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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, that is, "50 mm", or a graded size, that is, 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 was 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 15% passing size, is required.

Keywords

Drain envelopes • drainage materials • 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), made from waste synthetic fibres and geotextiles, which may be woven, non-woven or knitted (Stuyt *et al.*, 2005). The type of materials (mineral, organic or synthetic) in use in many countries is guided by the availability, relative cost and established criteria in use in the country. In the Republic of Ireland (henceforth Ireland), e.g. 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.

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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 (Clagnan *et al*., 2018; Tuohy *et al*., 2018a, 2018b; Valbuena-Parralejo *et al*., 2019). 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 e-mail 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); and aggregate sizes (henceforth “quarry size” or “Q size”) sold (three selections maximum), which represents an approximation of the size of aggregate in mm as specified by the quarry. This can be a single size (where the gradation is unknown) or, in some cases, a size range (where the gradation is indicated). 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).

In order to observe potential differences between the stated particle size distribution (PSD) sizes under the quarry labelled sizes (Q size, either as a single size or graded figure) across different quarries, and the actual PSD sizes, 74 samples were prepared for PSD analysis according to ASTM (2018) and a dry sieve analysis was conducted according to ASTM (2019a). The four most popular indicative Q sizes from the survey will be used for 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, respectively), grouped under the individual Q sizes.

