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# Empirical correlations for the compression index of Irish soft soils

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**Abstract**

Numerous correlations have been developed in the literature relating the compression index $C_c$ of soft soils to simple index properties that serve as a useful reality check on oedometer test results. However, many of these empirical correlations are specific to soils of a certain geographic region and/or geological origin and therefore may not be applicable in other contexts. Compression index data and corresponding index properties, specific to a good geographic spread of Irish soft soil sites, have been compiled in this paper. Of all the forms of correlation considered, the relationship between compression ratio $C_c$ and the natural water content is the most fruitful in terms of allowing preliminary predictions of compression index to be made.

## 1. INTRODUCTION

The compression index $C_c$, usually determined by oedometer testing, is an important 1-D compressibility parameter with particular relevance to primary settlement calculations for normally consolidated or lightly overconsolidated natural soils. In geotechnical practice, the extent of oedometer testing specified for these softer soils is often insufficient in light of their inherent variability. Furthermore, the reliability of oedometer-derived parameters (including $C_c$) is heavily dependent upon the appropriateness and quality of the sampling method used. For example, Long (2007) has provided specific recommendations for sampling of estuarine silts. Unfortunately, ideal sample retrieval standards are not always delivered, due to the associated cost and a lack of appreciation of the impact of sample disturbance on laboratory-derived parameters.

Numerous empirical correlations exist between $C_c$ and other properties that are more straight-forward to determine accurately and at significantly less expense. A selection of such correlations is provided in Table 1, from which it can be seen that relationships with the natural water content $w_n$, liquid limit $w_L$ and initial void ratio $e_0$ are popular. Disturbed samples are sufficient for these tests. While such correlations should never be used in isolation for detailed design, even in routine projects, they can serve as a useful reality-check on oedometer-derived $C_c$ values. Should suitable agreement be found between the empirically-derived and (generally sparser) measured $C_c$ values, a more complete profile of $C_c$ with depth may be inferred from the empirically-derived $C_c$ values.

Correlations such as those shown in Table 1 are widely referenced by geotechnical designers, although strictly they should not be applied to soils elsewhere without consideration of soil origin and sampling method (i.e. Azzouz *et al.*, 1976). This point is made in Figs. 1a-c in which those correlations between $C_c$ and a single index parameter from Table 1 have been plotted; the correlations with $w_L$ (Fig. 1a) and $e_0$ (Fig. 1c) vary widely. In light of this, the purpose of this article is to collate published data from soft soil sites with a view to providing local empirical guidance for $C_c$ in Irish fine soils.

## 2. SETTLEMENT EQUATIONS

Eqns [1] and [2] describe how $C_c$ is used to calculate the 1-D primary settlement $\Delta H$ of a soil layer of thickness $H_0$ subjected to an increase in vertical effective stress of $\sigma'_{v0}$ to ($\sigma'_{v0}$ + $\Delta\sigma'_v$) at its centre. The settlement of a normally consolidated soil is given by:

$$\Delta H = \frac{C_c}{1+e_0} \log\left(\frac{\sigma'_{v0}+\Delta\sigma'_v}{\sigma'_{v0}}\right) H_0 \qquad [1]$$

In reality, few soils are truly normally consolidated unless the deposit has been loaded by human activities. The settlement of lightly overconsolidated soils (assuming that they have become normally consolidated by the end of loading) can be computed as:

$$\Delta H = \left[\frac{C_c}{1+e_0} \log\left(\frac{\sigma'_{v0}+\Delta\sigma'_v}{\sigma'_p}\right) + \frac{C_s}{1+e_0} \log\left(\frac{\sigma'_p}{\sigma'_{v0}}\right)\right] H_0 \qquad [2]$$

where $\sigma'_p$ is the preconsolidation pressure and $C_s$ is the swelling index. For a majority of soils, $C_c$ is typically to 5-10 times larger than $C_s$ (i.e. Budhu 2007) so the $C_c$ term in eqn [2] is often dominant.


## 3. DEVELOPMENT OF COMPRESSION INDEX DATABASE

A compression index database has been developed from testing of samples from a number of soft soil sites in Ireland (Fig. 2). Approximately three-quarters of the oedometer tests in the database indicate overconsolidation ratios ($\sigma'_p/\sigma'_{v0}$) in the range 1.0 to 1.6. The soil descriptions have been provided in Table 2; the references are mostly theses or published papers derived from academic studies. The interpretation of those data marked with an asterisk has been carried out by the authors of this article. A total of 61 $C_c$ values and corresponding index properties are presented in Table 3.

The criteria used for inclusion of data and the steps taken to ensure consistency in interpretation are summarised below:

$C_c$ values:

(i)     Only tests having $C_c$ values derived from standard incremental load oedometer tests on high quality piston or block samples have been included in the database. The ratio $\Delta e/e_0$ (where $\Delta e$ is the difference between $e_0$ and the void ratio at the in situ vertical effective stress in the oedometer test) was used at the basis of eliminating some data.

(ii)    Laboratory-to-field correction (such as Schmertmann 1953) has not been applied. The reasoning for this is that many earlier correlations do not specify whether this correction has been applied or not, and it is suspected that it was not applied.

(iii)   $C_c$ values have been determined over the vertical stress range of $\sigma'_p$ to $[4-5]\sigma'_p$.

Index testing:

(iv) In a significant number of cases, the water contents were determined from the trimmings of the sample prepared for oedometer testing. Otherwise, the water content reported is from the same depth as the oedometer samples; the same is true of the Atterberg limit values.

