Assessment of materials used in land drainage systems

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Abstract

Agricultural land drainage is one of a number of critical components to sustaining food production on poorly drained mineral soils. The key to efficient and consistent drainage system performance is an appropriate type and size of envelope material to surround the in-field drainage pipe that matches soil characteristics. The drain envelope must offer proficiency in a number of functions, such as protecting the pipe from excessive sedimentation and reducing water entry resistance around the pipe and surrounding soil. An efficient drainage envelope must perform well from both filtration and hydraulic perspectives. In Ireland, guidelines on aggregate size ranges that perform well from both filtration and hydraulic perspectives were never formally tested under scientific conditions. Such guidelines were based on the local availability of aggregates and stemmed from practical experience and localised field observations. In addition, alternative envelope materials (e.g., synthetic) are coming to market in Ireland. These have been used by landowners but remain untested in heavy-textured mineral soil. Indeed, there have been no experiments that compare filtration and hydraulic performance together with costs for various envelope types in Ireland.

Therefore, the aims of this study were to: (1) quantify the size, type and popularity of aggregates supplied for use in agricultural land drainage systems, and to evaluate their suitability for use in mineral soils (2) provide guidance for contractors and farmers on the selection of suitable aggregate material, taking cognisance of performance, cost and lifespan (3) assess the hydraulic and filter performance of different drainage stone aggregates to elucidate an optimum size range for use in clay-textured soils, and (4) investigate the suitability of synthetic envelopes as an alternative to, or used in conjunction with, stone aggregate in clay-textured soils.

Before the experimental phase of the work, the availability of stone aggregate used for land drainage works was established. A national survey was conducted across eighty-six quarries throughout Ireland to gather data on quarry distribution, aggregate type, sizes, popularity, and availability, and determine their suitability based on existing filter design criteria. The results indicated that limestone and river-run gravel (80% of all lithologies available at quarries) are widespread throughout the country. The quarry aggregate sizes changed across lithology and region and were, in most cases, larger than what is currently recommended by Ireland’s national agricultural research and advisory agency, Teagasc, (10 to 40 mm) for agricultural land drainage. The suitability of these aggregates as drainage envelopes in five soils of different textures was evaluated using three established design criteria. It was found that most of the aggregate in use is too large for heavy soil textures and is therefore unsuitable as drainage envelope material.

Laboratory experiments were designed and conducted to quantify aggregate and synthetic envelope filter and hydraulic performance in clay-textured mineral soils using various aggregate and synthetic envelope configurations. The results indicated that only aggregates in the 0.7 to 19 mm size range performed adequately from both the filtration and hydraulic perspectives and were deemed suitable for use with a clay-textured soil. Based on this study, the use of synthetic envelopes, either alone or in combination with stone aggregate, is not recommended in Ireland, from both performance and cost perspectives.

Declaration

I hereby certify that the submitted work, unless otherwise acknowledged, is my own work and was completed while registered as a candidate for the degree stated on the Title Page. I have not obtained a degree elsewhere on the basis of the research presented in this submitted work.

Ian Byrne

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I would like to thank my three supervisors, who played a major role in this research: Prof. Mark Healy, Prof. Owen Fenton, and Dr. Patrick Tuohy. Their support, encouragement, honesty, and time spent reviewing all aspects of my work were greatly appreciated.

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I would like to thank Dr. Patrick Tuohy and John Paul Murphy for the development of a purpose-built laboratory in which to conduct my research. Many thanks to the quarries across Ireland that provided the large quantity of aggregate necessary to make this study possible.

Completing a PhD is not easy, and I'd like to thank my friends for their unwavering support during this time. That support has come with an insight into knowing when to be an ear for me to discuss all aspects of the PhD and when to tell me to be quiet, forget about it, and enjoy myself for a while.

I would especially like to thank Paola for her patience, especially on the endless weekends spent writing, and her constant support and encouragement throughout the whole process.

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Abbreviations

ANOVA	Analysis of Variance
ASL	Above Sea Level
CH_4	Methane
CO_2	Carbon Dioxide
D_{xx}	Percentage passing value
DRP	Dissolved Reactive Phosphorus
GIS	Geographical Information System
K_s	Saturated Hydraulic Conductivity
MTCO2e	Metric Tonnes of Carbon Dioxide Equivalent
N	Nitrogen
PLMs	Prewrapped Loose Materials
PROC	Programmed Random Occurrence
PSD	Particle Size Distribution
Qs	Quarry Size
TSS	Total Suspended Solids
µm	Micron or Micrometre
VAT	Value Added Tax
VDA	Visual Drainage Assessment

Chapter 1 – Introduction

1.1 Overview

Artificial underground drainage in agriculture plays an important role in the removal of excess surface and subsurface water from poorly drained, heavy textured 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 in mineral soils has many benefits, including increased trafficability and crop yield, reduced surface runoff, improved soil structure, and reduced greenhouse gas (GHG) and phosphorus (P) losses (Daly et al., 2017). Negative aspects include loss of the attenuation capacity of the soil profile, with nitrogen (N), dissolved reactive phosphorus (DRP), and sediment losses occurring in this drainage water (Ibrahim et al., 2013; Moloney et al., 2020).

The drain envelope has typically three main roles: filtration of sediment, hydraulic function (facilitation of water movement to the drain), and support (to prevent damage to the pipe wall). Envelope materials may be composed of mineral, organic or synthetic materials. The material used is typically guided by availability, relative cost and established criteria in a specific country. In the Republic of Ireland, for example, mineral aggregate (crushed stone and river-run gravel) is selected on the basis of cost, availability and convenience, and not on established design criteria or its appropriateness for a given soil texture (Teagasc, 2022).

1.2 Knowledge gaps

This study aims to address several key gaps in envelope design in clay-textured soils in Ireland:

- The distribution, type, popularity, size, and availability of aggregate for drainage envelopes are currently unknown. An aggregate gradation of 10 to 40 mm has been recommended based on field observations (Teagasc, 2022), but the facility to apply these recommendations throughout the country is unknown.
- Most of the detailed drainage research in Ireland was carried out from the 1960-1980s, with very little research since then being carried out before the

introduction of the Teagasc Heavy Soils Programme in 2011. Many of the problems associated with drainage in Ireland currently are the same as those encountered in the research in the 1960-1980s. No research has been carried out on the availability and suitability of envelope systems in Ireland.

- While numerous specifications are available to determine suitable aggregate gradations for specific soil textures, these specifications are not consistent, and the suitability of various aggregate gradations for use with standard corrugated pipes is unknown.

1.3 Research aims

The overall objective of this study was to establish guidelines on the performance, cost, and lifespan of a range of envelope materials used in agricultural land drainage systems by examining the availability of currently available stone aggregate, assessing the hydraulic and filter performance of these currently available aggregates, and investigating synthetic envelopes as an alternative or complement to stone aggregate.

Specific Objectives:

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

- Assess the hydraulic and filter performance of different drainage stone aggregates to elucidate an optimum size range for use in clay-textured soils.

- Investigate the suitability of synthetic envelopes as an alternative to, or used in conjunction with, stone aggregate in clay-textured soils.

1.4 Thesis structure and objectives

The thesis contains six chapters (Figure 1.1). Chapter 2 reviews the development of land drainage, drainage system materials, and drainage system design both internationally and within Ireland. It then provides further detail on the different types of drainage systems employed and the situations in which they should be applied. Chapter 3 describes 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. Chapter 4 assesses the hydraulic and filter performance of different drainage stone aggregates to elucidate an optimum size range for use in clay-textured soils. Chapter 5 investigates the suitability of synthetic envelopes as an alternative or complement to stone aggregate in clay-textured soils in Ireland. Chapter 6 discusses the overall conclusions of the thesis, along with recommendations for future work.

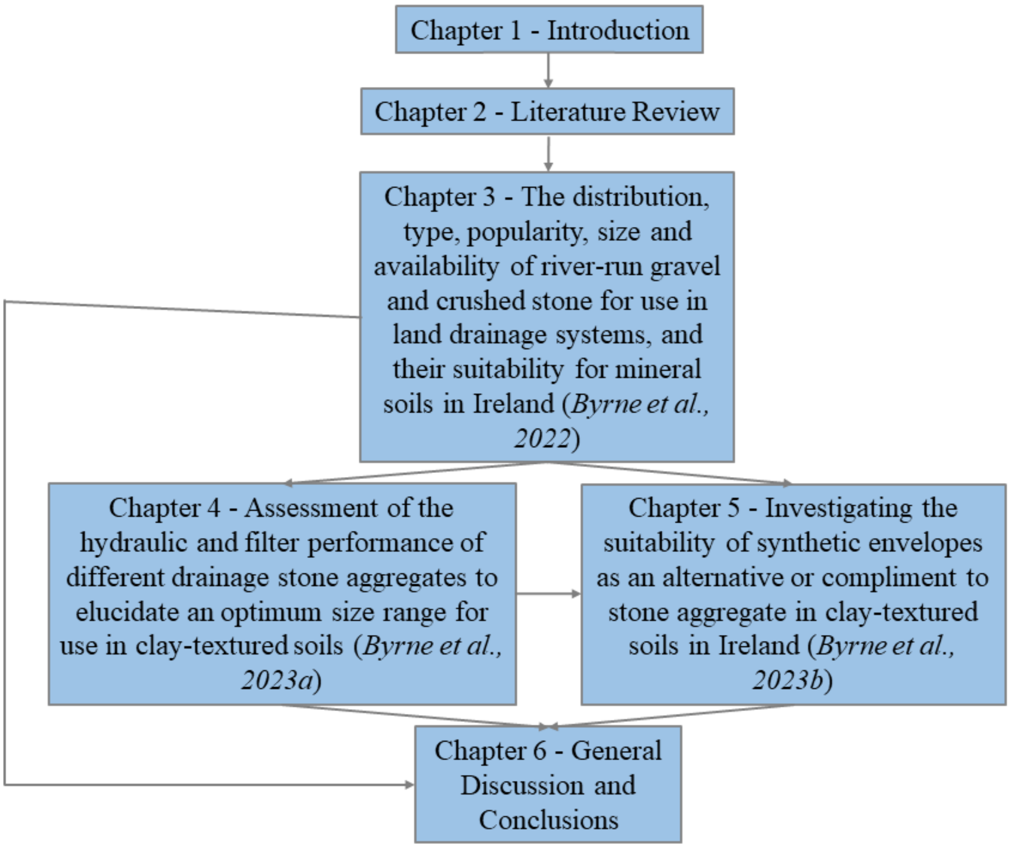


Figure 1.1 Flow chart for the thesis.

1.5 Contribution to Existing Knowledge

1.5.1 Journal Articles (Published)

Byrne, I., Healy, M.G., Fenton, O. and Tuohy, P. 2022. 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. *Irish Journal of Agricultural and Food Research*. DOI: 10.15212/ijafr-2022-0006.

Byrne, I., Healy, M.G., Fenton, O. and Tuohy, P. 2023a. Assessment of the hydraulic and filter characteristics of different drainage stone aggregates to elucidate an optimum size range for use in heavy textured soils. *Agricultural Water Management,* 278, 108164. DOI: 10.1016/j.agwat.2023.108164.

Byrne, I., Healy, M.G., Fenton, O. and Tuohy, P. 2023b. Investigating the suitability of synthetic envelopes as an alternative or complement to stone aggregate in clay-textured soils in Ireland. *Geoderma Regional*, 32, e00598. DOI: 10.1016/j.geodrs. 2022.e00598.

1.5.2 Technical Publications

Byrne, I., Healy, M.G., Fenton, O. and Tuohy, P. 2022. Investigating the suitability of geotextile envelopes as an alternative to stone aggregate in clay-textured soils in Ireland. *11th International Drainage Symposium*, 30th August 2022, Des Moines, Iowa. Poster presentation.

Byrne, I., Healy, M.G., Fenton, O. and Tuohy, P. 2022. Building drainage systems for the future: How drainage material selection plays an important role in optimal functionality in an increasingly volatile climate. *International Symposium on Climate-Resilient Agri-Environmental Systems (ISCRAES),* 28th August 2022, Talbot Hotel Stillorgan, Dublin. Poster presentation.

Byrne, I., Healy, M.G., Fenton, O. and Tuohy, P. 2020. The suitability of available aggregates for use in land drainage systems in Ireland. *Walsh Scholarships Programme National Forum*. Teagasc Ashtown, Co Meath. Poster presentation.

Byrne, I., Healy, M.G., Fenton, O. and Tuohy, P. 2019. How the availability and cost of aggregates across Ireland can influence the selection of poor-quality materials for land drainage systems. *Teagasc SRUC Conference*. 6th December 2019, Teagasc Ashtown, Co Meath. Poster presentation.

