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The distribution, type, popularity, size and availability of river-run gravel and crushed stone for use in land drainage systems, and their suitability for mineral soils in Ireland

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Abstract

The performance of land drainage systems installed in mineral soils in Ireland is highly variable, and is dependent on, amongst other factors, the quality and suitability of the aggregate used. In Ireland, aggregate for land drainage systems is usually river-run gravel and crushed stone. This study classified the distribution, type, popularity, size and availability of aggregates for land drainage systems throughout Ireland and quantified their suitability for use in mineral soils. Eighty-six quarries were surveyed. Limestone and river-run gravel (80% of lithologies) are widespread throughout the country. The quarry aggregate sizes ("Q sizes"), reported by the quarries as either a single size i.e. "50 mm" or a graded size i.e. 20 – 40 mm, were variable, changed across lithology and region, and were, in most cases, larger than what is currently recommended. A particle size distribution analysis of 74 samples from 62 quarries, showed that individual Q sizes increased in variability with increasing aggregate size. In some regions, the aggregate sold does not meet current national regulations, which specify an aggregate size ranging from 10 to 40 mm. The suitability of these aggregates for drainage in five soils of different textures were compared using three established design criteria. It was found that the aggregate in use is too large for heavy soil textures and is therefore unsuitable as drainage envelope material. Guidance for contractors, farmers, and quarry owners will be required, and investment may be needed by quarries to produce aggregate that satisfies design criteria. An aggregate size, based on one or a combination of established aggregate design criteria, where an analysis of the soil texture is conducted and an appropriate aggregate is chosen based off its fifteen percent passing size, is required.

Keywords: Drainage materials; Drain envelopes; Hydrology; Land use; Soil management.

Introduction

Subsurface drainage in agriculture plays an important role in the removal of excess surface and subsurface water from poorly drained soils. Drainage of mineral soils supports increased production and, together with other technologies and optimised soil fertility, facilitates productive grasslands (Tuohy et al., 2018a). The removal of excess water has many benefits, including increased trafficability and crop yield, reduced surface runoff, improved soil structure and reduced total phosphorus losses (Ibrahim et al., 2013; Daly et al., 2017). A typical subsurface field drainage system consists of a network of corrugated or smooth perforated pipes surrounded by an envelope material (Vlotman et al., 2001). The drain envelope has three primary roles: filtration to prevent or restrict soil particles entering the pipe, where they may settle and eventually clog the pipe; reduction of water entry resistance to the pipe; and the provision of support to the pipe to prevent damage due to the soil load (Ritzema et al., 2006).

Envelope materials may be divided into three categories: mineral (sand and river-run gravel, crushed stone, shells etc.), organic (straw, woodchips, heather bushes, peat litter, coconut fibre etc.), and synthetic (pre-wrapped loose materials (PLMs)), made from waste synthetic fibres and geotextiles, which may be woven, non-woven, or knitted) (Stuyt et al., 2005). The type of materials in use in many countries depends on cost and availability. In the Republic of Ireland (henceforth Ireland), for example, the typical envelope material used is mineral aggregate (crushed stone and river-run gravel), which is based not on the appropriateness of a given material for a particular soil or appropriate international criteria, but on other factors such as cost, convenience and availability.

Research on land drainage systems in Ireland has mainly focused on drainage practices (Galvin, 1986; Ryan, 1986), and more recently on field drainage design, field drainage performance and environmental losses (Tuohy et al., 2018a; Clagnan et al., 2018; Valbuena-Parralejo et al., 2019; Tuohy et al., 2018b). The performance and lifespan of land drainage systems in Ireland are highly variable and poorly understood (Tuohy et al., 2018a), and are dependent on, amongst other factors, the quality and suitability of the materials used in field drains, and on keeping such drains well maintained. Dierickx (1993) observed that the majority of problems in selecting appropriate materials are due to uncertainties about aggregate specifications, aggregate form (rounded or angular), lack of uniform aggregate quality, segregation during transportation and installation, or poor availability of appropriate aggregate for a given soil type. The relative costs of stone aggregate can direct the farmer or contractor towards unsuitable materials in many cases.

Aggregate material can also vary widely in type and size, due to a geographical bias in geology type, local preference and quarry processing (Gallagher et al., 2014). The National Standards Authority of Ireland (NSAI) provides guidance on the size and type of materials for use in civil engineering work and road construction (NSAI, 2002). Most quarries comply with this guidance and therefore the sizes and types of material available are mostly guided by these standards, without a particular focus on aggregate specification for land drainage purposes. Currently Teagasc (2013) recommends an aggregate size in the 10 – 40 mm range. There is currently no scientific basis on which this recommendation is made and the aggregate distribution is not defined adequately.

