	149	149	149	149	149	149	149
Time	Pearson Correlation	.857**	1	.479**	.535**	-.468**	-.060	-.080	.183*
	Sig. (2-tailed)	.000		.000	.000	.000	.467	.333	.026
	N	149	149	149	149	149	149	149	149
Binder	Pearson Correlation	.732**	.479**	1	.263**	-.112	-.145	-.162*	-.055
	Sig. (2-tailed)	.000	.000		.001	.174	.078	.049	.502
	N	149	149	149	149	149	149	149	149
RawMC	Pearson Correlation	.511**	.535**	.263**	1	-.403**	-.383**	-.060	.112
	Sig. (2-tailed)	.000	.000	.001		.000	.000	.470	.176
	N	149	149	149	149	149	149	149	149
Temp	Pearson Correlation	-.380**	-.468**	-.112	-.403**	1	-.022	-.040	-.177*
	Sig. (2-tailed)	.000	.000	.174	.000		.793	.630	.030
	N	149	149	149	149	149	149	149	149
Density	Pearson Correlation	-.137	-.060	-.145	-.383**	-.022	1	.051	-.071
	Sig. (2-tailed)	.096	.467	.078	.000	.793		.538	.389
	N	149	149	149	149	149	149	149	149
Depth	Pearson Correlation	-.087	-.080	-.162*	-.060	-.040	.051	1	.634**
	Sig. (2-tailed)	.293	.333	.049	.470	.630	.538		.000
	N	149	149	149	149	149	149	149	149
Organic	Pearson Correlation	.086	.183*	-.055	.112	-.177*	-.071	.634**	1
	Sig. (2-tailed)	.296	.026	.502	.176	.030	.389	.000	
	N	149	149	149	149	149	149	149	149

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

PIRT Room Cured Mould Sample Correlations

Correlations

		UCS	Time	Binder	Density	Raw	LabTemperature	Organics
UCS	Pearson Correlation	1	.807**	.730**	.042	.436**	-.102	.058
	Sig. (2-tailed)		.000	.000	.791	.004	.518	.718
	N	42	42	42	42	42	42	42
Time	Pearson Correlation	.807**	1	.352*	-.037	.560**	-.370*	.262
	Sig. (2-tailed)	.000		.022	.815	.000	.016	.093
	N	42	42	42	42	42	42	42
Binder	Pearson Correlation	.730**	.352*	1	.245	.177	-.132	-.107
	Sig. (2-tailed)	.000	.022		.118	.261	.403	.500
	N	42	42	42	42	42	42	42
Density	Pearson Correlation	.042	-.037	.245	1	-.600**	.093	-.129
	Sig. (2-tailed)	.791	.815	.118		.000	.560	.417
	N	42	42	42	42	42	42	42
Raw	Pearson Correlation	.436**	.560**	.177	-.600**	1	-.463**	.197
	Sig. (2-tailed)	.004	.000	.261	.000		.002	.211
	N	42	42	42	42	42	42	42
LabTemperature	Pearson Correlation	-.102	-.370*	-.132	.093	-.463**	1	-.193
	Sig. (2-tailed)	.518	.016	.403	.560	.002		.222
	N	42	42	42	42	42	42	42
Organics	Pearson Correlation	.058	.262	-.107	-.129	.197	-.193	1
	Sig. (2-tailed)	.718	.093	.500	.417	.211	.222	
	N	42	42	42	42	42	42	42

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

G.2 PIRT Room-Cured Mould SPSS Models

PIRT Room-Cured Mixed Model Analysis:
Model 1; UCS with Time & Binder Content

Descriptive Statistics

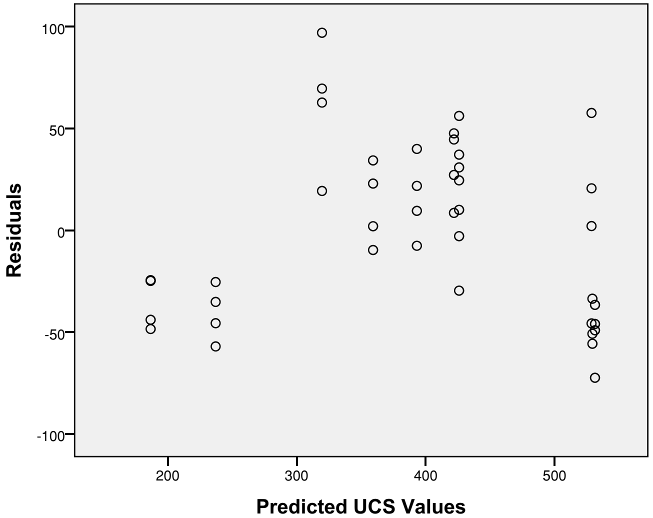
	Count	Mean	Standard Deviation	Coefficient of Variation
UCS	42	392.361	119.0733	30.3%
Time	42	6.7918	4.49614	66.2%
Binder	42	128.571	28.4623	22.1%

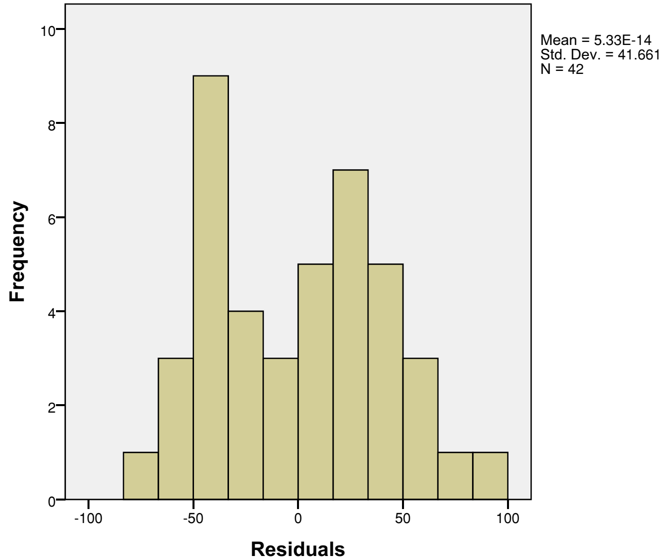
Totals that are aggregated over either a single category of a variable or a split file variable are omitted.

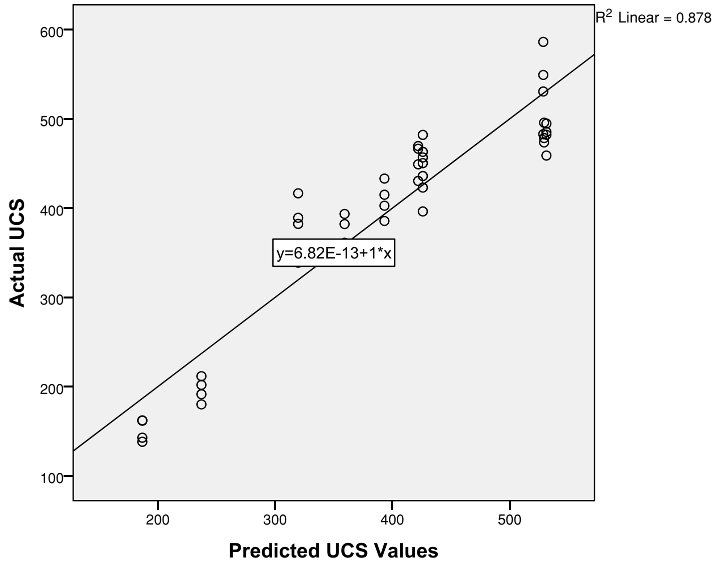
Estimates of Fixed Effects[a]

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	5.891137	30.852334	39	.191	.850	-56.513599	68.295873
Time	16.625351	1.585260	39	10.487	.000	13.418859	19.831842
Binder	2.127646	.250421	39	8.496	.000	1.621122	2.634169

a. Dependent Variable: UCS.







PIRT Room-Cured Mixed Model Analysis:
Model 2; Ln(UCS) with Ln(Time) & Binder Content

Descriptive Statistics

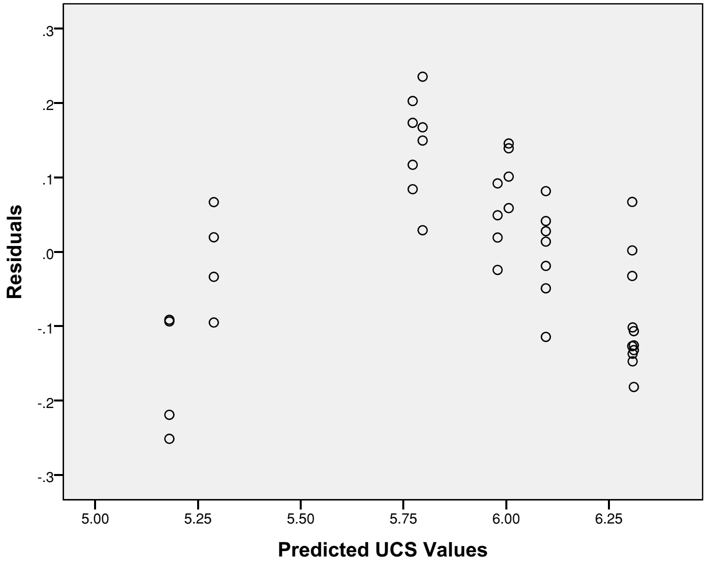
	Count	Mean	Standard Deviation	Coefficient of Variation
Ln_UCS	42	5.9085	.39602	6.7%
Ln_Time	42	1.6044	.88847	55.4%
Binder	42	128.571	28.4623	22.1%

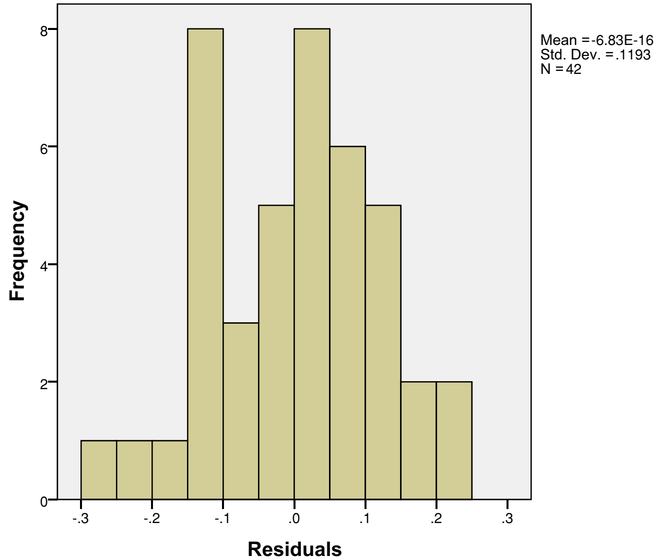
Totals that are aggregated over either a single category of a variable or a split file variable are omitted.