(v) The range of soil types is represented on Casagrande chart of plasticity index ($I_p$) against liquid limit ($w_L$) in Fig. 3. It should be noted that both the A-line has been extended beyond the range normally presented (i.e. beyond a liquid limit of $\approx 120\%$) to accommodate a number of extra data points on the plot. The upper bound of applicability of the chart, known as the U-line, is also included. It is evident from Fig. 3 that, in a few of the references, the soil descriptions given indicate a soil type which is not compatible with the side of the A-line on which they fall. Therefore, in the interests of consistency, these soils are reclassified for subsequent plots as clay or silt according to their position relative to the A-line plot. In addition, one datapoint for marl soils (a lacustrine post-glacial sediment rich in calcium carbonate) is represented under a separate classification.

(vi) Given that $C_c$ values pertain to normally consolidated soils (and those loaded into the normally consolidated region), it was important to impose some level of quality control on the measurements to which they would be correlated, to ensure that these represented soils that were at or relatively close to a normally consolidated state. This process helped eliminate soils that should not be considered soft, in addition to soils that might be soft but with unreliable measurements. The liquidity index ($I_L$) was used for this purpose, and only data in the range $0.5 < I_L < 1.5$ were included in the database. Given that the calculated $I_L$ values become increasingly sensitive to small changes in the Atterberg limit values as the plasticity index $I_p$ reduces, a lower limit of $I_p=0.15$ was imposed as a secondary quality control measure.

(vii) Where values of the initial void ratio $e_0$ were not provided, they were estimated using eqn [3] with $G_s=2.65$.

$$e_0 = w_n G_s \tag{3}$$

## 4. CORRELATIONS

The following correlations were investigated with a view to finding one or more suitable for practical use:

(i)     $C_c$ against $w_n$ (Fig. 4a): this is most rational as both $C_c$ and $w_n$ are influenced by soil composition and structure. In addition, there seems to have been greater consistency in the previous correlations between $C_c$ with $w_n$ (Figure 1b) than with $w_L$ or $e_0$ (Fig. 1a, 1c). The widely-used Mesri and Ajlouni (2007) correlation is included for reference, and although developed for peat, it is relatively typical of the majority of correlations between $C_c$ and $w_n$ in Fig. 1b.

(ii)    $C_c$ against $w_L$ (Fig. 5a): while $w_L$ is not influenced by structure, there have been many attempts to correlate these parameters, because they both pertain to the normally consolidated state (see Table 1). The closest correlations from Figure 1a, i.e. those of Yamagutshi (1959) and Mayne (1980), have been included.

(iii)   $C_c/1+e_0$ against $w_n$ (Fig. 6): this normalised version of $C_c$, referred to as the virgin compression ratio, is sometimes considered as the basis of correlation as it is convenient to use in conjunction with eqns [1] and [2]. However, a linear variation between $C_c$ and $e_0$ is implicit.

(iv)    $C_c/1+e_0$ against $w_L$ (Fig. 7).

## 5. RESULTS

An examination of Figs. 4 to 7 indicates the following:

(i)     Correlations between $C_c$ and $w_n$ or $w_L$ appear more promising than correlations between $C_c/1+e_0$ and $w_n$ or $w_L$. Interestingly, Long and Boylan (2013), reporting values of $C_c$ and $C_c/1+e_0$ for peats in three countries including Ireland, have also found that $C_c$ relationships with $w_n$ exhibit less scatter than $C_c/1+e_0$ relationships with $w_n$.

(ii)    The Mesri and Ajlouni (2007) relationship represents the data quite well for $w_n$ values in excess of 60% (Fig 4a). Moreover, Long and Boylan (2013) report that $C_c=0.01w_n$ provides a good fit to data on tests from block samples, with $C_c=0.008w_n$ more appropriate for tube samples ($C_c$ in this case has been determined for the stress range $\sigma'_p$ to $\sigma'_p$ +50kPa). All peat specimens had $w_n$ values in excess of $\approx$300%.

(iii)   For $w_n$ values less than 60%, the Mesri and Ajlouni (2007) relationship overpredicts compressibility considerably and is not appropriate for use. Therefore, the following best fit equation based on regression analyses, applicable to data having 35% <$w_n$ <150% is given in eqn [4] and plotted with the data in Fig. 4b ($r^2$=0.858). The marl datapoint is excluded from the correlation. This equation captures an increase in $C_c$

with $w_n$ in Irish soils that is sharper than in previous correlations, and the $r^2$ is at least as good as those found for the few correlations in Table 1 that reported them (e.g. the Azzouz et al. 1976 correlation with $w_n$ was based on n=717 points (Pearson's r=0.79).

$$C_c = 0.014(w_n - 22.7) \tag{4}$$

(iv)  The corresponding equation for correlations with $w_L$ (eqn [5]) is plotted on Fig. 5b and has a lower correlation coefficient ($r^2$=0.809):

$$C_c = 0.0118(w_L - 20.7) \tag{5}$$

(v)   The correlation coefficients for the $C_c/1+e_0$ data in Figs. 6 and 7 are typically about 0.6 and less suitable for use than the $C_c$ correlations. This could be related in part to uncertainty in the estimation of $e_0$ in the absence of $G_s$ measurements.

(vi)  There is no evidence in Figs. 4 to 7 to suggest any systematic difference in compression behaviour between Irish clays and silts.