The objectives of this study were to: (1) formulate a database classifying the distribution, type, popularity, size and availability of aggregate for land drainage systems throughout Ireland. The generated database will then be used in conjunction with established design criteria to assess the appropriateness of aggregates in use for specific soil types. The database may also be used in the future to assess the availability of materials based on a recommendation that considers both hydraulic and filter function of the envelope (2) Determine if there is variation in the grades of aggregate sold under a single label size (e.g. "50 mm") or a size range (e.g. 20 – 40 mm). (3) Determine the suitability of the currently available sizes of aggregate for use in mineral soils in Ireland, based on established international filter criteria.

Materials and methods

Survey

Information on quarries in Ireland, including their addresses, contact information, location coordinates, and lithology was obtained from Gallagher et al. (2014). In December 2018, a survey was sent via email to quarry managers. If no response was received, the respondents were contacted by phone. The survey sought the following information: confirmation of quarry name and company; lithology (limestone, sandstone, mixed, or other); aggregate sizes (henceforth "quarry size" or "Q size") sold, which represents an approximation of the size of aggregate in mm as specified by the quarry. This can be a single size or, in some cases, a size range. There were 60 respondents. As some respondents were responsible for multiple quarries, 86 quarries were represented in total. The respondents do not represent all quarries operational in Ireland, only a proportion (37%, based on data from Gallagher et al. (2014)) who replied with information on aggregate types and sizes available for land drainage. Quarry locations were mapped using a Geographical Information System.

Sample collection and characterisation

Seventy-four individual samples of aggregate, each 60 kg in weight, were collected from 62 quarries, representing 12 of the 26 counties in Ireland. The other 24 quarries, detailed above, were omitted. The samples collected adequately represented the size, type (round or chip) and lithologies available throughout the country. To get a 60 kg representative sample, the following procedure was followed at all locations: samples were collected from the top, middle and bottom of stockpiles, where the surface layer was taken off and the aggregate underneath was collected in accordance with standard methods (ASTM, 2019b).

To quantify the difference between the indicative Q size, as specified by the quarry owners, and the measured particle size distribution, seventy-four samples were prepared for particle size distribution (PSD) analysis according to ASTM (2018) and a dry sieve analysis was conducted according to ASTM (2019a). From a semi-logarithmic plot of the aggregate size (mm) versus their equivalent mass passing through each sieve, aggregates with diameters less than 90%, 50% and 10% of the total mass (henceforth D_{90}, D_{50} and D_{10} values) were estimated.

Aggregate suitability for Irish mineral soils

The envelope provides three main functions: (1) hydraulic function, which, with an appropriately sized aggregate, increases the hydraulic circumference and limits the resistance of water movement from soil to pipe (2) bedding function, which provides protection for the pipe, and (3) filter function, which helps to prevent soil incursion into the envelope and aids in the hydraulic function of the envelope. The focus of this paper will be on aggregate size, to determine the suitability of aggregate sizes for agricultural land drainage.

Three criteria for aggregates were applied to five low permeability Irish soils of varying textures: the US Soil Conservation Service (SCS, 1988), Terzaghi's criteria (Terzaghi and

Peck, 1961), and criteria developed by Sherard et al. (1984) for filters to protect hydraulic structures, but which may also be applied to the design of aggregate envelopes. (Further information on the three criteria can be found in Stuyt et al., 2005). To facilitate comparison of the surveyed aggregate size to the three criteria, the D_{15} was calculated for all 74 aggregates. Five soil textures from Galvin (1983) were used: clay, clay loam, loam, silty clay loam, and silt loam. The Irish Soils Information System, using soil drainage class maps (Simo et al., 2014), was used to validate if these soils represented poorly drained soils in Ireland.

Statistical analysis of the particle size distribution data.

Aggregate size parameters (D_{10}, D_{50} and D_{90}) were analysed by an analysis of variance with Q size as a factor. Comparisons between Q sizes were made using the PROC GLM procedure in SAS version 9.1.3 (SAS, 2006).

Results

Survey

The distribution and lithologies of quarries located throughout Ireland based on survey results (of 86 quarries) are presented in Figure 1. Limestone was distributed in quarries throughout the country; sandstone is mostly located in quarries within the southern region, while river-run gravel quarries are mostly located in the midlands (Figure 1). Limestone (42 %) and river-run gravel (38 %) together make up eighty percent of the total lithologies surveyed, with sandstone making up another eleven percent (Figure 2).

The Q sizes, as reported by the quarries, were variable and showed that a wide range of material sizes were in use for land drainage installation across the country (Figure 3 and 4). By lithology, the most popular limestone Q sizes are 50 mm, 20 mm and 20 – 40 mm; for sandstone, 50 mm and 100 mm are most popular. River-run gravel had a similar trend to limestone with 50 mm, 20 mm, 25 mm and 20 – 50 mm being the most popular quarry sizes. There were also regional variations in Q sizes (Figure 5): the results showed that the average Q size in Munster was 53 mm, while the average Q size in Leinster was 31 mm.