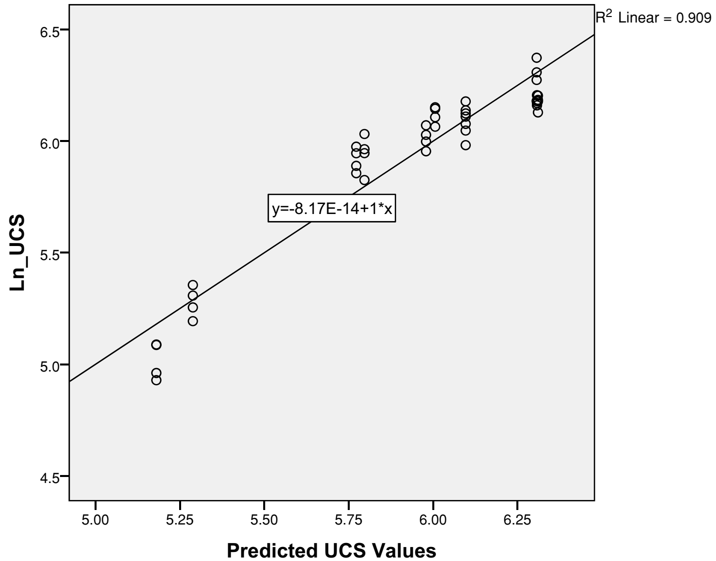
Estimates of Fixed Effects[a]

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	4.656711	.088582	39	52.570	.000	4.477538	4.835885
Binder	.006002	.000760	39	7.892	.000	.004463	.007540
Ln_Time	.299236	.024362	39	12.283	.000	.249958	.348513

a. Dependent Variable: Ln_UCS.







PIRT Room-Cured Mixed Model Analysis:
Model 3; Ln(UCS) with Ln(Time), Binder Content & Raw Moisture Content

Descriptive Statistics

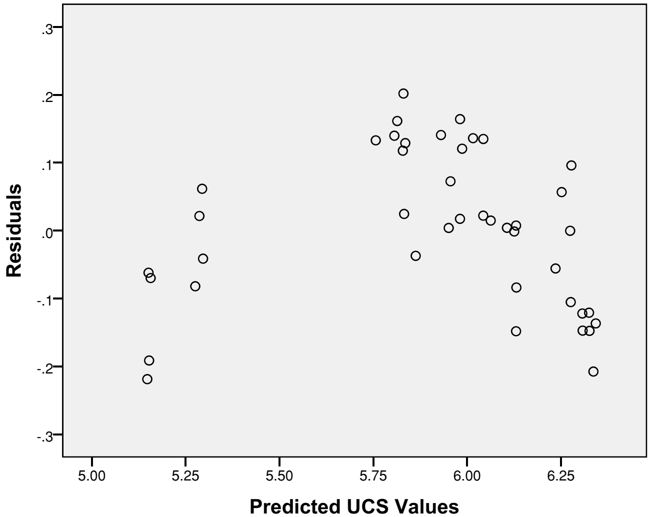
	Count	Mean	Standard Deviation	Coefficient of Variation
Ln_UCS	42	5.9085	.39602	6.7%
Ln_Time	42	1.6044	.88847	55.4%
Binder	42	128.571	28.4623	22.1%
Raw	42	.48616	.033071	6.8%

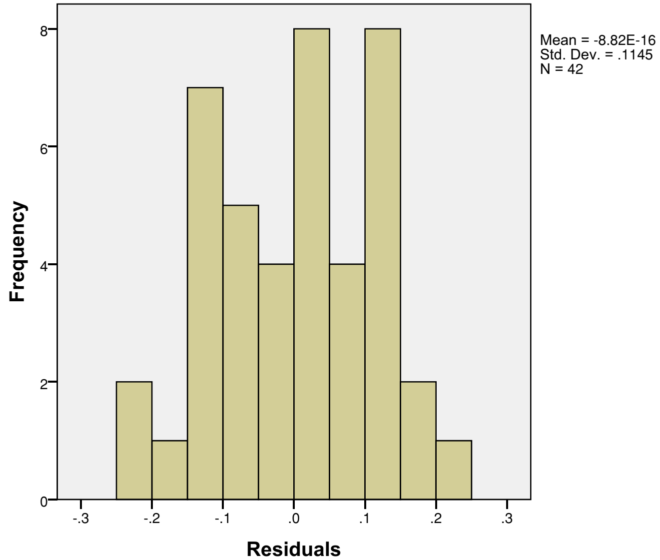
Totals that are aggregated over either a single category of a variable or a split file variable are omitted.

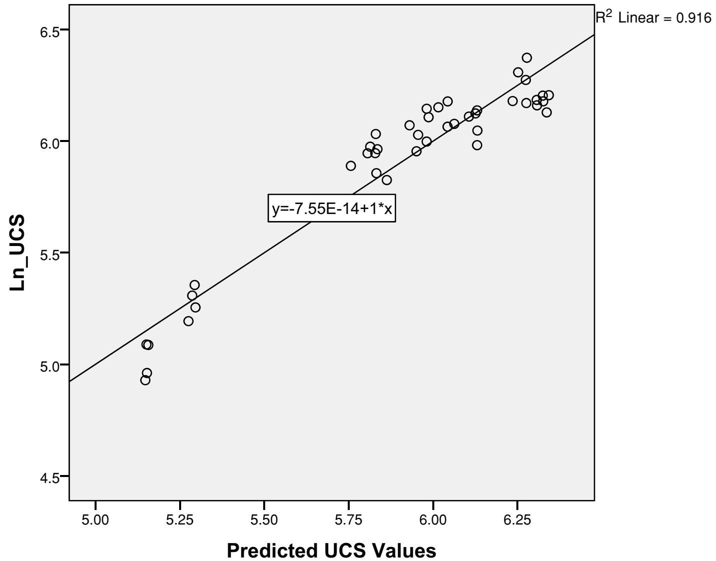
Estimates of Fixed Effects[a]

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	5.204541	.315451	38	16.499	.000	4.565945	5.843137
Binder	.005897	.000742	38	7.951	.000	.004395	.007398
Ln_Time	.322908	.027074	38.000	11.927	.000	.268100	.377716
Raw	-1.177193	.652098	38	-1.805	.079	-2.497297	.142911

a. Dependent Variable: Ln_UCS.







PIRT Room-Cured Mixed Model Analysis:
Model 4; Ln(UCS) with Ln(Time), Binder Content, Raw Moisture Content & Temperature

Descriptive Statistics

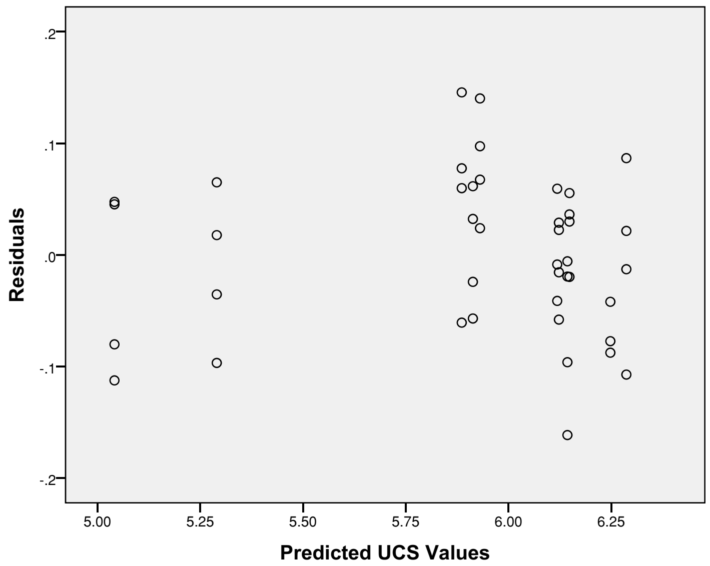
	Count	Mean	Standard Deviation	Coefficient of Variation
Ln_UCS	42	5.9085	.39602	6.7%
Ln_Time	42	1.6044	.88847	55.4%
Binder	42	128.571	28.4623	22.1%
Temp	42	18.154	.6540	3.6%

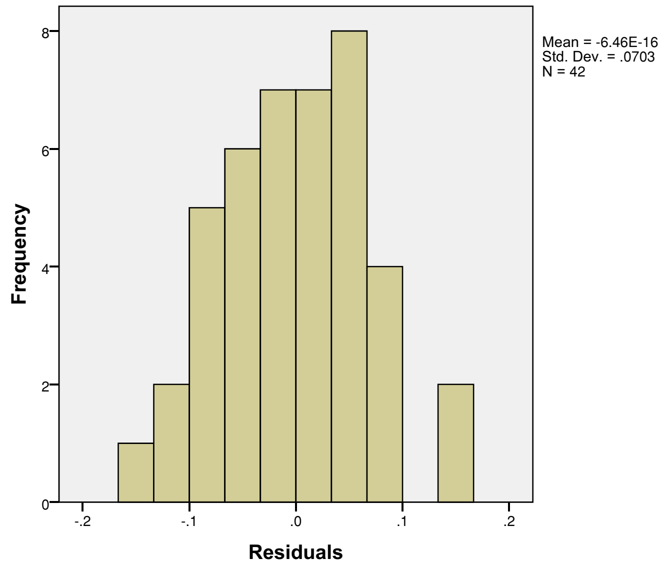
Totals that are aggregated over either a single category of a variable or a split file variable are omitted.