**Conclusions**

In this paper, a potential correlation between the compression index and index properties of Irish soft soils has been investigated for the first time. Only high quality samples were considered and the liquidity index was used as a basis for inclusion in the database.

There is strong evidence of a relationship between the compression index and the natural water content. The widely referenced Mesri and Ajlouni (2007) correlation is suitable for natural water contents above 60% only. A new simple expression (with $r^2$=0.86) is presented which reflects the steeper relationship between compression index and water content in the range 35%-150%. This expression is appropriate for use with clay and silt soils. Correlations with $C_c/1+e_0$ were also considered but were found to have greater scatter, in keeping with findings in peat soils by Long and Boylan (2013).

The new correlation provides useful guidance for preliminary assessments of the compressibility of Irish soils, but should not be used as a substitute for oedometer tests on high quality samples.

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**Table 1.** Existing empirical correlations for the compression index $C_c$

| Reference | Correlation | Applicability |
| --- | --- | --- |
| Skempton (1944) | $C_c = 0.009(w_L - 10)$ | Remoulded clays |
| Yamagutshi (1959) | $C_c = 0.013(w_L - 13.5)$ | Various clays |
| Cozzolino (1961) | $C_c = 0.0046(w_L - 9)$ | Brazilian clays |
| Shouka (1964) | $C_c = 0.017(w_L - 20)$ | Various clays |
| Terzaghi and Peck (1967) | $C_c = 0.009(w_L - 10)$ | Normally consolidated clays |
| Schofield and Wroth (1968) | $C_c = 0.0083(w_L - 9)$ | Various clays |
| Azzouz et al. (1976) | $C_c = 0.006(w_L - 9)$ | Various clays with $w_L < 100\%$ |
| Mayne (1980) | $C_c = 0.0092(w_L - 13)$ | Various clays |
| Pandian and Nagaraj (1990) | $C_c = 0.003\, w_L\,(1+e_0)$ | Various clays |
| Peck and Reed (1954) | $C_c = 17.66*10^{-5}w_n^2 + 5.93*10^{-3}w_n - 1.35*10^{-1}$ | Chicago clays |
| Moran et al. (1958) | $C_c = 0.0115w_n$ | Organic soils |
| Azzouz et al. (1976) | $C_c = 0.01(w_n - 5)$ | Various clays |
| Azzouz et al. (1976) | $C_c = 0.40(e_0 + 0.001w_n - 0.25)$ | Various clays |
| Herrero (1980) | $C_c = 0.01(w_n - 7.549)$ | Various clays |
| Koppula (1981) | $C_c = 0.01w_n$ | Various clays |
| Nagaraj and Murthy (1985) | $C_c = 0.2343w_n G_s$ | Various clays |
| Bowles (1989) | $C_c = 0.0115w_n$ | Organic silt and clays |
| Al Khafaji and Andersland (1992) | $C_c = 0.01w_n$ | Various clays |
| Mesri and Ajlouni (2007) | $C_c = 0.01w_n$ | Fibrous peats |
| Nishida (1956) | $C_c = 0.54(e_0 - 0.35)$ | Various clays |
| Hough (1957) | $C_c = 0.35(e_0 - 0.5)$ | Organic soils |
| Cozzolino (1961) | $C_c = 0.43(e_0 - 0.25)$ | Brazilian clays |
| Sowers (1970) | $C_c = 0.75(e_0 - 0.5)$ | Soils with low plasticity |

**Table 2.** Database of Irish soft soils- authors' description

| Label | Reference | Site location | Soil description | Test type |
|---|---|---|---|---|
| 1* | Buggy & Peters (2008) | Limerick Tunnel | Silt | Std |
| 2* | Farrell (unpublished data) | Mullingar | Marl | Std |
| 3* | Farrell (unpublished data) | Mullingar | Clay | Std |
| 4* | Joyce (1988) | Letterkenny | Grey clayey silt | Std |
| 5 | Kelln et al. (2007) | Limavady Roe Valley | Silty clay | Std |
| 6 | Kelln et al. (2007) | Limavady Curly Valley | Silty clay | Std |
| 7* | Long (unpublished data) | Carrick-on-Shannon | Alluvium | Std |
| 8* | Long et al. (2007) | Loughmore | Brown clay | Std |
| 9* | Long (unpublished data) | Sligo | Clay | Std |
| 10* | Long (unpublished data) | Portumna | Clay | Std |
| 11* | McCabe (2002) | Belfast | Estuarine silt | Std |
| 12 | O'Kelly (2006) | Carrick-on-Shannon | Grey silt | Std |
| 13 | O'Kelly (2006) | Carrick-on-Shannon | Dark grey clay | Std |
| 14 | O'Kelly (2006) | Carrickmacross | Grey-brown clay | Std |
| 15 | O'Kelly (2006) | Shannon | Black peaty silt | Std |
| 16 | O'Kelly (2006) | Waterford | Grey-brown silt | Std |