PSD Analysis

The results of the PSD analysis (of 74 samples) are presented in Figure 6 and show a wide variation in the size of material passing each of ninety, fifty and ten percent marks for a single Q size. This variation increased with increasing Q size. The median D_{90} values corresponded closest to the associated Q sizes. Statistical analysis indicated significant differences in actual size between Q sizes for D_{10}, D_{50} and D_{90} parameters (P<0.0001). However, Q10 and Q20 sizes did not have significantly different D_{10}, D_{50} and D_{90} values, and Q20 and Q20-40 did not have significantly different D_{90} values.

Aggregate suitability for Irish mineral soils

Figure 7 shows the suitability of the 74 aggregates as a filter material when the three aggregate design specifications were applied to five soil textures common to Irish mineral soils. None of the aggregates characterised met the three criteria in any soil type, with the exception of a loam soil where of the 74 samples analysed, 31% (twenty-three aggregates comprising limestone, river-run gravel, and sandstone) of the aggregates meet SCS (1988) specifications and 11% (eight aggregates comprising limestone and river-run gravel) met Terzaghi and Peck (1961) specifications. (Sherard et al. (1984) was not applicable.)

Discussion

Survey

The wide variation of aggregates, across lithology and region, is likely to affect the type and size of material available to a farmer or contractor, if current practices are continued. The popularity of larger Q sizes indicates that the recommendations made by Teagasc (2013) for a clean aggregate in the 10 – 40 mm grading band are still not being fully adopted everywhere, with either the average or maximum aggregate size sold in some regions being larger than what is recommended. As this 10 – 40 mm size is not based on scientific evidence and only on visual field observations, using sizes larger than this recommendation will cause problems with the ability of the envelope to filter any soil material, and will affect the lifespan of the drain.

The abundance of limestone (42%) quarries may cause a problem with the availability of suitable aggregates. Stuyt et al. (2005) observe that limestone particles must be avoided, because a high percentage of lime in aggregate envelopes may be a source of encrustation. If limestone was not to be recommended as a drainage aggregate, farmers and contractors, especially in western counties, may have to travel unreasonable distances to source an alternative material. This should be considered in future studies on the selection of suitable drainage aggregates.

PSD analysis

The PSD analysis trends indicate that there is generally a large variation in actual aggregate sizes described by different Q sizes. Therefore, aside from aggregate Q sizes changing across lithology and region, the individual Q sizes (e.g. 50 mm) are also highly variable. This is likely to create problems in material selection and availability, as farmers or contractors may have limited options of aggregate size and lithology, depending on their location, and the size received may not accurately reflect what is specified by or requested from the quarry. This will have implications for both the performance and lifespan of drainage systems installed. A standardisation of the labelling of sizes is needed in order to ensure the contractor or farmer knows the size range of aggregate that they are purchasing. Reporting the given aggregate size in the format of 90% passing (D_{90}) and 10% passing (D_{10}) of the total mass (e.g. 20 – 5 mm) would give a standard range which would clearly represent the aggregate size purchased. If current practices are maintained, even the selection of a size that is perceived to be suitable for use, may not reflect the design criteria of aggregate needed.

Aggregate suitability for Irish mineral soils

Very few of the 74 aggregate samples meet the required specifications, with only 31% meeting SCS (1988) criteria and 11% meeting Terzaghi and Peck (1961) criteria for a loam soil texture. Generally, loam soils are less inclined to require extensive artificial drainage, and most drainage works will be concentrated on heavier soil types. In this context, the suitability of some aggregates for loam soils may not have widespread applicability and, in most cases, it is likely that no aggregate would be suitable for use as per the three criteria. This indicates that there is a need for the reduction in the size of aggregate that is used in agricultural land drainage if the design criteria are to be achieved. Consultation with quarry owners would be required to determine if a suitable aggregate size could be produced in each quarry, with minimum or no investment, as the achievement of such size grading may require new equipment and/or new procedures on site. The aggregate currently sold for drainage works is far from ideal. Development and dissemination of appropriate standards and specifications of aggregates for land drainage works would be needed to allow quarries to produce an appropriate size of aggregate.

It is important to produce a suitable aggregate size, as an unsuitable aggregate may lead to sediment loss through drains (Ali, 2011). Sediment loss may lead to blocked drains or reduced outflow of water from drains. Fine sediment settlement is usually limited as long as adequate outflow and gradient are achieved, while coarser sand particles will settle in the drainage pipe (Teagasc, 2013; Stuyt et al., 2005). The amount of fine sediment lost through a drain can be a primary method for particulate phosphorus transfer and loss to drainage ditches (Shore et al., 2015), so the aim of a drainage envelope should be to minimize the loss of sediment from drains. This may not be achieved with the current specifications of aggregate available. While much of these criteria focus on filter performance, a filter would eventually become blocked, so an envelope has to conform to the often conflicting criteria of hydraulic performance and filter performance (Stuyt et al., 2005). This requires a study that looks at the performance of an aggregate envelope from both a hydraulic and filter performance point of view, while using soil with a heavy texture.