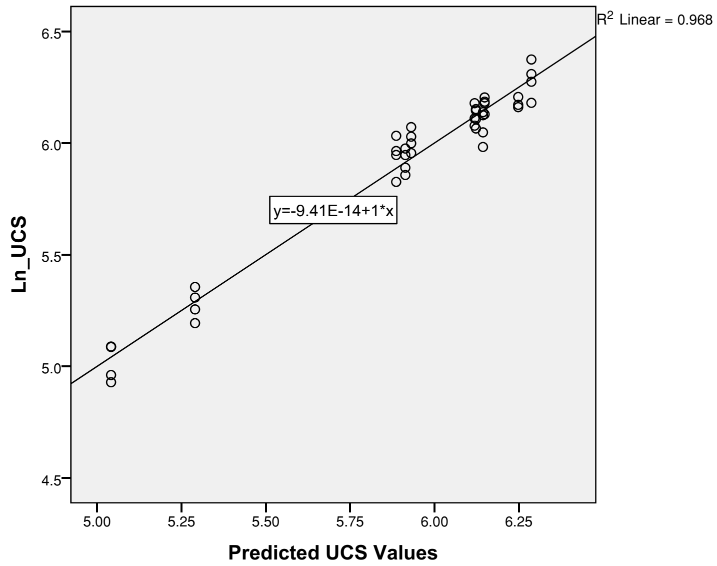
Estimates of Fixed Effects[a]

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Intercept	1.827734	.339075	38	5.390	.000	1.141312	2.514155
Binder	.006025	.000454	38	13.266	.000	.005106	.006944
Ln_Time	.329341	.014980	38.000	21.986	.000	.299016	.359666
Temp	.153005	.018114	38	8.447	.000	.116335	.189676

a. Dependent Variable: Ln_UCS.







PIRT Room-Cured Mixed Model Analysis:
Model 5; Ln(UCS) with Ln(Time), Binder Content, Raw Moisture Content & Temperature

Descriptive Statistics

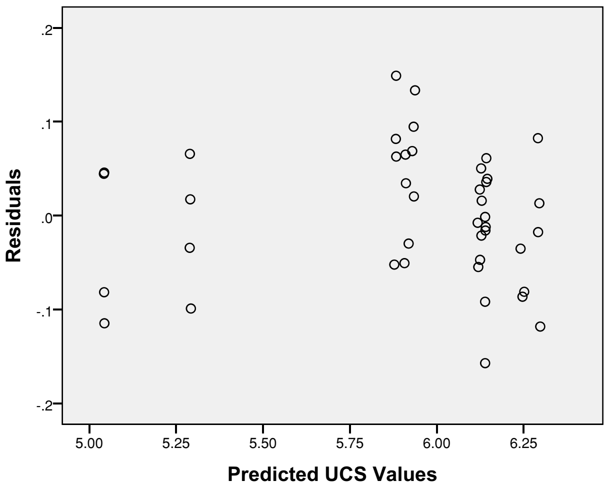
	Count	Mean	Standard Deviation	Coefficient of Variation
Ln_UCS	42	5.9085	.39602	6.7%
Ln_Time	42	1.6044	.88847	55.4%
Binder	42	128.571	28.4623	22.1%
Raw	42	.48616	.033071	6.8%
LabTemperature	42	18.154	.6540	3.6%

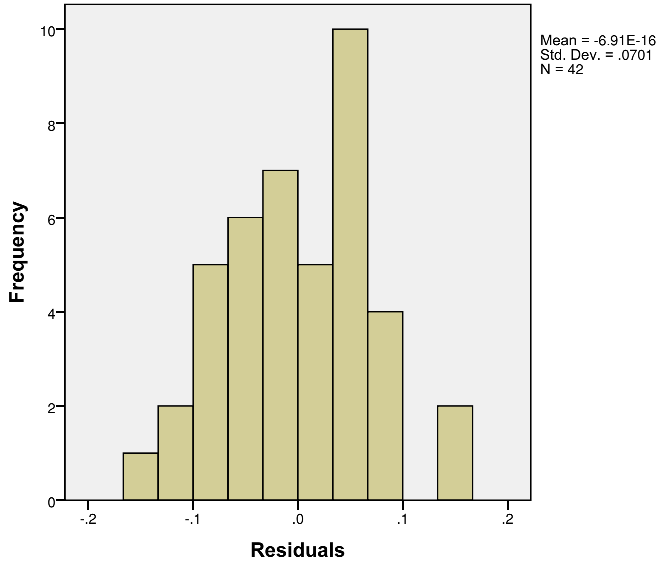
Totals that are aggregated over either a single category of a variable or a split file variable are omitted.

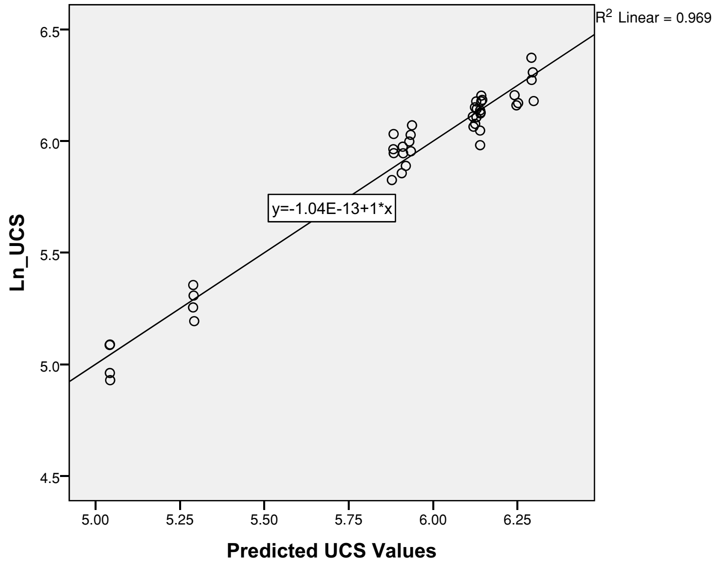
Estimates of Fixed Effects[a]

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	1.679050	.490262	37.000	3.425	.002	.685686	2.672415
Binder	.006042	.000461	37	13.108	.000	.005108	.006976
Ln_Time	.326238	.016818	37.000	19.398	.000	.292161	.360315
Temp	.156341	.019930	37	7.844	.000	.115959	.196724
Raw	.186954	.440716	37	.424	.674	-.706020	1.079929

a. Dependent Variable: Ln_UCS.







PIRT Room-Cured Mixed Model Analysis:
Model 6; Ln(UCS) with Ln(Time), Binder Content, Raw Moisture Content Temperature & Dens

Descriptive Statistics

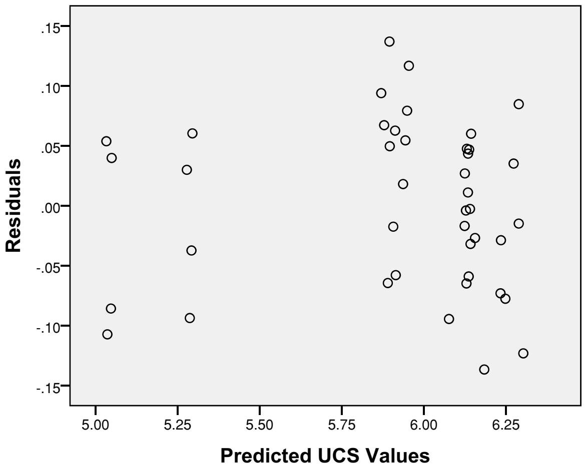
	Count	Mean	Standard Deviation	Coefficient of Variation
Ln_UCS	42	5.9085	.39602	6.7%
Ln_Time	42	1.6044	.88847	55.4%
Binder	42	128.571	28.4623	22.1%
Raw	42	.48616	.033071	6.8%
LabTemperature	42	18.154	.6540	3.6%
Density	42	1687.570	25.0423	1.5%

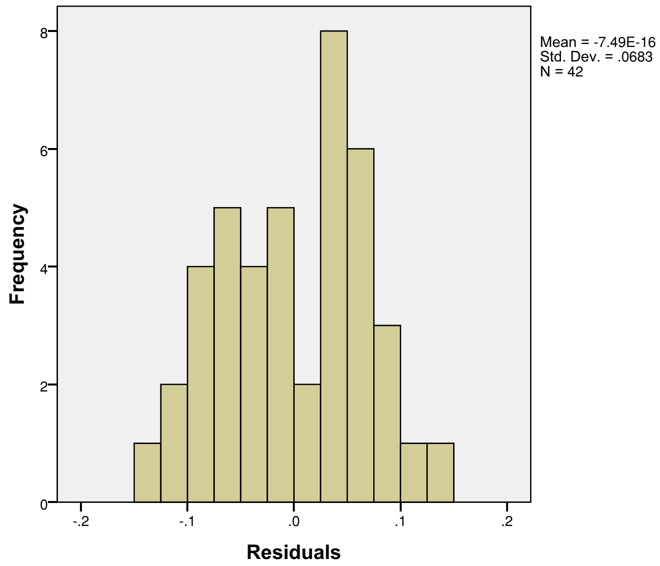
Totals that are aggregated over either a single category of a variable or a split file variable are omitted.

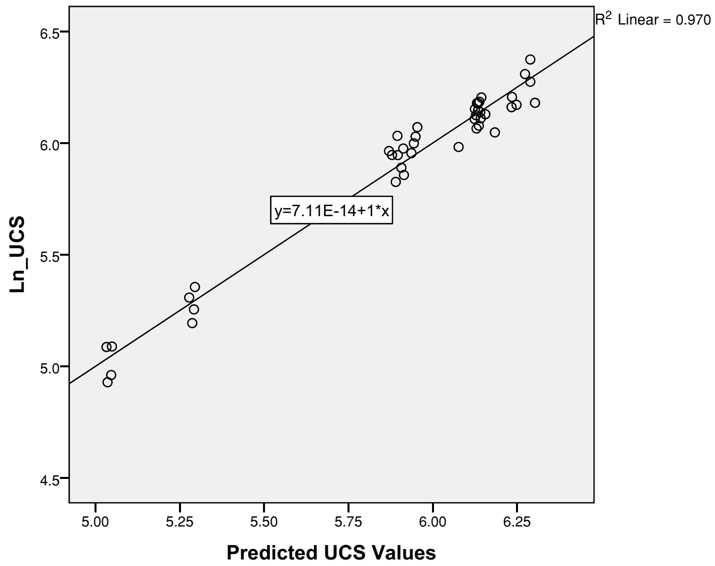
Estimates of Fixed Effects[a]

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	3.688955	1.528269	36.000	2.414	.021	.589481	6.788428
Binder	.006253	.000480	36.000	13.028	.000	.005279	.007226
Ln_Time	.333090	.017332	36.000	19.218	.000	.297940	.368241
Temp	.148785	.020426	36	7.284	.000	.107359	.190212
Raw	-.439260	.627266	36.000	-.700	.488	-1.711415	.832895
Density	-.000952	.000686	36.000	-1.387	.174	-.002344	.000440

a. Dependent Variable: Ln_UCS.