1.5.3 Practical/Popular publications

Byrne, I., Healy, M.G., Fenton, O. and Tuohy, P. 2021. Evaluation of land drainage system materials. Irish Dairying – Delivering Sustainability, *Moorepark '21 Open Day*, 14th September 2021, pp. 268.

Byrne, I., Healy, M.G., Fenton, O. and Tuohy, P. 2021. Aggregate suitability for drainage systems. Irish Dairying – Delivering Sustainability, *Moorepark '21 Open Day*, 14th September 2021.

Byrne, I., Healy, M.G., Fenton, O. and Tuohy, P. 2019. Aggregates in land drainage systems. Irish Dairying – Growing Sustainably, *Moorepark '19 Open Day*, 3rd July 2019.

Byrne, I., Healy, M.G., Fenton, O. and Tuohy, P. 2019. Drainage: choosing your aggregates. *Today's Farm*. July – August 2019, 28-29. Available at: https://www.teagasc.ie/media/website/publications/2019/Drainage-choosing-your-aggregates.pdf. Accessed on: 01/06/2022.

Chapter 2 – Literature Review

2.1 Overview

The land use, soil types and current and historical drainage systems used in Ireland are reviewed in this chapter, highlighting the problems associated with the implementation of envelope design criteria and the shortcomings of currently used drainage envelope systems in Ireland.

2.2 Agricultural land use in Ireland

Agricultural land in Ireland accounts for 68% of the national land cover. Pastureland is the main agricultural class in Ireland (55% of the national land cover) (EPA, 2018). Food Wise 2025, an initiative set up by the Department of Agriculture, Food and the Marine, aims to grow food exports to €19bn by 2025 while increasing agricultural sustainability. Food Wise aims to increase the grassland utilisation on livestock farms by 2 t/ha (circa 20-30% yield increase) while maintaining sustainable practices (DAFM, 2015). Food Vision 2030, the new replacement strategy to guide the agri-food industry until 2030, places economic and environmental sustainability at the forefront of future policy (DAFM, 2021).

Draining wet mineral soils in Ireland can contribute to environmental sustainability by potentially abating 0.2 MTCO2e (metric tons of carbon dioxide equivalent), as nitrous oxide (N_2O) is highest in saturated soils (by draining 20% of grassland) (Lanigan and Donnellan, 2019). This is a key component of the Marginal Abetment Cost Curve, a strategy formulated by Teagasc (the National Agriculture and Food Authority in Ireland) to reduce methane (CH_4) and N_2O emissions in Irish agriculture (Lanigan and Donnellan, 2019). Increased economic sustainability is also achieved by an extended grazing season and increased grass growth in soils where the drainage class is predominately imperfectly or poorly drained. Environmental sustainability can be achieved through reduced CH_4 emissions due to improved manure management practices associated with an extended grazing season (Lanigan and Donnellan, 2019).

2.3 Irish soils and climate

Agricultural drainage conditions worldwide can be broadly grouped into three zones: the temperate zone, the semi-arid tropical zone, and the semi-humid tropical zone (Vlotman et al., 2020). Ireland is within the temperate zone, where the main role of drainage is to prevent waterlogging due to excess water from surplus rainfall and provide good trafficability conditions for farm machinery (Schultz et al., 2007). Soil drainage problems in Ireland have been well documented (Galvin, 1971). Seepage and springs (38%), impermeable soils (31%), and high-water table (24%), were found to be the main issues (Galvin, 1966; Galvin, 1969; Galvin, 1971). The main soil class with poor drainage characteristics are gley soils (poorly drained Luvisols and Podzols), which are mainly slow-draining and have high silt and clay contents. Gley soils are divided into two main groups: surface and groundwater gleys (Figure 2.1). Surface water gleys have perched water tables with an impermeable layer in the top 40 cm that does not allow the vertical movement of water through the soil. Groundwater gleys are caused by a high-water table close to the surface of the ground in low-lying topography that may either have free-draining or impervious layers on top (Mulqueen, 1998).

Average annual Irish rainfall is approximately 1230 mm (1981 – 2020) (Figure 2.2). The driest months are April through July, with an average of 80 mm each month, while October through January average approximately 130 mm (Walsh, 2012). The main impacts of climate change on Ireland will result in increased rainfall intensity with expected decreases in rainfall in the spring and summer periods, while increased rainfall will be observed during the winter and autumn months, and greater rainfall will occur in the west and less rainfall will occur in the east (Nolan et al., 2017; Nolan and Flanagan, 2020). Increased rainfall intensity has been identified as a constraint to achieving agricultural productivity and environmental targets. Figure 2.3 shows the annual average actual evapotranspiration and annual average soil moisture deficit Ireland (EPA, 2019). Escalations in rainfall intensity will likely result in increased trafficability issues and reduced yields (Kiely, 1999). To reduce problems associated with excess water, effective and site-specific land drainage design is required to achieve adequate discharge levels from a particular soil (Tuohy et al., 2018b).

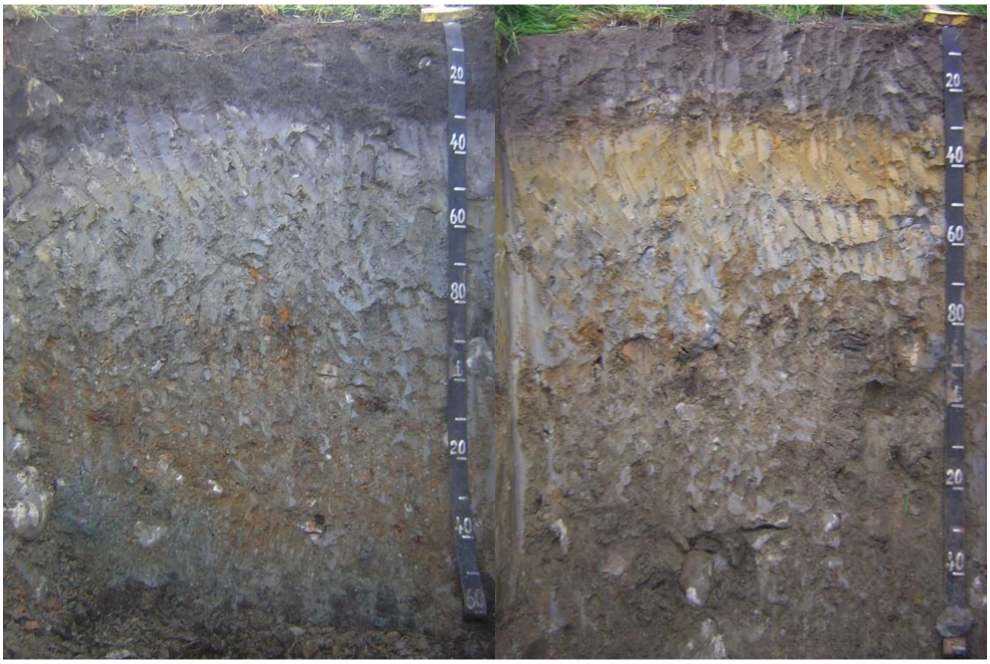


Figure 2.1 Surface (left) and Groundwater gleys (right).

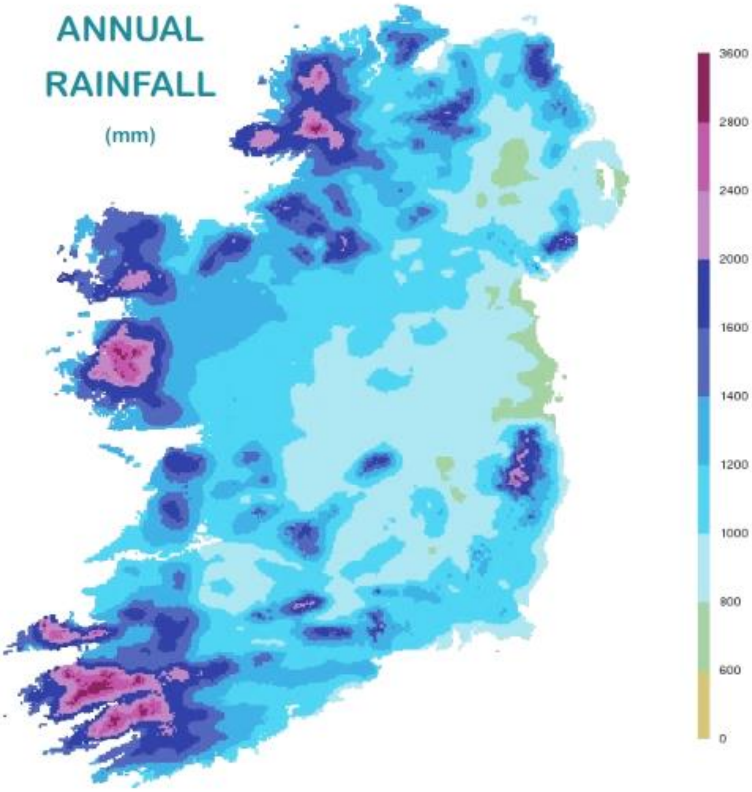


Figure 2.2 Mean annual rainfall in Ireland, 1981-2010 (Met Eireann, 2012).

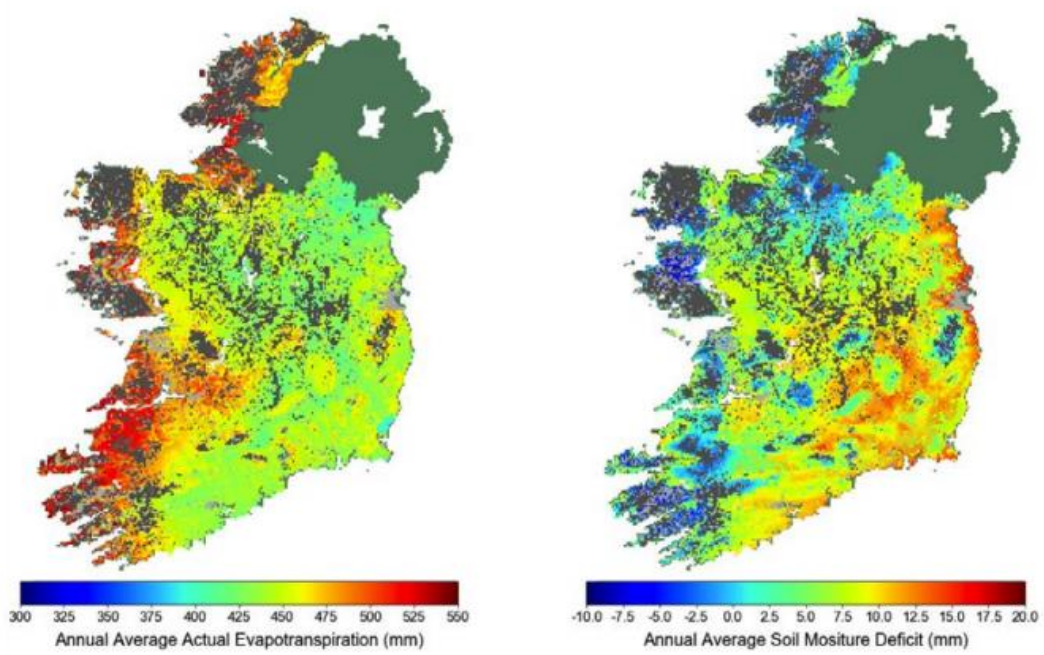


Figure 2.3 Annual average actual evapotranspiration and annual average soil moisture deficit Ireland (EPA, 2019).

2.4 History of land drainage in Ireland and abroad

In Ireland, agricultural land drainage is mainly undertaken by two governmental bodies and by farmers on a field-scale level. The Office of Public Works (OPW) carries out arterial drainage by developing main channels across low-lying areas, while field-scale drainage is carried out by farmers with advice on field drainage from Teagasc (formerly An Foras Taluntais) (Galvin, 1966; Ryan, 1986). Table 2.1 shows the approximate area drained across Ireland from the period of 1842 to 1979. From 1842 to 1949, the OPW worked primarily on the arterial drainage of low-lying river catchments and tributaries. Notable acts within this period were the 1842 Drainage and Navigation Act (115 schemes and 101,200 ha drained) and the 1945 Arterial Drainage Act (34 schemes and 262,800 ha drained).

Table 2.1 The approximate area drained by each drainage scheme from 1842 to 1979 (Burdon, 1986).