Conclusion

The current system of aggregates being identified by a single Q size, or a Q size of a specified grading range, does not give a fair reflection of the true gradation of aggregate being sold by quarries. To remove confusion, a standardisation of quarry aggregate specifications based on their grading range (D_{10}-D_{90}) is required. This approach would eliminate confusion over the size of aggregate being selected by the drainage contractor or farmer when purchasing drainage aggregate.

The sizes of aggregates currently in use in Ireland are larger than what was specified by Teagasc (2013), and the suitability and preference of the current sizes of aggregate for Irish mineral soils does not conform to three other aggregate design criteria for drainage systems, which specify a smaller aggregate size than what is currently in use. Further research is needed on the efficacy of materials currently in use in Irish drainage systems and to identify suitably sized aggregates for Irish mineral soils. Until this research is completed, it is preferential to select an aggregate size based on one or a combination of the aggregate design criteria identified in this paper, where an analysis of the soil texture is conducted and an appropriate aggregate is chosen.

A survey of quarries using the methodology developed in this study could be carried out in other countries. In any country this information would be important to optimise advice over time. For example, information regarding the ranges of aggregate proposed for land drainage works versus what is available in (and reported by) quarries would be useful.

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Figure 4. The most popular aggregate Q sizes (sizes as reported by quarries, left; single size and right; grading band) for land drainage from quarries surveyed by lithology.

Figure 5. The average, minimum and maximum Q sizes (Inclusive of all lithologies) within each province based on survey data collected. The recommended size range of 10-40 mm from Teagasc (2013) is highlighted in red.

Figure 6. Estimated ten, fifty, and ninety percent passing (D_{10}, D_{50} and D_{90}) figures taken from percentage graphs representing the gradation of grouped Q sizes, which represents an approximation of the size of aggregate in mm as specified by the quarry.

Figure 7. Recommended aggregate size using three filter design criteria [Terzaghi's (Terzaghi and Peck, 1961) ("TZ"); US Soil Conservation Service (SCS, 1988) ("US SCS"); Filters for Silts and Clays (Sherard et al. 1984) ("S&C")] applied to five soil textures,showing the suitability of seventy-four gravels characterised in this study. Aggregate size is the percentage of aggregates with a particle size less than 15% of the total mass (D_{15}).

Fig 1.