PIRT Room-Cured Mixed Model Analysis:
Model 8; Ln(UCS) with Ln(Time), Binder Content, Raw Moisture Content Temperature, Density & Organics

Descriptive Statistics

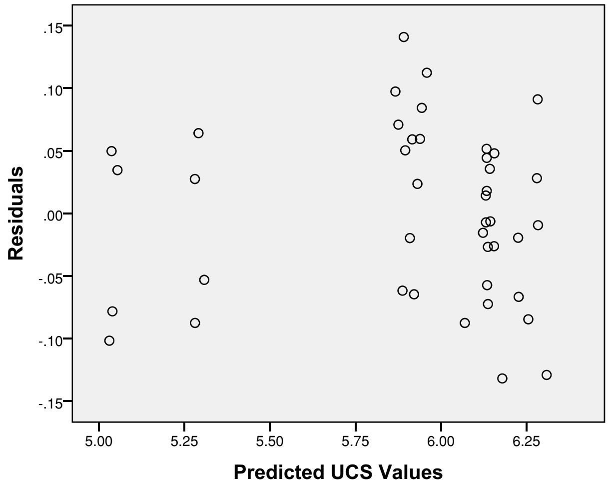
	Count	Mean	Standard Deviation	Coefficient of Variation
Ln_UCS	42	5.9085	.39602	6.7%
Ln_Time	42	1.6044	.88847	55.4%
Binder	42	128.571	28.4623	22.1%
Raw	42	.48616	.033071	6.8%
Temp	42	18.154	.6540	3.6%
Density	42	1687.570	25.0423	1.5%
Organics	42	3.174	.6603	20.8%

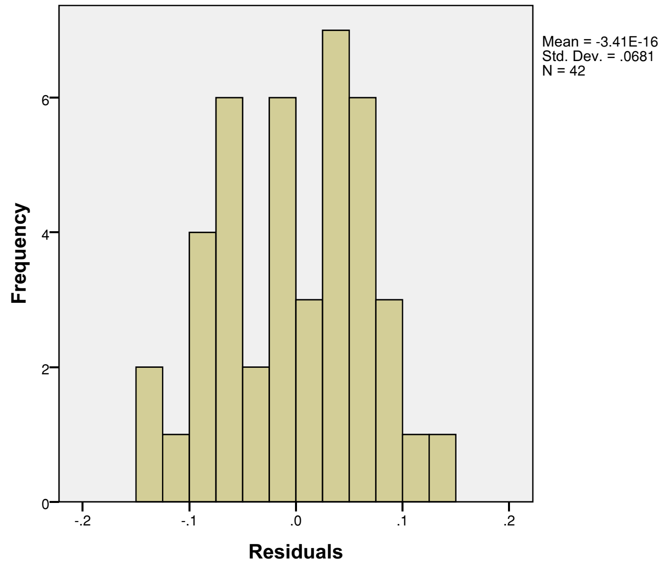
Totals that are aggregated over either a single category of a variable or a split file variable are omitted.

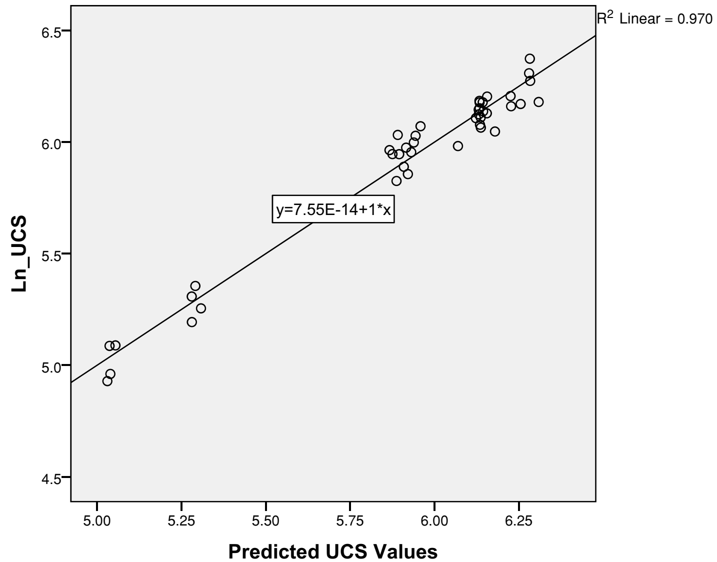
Estimates of Fixed Effects[a]

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	3.627110	1.547880	35.000	2.343	.025	.484747	6.769473
Binder	.006302	.000493	35	12.774	.000	.005300	.007303
Ln_Time	.331805	.017668	35.000	18.780	.000	.295936	.367673
Temp	.150164	.020790	35	7.223	.000	.107958	.192370
Raw	-.453216	.634089	35.000	-.715	.480	-1.740484	.834052
Density	-.000947	.000693	35.000	-1.366	.181	-.002355	.000461
Organics	.009825	.018286	35	.537	.594	-.027297	.046948

a. Dependent Variable: Ln_UCS.







PIRT Room-Cured Mixed Model Analysis:
Model 7; Ln(UCS) with Ln(Time), Binder Content, Raw Moisture Content Temperature & Density
Includes Raw Moisture Content-Density Interaction

Descriptive Statistics

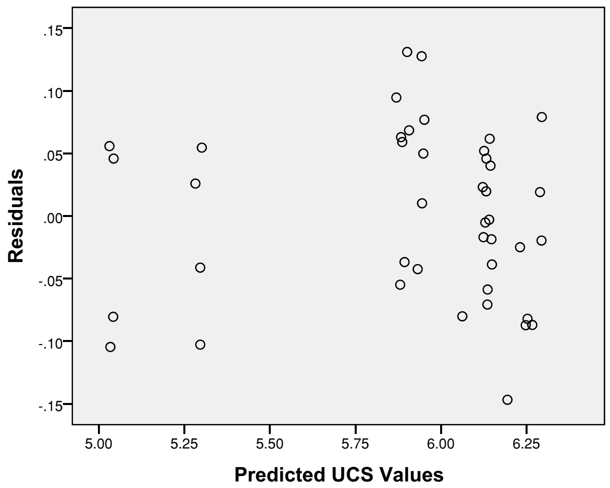
	Count	Mean	Standard Deviation	Coefficient of Variation
Ln_UCS	42	5.9085	.39602	6.7%
Ln_Time	42	1.6044	.88847	55.4%
Binder	42	128.571	28.4623	22.1%
Raw	42	.48616	.033071	6.8%
Temp	42	18.154	.6540	3.6%
Density	42	1687.570	25.0423	1.5%

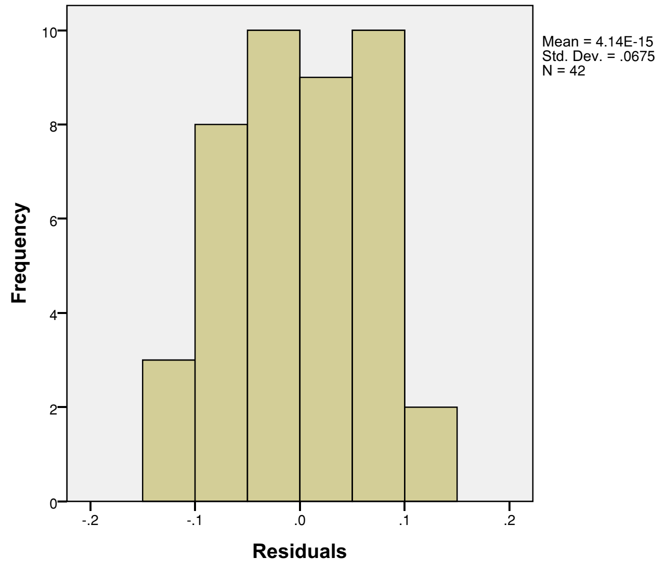
Totals that are aggregated over either a single category of a variable or a split file variable are omitted.

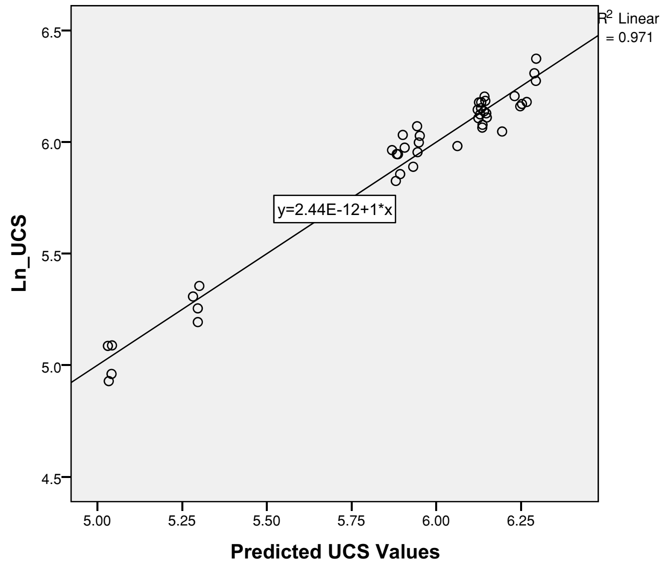
Estimates of Fixed Effects[a]

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	16.402660	14.102292	35.000	1.163	.253	-12.226507	45.031841
Binder	.006348	.000492	35.000	12.890	.000	.005348	.007348
Ln_Time	.329859	.017736	35.000	18.598	.000	.293853	.365866
Temp	.160807	.024393	35.000	6.592	.000	.111287	.210327
Raw	-27.802250	30.178464	35.000	-.921	.363	-89.067791	33.463285
Density	-.008698	.008569	35.000	-1.015	.317	-.026095	.008698
Raw*Density	.016387	.018069	35.000	.907	.371	-.020296	.053070

a. Dependent Variable: Ln_UCS.