Date	Title of the Act	Number of schemes	Approximate Area Drained	
			Hectares	Percentage area of island of Ireland
1842	Drainage and Navigation (1842-57)	115	101,200	1.46%
1863	Drainage and Land Improvement (1863-92)	63	52,500	0.76%
1866	Maintenance of Drainage	-	-	-
1924	Maintenance of Drainage	-	-	-
1925	Arterial Drainage	51	17,500	0.25%
1926	Owenmore Drainage	1	52,400	0.76%
1927	Barrow Drainage	-	-	-
1928	Arterial Drainage (Minor)	-	-	-
1929	Arterial Drainage	-	-	-
1929	Arterial Drainage (amendment)	-	-	-
1945	Arterial Drainage	34	262,800	3.81%
1946	Bord Na Mona	-	93,080	1.35%
1949	Land Reclamation	-	1,168,600	16.96%
1974	Farm Modernization Scheme	-	202,350	2.94%
1977	Water Pollution	-	-	-
1979	Western Drainage Scheme	-	80,940	1.17%
	Total drained under 10 acts/schemes		2,031,370	
	Total area of island of Ireland		6,890,000	

% drained under the acts/schemes	29.3%

The 1949 Land Rehabilitation Project, a scheme set up by the Department of Agriculture, provided financial aid for drainage works on farms. During this period, an estimated 1.2 million hectares were drained. It was estimated that at least half of Ireland’s land required either arterial or field drainage. By 1986, an estimated 60% of this had been completed, but drainage in some areas was not satisfactory, and additional measures were required (Burdon, 1986). After these measures, the first state-sponsored drainage schemes were conducted, where research initially focused on peat soils and subsequently on mineral soils. Peat drainage research mainly focused on drain spacing and water table control measures (Burke, 1961).

Research into the various drainage problems associated with mineral soils focused on the initial assessment of the problems encountered throughout Ireland. The problems encountered varied depending on the region, but the main sources of drainage problems were seepage and springs, impervious soils, and the water table. Additionally, it was determined that many of the drainage tiles installed under previous national schemes were either blocked or broken (43% on average) (Galvin, 1971). Galvin (1983) showed that both clay tile and plastic pipes were in use with a range of envelope materials. In clay tile drains, no envelope was used in most cases, with topsoil placed on top. Where plastic pipes were installed, an equal percentage of topsoil, organic materials, and stone aggregate was used.

After the assessment of drainage problems throughout Ireland, further research mainly focused on specific drainage research for shallow drainage systems, such as the advancement of mole and gravel mole systems, and the efficiency of these systems (Galvin, 1986; Mulqueen, 1985). In Europe and the United States during this time, considerable research was being conducted on envelope and pipe drain efficiency (1960s – late 1980s). Design criteria for mineral granular envelopes (the first generation of envelopes) were developed and have been successfully applied (Stuyt et al., 2005; Terzaghi and Peck, 1961; Willardson, 1974). While much of the envelope materials used in Ireland during this time (and currently) belong to this first generation of envelopes, no research was undertaken to determine the suitability of envelopes for Irish soil textures, and the design criteria developed were never formally adopted in Ireland.

Internationally, due to the high cost of granular envelopes, their high installation cost, and the scarcity or non-existence of suitable granular material, alternative envelope materials were sought. Initially, these alternative materials were organic fibres such as various crop residues or peat (organic materials were applied in Ireland in small quantities). Following this, materials were produced in strip form (organic or inorganic) and were laid down on top of the pipe (the second generation of envelopes). Organic envelope use has become widespread, but due to their susceptibility to microbiological decomposition, alternative materials were sought. Synthetic envelopes (the third generation of envelopes), made from synthetic fibres, gained popularity quite quickly, and their use is now commonplace in Europe and North America (Ghane et al., 2022). Synthetic envelopes are either loose synthetic fibres wrapped around a drainpipe or strips of thin geotextile material wrapped around the drainpipe (Stuyt et al., 2005; Yannopoulos et al., 2020). While the development of drain envelope materials from the 1960s to the present day occurred throughout Europe and North America, the development of drain envelope materials in Ireland never developed beyond granular envelopes (and, in smaller quantities, loose organic materials).

The development of land drainage system design had stalled since the late 1980s until the launch of the Heavy Soil Research Programme in 2011 (Teagasc, 2021). Drainage research conducted during this time mainly focused on mole (and gravel mole) drains (Tuohy et al., 2016a; Tuohy et al., 2018b) and on improving the performance and efficiency of drainage systems (Tuohy et al., 2016b; Tuohy et al., 2018a; Tuohy et al., 2021).

2.4.1 Drainage system types

The most widely used definition for drainage is the removal of excess surface and groundwater from any area. This may occur naturally or by virtue of man-made surface or subsurface conduits (International Commission on Irrigation and Drainage (ICID, 1996; Schultz et al., 2007). Man-made drainage systems can be divided into four groups: field systems, main systems, interceptor systems, and outfalls. These four groups are divided into two system types of subsurface drainage and surface/shallow drainage systems. Subsurface drainage can be defined as drainage, either natural or artificial, beneath the surface of the earth (Framji et al., 1987; Schultz, 1990). They are used in soil where excess water is able to infiltrate to the water table and then move as groundwater flow through the subsoil/substratum to the drains. Surface/shallow drainage systems are used where the infiltration of excess water is impeded at the surface or at a shallow depth in the root zone due to the presence of a poorly permeable layer (Oosterbaan and Nijland, 1994; Vlotman et al., 2020).

2.4.2 Research on heavy soil textures

In 2011, the Teagasc Heavy Soils Programme was established to develop a network of dairy farms on poorly drained, clay-textured soils as a means of testing strategies and management practices that could be implemented to improve the efficiency and performance of these poorly drained, clay-textured soil types. Thirty percent of Irish milk is produced on poorly drained soil in Ireland (O'Loughlin et al., 2012). The main areas within the programme are land drainage design, soil characterisation and land management, soil fertility and nutrient use efficiency, grassland management, and farm infrastructure (Teagasc, 2021). Across the 10 farms involved in the programme, milk solids per hectare have increased from 850 kg per hectare in 2011 to 1,405 kg/Ha in 2020, an increase of 65%, showing the clear benefit of the programme for implementing strategies and practices on poorly drained soils. The introduction of the programme highlighted a need for guidance in the implementation of drainage. In 2013, the Teagasc Manual on Drainage and Soil Management was published, which acted as a best practice manual for Ireland's farmers (Teagasc, 2013). A second edition of this was published in 2022 (Teagasc, 2022), including all the additional insight gained after 10 years of the Heavy Soils Programme.

The main lessons learned in the Heavy Soils Programme, from a land drainage point of view, were: the need to determine the soil drainage characteristics by carrying out a site and soil test pit investigation (visual drainage assessment (VDA)); the drainage method employed (shallow or groundwater system) should be determined by the presence or absence of a permeable soil layer identified during the VDA; drains are not effective unless they are placed in a permeable soil layer or complementary measures (mole drainage, sub-soiling etc.) are used to improve soil drainage capacity; and most of the stone used for land drainage is too big, with an optimum size range of aggregates being 10 to 40 mm (Teagasc, 2022). Regardless of the drainage method employed, a clear understanding of the soil parameters and properties is needed at a field-scale, and this can only be determined through a VDA prior to the commencement of drainage works.

2.5 Drainage systems

2.5.1 Drainage design procedure and visual drainage assessment

Prior to any drainage design procedure being undertaken, there is a need to conduct a soil survey to assess the soil's physical and hydrological properties on a field scale. Other important assessment criteria include topography, which plays a part in the design of subsurface drainage systems to determine alignment, grade, and overland relief; climate conditions within the area and water table determination, as information on real or perched water table depth is usually not determined in standard soil surveys (Vlotman et al., 2020).

When conducting drainage works, laboratory analysis is typically used to determine soil physical properties, but this method can be costly or time-consuming. Tuohy et al. (2016b) developed a VDA that relies on making an approximation of the permeability of different soil horizons using seven key indicators (water seepage, pan layers, texture, porosity, consistency, stone content, and root development). A design based on visual indicators would allow for the design of a drainage system at the lowest possible cost. When compared to an ideal design (that used soil physical measurements) and a standard design that used a model (that estimated water table control and drain discharge capacity), the VDA-based design performed equally well as the ideal system and significantly better than the standard system (Vlotman et al., 2020). The system designed depends on both the soil's physical properties and the permeability of soil horizons. If a soil horizon at any depth has a permeable layer, then a groundwater system is used. If there is no permeable layer present throughout the soil horizon, then a shallow drainage system is used.

2.5.2 Main drainage systems

Main drains are typically made up of open drains (typically V-shaped) placed at the edge of fields that discharge water to streams or rivers. They receive water from field drain systems (open and closed collector drains and subsurface drains), surface runoff, and groundwater (depending on the height of the water table and the soil's hydraulic conductivity) (Figure 2.4). Many of these main drainage systems were developed by the OPW in the arterial drainage schemes undertaken from 1842 to 1979 (see Section 2.4).

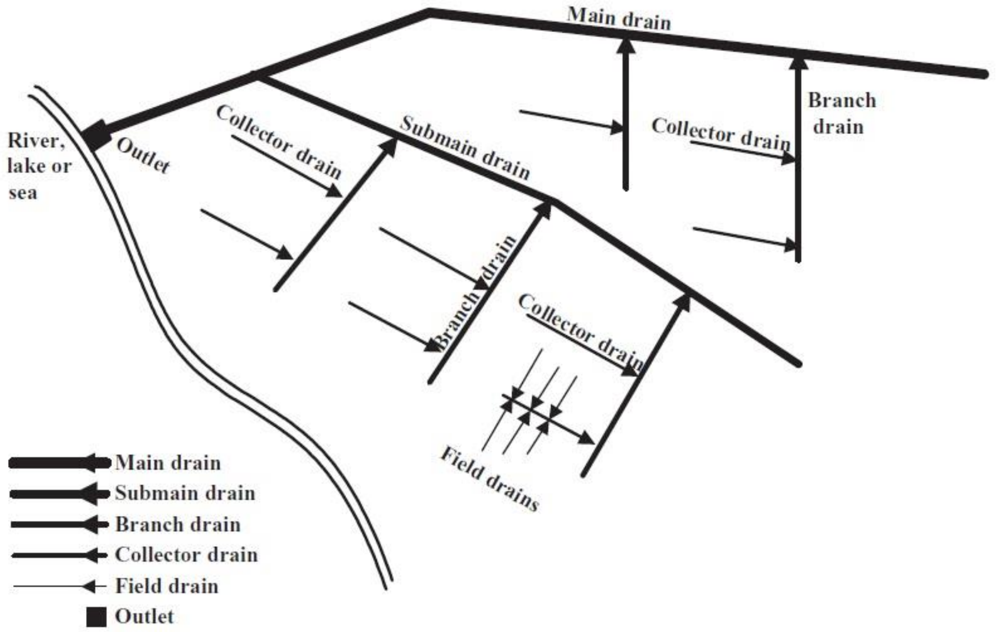


Figure 2.4 An overview of a drainage system featuring a main drainage system and field drainage (Schultz et al., 2007).

2.5.3 Groundwater drainage systems

A groundwater drainage system lowers the water table, allowing more water to infiltrate into the soil above, where free-draining soil exists throughout the soil profile, but the groundwater table is close enough to the surface to inhibit farmland activities and grass/crop growth. This system design is straightforward and drain spacing can be based on theoretical formulae (e.g., Hooghoudt) (Vlotman et al., 2020). Permeable layers in the soil facilitate the removal of water from the soil profile and lower the groundwater table (Figure 2.5). If the soil contains a permeable layer, a groundwater drainage system can be installed (Teagasc, 2022). The use of a drainage envelope helps in increasing the area of the groundwater drawdown in the surrounding soil. A drainage envelope also helps to reduce the entrance head loss by slowing the water as it converges towards the drainage pipe. By reducing the entrance head loss of water, the effective radius of an envelope is increased (Ghane, 2022).

Furthermore, groundwater drainage systems can be used on hilly terrain where seepage of groundwater onto the soil surface occurs because of groundwater and topography interaction (Figure 2.6). It can be applied locally to intercept this seepage of groundwater and direct its flow into a drainage system that is discharged into the main drains. Groundwater systems use a series of regular open drains or a series of subsurface drains. Subsurface drains are now more common due to the difficulties of machinery use with open drain systems (FAO, 1985). All three types of envelope materials (mineral granular, organic, and synthetic) can be utilised in this system. No additional soil disturbance measures are required in this system type due to the presence of a permeable soil layer (Vlotman et al., 2020).