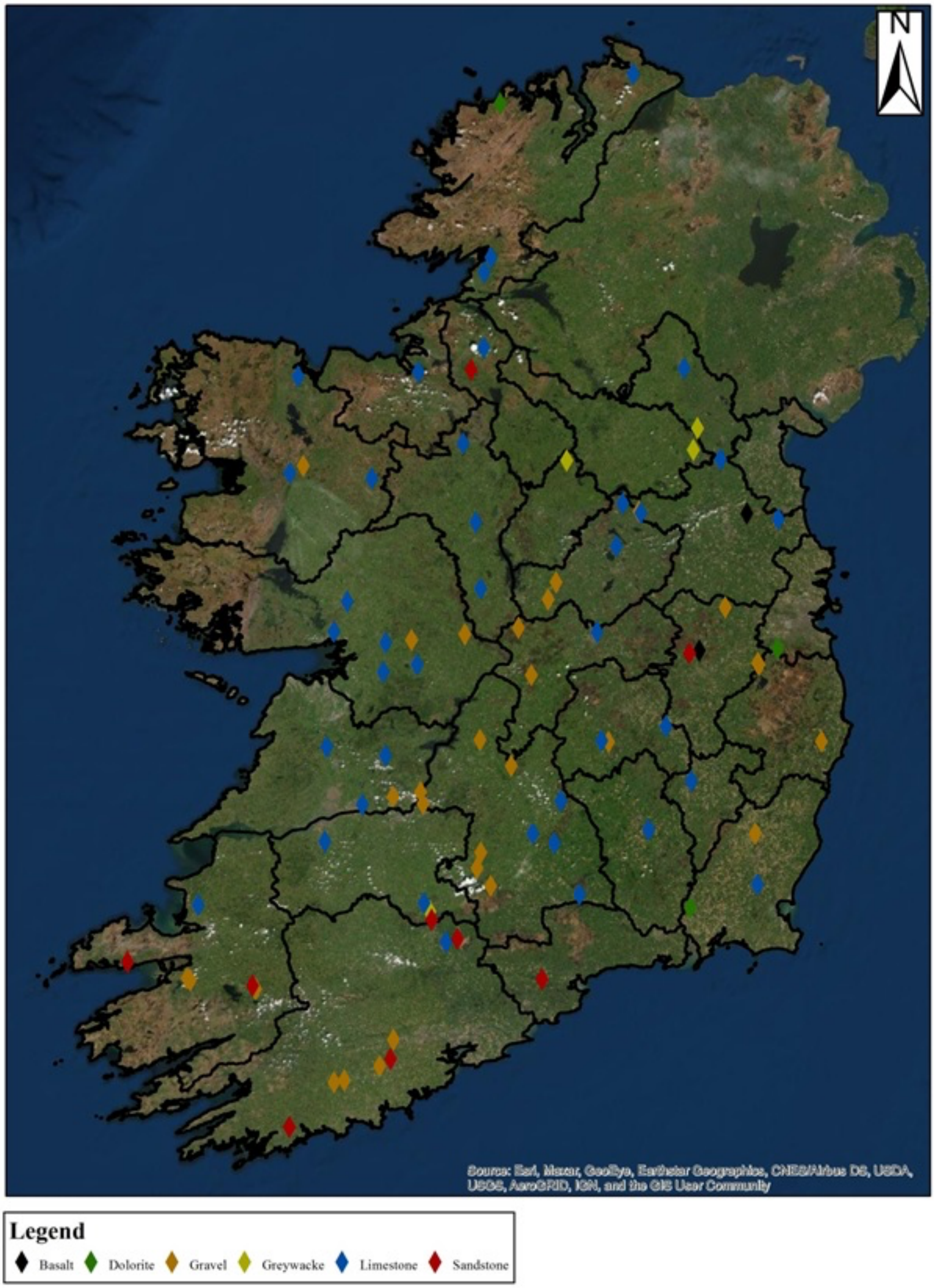

N
Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
Legend
Basalt
Dolorite
Gravel
Greywacke
Limestone
Sandstone