PIRT Room-Cured Mixed Model Analysis:

Model 9; Ln(UCS) with Ln(Time), Binder Content, Raw Moisture Content, Temperature, Density & Organics. Includes Raw Moisture Content-Density Interaction

Descriptive Statistics

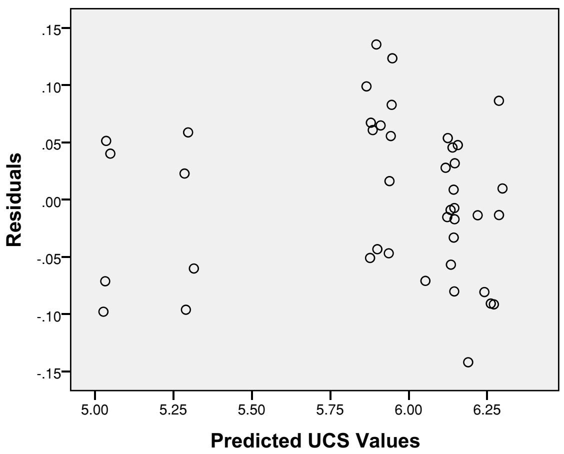
	Count	Mean	Standard Deviation	Coefficient of Variation
Ln_UCS	42	5.9085	.39602	6.7%
Ln_Time	42	1.6044	.88847	55.4%
Binder	42	128.571	28.4623	22.1%
Raw	42	.48616	.033071	6.8%
LabTemperature	42	18.154	.6540	3.6%
Density	42	1687.570	25.0423	1.5%
Organics	42	3.174	.6603	20.8%

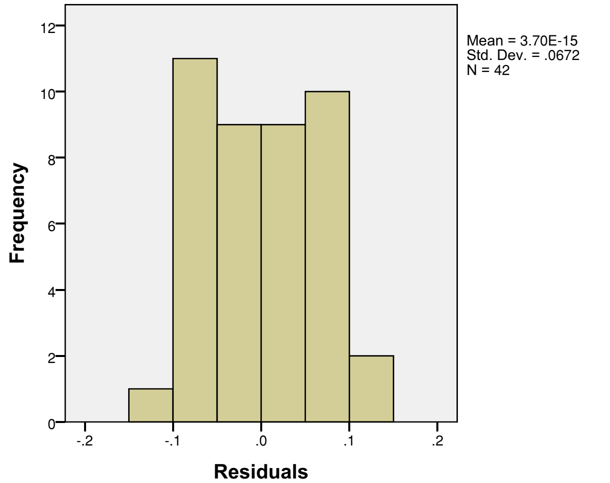
Totals that are aggregated over either a single category of a variable or a split file variable are omitted.

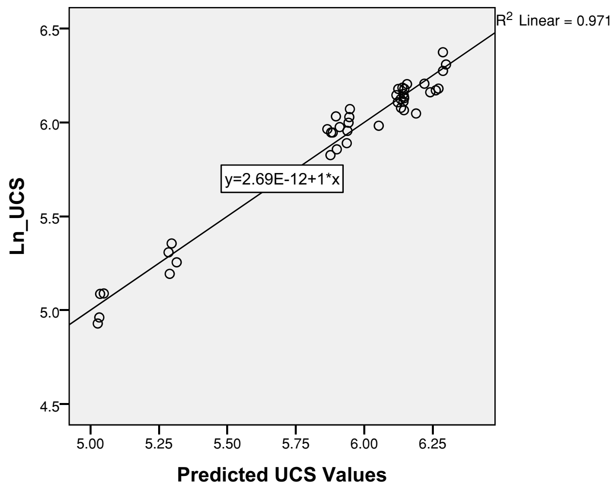
Estimates of Fixed Effects[a]

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Intercept	17.237351	14.286526	34.000	1.207	.236	-11.796362	46.271065
Binder	.006413	.000507	34.000	12.640	.000	.005382	.007444
Ln_Time	.328109	.018104	34.000	18.123	.000	.291317	.364902
Temp	.163294	.024919	34.000	6.553	.000	.112652	.213936
Raw	-29.772474	30.601105	34.000	-.973	.337	-91.961403	32.416454
Density	-.009246	.008687	34.000	-1.064	.295	-.026901	.008409
Raw*Density	.017557	.018321	34.000	.958	.345	-.019675	.054790
Organics	.011610	.018402	34.000	.631	.532	-.025787	.049007

a. Dependent Variable: Ln_UCS.







G.3 PORT Column SPSS Models

PORT Column Mixed Model Analysis:
Model 1; UCS with Time & Binder Content

Descriptive Statistics

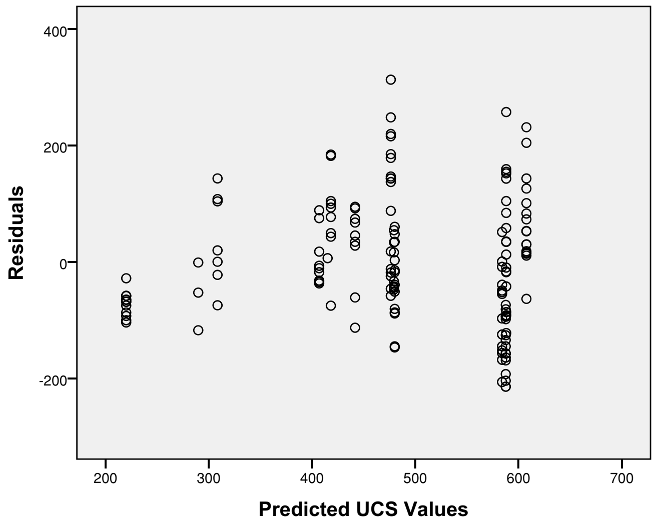
	Count	Mean	Standard Deviation	Coefficient of Variation
UCS	151	483.840	158.7173	32.8%
Time	151	8.4814	4.16908	49.2%
Binder	151	139.40	20.501	14.7%

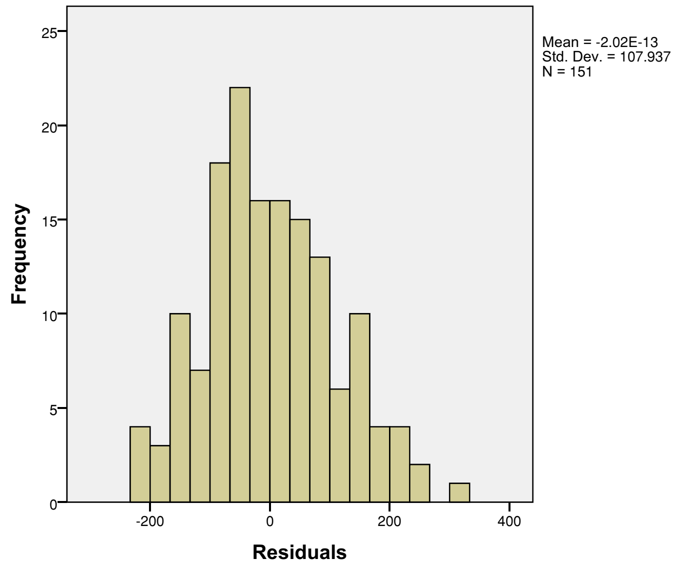
Totals that are aggregated over either a single category of a variable or a split file variable are omitted.

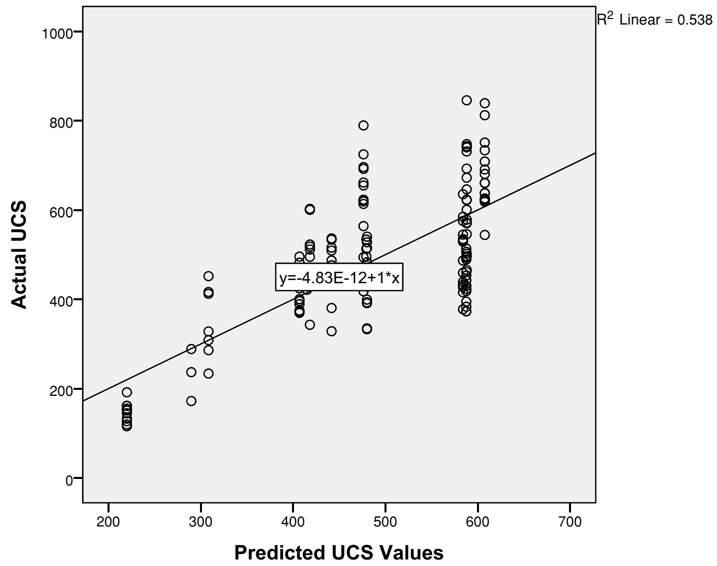
Estimates of Fixed Effects[a]

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Intercept	-140.111104	60.974167	148.000	-2.298	.023	-260.603527	-19.618681
Time	18.019311	2.229043	148	8.084	.000	13.614449	22.424174
Binder	3.379543	.453288	148	7.456	.000	2.483790	4.275295

a. Dependent Variable: UCS.







PORT Column Mixed Model Analysis
Model 2; Ln(UCS) with Ln(Time) + Binder Content

Descriptive Statistics

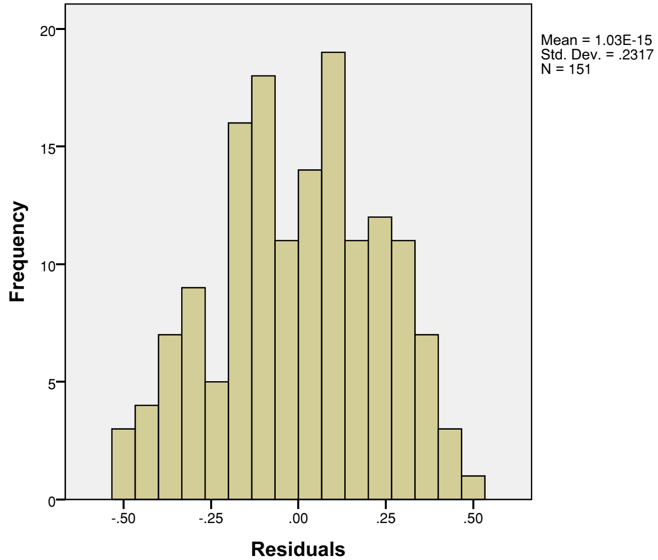
	Count	Mean	Standard Deviation	Coefficient of Variation
Ln_UCS	151	6.1097	.41972	6.9%
Ln_Time	151	1.9472	.71285	36.6%
Binder	151	139.40	20.501	14.7%

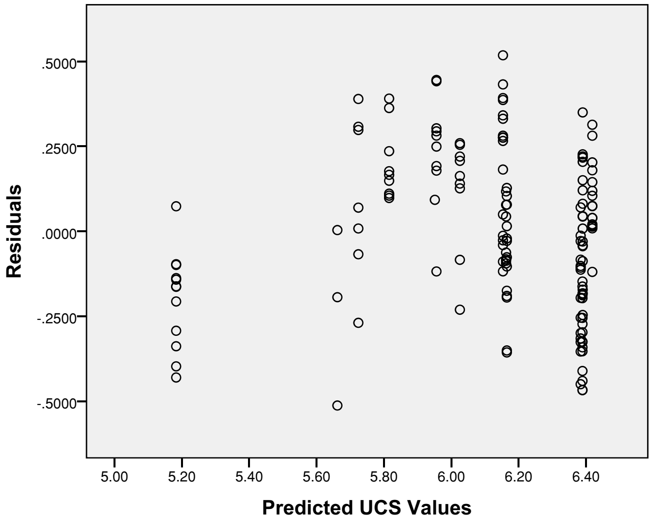
Totals that are aggregated over either a single category of a variable or a split file variable are omitted.