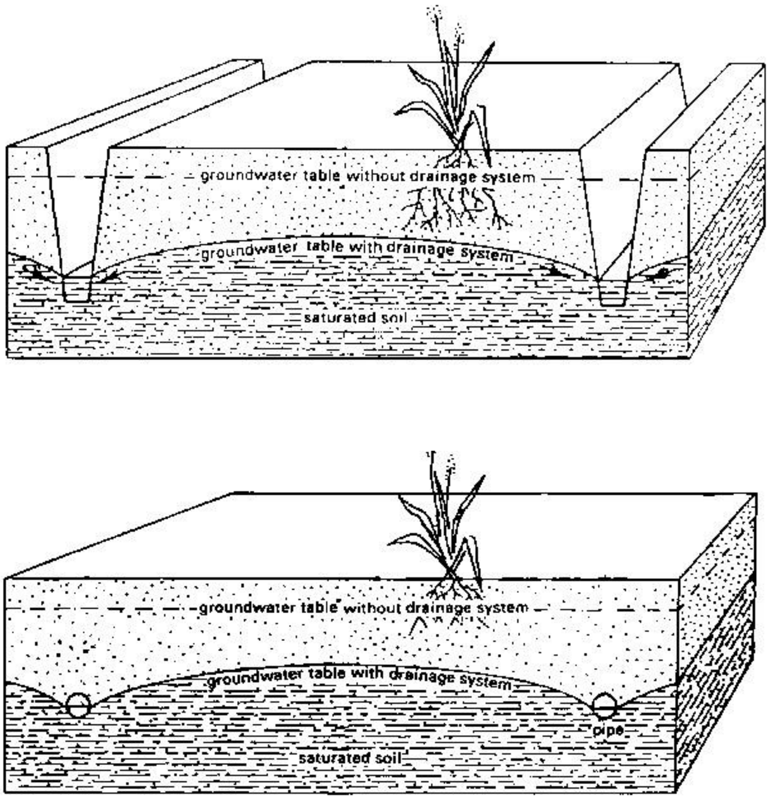


Figure 2.5 Control of the groundwater table with open drain and subsurface drain systems (FAO, 1985).

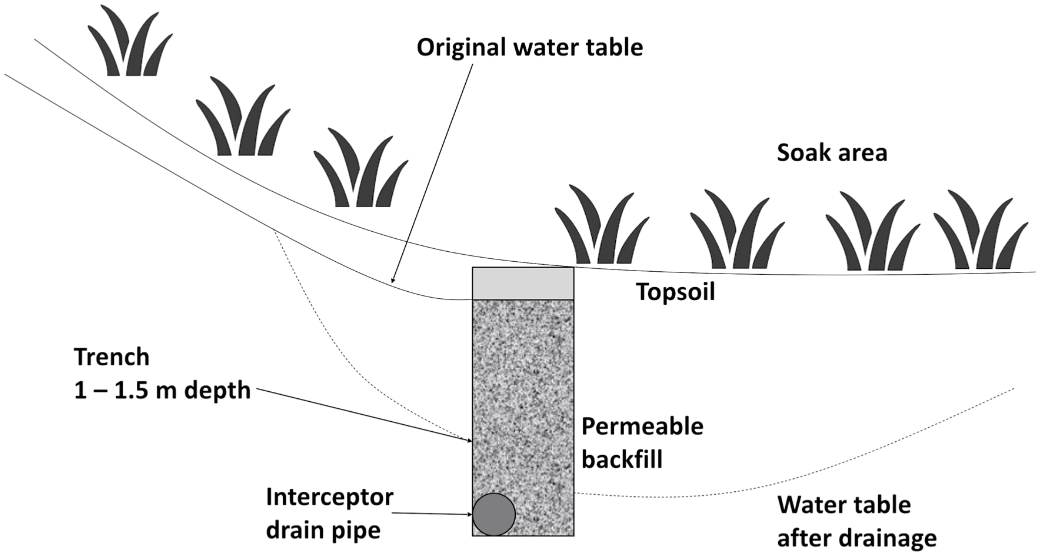


Figure 2.6 Interceptor drain used to control the flow and spread of water downhill on hilly terrain (Agriculture Victoria, 2023).

2.5.4 Shallow drainage systems

Shallow drainage systems are installed where there is no permeable layer in the soil profile at any depth. Soil permeability is low throughout the soil profile, and excess water cannot flow through these low-permeability layers. Shallow subsurface drains installed (up to 100 cm depth) in low-permeability soils mainly collect surface water, while very little water from the surrounding soil is collected unless new pathways for water in the soil are created using complementary measures to increase the soil's permeability (Figure 2.7).

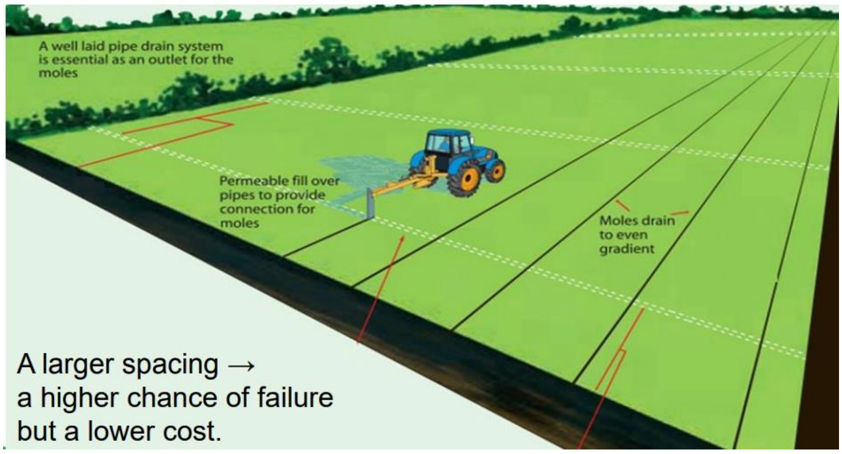


Figure 2.7 Shallow drainage system design (Teagasc, 2013).

Measures taken to improve soil permeability in these soils include mole drainage, gravel mole drainage, sub-soiling, and land forming. Mole drainage is a process of improving soil permeability by fracturing the soil with the use of a mole plough (torpedo-like cylindrical foot attached to a narrow leg, with a wider expander following behind). The mole plough creates a zone of increased permeability through fracturing and a channel through which the water can flow. The mole channel transfers the water to a pipe collector, which usually runs at right angles to the mole channel. Mole drains are suitable only in heavy-textured soils (Figure 2.8). Their applicability in other soil textured are increased using gravel mole drainage, where gravel is placed into the mole channel to keep this channel from collapsing and increase their lifespan (Teagasc, 2022).

The envelope system is used to provide initial sediment filtration in shallow drainage systems with low-permeability soils. When settlement has occurred, the envelope acts to improve the flow of water into the drainpipe. A larger envelope radius is used to both improve the flow of water into the drainpipe, reduce the resistance of water movement from soil to the pipe and to provide a direct connection between the complementary measures (mole drainage, gravel mole drainage, and sub-soiling) and the drainpipe, and to increase soil permeability and water movement through the soil. Mineral or organic envelopes are only suitable for shallow drainage systems with complementary measures due to the damage that would occur to the envelope system when using synthetic envelope systems and mole ploughs or sub-soilers.

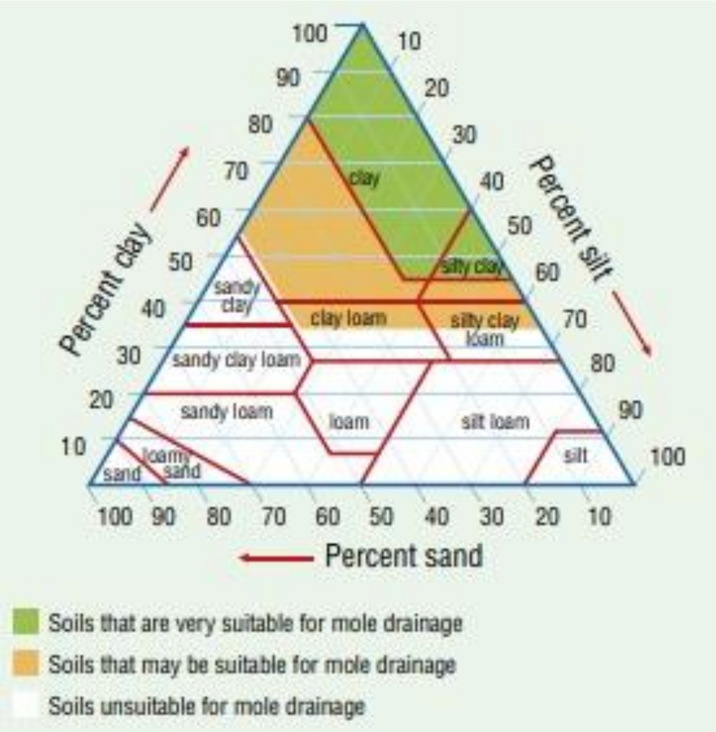


Figure 2.8 Mole drainage suitability depending on soil texture (Teagasc, 2022).

2.5.5 Drainage installation methods

A number of drainage installation methods are employed for various purposes but can be subdivided into trenched and trenchless methods. The most common and simple trenched method is the manual trench and backfill method, which involves the trench being dug to the required depth with either a square or V-shaped bucket. The appropriate pipe and envelope material are then installed into the trench, and the excavated backfill is subsequently replaced back on top of the drainage system. Commonly used installation methods comprise using only the chain trencher to install the drainage pipe, on its own or prewrapped in geotextile materials, or the drainage pipe followed by a gravel hopper, depending on the machine and envelope materials used (Figure 2.9). A machine is required to fill in the backfill subsequently.

Figure 2.9 Chain trencher machine installing prewrapped geotextile (PLM) drainpipe (Mastenbroek, 2022).

Trenchless methods of installation are faster, cheaper, and have become popular where extensive drainage installation is undertaken due to the high initial cost of machinery purchase and maintenance. They are typically installed with a plough (slit or V-shaped) (Figure 2.10), where the drainage pipe, prewrapped drainage pipe, or drainage pipe followed by a gravel hopper is used to install the envelope system seamlessly into the ground with minimal soil disturbance. Salo et al. (2019) investigated the difference between the performance of the trencher and trenchless machines by observing groundwater levels for two years after installation. Both methods used a filter fabric material, and the experimental setup was designed to minimize the differences between the field sections to provide a comparison between the trenched and trenchless methods. It was found that groundwater levels were mainly higher in the trenchless drainage, but the differences were not great enough to affect cultivation. However, the differences were more pronounced during harvest (late summer) where the trenchless method had a lower drainage performance than the trenched method (based on groundwater levels observed). The method's effect was also more pronounced in finer soil textures. As most drainage works in Ireland are carried out in finer-textured soils, the trenchless method of installation may be less suitable when compared to a trenched method.

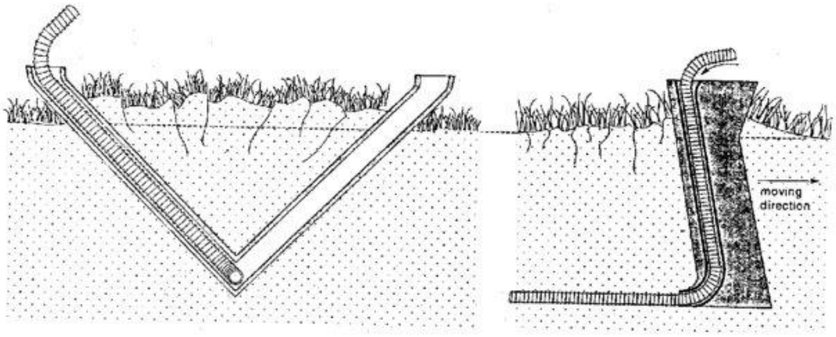


Figure 2.10 V-shaped trenchless drain plough (left) and vertical/ slit plough (right) (Ritzema et al., 1996).

2.5.6 Artificial drainage: advantages and disadvantages

An effective land drainage system can increase crop yield and lower production costs (Van der Molen et al., 2007). This is achieved by removing excess soil water to reduce or eliminate waterlogging. This helps to improve soil aeration, trafficability, soil structure, increase root development, and increase the length of the growing season (O'Sullivan et al., 2015; Smedema et al., 2004; Vlotman et al., 2020). Artificial drainage is typically considered as a method of removing excess water from the soil but is now being adopted for its potential to both eliminate waterlogging and increase nutrient use efficiency through the adoption of new technologies in drainage (Parsinejad and Akram, 2018). Skaggs et al. (2009) have indicated from findings from several studies that artificial drainage systems reduce surface runoff by providing a higher water storage capacity in the soil by reducing the groundwater level, which has beneficial effects for reduced sediment loss and increased nutrient use efficiency. This role will become more important with increasing rainfall intensity associated with climate change and the need for a more effective water management strategy in western parts of Ireland where poor drainage classes are predominant (Deelstra, 2015; EPA, 2007; Ritzema and Stuyt, 2015; Tuohy et al., 2016a).

Drainage can have both positive and negative effects on the hydrology and water quality, and now it must be designed to consider both agricultural and environmental goals (Skaggs et al., 2009). Nutrient losses from agricultural land are mainly concerned with P and N losses (Moloney et al., 2020; Valbuena-Parralego et al., 2019). Phosphorus losses mainly occur through losses related to overland flow. Losses are mainly associated with the timing of P application and high rainfall event-related losses, which play a major role in total P losses (Hart et al., 2004). A study conducted by Valbuena-Parralejo et al. (2019a) on the effect of P and N in soils with high clay contents where mole and gravel-mole systems were implemented showed that soil permeability was enhanced, decreasing overland flow and increasing soil P sorption, which decreased total P and DRP losses. Nitrogen losses from agricultural land in relation to drainage can be divided into losses due to gaseous emissions and losses to groundwater. Draining saturated clay soils from excess rainfall or high groundwater levels reduces N_2O and nitrogen gas emissions that occur from denitrification to about 65% of the undrained soil (Colbourn and Harper, 2006).