Fig 2

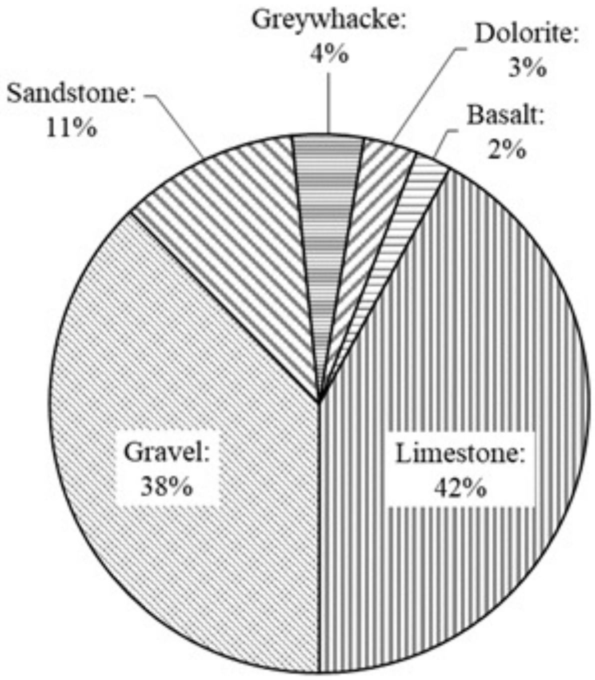

Greywhacke: 4%
Dolorite: 3%
Sandstone: 11%
Basalt: 2%
Gravel: 38%
Limestone: 42%

Fig 3

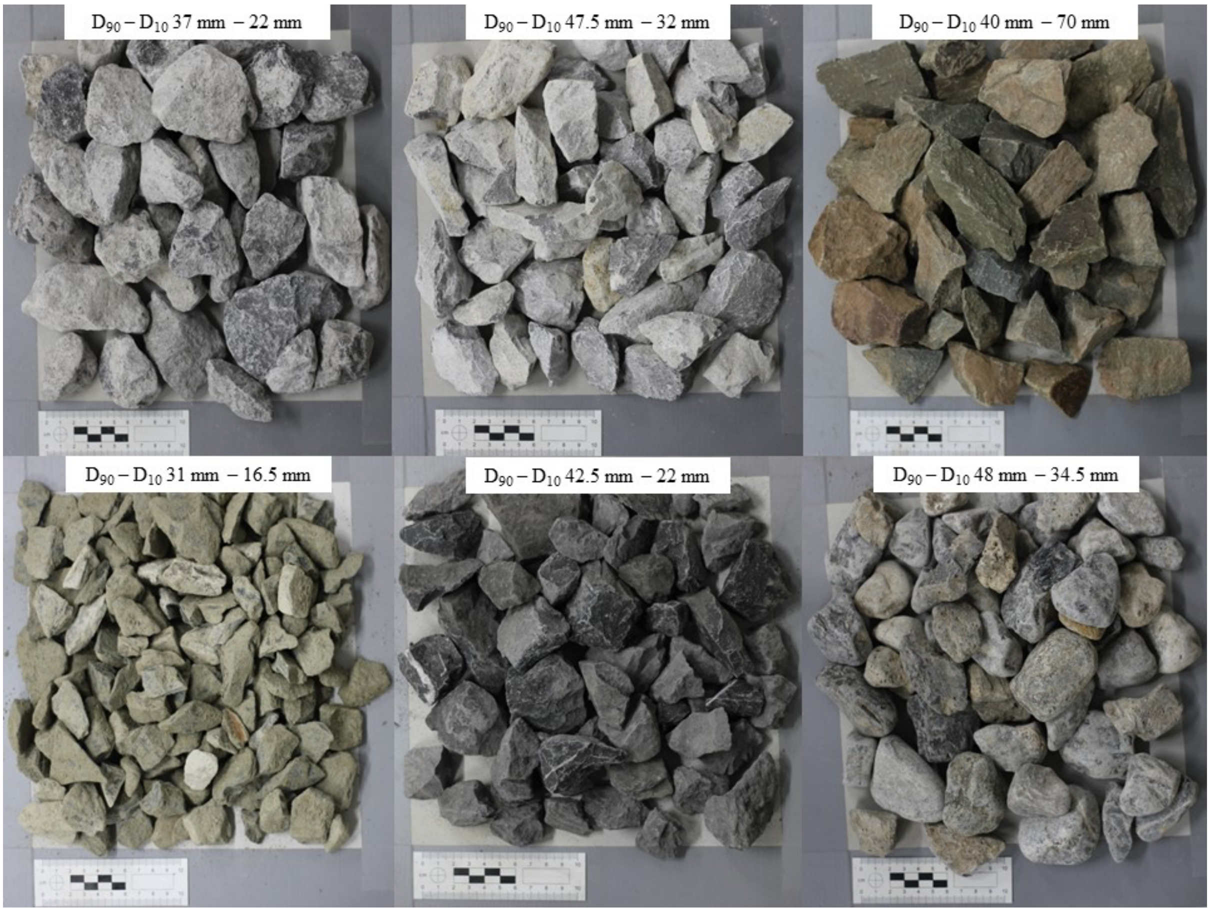
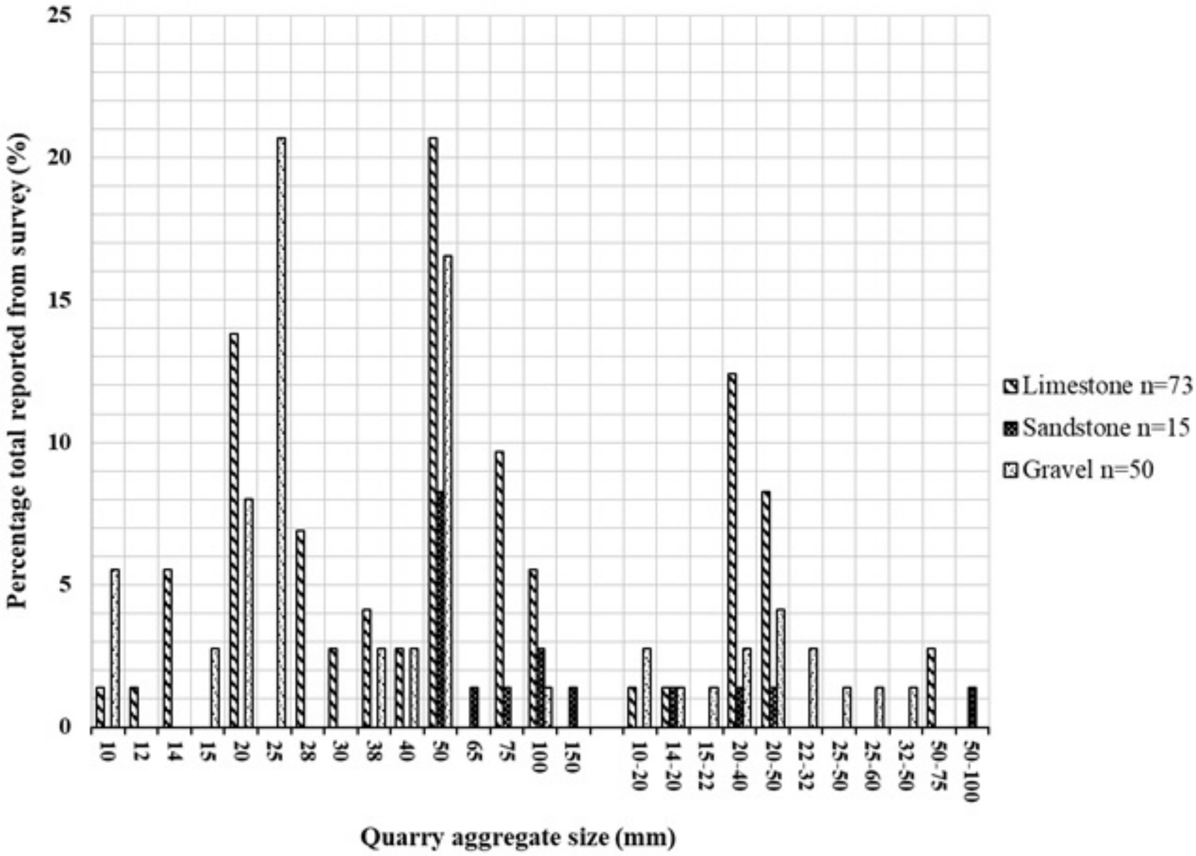