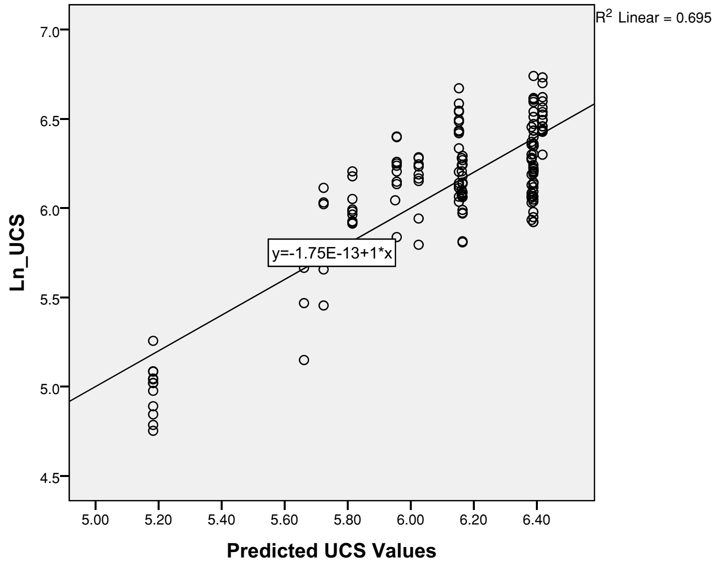
Estimates of Fixed Effects[a]

						95% Confidence Interval	
Parameter	Estimate	Std. Error	df	t	Sig.	Lower Bound	Upper Bound
Intercept	4.247733	.130917	148.000	32.446	.000	3.989024	4.506441
Ln_Time	.336425	.029058	148	11.578	.000	.279002	.393847
Binder	.008657	.001010	148	8.569	.000	.006661	.010654

a. Dependent Variable: Ln_UCS.







PORT Column Mixed Model Analysis:
Model3;Ln(UCS) with Ln(Time), Binder Content & Raw Moisture Content

Descriptive Statistics

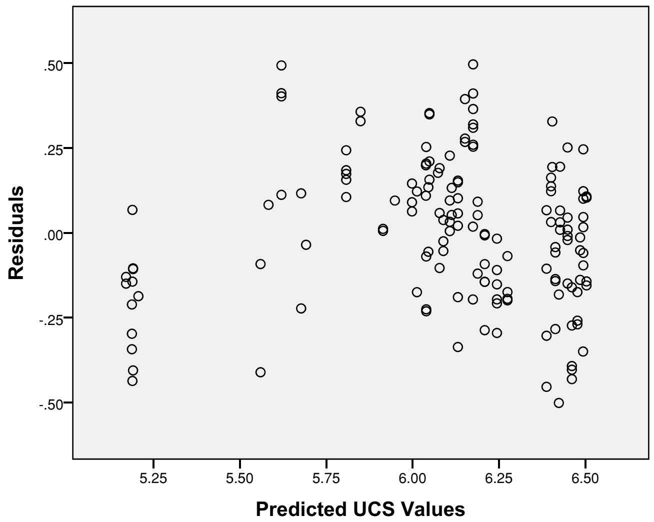
	Count	Mean	Standard Deviation	Coefficient of Variation
Ln_UCS	151	6.1097	.41972	6.9%
Ln_Time	151	1.9472	.71285	36.6%
Binder	151	139.40	20.501	14.7%
RawMC	151	.54896	.057712	10.5%

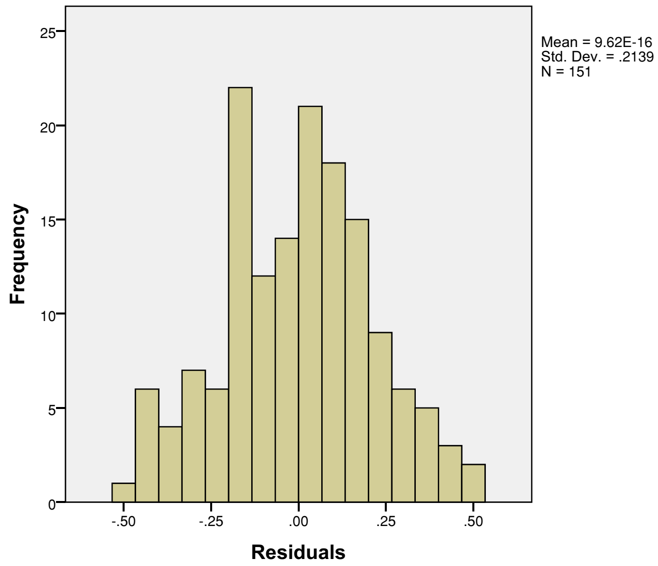
Totals that are aggregated over either a single category of a variable or a split file variable are omitted.

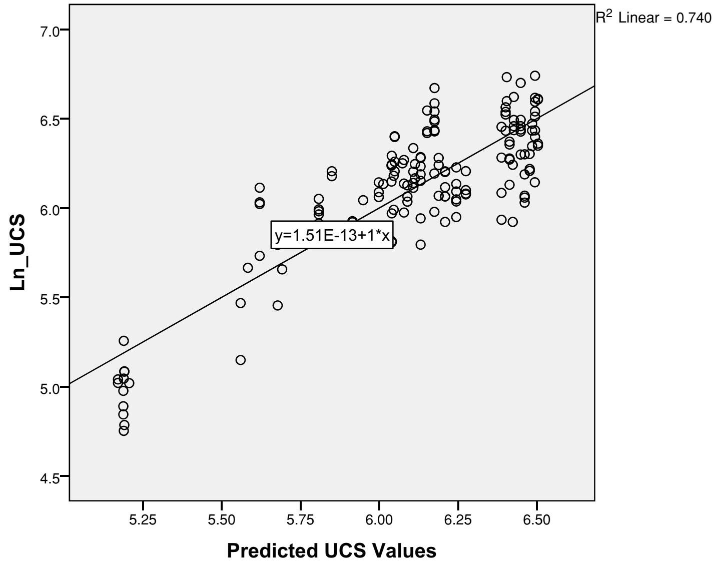
Estimates of Fixed Effects[a]

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	4.948862	.184101	147	26.881	.000	4.585036	5.312688
Ln_Time	.368186	.027630	147	13.326	.000	.313583	.422789
Binder	.009830	.000964	147	10.199	.000	.007925	.011734
RawMC	-1.687532	.333481	147	-5.060	.000	-2.346569	-1.028494

a. Dependent Variable: Ln_UCS.







PORT Column Mixed Model Analysis:
Model 4; Ln(UCS) with Ln(Time), Binder Content & Temperature

Descriptive Statistics

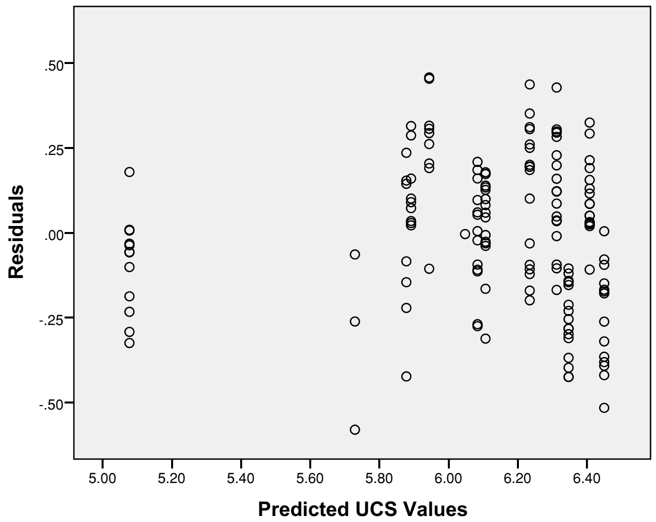
	Count	Mean	Standard Deviation	Coefficient of Variation
Ln_UCS	151	6.1097	.41972	6.9%
Ln_Time	151	1.9472	.71285	36.6%
Binder	151	139.40	20.501	14.7%
Temp	151	16.318	2.4559	15.1%

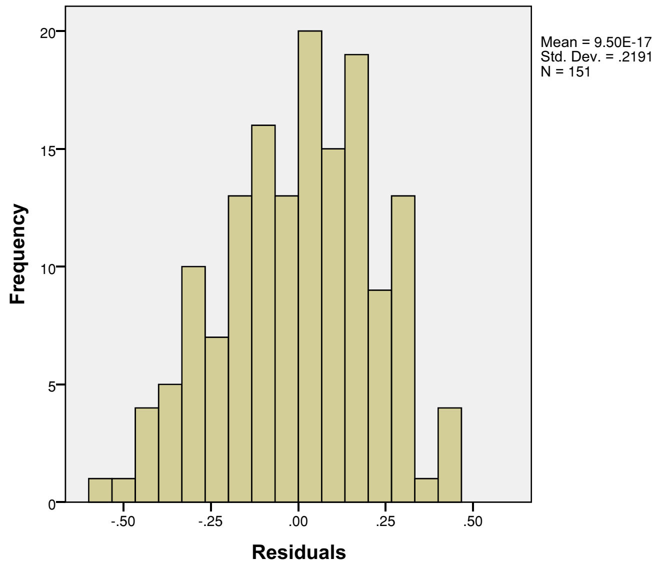
Totals that are aggregated over either a single category of a variable or a split file variable are omitted.