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

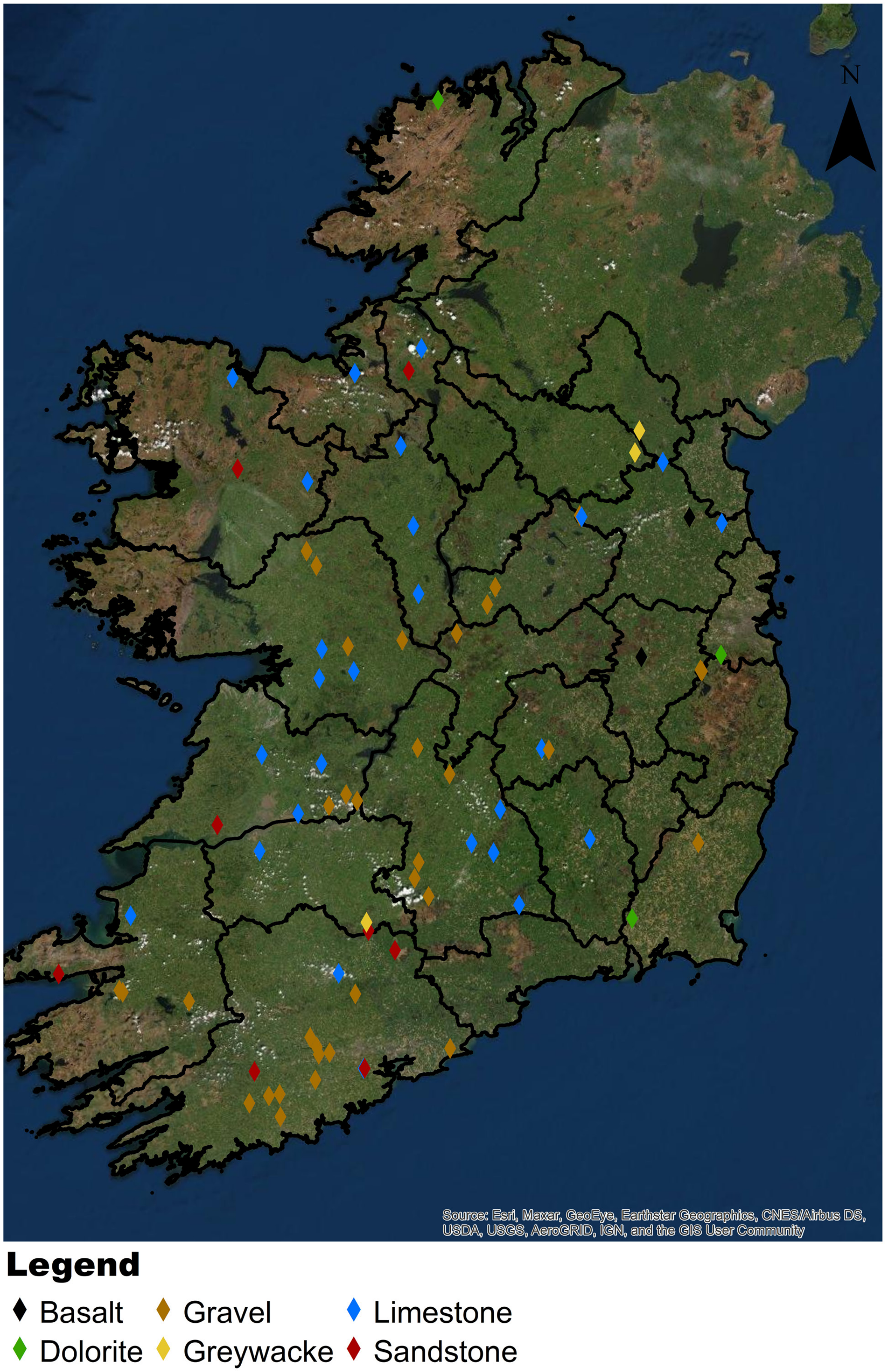

Figure 1. Surveyed quarry locations across Ireland, by lithology.

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 & Peck, 1961), and filter criteria developed by Sherard *et al.* (1984) for protection of hydraulic structures. While not intended for application in subsurface drainage, the principles may equally well be applied for the design of gravel envelopes (Stuyt *et al.*, 2005). To facilitate comparison of the surveyed aggregate size to the three filter criteria, the D_{15} was calculated for all 74 aggregates. The D_{15} is used by all three of the above criteria to limit the loss of fine soil material (filter function) into the drainage envelope and through the drain, where 85% of all soil material would be prevented from entering the envelope, while still maintaining hydraulic function of the envelope. This D_{15} value originated from Terzaghi's considerations on laboratory experiments, to limit the loss of fine sediment (Terzaghi & Peck, 1961; Dierickx, 1993). While Dierickx (1993) states that "it can be seen that the criteria of various sources do not match, even taking into account the distinction between filter material (mechanical function) and envelope function (hydraulic function)", the two other criteria (Sherard *et al.*, 1984; SCS, 1988) have been designed based on this work carried out by Terzaghi and thus the D_{15} criteria can be used as a comparison for the suitability of these aggregates based on different soil textures. 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. A univariate analysis of the data was conducted to determine normality. The data were shown to have a normal distribution of data. Following this, comparisons between the indicative Q sizes and the D_{10}, D_{50} and D_{90} values were made using a PROC ANOVA analysis with Bonferroni (Dunn) t test 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. Based on visual observation from 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 80% of the total lithologies surveyed, with sandstone making up another 11% (Figure 2).

The Q sizes, as reported by the quarries, were variable being reported as a single indicative size or a size range, and showed that a wide range of material sizes were in use for land drainage installation across the country (Figure 3). Figure 4 shows the most popular Q sizes by lithology. For limestone, the 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, 25 mm, 20 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 90%, 50% and 10% marks for a single Q size. This variation increased with increasing Q size. The mean D_{90} values corresponded closest to the associated Q sizes. Statistical analysis indicated significant differences in actual