Losses to groundwater from shallow mole and gravel-mole drainage systems showed increased losses of nitrate-N and ammonium-N in drainage flow and also in losses to groundwater (Valbuena-Parralego et al., 2019a). Similar findings were found in Clagnan et al. (2018), where shallow drainage systems could potentially result in increased water quality impacts from nutrient loading in drainage. Valbuena-Parralejo et al. (2019b) found that following the installation of mole and gravel-mole drainage, there was no impact on soil greenhouse gas fluxes. Currently, much of the drainage research emphasis is being placed on edge of field and drainage ditch practices to help mitigate some of the negative effects associated with nutrient losses from drainage systems (SWCS, 2022). Measures taken can relate to the reduction of N (Faust et al., 2016; Faust et al., 2020), P (Dantas Mendes, 2020), or both (Taylor et al., 2020) from discharge waters.

2.6 Drainage envelope design

2.6.1 The need for a drain envelope

A drainage envelope has three primary functions: filtration, improving permeability around the drain, and a mechanical and bedding function (mainly associated with aggregate envelopes). The ‘filtration’ performance (or bridging factor) of an envelope should function to prevent large quantities of soil particles from entering the drainpipe and envelope system. A drain envelope acting as a true filter would impede all particles from entering the drainpipe and envelope and would eventually become clogged where particles are deposited on or in the envelope. Therefore, the envelope should function to allow small quantities of soil particles to pass through the envelope without causing clogging (Stuyt et al., 2005; Vlotman et al., 2020).

As the water moves towards the drain, it converges through a small area of drainpipe perforation openings and the hydraulic pressure increases ("exit gradient" or "approach flow resistance" are terms used to describe the pressure difference between the soil immediately beside the envelope system and the pressure within the drainpipe). This drain envelope increases the permeability directly around the drainpipe and, by reducing large cavity sizes around the drainpipe (by increasing soil-gravel and gravel-pipe contact), also helps to improve and slow the flow of water to the drainpipe ("approach flow resistance"). The envelope also provides a mechanical function, which provides support for the pipe and prevents damage to the pipe due to soil load. The bedding function provides a base to prevent vertical movement of the drainpipe due to soil load, which can affect gradients in the pipe and the flow of water through it (Vlotman et al., 2020).

Drain envelopes can be either designed to perform a filter function (or bridging factor) or a hydraulic function. A combination of the two functions is typically applied, so an effective envelope should be designed to limit sediment incursion into the envelope while maximising the hydraulic function, but, over time, movement of sediment into the envelope may fill pores and partially or fully block openings. Because of this, a reduction of hydraulic conductivity may be observed over time (Stuyt et al., 2005). In most cases, a drain envelope is intended to act as a filter, preventing excessive incursion of non-cohesive or weakly cohesive soils into the drainpipe, and aids in preventing excessive incursion of sediment into the envelope. In soils with a high clay content, envelopes are installed to increase the hydraulic function of the drainpipe (commonly employed in Irish soil types). Other factors, such as the installation conditions of the drain, also affect the need for a drainage envelope. Dry, loose overburden can result in the initial movement of the soil into the envelope before consolidation has occurred. The decision to install an envelope in a particular soil type is usually based on local experience (Vlotman et al., 2000).

Various design criteria have been developed in an attempt to simplify and determine if certain soil types need an envelope. These criteria were primarily developed based on the filter function of the envelope. Stuyt et al. (2005) outline these guidelines and discuss the various factors (soil texture, structural stability, moisture content, and chemical properties of the soil) involved in determining the need for a drain envelope. In cohesionless or weakly cohesive soils, envelopes are recommended and are typically determined using the plasticity index (resistance to mechanical deformation and rupture) and the coefficient of uniformity (a metric determining the distribution of sand, silt, and clay). Envelope selection should be determined based on the filtration capabilities of the envelope for these soils (as a priority). In cohesive heavy clay soils, envelopes are not needed where the clay percentage is >60% (or 25–30% in humid climates) (Vlotman et al., 2020). In the Netherlands, a 25% limit is accepted (Stuyt et al., 2005), while in Egypt it should be at least 30% (Vlotman et al., 2020).

The design criteria for clay-textured soils are based on the filtration function only and do not consider the hydraulic function of the envelope. These recommendations are based only on the filtration function of the envelope, with local experience being an important factor in their recommendation (Dierickx, 1993). ADHB (2018), Bahceci et al. (2018), and Teagasc (2022) recommend the use of permeable backfill (because local experience has indicated it is necessary), even in consolidated clay-textured soils, to maintain the permeability in the drain trench and maintain an increased effective radius, even as the permeability of the trench backfill reduces over time.

The method of installation also has an effect on the need for a drainage envelope. Where trenchless methods of installation occur, minimal disturbance of the soil occurs, limiting changes in the bulk density of the soil (bulk density is a key indicator of hydraulic conductivity in soil, affecting particle movement). In trenched methods, bulk density can be significantly altered in the trenched overburden. A study conducted by Chow et al. (1993) showed that bulk density was affected by any installation method employed, but the bulk density in the disturbed overburden was significantly higher than that of the undisturbed soil. This was confirmed by Salo et al. (2019), who showed that both the drainage installation method (trenchless versus trenched) and the soil type were important factors in the groundwater levels above the drain. The effect was more pronounced in finer soil textures than in coarse soil textures, which was attributed to the finer textured soils' greater transformation. The need for local or site-specific drainage solutions (Tuohy et al., 2016b) was further highlighted in this study. With the transformation of these soils, where trenchless methods of installation are primarily employed, the use of a drainage envelope may still be required in heavy-textured Irish soils due to the transformation of the soil overburden and potential associated sediment movement that may occur, and to enable the increase of the hydraulic conductivity around the drainpipe in these soils.

2.6.2 Envelope material selection

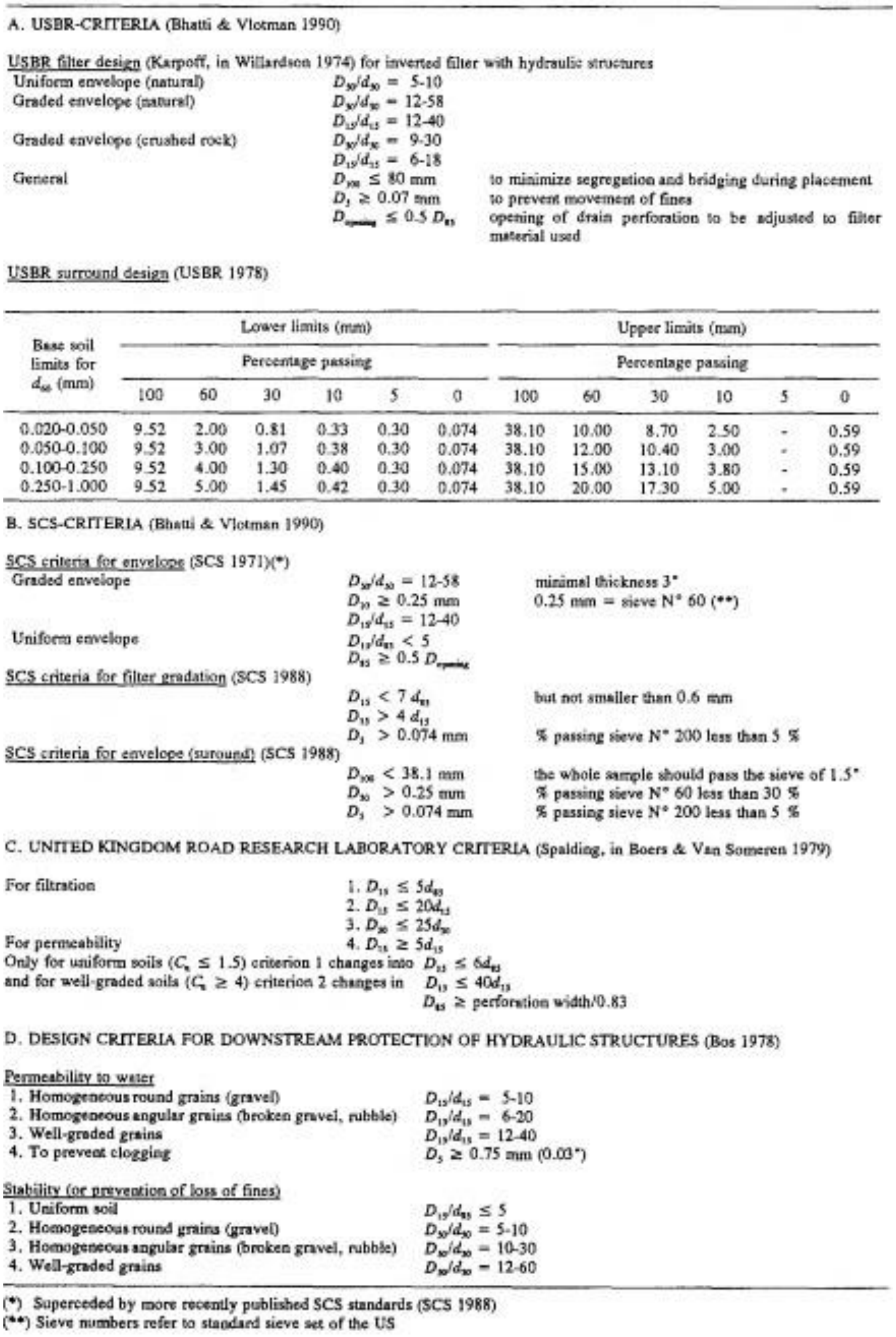
The selection of envelope materials depends on various factors such as availability, cost, envelope function required (hydraulic or filter function), envelope thickness required, handling characteristics of the envelope, danger of biochemical clogging, climate conditions, drainage installation methods employed (trenched or trenchless), and drainage system employed (groundwater or shallow). The use of different envelope materials typically depends on the soil's physical properties, but in practice their selection is mainly based on their availability and cost (Stuyt et al., 2005; Vlotman et al., 2020). Dierickx (1993) highlights the importance of the exchange of information between countries based on previous research in introducing new materials into an area to improve drainage performance. This is particularly evident in the shift from aggregate to prewrapped drainpipes in Egypt, where locally available synthetic materials were assessed (El-Sadany Salem et al., 1995; Sallam, 2017).

The availability of envelope materials typically depends on the resources available (an abundance of quarries to produce aggregate or manufacturing industries to produce synthetic materials) in a particular country and the historic use of a particular envelope material. In Ireland, aggregate quarries are abundant (ca. 350; IFI, 2023), and aggregate has been used as a drainage envelope since the 1960s, while in the Netherlands, aggregate is rare and has associated high transport costs (Vlotman et al., 2001). In the past, organic prewrapped envelope materials were used, but these have been gradually replaced by voluminous synthetic envelopes (Vlotman et al., 2020). Research on envelope systems can be broken into two main groups: gravel envelope design criteria and synthetic envelope design criteria.

2.6.3 Aggregate envelope design criteria

The general method for selecting a suitable aggregate gradation involves determining the particle size distribution of both the soil and envelope material, and based on a set of criteria, their suitability is assessed (Dierickx, 1993). The initial criteria were those developed by Terzaghi and Peck (1961) for the control of seepage under a dam and were thereafter applied for envelopes around subsurface drains. Much of the proceeding work on aggregate envelopes has been based on these criteria and laboratory experiments. Dierickx (1993) combines all the various existing criteria, as shown in Table 2.2. Dierickx (1993) makes note of how the aggregate criteria from various sources do not match, even when the distinction between the filter function and hydraulic function of the envelope is made. This is attributed to uncertainties about aggregate specifications, the roundness or angularity of the aggregate, the lack of uniform aggregate quality, segregation during transportation, flowability in the supply tube, unequal distribution around the drain, and the lack of aggregate according to the designed gradation curve. These shortcomings show the need to determine the nature, specification, and availability of aggregate, while also highlighting the need to determine aggregate suitability based on local soil textures for drainage. One such study is that conducted by Vlotman et al. (1993) on the selection and design criteria for granular envelopes in Pakistan.

Table 2.2 Existing design criteria for gravel envelopes (Dierickx, 1993).