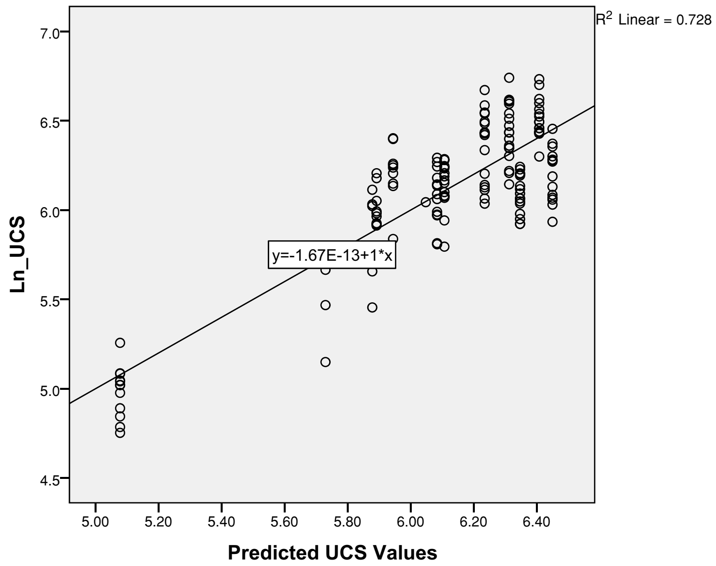
Estimates of Fixed Effects[a]

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	3.744671	.172967	147	21.650	.000	3.402847	4.086495
Ln_Time	.370101	.028720	147.000	12.887	.000	.313344	.426858
Binder	.008043	.000970	147	8.295	.000	.006127	.009959
Temp	.032059	.007672	147	4.179	.000	.016897	.047221

a. Dependent Variable: Ln_UCS.







PORT Column Mixed Model Analysis:
Model 5; Ln(UCS) with Ln(Time), Binder Content, Raw Moisture Content & Temperature

Descriptive Statistics

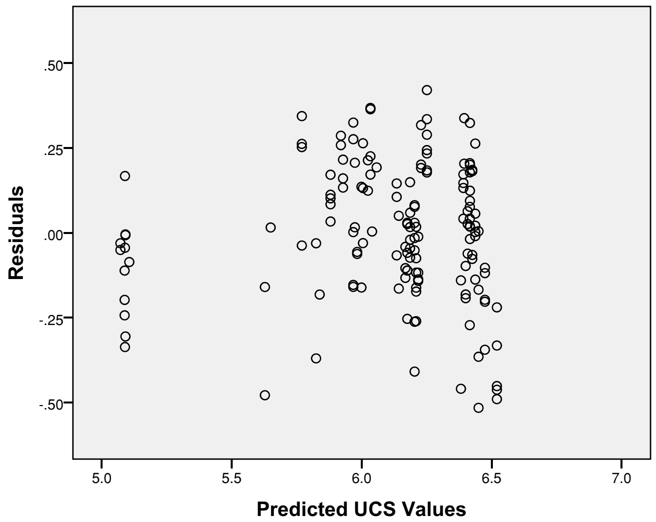
	Count	Mean	Standard Deviation	Coefficient of Variation
Ln_UCS	151	6.1097	.41972	6.9%
Ln_Time	151	1.9472	.71285	36.6%
Binder	151	139.40	20.501	14.7%
RawMC	151	.54896	.057712	10.5%
Temp	151	16.318	2.4559	15.1%

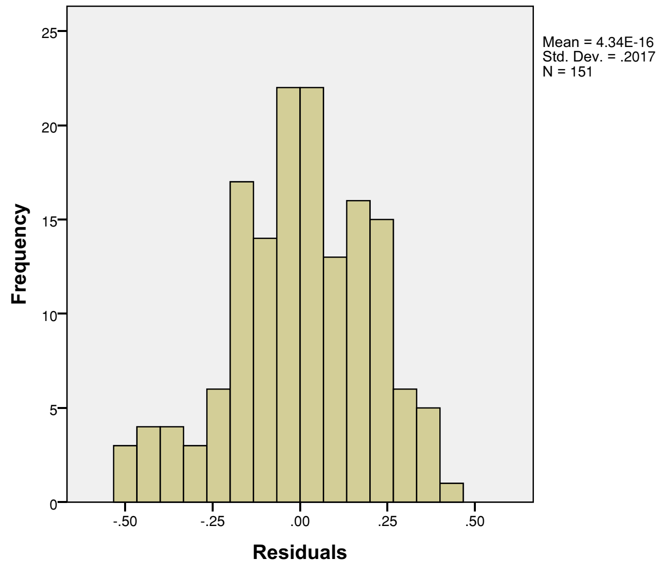
Totals that are aggregated over either a single category of a variable or a split file variable are omitted.

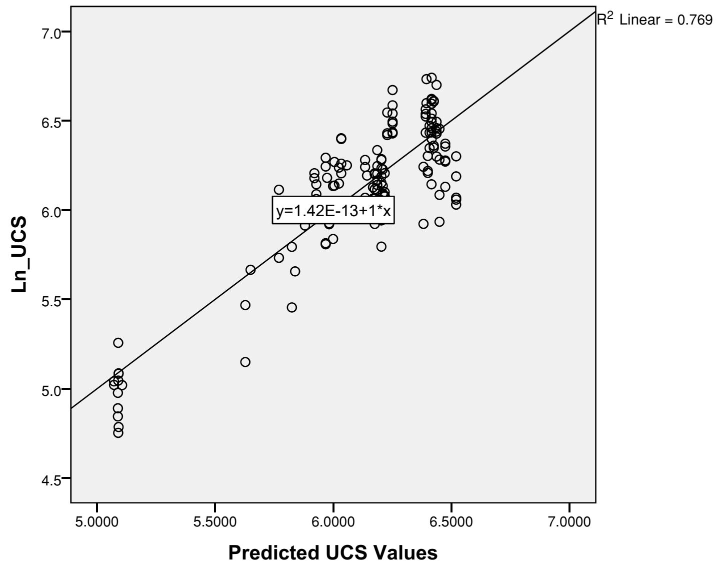
Estimates of Fixed Effects[a]

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Intercept	4.446354	.210257	146	21.147	.000	4.030813	4.861895
Ln_Time	.398741	.027105	146	14.711	.000	.345173	.452310
Binder	.009204	.000924	146.000	9.964	.000	.007378	.011029
RawMC	-1.621409	.315903	146	-5.133	.000	-2.245743	-.997075
Temp	.030273	.007094	146	4.267	.000	.016252	.044293

a. Dependent Variable: Ln_UCS.







PORTColumnMixed Model Analysis:
Model6;Ln(UCS) with Ln(Time), Binder Content, Raw Moisture Content, Temperature, Density & Depth

Descriptive Statistics

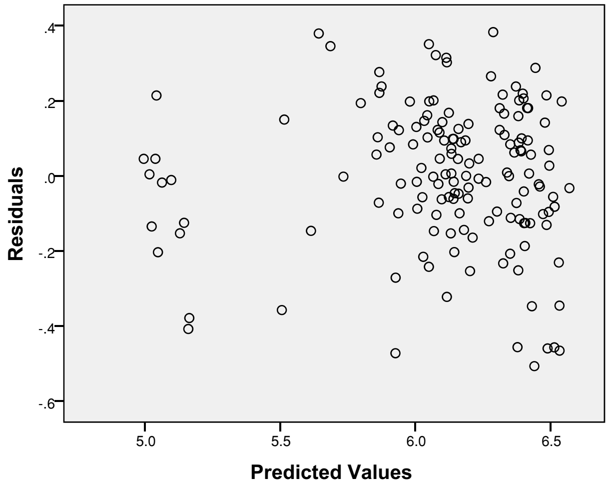
	Count	Mean	Standard Deviation	Coefficient of Variation
Ln_UCS	151	6.1097	.41972	6.9%
Ln_Time	151	1.9472	.71285	36.6%
Binder	151	139.40	20.501	14.7%
RawMC	151	.54896	.057712	10.5%
Temp	151	16.318	2.4559	15.1%
Density	151	1715.667	53.4167	3.1%
Depth	151	395.470	247.8886	62.7%

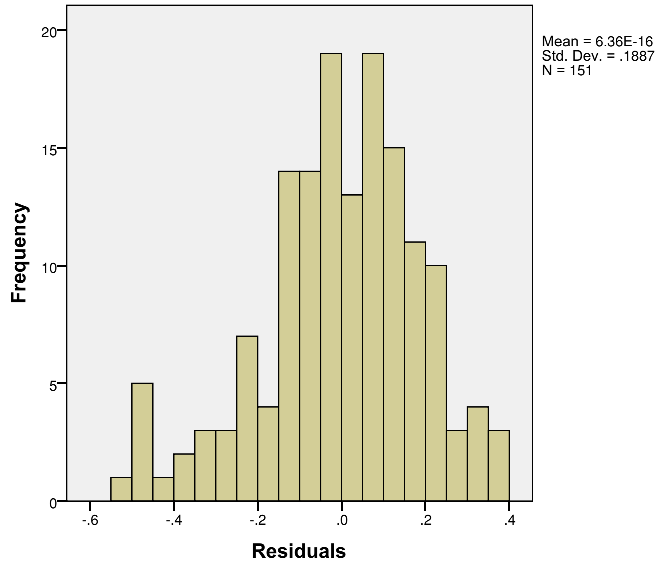
Totals that are aggregated over either a single category of a variable or a split file variable are omitted.

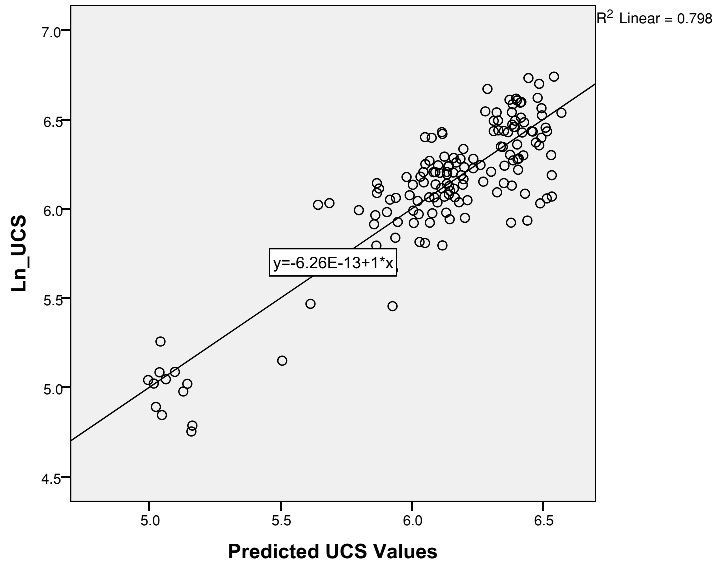
Estimates of Fixed Effects[a]

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval Lower Bound	Upper Bound
Intercept	1.768442	.719552	144	2.458	.015	.346192	3.190691
Ln_Time	.393927	.025562	144	15.410	.000	.343401	.444453
Binder	.009056	.000872	144.000	10.390	.000	.007333	.010779
RawMC	-1.079476	.330513	144	-3.266	.001	-1.732759	-.426193
Temp	.041198	.007115	144.000	5.791	.000	.027135	.055261
Density	.001264	.000341	144.000	3.709	.000	.000590	.001937
Depth	.000162	6.454176E-005	144	2.502	.013	3.393775E-005	.000289

a. Dependent Variable: Ln_UCS.