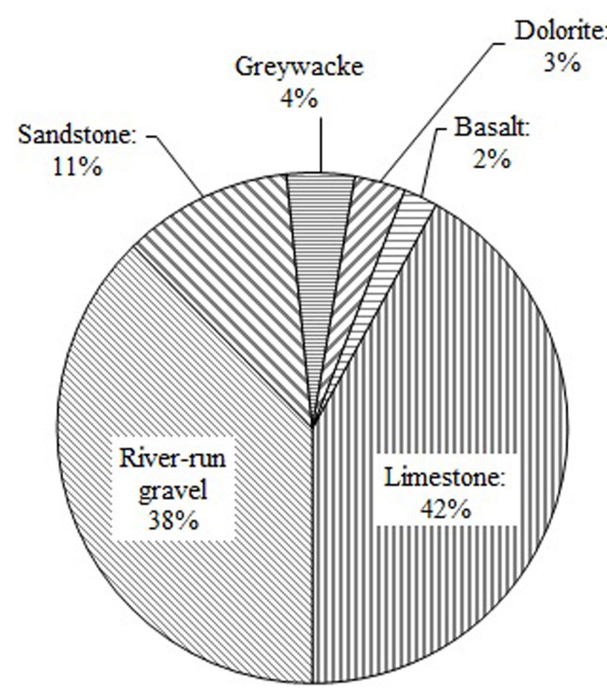

Figure 2. The most common quarry types in Ireland, by lithology (n = 100).

Figure 3. A selection of Q50 mm aggregates of different lithologies.

size between Q sizes for D_{10}, D_{50} and D_{90} parameters ($P < 0.0001$). However, Q10 (quarry size in mm) 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. When the specifications were applied (based on the D15/15% passing size of an aggregate) to the five soil textures to determine aggregate suitability, only a proportion of aggregates were suitable for the loam soil, where 31% (23 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) meet Terzaghi & Peck (1961) specifications.

When the four other soil textures were applied to the specifications, none of the aggregates were shown to be a suitable aggregate to act as a filter for these soil textures.

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

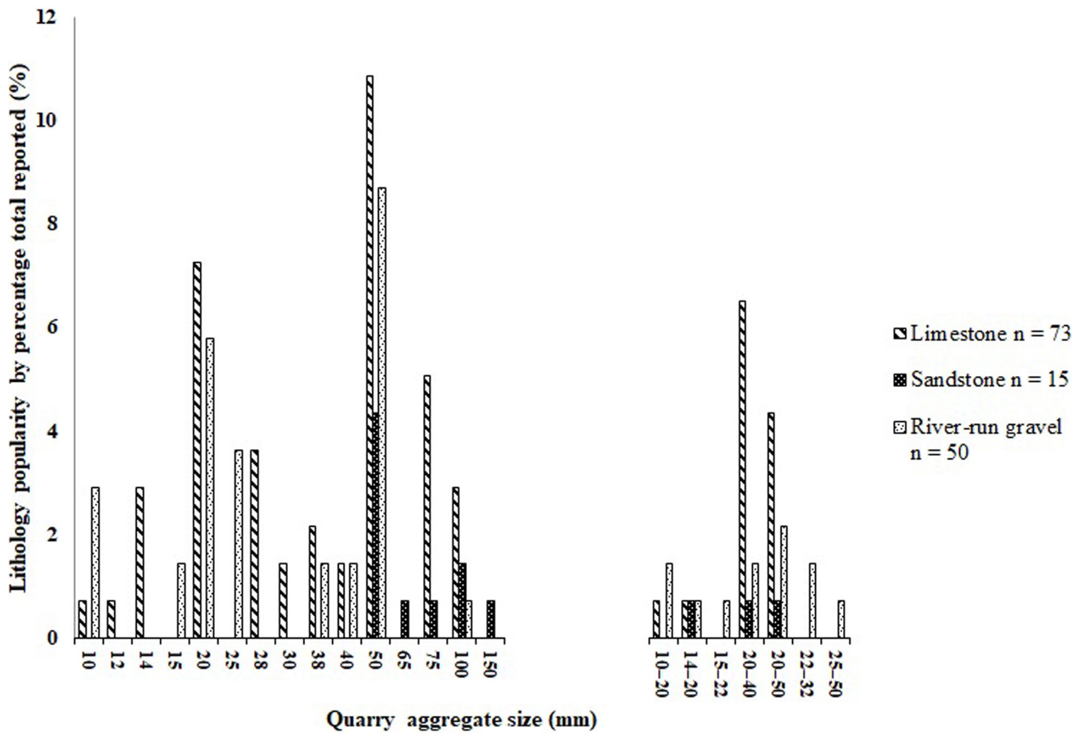

Figure 4. The most popular aggregate Q sizes (indicative sizes as reported by quarries, left: single size and right: grading band) for land drainage from quarries surveyed by lithology (n = 138).