*Data interpreted by authors

**Table 3.** Compression index database

| Label | $w_n$ (%) | $w_L$ (%) | Cc | $e_0$ |
|---|---|---|---|---|
| | 47.1 | 63 | 0.34 | 1.20 |
| | 69.7 | 93 | 0.7 | 1.85 |
| | 57.4 | 73 | 0.6 | 1.54 |
| | 59.9 | 72 | 0.49 | 1.51 |
| | 93 | 113 | 0.61 | 1.77 |
| | 63.6 | 75 | 0.48 | 1.64 |
| | 65.2 | 78 | 0.6 | 1.69 |
| | 53 | 60 | 0.5 | 1.39 |
| | 61.7 | 70 | 0.61 | 1.60 |
| 1 Limerick Tunnel | 50 | 55 | 0.28 | 1.28 |
| | 49.8 | 54 | 0.37 | 1.32 |
| | 132 | 143 | 1.55 | 3.52 |
| | 84.8 | 93 | 0.79 | 2.21 |
| | 57.6 | 62 | 0.39 | 1.50 |
| | 54 | 57 | 0.6 | 1.38 |
| | 102 | 108 | 1.07 | 2.93 |
| | 57 | 54 | 0.39 | 1.50 |
| | 44.9 | 48 | 0.23 | 1.14 |
| | 80.2 | 84 | 1.06 | 2.11 |
| | 36 | 32 | 0.21 | 0.93 |
| 2 Mullingar | 244.1 | 199 | 2.2 | 5.98 |
| 3 Mullingar | 58.9 | 50 | 0.64 | 1.57 |
| | 31.7 | 34 | 0.23 | 0.89 |
| | 40.6 | 48.5 | 0.32 | 1.08 |
| | 62.2 | 75.2 | 0.502 | 1.65 |
| | 46.5 | 57.8 | 0.385 | 1.23 |
| | 67.5 | 76.5 | 0.66 | 1.79 |
| | 72.5 | 81 | 0.807 | 1.92 |
| | 57.5 | 63.6 | 0.48 | 1.52 |
| 4 Letterkenny | 58.6 | 64 | 0.52 | 1.55 |
| | 66.1 | 70.8 | 0.61 | 1.75 |
| | 93.4 | 98.8 | 1.3 | 2.48 |
| | 60 | 63.2 | 0.47 | 1.59 |
| | 62.2 | 65.2 | 0.51 | 1.65 |
| | 79.4 | 82.6 | 0.76 | 2.10 |
| | 80.9 | 82.2 | 0.84 | 2.14 |