A. USBR-CRITERIA (Bhatti & Vlotman 1990)

USBR filter design (Karpoff, in Willardson 1974) for inverted filter with hydraulic structures

Uniform envelope (natural) $D_{50}/d_{50} = 5\text{-}10$
Graded envelope (natural) $D_{50}/d_{50} = 12\text{-}58$
$D_{15}/d_{15} = 12\text{-}40$
Graded envelope (crushed rock) $D_{50}/d_{50} = 9\text{-}30$
$D_{15}/d_{15} = 6\text{-}18$
General $D_{100} \leq 80$ mm to minimize segregation and bridging during placement
$D_5 \geq 0.07$ mm to prevent movement of fines
$D_{opening} \leq 0.5\ D_{85}$ opening of drain perforation to be adjusted to filter material used

USBR surround design (USBR 1978)

Base soil limits for d_{60} (mm)	Lower limits (mm)						Upper limits (mm)					
	Percentage passing						Percentage passing					
	100	60	30	10	5	0	100	60	30	10	5	0
0.020-0.050	9.52	2.00	0.81	0.33	0.30	0.074	38.10	10.00	8.70	2.50	-	0.59
0.050-0.100	9.52	3.00	1.07	0.38	0.30	0.074	38.10	12.00	10.40	3.00	-	0.59
0.100-0.250	9.52	4.00	1.30	0.40	0.30	0.074	38.10	15.00	13.10	3.80	-	0.59
0.250-1.000	9.52	5.00	1.45	0.42	0.30	0.074	38.10	20.00	17.30	5.00	-	0.59

B. SCS-CRITERIA (Bhatti & Vlotman 1990)

SCS criteria for envelope (SCS 1971)(*)

Graded envelope $D_{50}/d_{50} = 12\text{-}58$ minimal thickness 3"
$D_{30} \geq 0.25$ mm 0.25 mm = sieve N° 60 (**)
$D_{15}/d_{15} = 12\text{-}40$
Uniform envelope $D_{15}/d_{85} < 5$
$D_{85} \geq 0.5\ D_{opening}$

SCS criteria for filter gradation (SCS 1988)

$D_{15} < 7\ d_{85}$ but not smaller than 0.6 mm
$D_{15} > 4\ d_{15}$
$D_5 > 0.074$ mm % passing sieve N° 200 less than 5 %

SCS criteria for envelope (suround) (SCS 1988)

$D_{100} < 38.1$ mm the whole sample should pass the sieve of 1.5"
$D_{30} > 0.25$ mm % passing sieve N° 60 less than 30 %
$D_5 > 0.074$ mm % passing sieve N° 200 less than 5 %

C. UNITED KINGDOM ROAD RESEARCH LABORATORY CRITERIA (Spalding, in Boers & Van Someren 1979)

For filtration 1. $D_{15} \leq 5d_{85}$
2. $D_{15} \leq 20d_{15}$
3. $D_{50} \leq 25d_{50}$
For permeability 4. $D_{15} \geq 5d_{15}$
Only for uniform soils ($C_u \leq 1.5$) criterion 1 changes into $D_{15} \leq 6d_{85}$
and for well-graded soils ($C_u \geq 4$) criterion 2 changes in $D_{15} \leq 40d_{15}$
$D_{85} \geq$ perforation width/0.83

D. DESIGN CRITERIA FOR DOWNSTREAM PROTECTION OF HYDRAULIC STRUCTURES (Bos 1978)

Permeability to water

1. Homogeneous round grains (gravel) $D_{15}/d_{15} = 5\text{-}10$
2. Homogeneous angular grains (broken gravel, rubble) $D_{15}/d_{15} = 6\text{-}20$
3. Well-graded grains $D_{15}/d_{15} = 12\text{-}40$
4. To prevent clogging $D_5 \geq 0.75$ mm (0.03")

Stability (or prevention of loss of fines)

1. Uniform soil $D_{15}/d_{85} \leq 5$
2. Homogeneous round grains (gravel) $D_{50}/d_{50} = 5\text{-}10$
3. Homogeneous angular grains (broken gravel, rubble) $D_{50}/d_{50} = 10\text{-}30$
4. Well-graded grains $D_{50}/d_{50} = 12\text{-}60$

(*) Superceded by more recently published SCS standards (SCS 1988)
(**) Sieve numbers refer to standard sieve set of the US

2.6.4 Synthetic envelope design criteria

The synthetic envelope design criterion is primarily based on the filter criterion (or bridging factor), which specifies an O_x/d_x ratio value (for which O is the characteristic pore size of the envelope, d is the characteristic textural size of the soil material and x is percentage value of the characteristic pore size or characteristic textural size). This ratio value is typically $O_{90}/d_{90,}$ for which 90 percent of the envelope pores are smaller (O_{90}) and $d_{90,}$ in which 90 percent of the soil textural particles are larger (Dierickx, 1993; Stuyt et al., 2005). The thickness of an envelope is also an important criterion when selecting a synthetic envelope for soil retention and clogging factors. Thin envelopes are generally less accepting of a higher O_{90}/d_{90} ratio than that of thicker, voluminous envelopes, which can accept a higher O_{90}/d_{90} ratio and still be successfully applied in the field without excessive soil incursion or greatly reduced hydraulic conductivity due to clogging or blocking factors (El-Sadany Salem et al., 1995). Thin synthetic envelopes need careful consideration of both soil and geotextile characteristics. Elzoghby et al. (2021) concluded that the ratio of O_{90}/d_{90} is a good predictor of clogging and soil loss in subsurface drainage pipes. The hydraulic conductivity of the envelope should be greater than that of the soil to aid in reducing the entrance resistance (or approach flow resistance) of water towards the envelope, and problems in this regard are mainly related to the filter function of the envelope and the associated clogging of the envelope by soil particles from either a high approach flow resistance or poor selection of envelope materials based on the filter criterion (or bridging factor). The various filter criteria that have been developed are highlighted in Table 2.3. Laboratory experiments can be used to comparatively determine the hydraulic and filter performance of synthetic envelopes specifications, but also in evaluating materials for local soil types.

Table 2.3 Various existing design criteria for geotextiles (Dierickx, 1993).

Reference	Geotextile	Soil	Criteria	Remarks
Calhoun (1972)	woven	cohesionless ($d_{50} \geq 74$ mm)	$O_{95}/d_{85} \leq 1$	dry sieving, glass bead fractions
		cohesive ($d_{50} < 74$ mm)	$O_{95} \leq 200$ μm	
Ogink (1975)	woven	sand	$O_{90}/d_{90} \leq 1$	dry sieving, sand fractions
	nonwoven	sand	$O_{90}/d_{90} \leq 1.8$	
Zitscher (1975) in Rankilor (1981)	woven	$C_u \leq 2$ 100 μm $\leq d_{50} \leq$ 300 μm	$O_{50}/d_{50} \leq 1.7\text{-}2.7$	
Sweetland (1977)	nonwoven	$C_u = 1.5$	$O_{15}/d_{85} \leq 1$	
		$C_u = 4.0$	$O_{15}/d_{15} \leq 1$	
ICI Fibers (1978) in Rankilor (1981)	nonwoven	20 μm $\leq d_{85} \leq$ 250 μm	$O_{50}/d_{85} \leq 1$	
		$d_{85} > 250$ μm	$O_{15}/d_{15} \geq 1$	
Schober & Teindl (1979)	woven and thin nonwoven ($T_g \leq 1$ mm)	sand	$O_{90}/d_{50} \leq B_1\ (C_u)$	dry sieving, sand fractions $B_1(C_u) < B_2\ (C_u)$ and are factors depending on the coefficient of uniformity C_u
	thick nonwoven ($T_g \geq 1$ mm)	sand	$O_{90}/d_{50} \leq B_2\ (C_u)$	$B_1\ (C_u) = 2.5 - 4.5$; $B_1\ (C_u) = 4.5 - 7.5$
Millar, Ho & Turnbull (1980)	woven and nonwoven		$O_{50}/d_{85} \leq 1$ $O_{50}/d_{15} \geq 1$	
Giroud (1982)	needle-punched nonwoven	cohesionless		
		less dense		
		$1 < C_u < 3$	$O_{95}/d_{50} < C_u$	
		$C_u > 3$	$O_{95}/d_{50} < 9/C_u$	
		moderate dense		
		$1 < C_u < 3$	$O_{95}/d_{50} < 1.5\ C_u$	
		$C_u > 3$	$O_{95}/d_{50} < 13.5/C_u$	
		dense		
		$1 < C_u < 3$	$O_{95}/d_{50} < 2\ C_u$	
		$C_u > 3$	$O_{95}/d_{50} < 13.5/C_u$	
	woven and heat bonded nonwoven	$1 < C_u < 3$	$O_{95}/d_{50} < C_u$	
		$C_u > 3$	$O_{95}/d_{50} < 9/C_u$	
Heerten (1983)	woven and nonwoven	cohesionless ($d_{50} \geq 60$ μm)		wet sieving, graded soil
		$C_u > 5$	$O_{90}/d_{50} < 10$ $O_{90}/d_{90} < 1.0$	
		$C_u < 5$	$O_{90}/d_{50} < 2.5$ $O_{90}/d_{90} < 1$	
		cohesive ($d_{50} \leq 60$ μm)	$O_{90}/d_{50} < 10$ $O_{90}/d_{90} < 1$ $O_{90} \leq 100$ μm	
Carroll (1983)	woven and nonwoven		$O_{95}/d_{85} \leq 2\text{-}3$	
Cristopher & Holtz (1985)		dependent on C_u	$O_{95}/d_{85} \leq 1\text{-}2$ $O_{95}/d_{15} \geq 3$	
CFGG (1986)	woven and nonwoven		$O_{95}/d_{85} \leq C$ $C = C_1C_2C_3C_4$	hydrodynamic sieving, graded soil
		$C_u > 4$	$C_1 = 1$	
		$C_u < 4$	$C_1 = 0.8$	
		less dense	$C_2 = 0.8$	
		dense	$C_2 = 1.25$	
		$i < 5$	$C_3 = 1$	
		$5 < i < 20$	$C_3 = 0.8$	
		$20 < i < 40$	$C_3 = 0.6$	
		filter	$C_4 = 1$	
		filter and drainage	$C_4 = 0.3$	
		cohesive	$O_{95} \geq 50$ μm	

2.6.5 Research on envelope materials

In situ investigation of drainage materials in the field remains the most accurate method of determining the suitability of envelope materials for a particular soil texture, as no laboratory research methods can fully reproduce the physical processes occurring in the field (Stuyt et al., 2005). The shortcomings of this investigation method are that in situ investigation of envelope materials is expensive, takes a long time, and causes a large variability in results depending on the field conditions.

Initial laboratory research on drainage materials was conducted using sand tank models (Wesseling and Homma, 1967). This mainly dealt with theoretical studies of drainage pipe and envelope interaction. Subsequently, research developed into obtaining information on the need for a drainage envelope using permeameter setups (Dierickx, 1980; Sherard et al., 1984). Drainage envelope research is usually distinguished by investigations on the suitability evaluation of specific envelopes with a soil type using sand tank setups or investigations to reveal the factors and parameters that determine the applicability of envelopes using permeameter type setups. Subsequently, research of envelope material interaction with local soils was investigated extensively in the late 1980s and 1990s (McAuliffe, 1986; Lesaffre, 1989; Bhatti and Vlotman, 1990; Vlotman et al., 1993; Choudhry et al., 1995; El-Sadany Salem et al., 1995) and continued into the 2000s (Kumbhare and Ritzema, 2000; Rimidis and Dierickx, 2003; Mulqueen, 2005; Maticic and Steinman, 2007). During the 1990s and 2000s several articles were published highlighting the overall research, development, and design of subsurface drainage systems (Dierickx, 1993; Vlotman et al., 2001; Nijland et al., 2005; Stuyt et al., 2005; Ritzema et al., 2006). In 2013, national guidelines on the drainage practices in Ireland, including all aspects of drainage, were published. The second edition of this was published in 2022 (Teagasc, 2013; Teagasc 2022).

Alternative envelope designs have been extensively researched in an effort to reduce the high costs and design flaws associated with conventional envelope systems. Efforts made in reducing costs was notable in the testing of rice husk as an envelope material in Iran (Kaboosi et al., 2012), while efforts were made to reduce design flaws by the introduction of the HYDROLUIS drain (Bahceci et al., 2018). Recent envelope design research has focused on the suitability and use of geotextile materials for drainage systems (Elzoghby et al., 2021; Ghane, 2022; Ghane et al., 2022; Khorramian et al., 2022).

2.7 Conclusions

This chapter reviewed land drainage system and land drainage envelope design research, and their development both in Ireland and abroad. How drainage research evolved and was applied differently in Ireland is one of the key reasons that much of the drainage envelope design established abroad was never applied and used on a large scale in Ireland.