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 & Peck (1961) criteria for a loam soil texture. Generally, loam soils are less inclined to require extensive artificial drainage, and most drainage works will

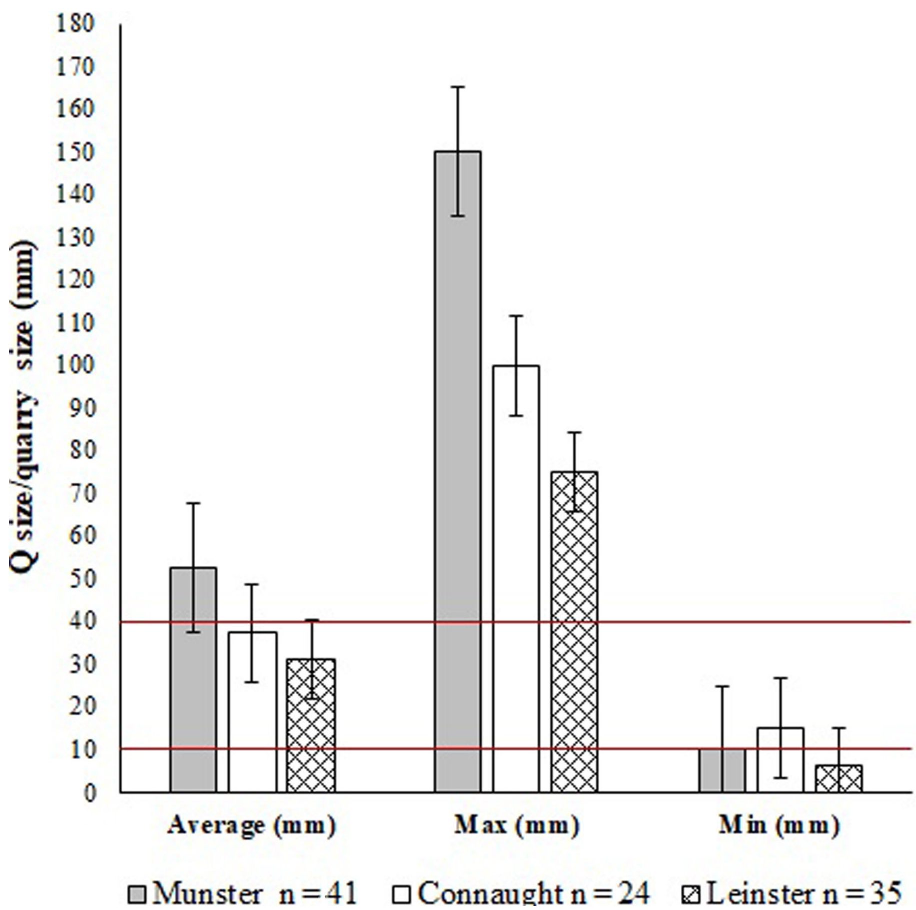

Figure 5. The average (mean of the mean), minimum (mean of the minimum) and maximum (mean of the maximum) Q sizes (inclusive of all lithologies) within each province based on survey data collected. The recommended size range of 10–40 mm from Teagasc (2013) is highlighted in red.

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 (Stuyt *et al.*, 2005; Teagasc, 2013). 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 minimise 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