$D_{90} – D_{10}$ 37 mm – 22 mm
$D_{90} – D_{10}$ 47.5 mm – 32 mm
$D_{90} – D_{10}$ 40 mm – 70 mm
$D_{90} – D_{10}$ 31 mm – 16.5 mm
$D_{90} – D_{10}$ 42.5 mm – 22 mm
$D_{90} – D_{10}$ 48 mm – 34.5 mm

Fig 4



Percentage total reported from survey (%)
25
20
15
10
5
0
10
12
14
15
20
25
28
30
38
40
50
65
75
100
150
10-20
14-20
15-22
20-40
20-50
22-32
25-50
25-60
32-50
50-75
50-100
Quarry aggregate size (mm)
Limestone n=73
Sandstone n=15
Gravel n=50

Fig 5

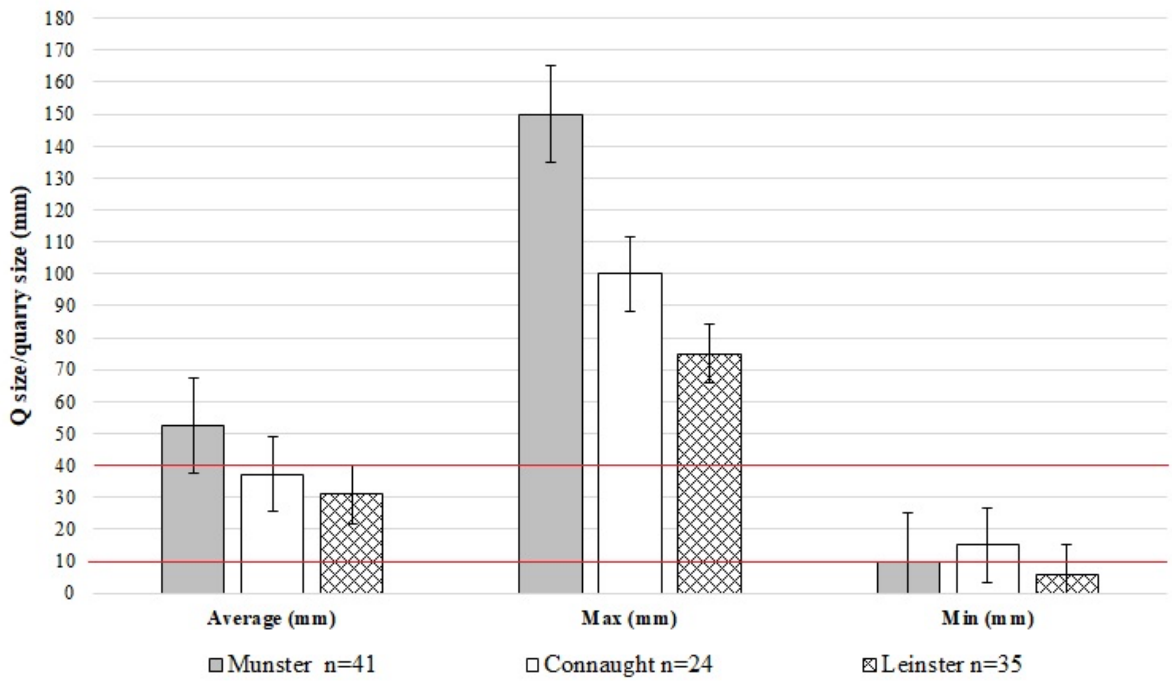

Q size/quarry size (mm)
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
Average (mm)
Max (mm)
Min (mm)
Munster n=41
Connaught n=24
Leinster n=35