Much of the research conducted in Ireland from the 1960 to the 1980s focused on diagnosing the problems associated with poor drainage, while in the USA and central Europe during this time research focused on advancing envelope design. Subsequently, very little research was conducted to apply these design criteria to Irish heavy soils textures. This led to the continued use of first-generation aggregate envelopes in Ireland to the present day that are not based on any established design criteria.

With the introduction of the Teagasc Heavy Soils Programme in 2011 and the Teagasc Drainage Manual in 2013, efforts were made to formalise the assessment of drainage system design based on the Visual Drainage Design method. Even with these efforts, recommendations of aggregate envelope size were only based on field observations and no work had been conducted to determine the suitability of aggregate envelopes or cheaper synthetic envelopes in Irish soil textures.

2.8 Summary

Based on the findings of the literature review, the suitability of aggregate materials as envelope material will be quantified against established international filter design criteria. This will establish a reference point from which further research may be conducted to determine the suitability of aggregate envelopes in Irish clay textured soils.

2.9 References

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Chapter 3 – 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

The aim of this chapter was to classify the distribution, type, popularity, size, and availability of aggregates for land drainage systems throughout Ireland and quantify their suitability for mineral soils. Eighty-six quarries were surveyed, and the suitability of these aggregates for drainage was determined in five soils of different textures.

This study has been published in the Irish Journal of Agricultural and Food Research (Byrne, I., Healy, M.G., Fenton, O. and Tuohy, P., 2022: DOI: 10.15212/ijafr-2022-0006). **Ian Byrne:** Methodology, Formal analysis, Investigation, Data Curation, Writing (Original Draft), Writing (Reviewing and Editing), Visualisation. **Mark G. Healy:** Conceptualization, Methodology, Resources, Writing (Reviewing and Editing), Supervision. **Owen Fenton:** Conceptualization, Methodology, Resources, Writing (Reviewing and Editing). **Pat Tuohy:** Conceptualization, Methodology, Resources, Writing (Reviewing and Editing), Supervision, Project Administration.

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 objective is chosen based off its 15% passing size, is required.

3.1 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: (1) filtration to prevent or restrict soil particles entering the pipe, where they may settle and eventually clog the pipe; (2) reduction of water entry resistance to the pipe; (3) 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 (Vlotman et al., 2020). 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.

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.

3.2 Materials and methods

3.2.1 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 (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 of them (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.

3.2.2 Sample collection and characterisation

Seventy-four individual samples of aggregate, each weighing 60 kg, 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 the differences between the stated PSD sizes under the quarry labelled sizes (Q size, either as a single size or graded figure) across different quarries, 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). 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), will be grouped under the individual Q sizes.

3.2.3 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) the bedding function, which provides protection for the pipe; and (3) the 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), developed filter criteria 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 with 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 (Dierickx, 1993; Terzaghi and Peck, 1961). While Dierickx (1993) states "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 (SCS, 1988; Sherard et al., 1984) 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.

3.2.4 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 was 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 Tests procedure in SAS version 9.1.3 (SAS, 2006).

3.3 Results

3.3.1 Survey

The distribution and lithologies of quarries located throughout Ireland based on survey results (of 86 quarries) are presented in Figure 3.1. Based on visual observation from Figure 3.1, Limestone is distributed in quarries throughout the country, sandstone is mostly located in quarries within the southern region and river-run gravel quarries are mostly located in the midlands (Figure 3.1). 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 3.2).

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 3.3). Figure 3.4 shows the most popular Q sizes by lithology. For limestone these are, the Q sizes: 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 3.5): the results showed that the average Q size in Munster was 53 mm, while the average Q size in Leinster was 31 mm.

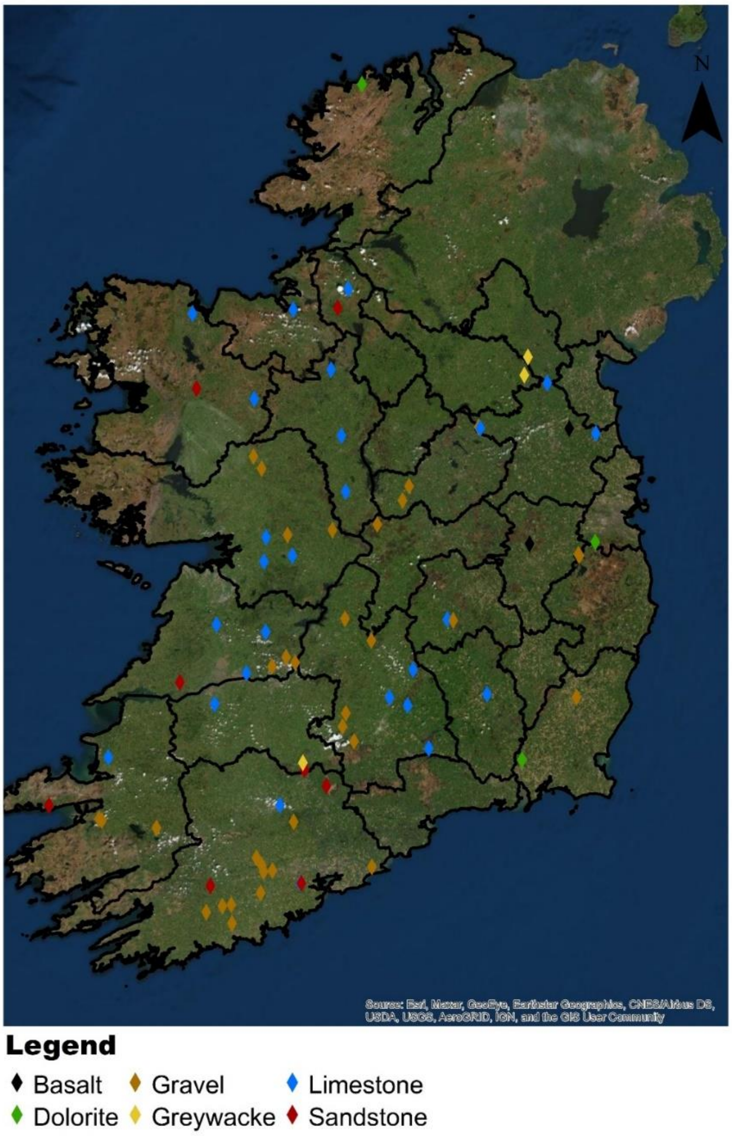

Figure 3.1 Surveyed quarry locations across Ireland by lithology.

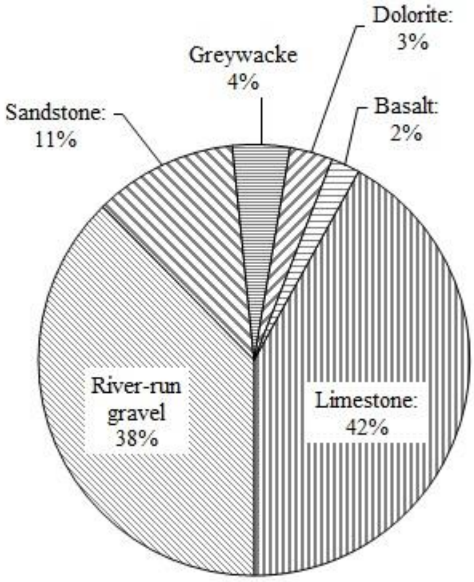

Figure 3.2 The most common quarry types in Ireland, by lithology (n = 100).

Figure 3.3 A selection of Q50 mm aggregates of different lithologies.

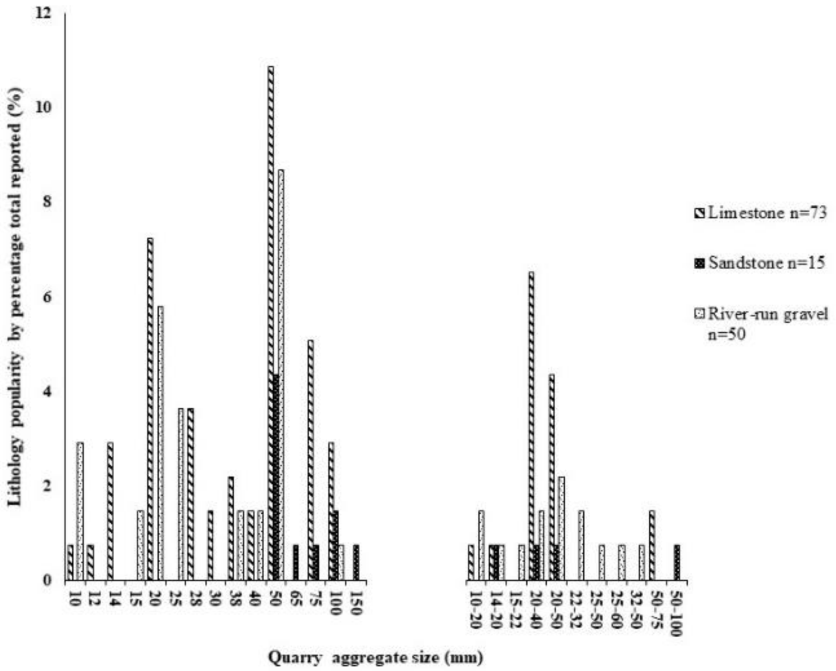

Figure 3.4 The most popular aggregate Q sizes (indicative sizes as reported by quarries, left; single size; and right; grading band) for land drainage from quarries surveyed by lithology (n = 136).

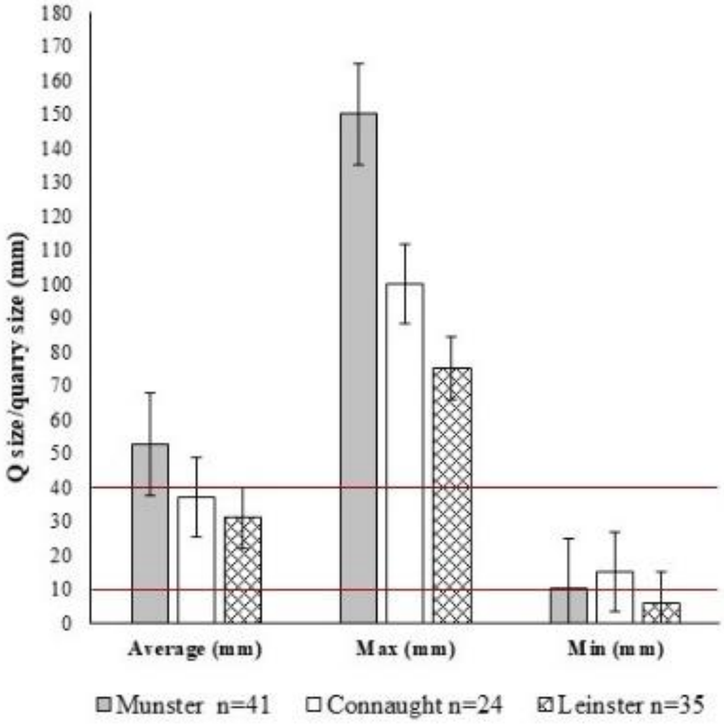

Figure 3.5 The average (mean of the mean), minimum (mean of the minimum), and maximum (mean of the maximum) Q sizes (inclusive of all lithologies) within each province are based on survey data collected. The recommended size range of 10–40 mm from Teagasc (2013) is highlighted in red.

3.3.2 PSD analysis

The results of the PSD analysis (of 74 samples) are presented in Figure 3.6 and show a wide variation in the size of material passing each of the ninety, fifty, and ten percent 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 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.

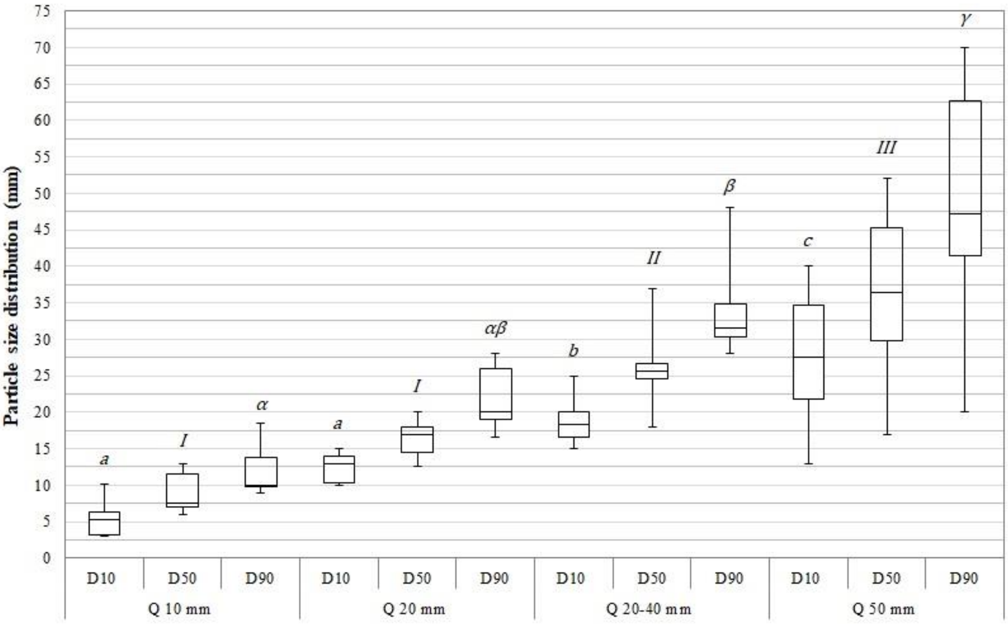

Figure 3.6 Q sizes, representing an approximation of the size of aggregate in mm as specified by the quarry, show estimated ten, fifty, and ninety percent passing (D_{10}, D_{50}, and D_{90}) figures, indicating labelling variation across different quarries. Means with the same symbol are not significantly 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.