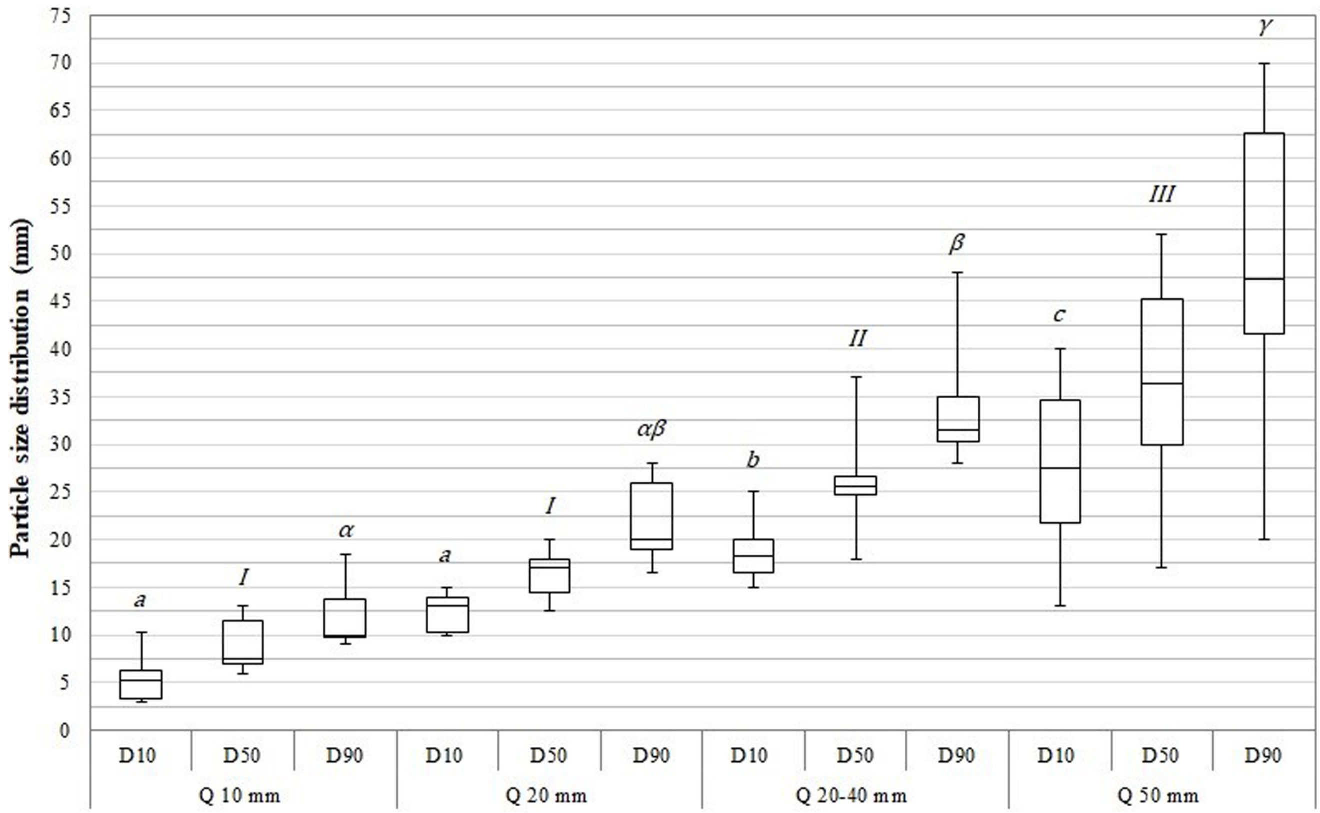

Figure 6. Q sizes, representing an approximation of the size of aggregate in mm as specified by the quarry, showing estimated 10%, 50% and 90% passing (D_{10}, D_{50} and D_{90}) figures indicating labelling variation across different quarries. Means with the same symbol are not significantly different from each other. D_{10} values are denoted using a, b, c; D_{50} values are denoted using I, II, III; D_{90} values are denoted using α, β, γ.

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 (soils rich in clay particles).

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_{90}–D_{10}) 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 filter 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.