PORTColumnMixed Model Analysis:
Model7;Ln(UCS) with Ln(Time), Binder Content, Raw Moisture Content, Temperature, Density & Depth. Includes Raw Moisture Content-Density Interaction

Descriptive Statistics

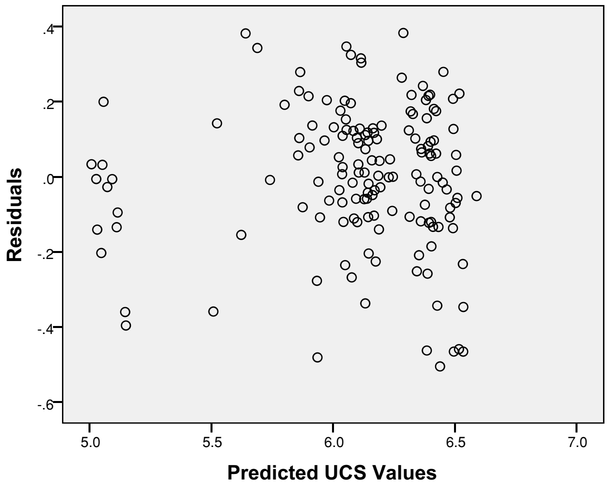
	Count	Mean	Standard Deviation	Coefficient of Variation
Ln_UCS	151	6.1097	.41972	6.9%
Ln_Time	151	1.9472	.71285	36.6%
Binder	151	139.40	20.501	14.7%
RawMC	151	.54896	.057712	10.5%
Temp	151	16.318	2.4559	15.1%
Density	151	1715.667	53.4167	3.1%
Depth	151	395.470	247.8886	62.7%

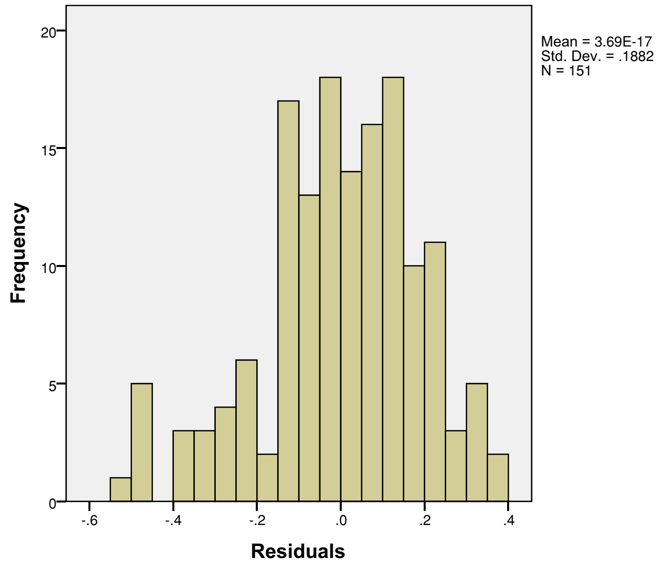
Totals that are aggregated over either a single category of a variable or a split file variable are omitted.

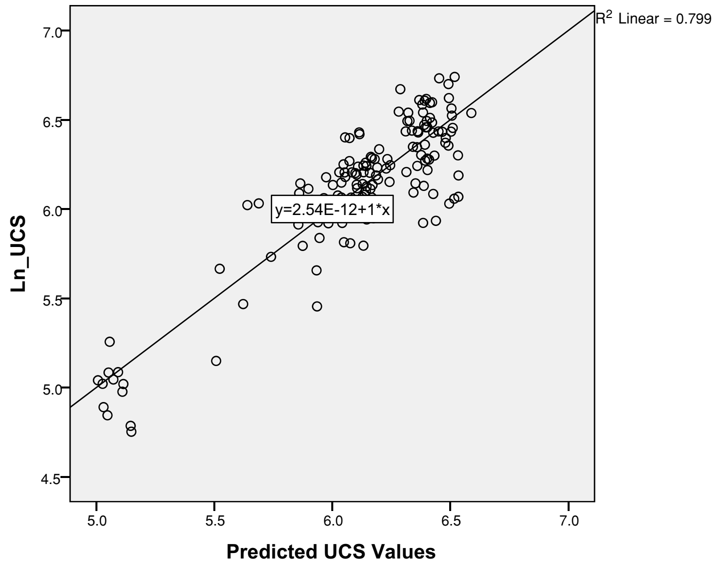
Estimates of Fixed Effects[a]

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Intercept	6.175988	5.290180	143.000	1.167	.245	-4.281069	16.633045
Ln_Time	.396992	.025847	143.000	15.359	.000	.345901	.448083
Binder	.008887	.000895	143.000	9.928	.000	.007118	.010657
RawMC	-9.024631	9.453198	143.000	-.955	.341	-27.710694	9.661431
Temp	.040474	.007174	143.000	5.642	.000	.026294	.054655
Density	-.001301	.003068	143.000	-.424	.672	-.007366	.004765
Depth	.000153	6.535648E-005	143.000	2.344	.020	2.402227E-005	.000282
RawMC * Density	.004664	.005545	143.000	.841	.402	-.006298	.015625

a. Dependent Variable: Ln_UCS.







G.4 PIRT Column SPSS Models

PIRT Column Mixed Model Analysis:
Model 1; UCS with Time & Binder Content

Descriptive Statistics

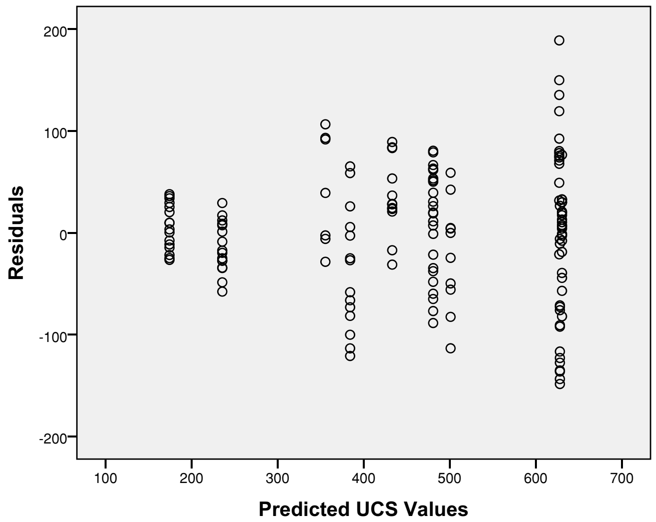
	Count	Mean	Standard Deviation	Coefficient of Variation
UCS	149	453.794	170.2087	37.5%
Time	149	6.9890	4.64214	66.4%
Binder	149	130.87	28.235	21.6%

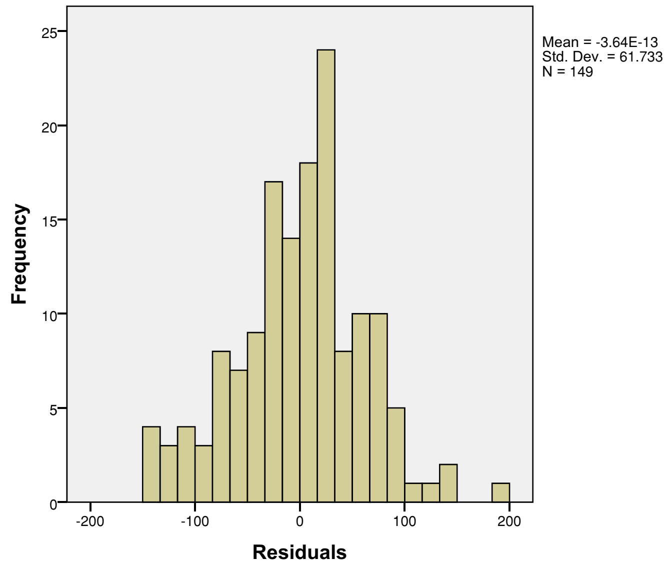
Totals that are aggregated over either a single category of a variable or a split file variable are omitted.

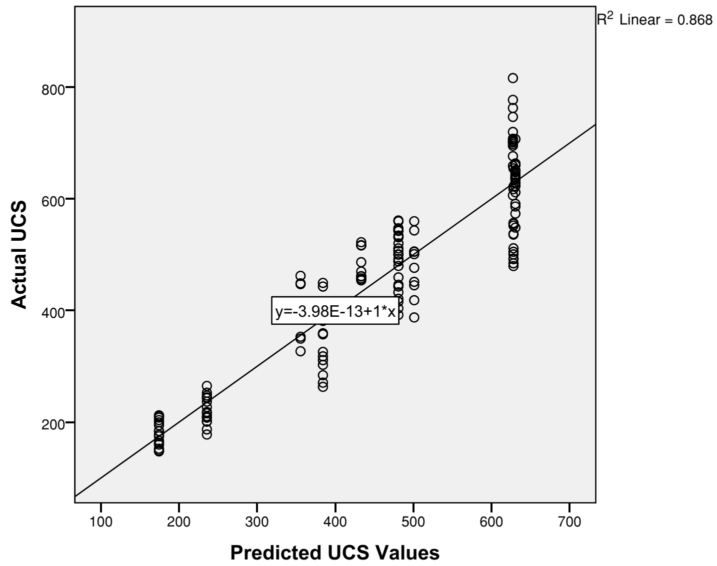
Estimates of Fixed Effects[a]

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	-43.955161	24.576294	146	-1.789	.076	-92.526412	4.616090
Time	24.083811	1.253650	146	19.211	.000	21.606166	26.561457
Binder	2.517168	.206115	146	12.212	.000	2.109814	2.924522

a. Dependent Variable: UCS.







PIRT Column Mixed Model Analysis:
Model 2; Ln(UCS) with LN(Time) & Binder

Descriptive Statistics

	Count	Mean	Standard Deviation	Coefficient of Variation
Ln_UCS	149	6.0301	.44766	7.4%
LnTime	149	1.6070	.92369	57.5%
Binder	149	130.87	28.235	21.6%

Totals that are aggregated over either a single category of a variable or a split file variable are omitted.

Estimates of Fixed Effects[a]

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	4.729932	.051966	146	91.020	.000	4.627229	4.832634
LnTime	.334691	.014344	146	23.333	.000	.306343	.363039
Binder	.005825	.000469	146	12.413	.000	.004897	.006752

a. Dependent Variable: Ln_UCS.