| | | | | |
|---|---|---|---|---|
| | 74.3 | 72.3 | 0.59 | 1.97 |
| | 68 | 73 | 0.92 | 1.8 |
| 5 Limavady Roe Valley | 66 | 70 | 0.74 | 1.75 |
| | 70 | 70 | 1.01 | 1.86 |
| 6 Limavady Curly Valley | 54 | 56 | 0.48 | 1.43 |
| | 51 | 52 | 0.53 | 1.35 |
| 7 Carrick-on-Shannon | 108 | 106 | 1.00 | 3.10 |
| | 40 | 45 | 0.24 | 1.14 |
| | 43 | 47 | 0.28 | 1.19 |
| 8 Loughmore | 47 | 45 | 0.16 | 1.18 |
| | 49 | 43 | 0.25 | 1.09 |
| 9 Sligo | 57 | 61.4 | 0.31 | 1.50 |
| 10 Portumna | 51.7 | 48 | 0.25 | 1.34 |
| | 51.9 | 48 | 0.28 | 1.41 |
| | 62 | 71 | 0.68 | 1.66 |
| | 67.5 | 77 | 0.65 | 1.72 |
| 11 Belfast | 50 | 58 | 0.4 | 1.34 |
| | 63 | 71 | 0.62 | 1.69 |
| | 66.3 | 71 | 0.5 | 1.78 |
| 12 Carrick-on-Shannon | 72 | 91 | 0.64 | 1.91 |
| 13 Carrick-on-Shannon | 134 | 143 | 1.40 | 3.55 |
| 14 Carrickmacross | 45 | 42 | 0.29 | 1.19 |
| 15 Shannon | 143 | 170 | 1.77 | 3.79 |
| 16 Waterford | 52 | 58 | 0.29 | 1.38 |
| | 66 | 74 | 0.47 | 1.75 |
| | | | | |
| No. data points | 61 | 61 | 61 | 61 |
| Max value | 244.1 | 199.0 | 2.2 | 6.0 |
| Mean value | 68.1 | 73.1 | 0.6 | 1.8 |
| Min value | 31.7 | 32.0 | 0.2 | 0.9 |
| Standard deviation | 31.9 | 30.3 | 0.4 | 0.8 |
| Coefficient of variation | 0.47 | 0.41 | 0.63 | 0.45 |
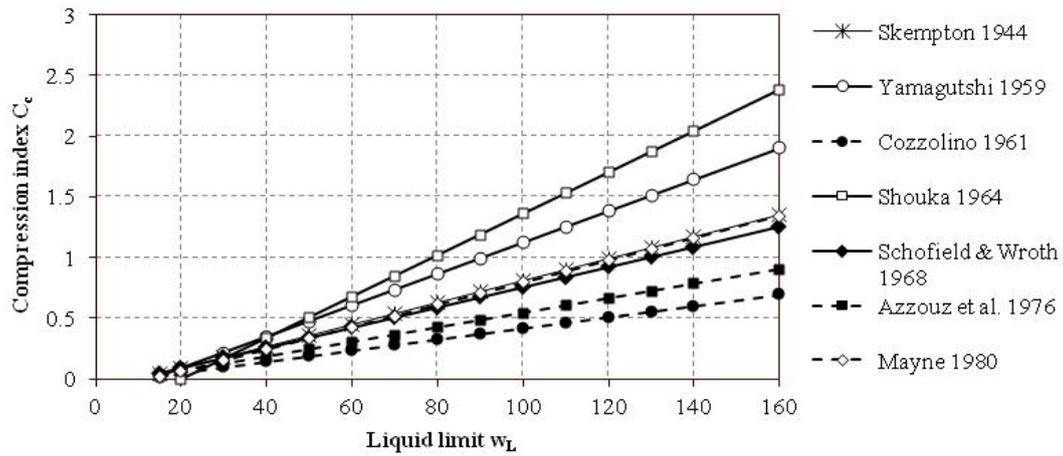
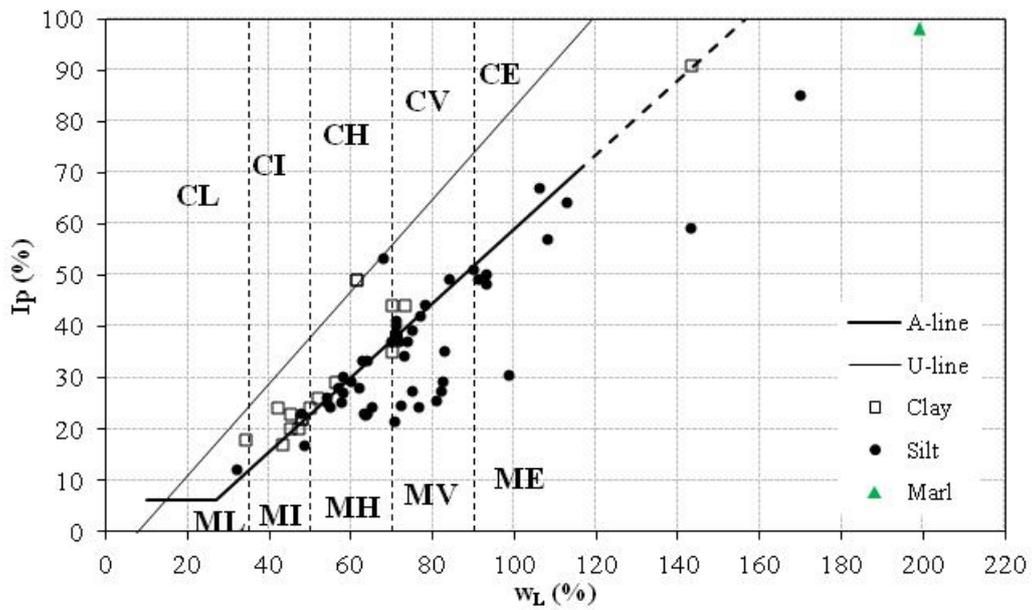**Fig. 1a** Existing correlations for $C_c$ Vs $w_L$
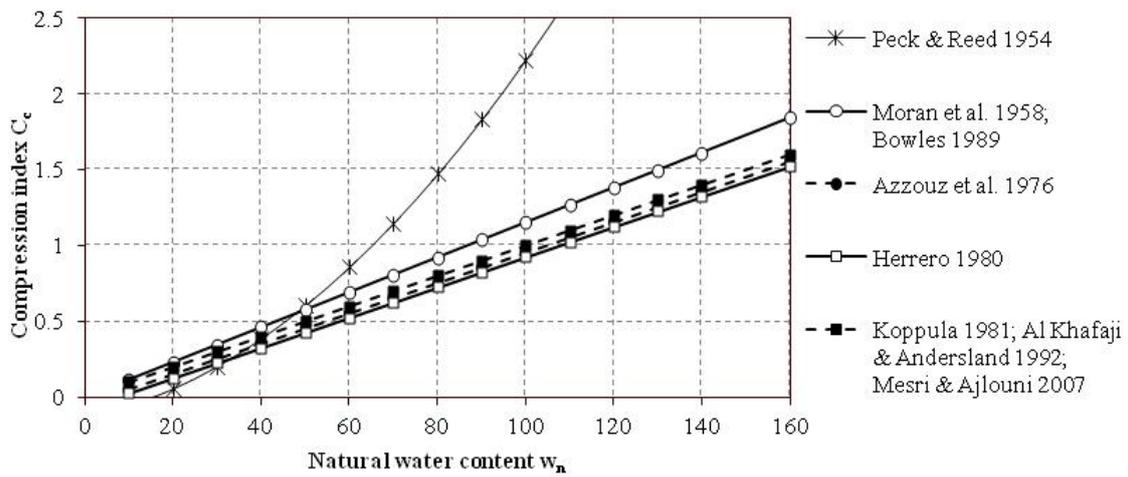