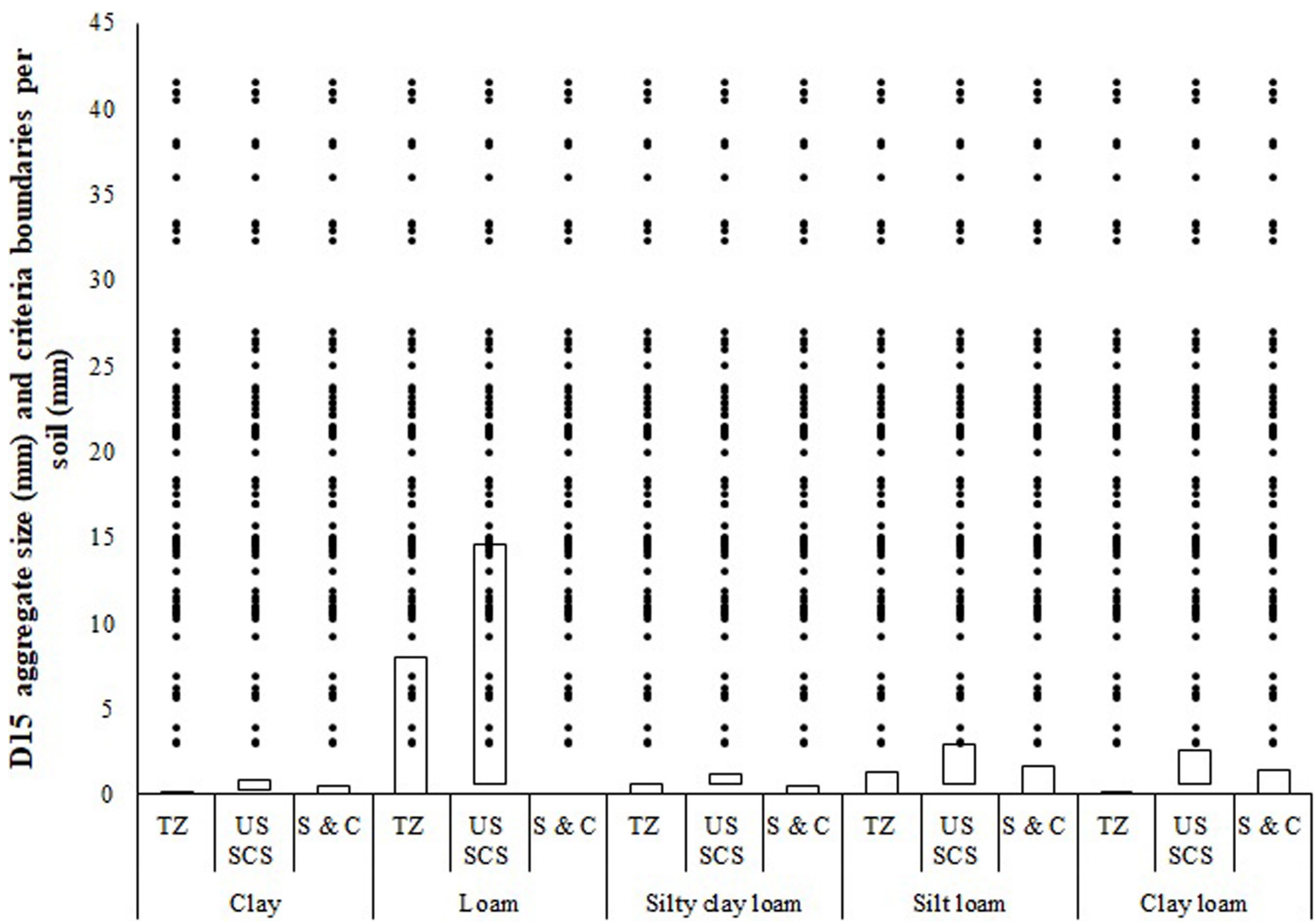

Figure 7. Recommended aggregate size using three filter design criteria (Terzaghi's [Terzaghi & Peck, 1961] ["TZ"]; US Soil Conservation Service [SCS, 1988] ["US SCS"]; Filters for Silts and Clays [Sherard *et al*., 1984] ["S & C"]) applied to five soil textures, showing the suitability of 74 gravels characterised in this study. Aggregate size is the percentage of aggregates with a particle size <15% of the total mass (D_{15}).

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