Fig 6

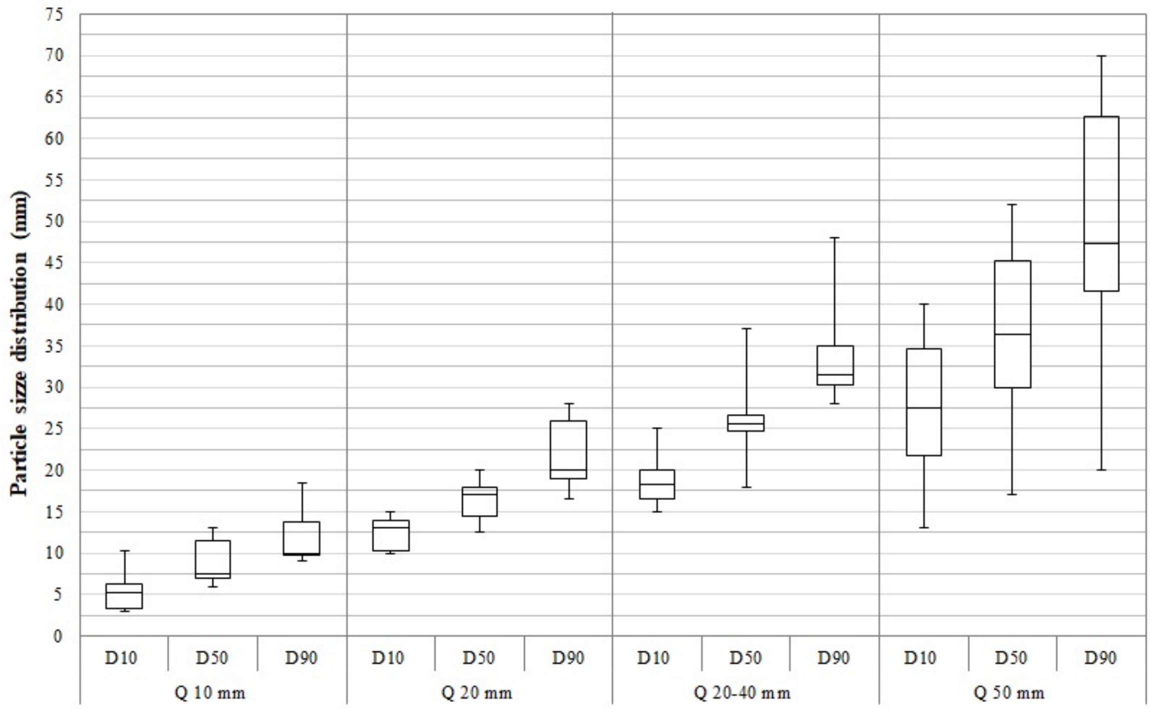
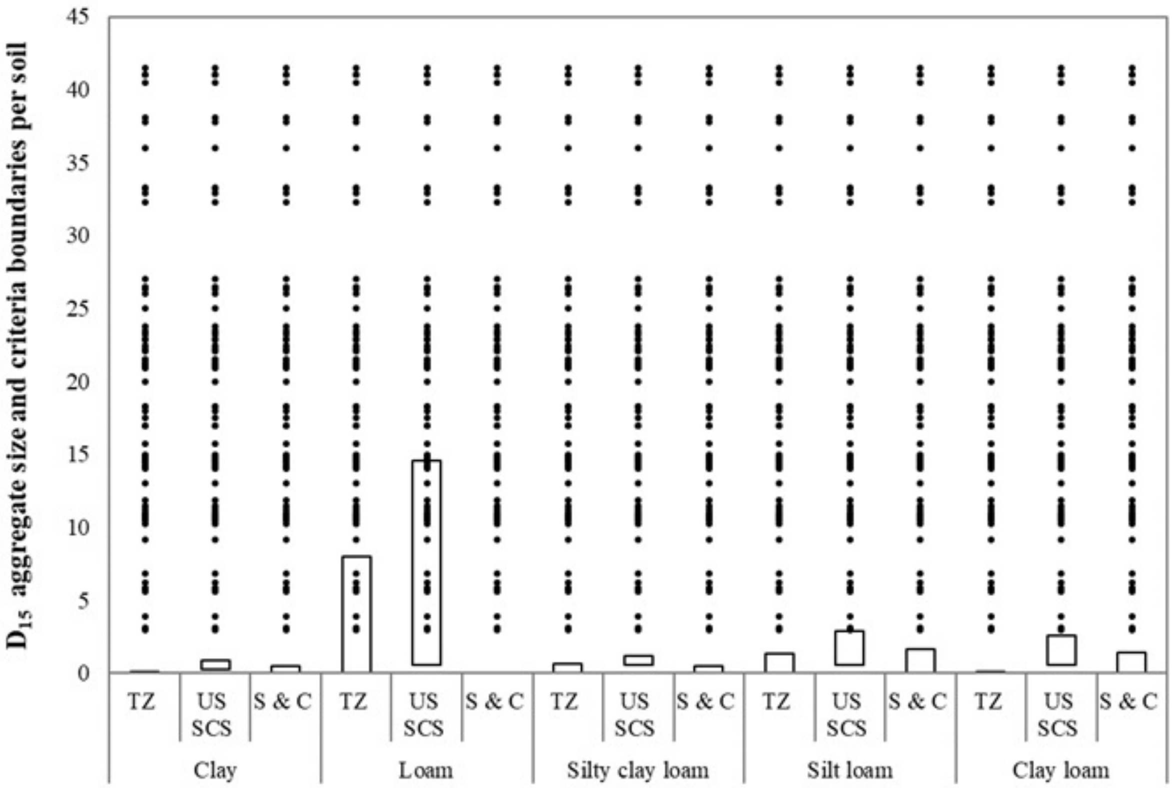

Particle size distribution (mm)
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
D10
D50
D90
Q 10 mm
Q 20 mm
Q 20-40 mm
Q 50 mm

Fig 7



D15 aggregate size and criteria boundaries per soil
45
40
35
30
25
20
15
10
5
0
TZ
US SCS
S & C
Clay
Loam
Silty clay loam
Silt loam
Clay loam