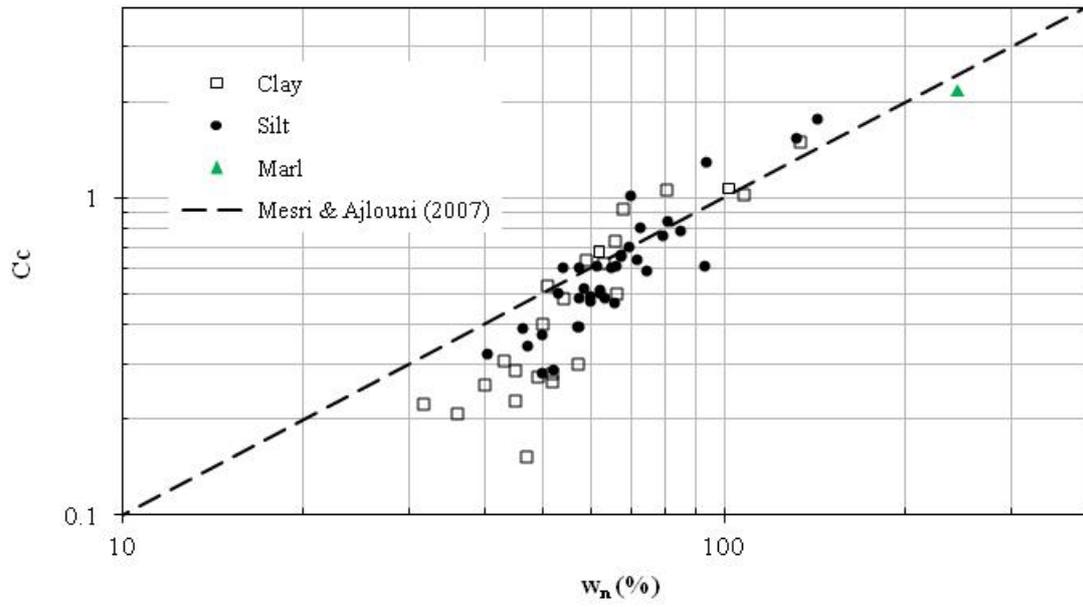**Fig. 1b** Existing correlations for $C_c$ Vs $w_n$
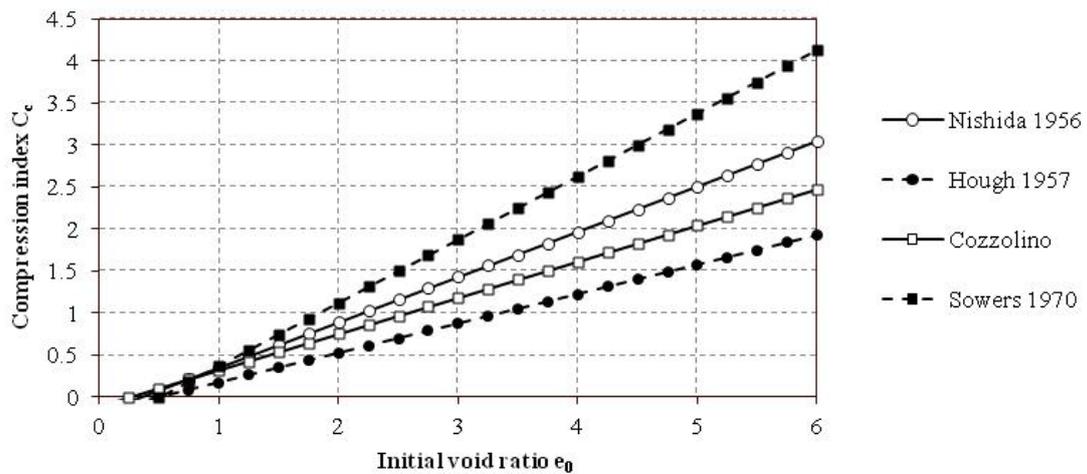


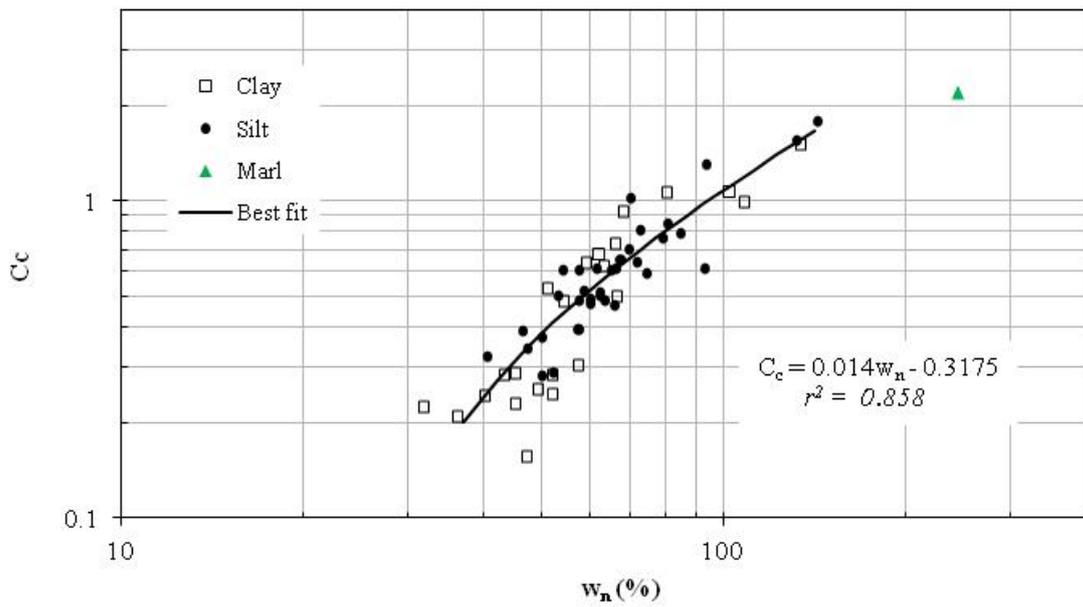**Fig. 1c** Existing correlations for $C_c$ Vs $e_0$
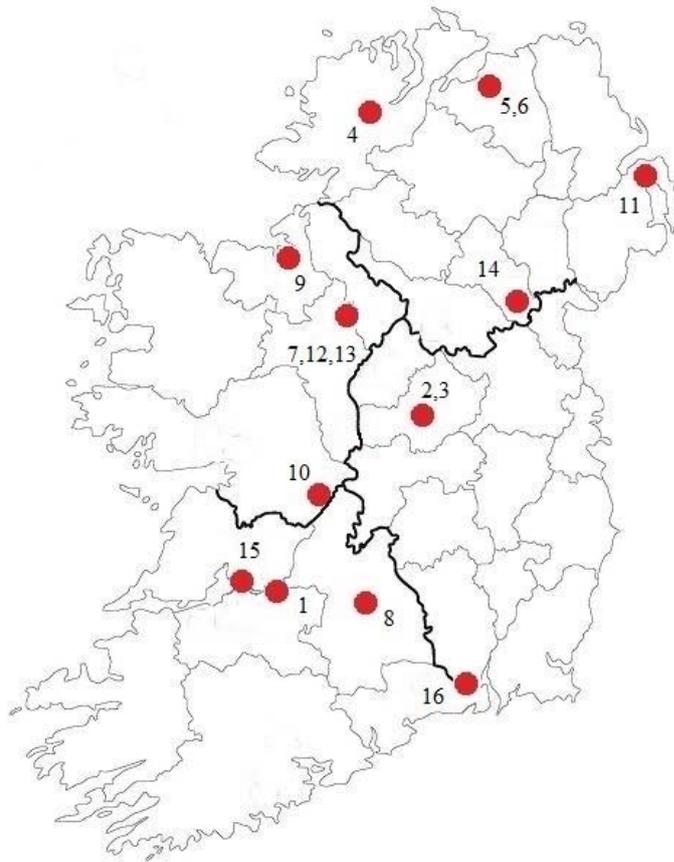
**Fig. 2** Site locations



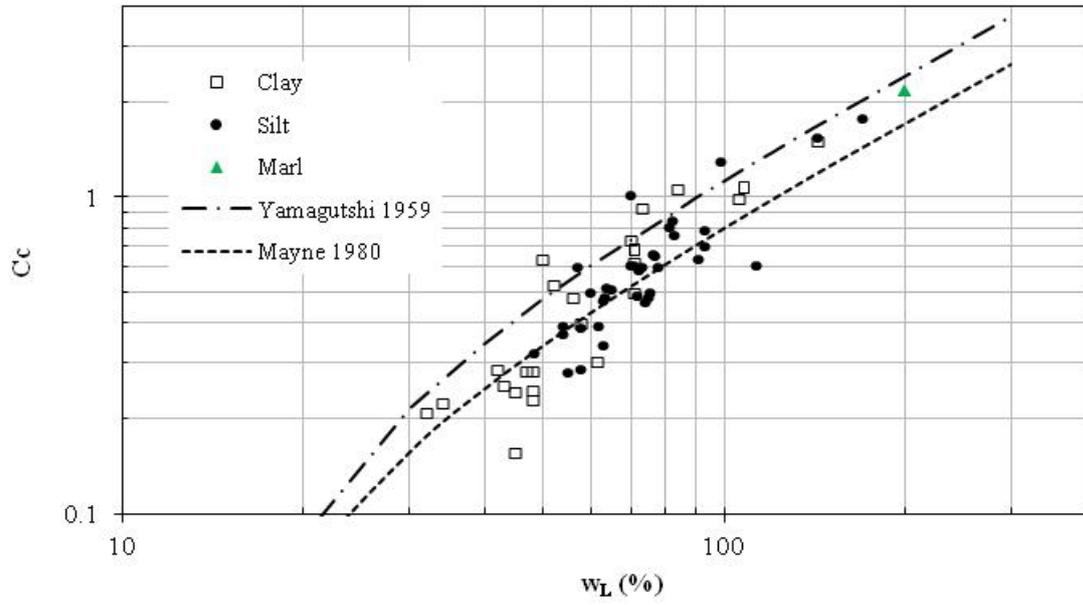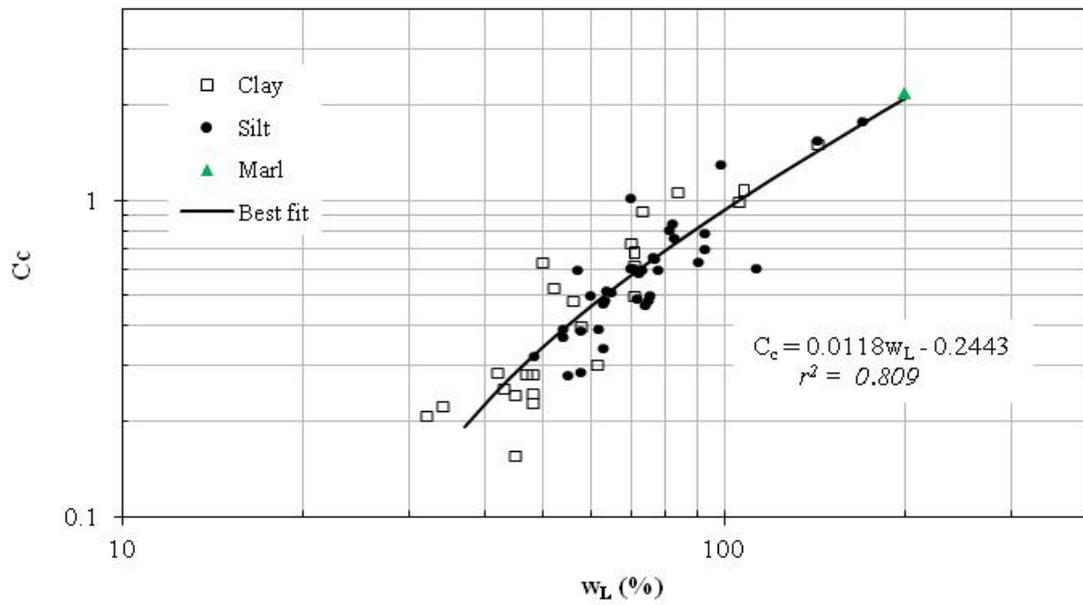**Fig. 3** Casagrande chart: plasticity index against liquid limit
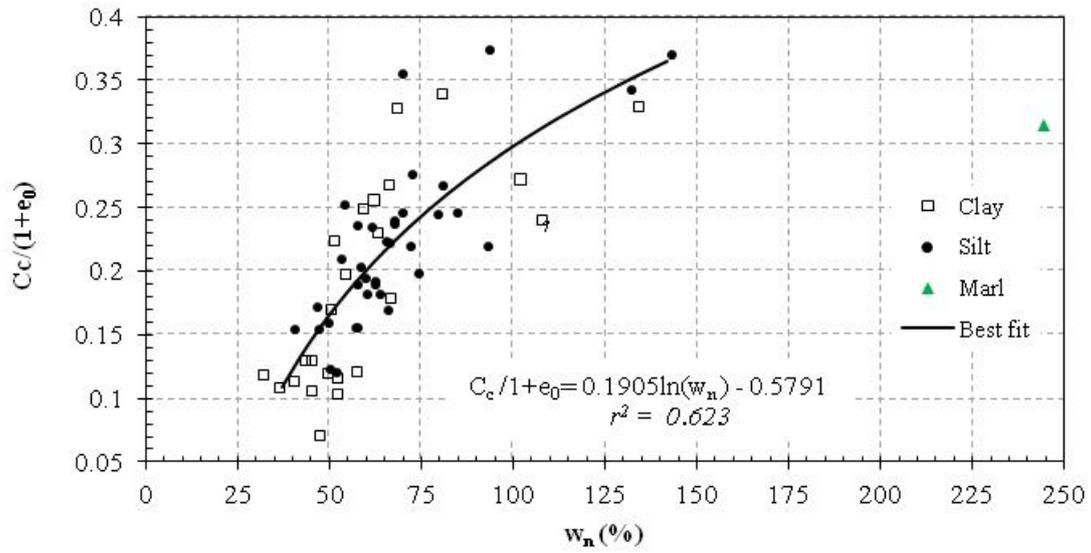
**Fig. 4a** Plot of $C_c$ against $w_n$



$$C_c = 0.014w_n - 0.3175$$
$$r^2 = 0.858$$

**Fig. 4b** Present correlation between $C_c$ and $w_n$

**Fig. 5a** Plot of $C_c$ against $w_L$



$$C_c = 0.0118w_L - 0.2443$$
$$r^2 = 0.809$$
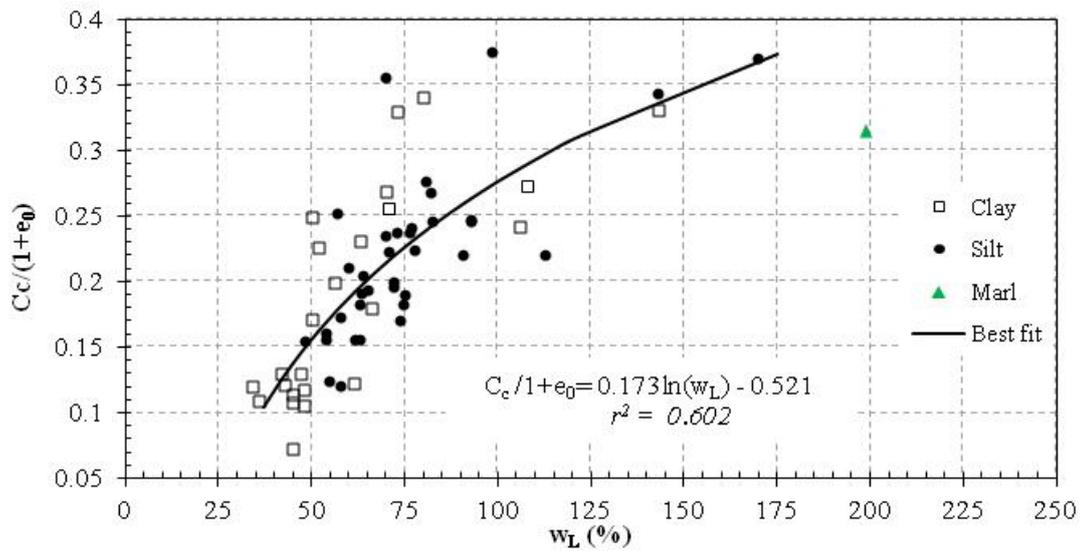
**Fig. 5b** Present correlation between $C_c$ and $w_L$

**Fig. 6** Plot of $C_c/1+e_0$ against $w_n$



**Fig. 7** Plot of $C_c/1+e_0$ against $w_L$