3.3.3 Aggregate suitability for Irish mineral soils

Figure 3.7 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 D_{15}/15% passing size of an aggregate) to the five soil textures to determine the suitability of the 74 aggregates, only the loam soil, where 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) were not applicable). 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.

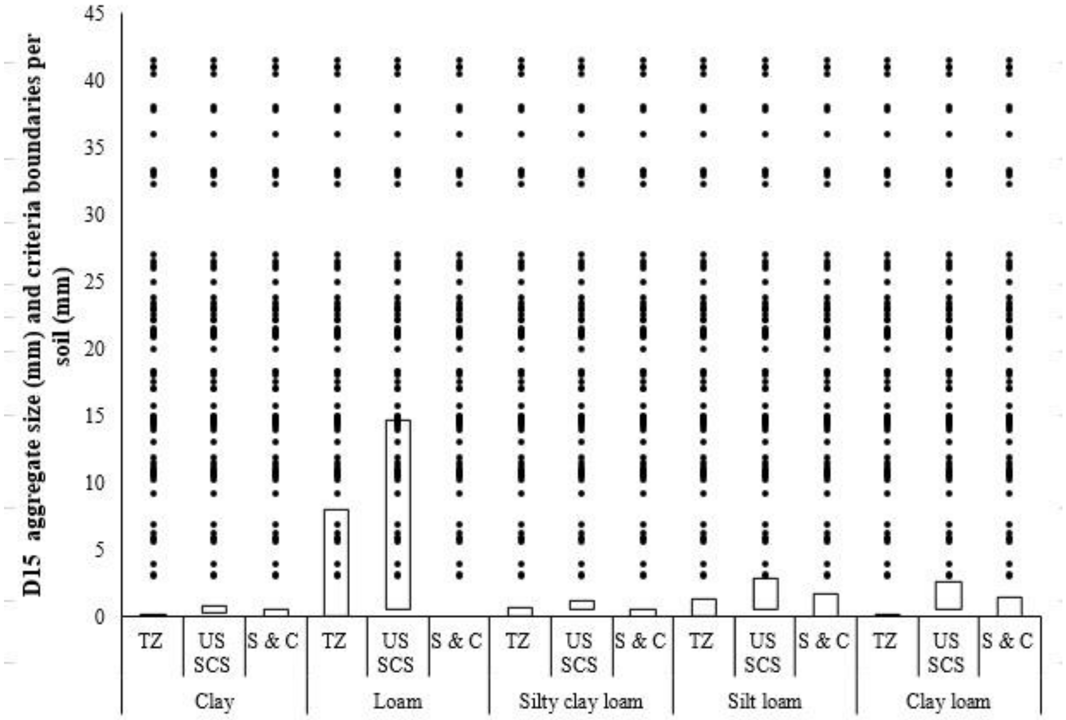

Figure 3.7 Recommended aggregate size using three filter design criteria [Terzaghi's (Terzaghi and Peck, 1961) ("TZ"); US Soil Conservation Service (SCS, 1988) ("US SCS"); and Filters for Silts and Clays (Sherard et al., 1984) ("S&C")] applied to five soil textures shows the suitability of seventy-four 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}).

3.4 Discussion

3.4.1 Survey

If current practices are continued, the wide variation of aggregates, based on distribution of geology, is likely to affect the type and size of material available to a farmer or contractor. 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 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 but 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 is not 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.

3.4.2 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 that 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 that 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 for the aggregate needed.

3.4.3 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 work 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 a 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 a 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 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 (soils rich in clay particles).

3.5 Conclusion

The current system of aggregates being identified by a single Q size or a Q size within 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 do 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 preferable 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. Information on the ranges of aggregate proposed for land drainage works versus what is available in (and reported by) quarries, for example, would be useful.

3.6 Acknowledgements

We would like to acknowledge the assistance of the quarries throughout Ireland for providing detailed information on the availability & use of aggregate materials for land drainage systems and the quarries that kindly facilitated the collection of aggregate samples. This research was conducted with the financial assistance of the Walsh Scholarship Programme (grant number: RMIS-0047).

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Chapter 4 – Assessment of the hydraulic and filter performance of different drainage stone aggregates to elucidate an optimum size range for use in clay-textured soils

The aim of this chapter was to assess the hydraulic and filtration performance of commonly used gravel aggregates as envelope materials for use in clay-textured soils, and rank the aggregates based on their suitability for use. Nine aggregates (three replicates of each) were examined in laboratory units containing clay-textured soil, with a perforated drainpipe surrounded by an aggregate envelope ranging in size from 0.7 to 62 mm and a constant 0.4 m head of water above the soil surface.

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Assessment of the hydraulic and filter performance of different drainage stone aggregates to elucidate an optimum size range for use in clay-textured soils

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Abstract

On poorly drained grassland farms in Ireland, stone aggregates remain the only in-field drain envelope material used by contractors. A variety of aggregate sizes and lithologies are currently in use, but their performance in clay-textured mineral soils is unknown. In practice, this may result in ad-hoc system performance and a varied lifespan due to sediment ingress. The aim of this study was to evaluate the hydraulic and filter performance of a range of aggregate gradations in clay-textured mineral soils. Nine aggregates (three replicates of each) were examined in laboratory units containing clay-textured soil, with a perforated drainpipe surrounded by an aggregate envelope ranging in size from 0.7 to 62 mm and a constant 0.4 m head of water above the soil surface. To determine the hydraulic performance of the envelope, the discharge rate of water through the drainage pipe outlet was measured over 38 days. To determine the filter performance, sediment loss, sediment settlement in the drainpipe, and ingress of sediment into the envelope were measured. The results indicated that only aggregates in the 0.7–19 mm size range performed adequately from both the hydraulic and filter perspectives and were deemed suitable for use with a clay-textured soil. Discharge appeared to be inversely related to aggregate size, with larger discharges being measured in the smaller aggregate sizes and smaller discharges measured in the larger aggregate sizes (exception: Aggregate 2). For all aggregates examined, discharge was greatest at the start of the experiment before reducing over time. When the cost of the

aggregate material is also considered, aggregates in the lower size range are 18–50% more expensive than aggregates in the higher size range. Aggregates with particle sizes ranging from 0.7–19 mm are recommended for in situ field testing in clay-textured soils.

4.1 Introduction

Agricultural land drainage plays a key role in supporting food production on poorly drained soils (Tuohy et al., 2018; Castellano et al., 2019). A typical contemporary land drainage system comprises a network of subsurface drains, each consisting of perforated pipes wrapped in an envelope material (Stuyt et al., 2005; Teagasc, 2022). The key to efficient and consistent hydraulic and filter performance is an appropriate type and size of envelope material to surround the drainage pipe (Yannopoulos et al., 2020). The drain envelope must offer proficiency in a number of functions, such as protecting the drainpipe from excessive sedimentation and reducing water entry resistance around the pipe and surrounding soil. An envelope with a higher hydraulic conductivity than the surrounding soil reduces the entrance resistance (resistance of approach flow) into the pipe so that no hydraulic pressure will build up in the surrounding soil (Stuyt et al., 2005; Vlotman et al., 2020). In theory, the entrance resistance of a drainage system is a material constant, but in practice it may be seriously reduced due to particle deposits at the soil-envelope interface or in the envelope. The entrance resistance of a drainage system depends on soil texture and evolves with time (Dierickx, 1993).

Aggregates such as river-run gravel or crushed stone are commonly used in temperate climates with moderate to heavy (lower hydraulic conductivity) soil textures to keep the water table below a depth of 0.45 m in order to maximise grass growth and trafficability (Teagasc, 2022). They improve the hydraulic conductivity around the drainage pipe, reduce the entrance resistance, protect and support the pipe, and prevent the ingress of sediment (Vlotman et al., 2020). The antecedence of their use is due to a combination of factors, such as the scale and system of farming undertaken, the type of drainage system, the abundance of mineral aggregate, and the historical use of aggregate for drainage (Byrne et al., 2022). Typical aggregate sizes used in different regions range from 0.2 to 4.0 mm in

Finland (Luoko, 2020), 5–50 mm in the United Kingdom (AHDB, 2018), and 10–40 mm is recommended in Ireland (Teagasc, 2022).

Byrne et al. (2022) conducted a review of the availability of aggregate throughout Ireland. Eighty-six quarries across Ireland were surveyed, which classified the distribution, type, popularity, size, and availability of aggregates for land drainage systems. The average size of the aggregate available was 41 mm. The most commonly used sizes ranged from 2 to 62 mm, representing the vast majority of aggregate sizes available throughout Ireland. This study found that the most commonly used aggregate size is unsuitable for the majority of moderate to "heavy" (lower hydraulic conductivity) soil types encountered. Using 74 aggregates characterised in the study, three filter design criteria (SCS, 1988; Sherard et al., 1984; Terzaghi and Peck, 1961) were applied to five soil types (clay, clay loam, loam, silty clay loam, and silt loam). Only 31% met the SCS (1988) criterion and 11% met the Terzaghi and Peck (1961) criterion for a loam soil texture (the Sherard et al., 1984 design criterion was not applicable for this soil texture). The study concluded that there was a need for guidelines for aggregates based on both the hydraulic and filter performance of the drainage envelope in moderate to lower hydraulic conductivity soil types. Currently, the recommended 10–40 mm aggregate sizes are based on field observations (Teagasc, 2022), but no data exist on their applicability and suitability in clay-textured soils. These recommendations are primarily based on filtration recommendations, and although clay-textured soils have a higher structural strength after settlement, they may be needed to provide temporary filtering functions. It has been suggested that soil with a clay content of > 30% does not need an envelope around a drainpipe (Stuyt et al., 2005; Vlotman et al., 2020). However, the use of an aggregate envelope increases drain spacing by increasing the effective radius of the drainpipe and provides other additional benefits, such as a conduit of flow in shallow drainage systems where mole ploughs and sub-soilers have a direct connection to the drainpipe through the aggregate envelope. Therefore, there is a need to identify if hydraulic conductivity and effective radius can be maximised based on choosing a more suitable aggregate size, along with providing initial filtering capabilities.

Laboratory evaluation of an envelope system is useful as a simple and easily reproducible method for evaluating various envelope materials and scenarios at a low cost (Dierickx, 1989). It is also useful to test the functional properties of drain envelopes, such as their ability to retain soil particles and prevent invasion of soil particles into the envelope; the blocking or immediate reduction of hydraulic conductivity of an envelope in contact with soil; and the decrease in hydraulic conductivity of an envelope over time due to particle accumulation or if the envelope material is too fine (El-Sadany Salem et al., 1995).

In the current study, the range of aggregate gradations from 0.7 to 62 mm in size (representing the most commonly available aggregate sizes throughout Ireland (2–62 mm), and a 0.7–3 mm aggregate (satisfying the SCS, 1988 criterion) were tested in laboratory units to identify a subset of optimal aggregate ranges for use in clay-textured soils, which should subsequently be tested in situ in the field. The overall objective of this study was to evaluate the hydraulic and filter performance of a range of aggregate gradations in clay-textured mineral soils. To achieve this objective, the experiments aimed to: (1) assess the hydraulic and (2) filter performance of commonly used gravel aggregates as envelope materials for use in clay-textured soils; and (3) rank the aggregates based on their hydraulic and filter performance and cost for use in clay-textured soils.[1]

4.2 Materials and methods

4.2.1 Soil and stone aggregate selection

A clay-textured soil[2] was collected from the Teagasc Solohead Research Farm (latitude 52° 51' N; 08° 21' W; altitude 95 m a.s.l.) and dried in 2 kg batches for 24 hr at 110 ºC then milled to pass a 2 mm sieve grade. The textural class was determined according to ASTM (2021): 7% sand, silt 37%, clay 56 % (clay texture). Eight commonly used envelope material aggregates in Ireland were selected (Table

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[1] This study is a comparative study conducted using laboratory tests and is only indicative of performance. Field studies should be conducted on the findings of this study to determine their suitability in the field.

[2] Clay and clay loam-textured soils are the most common soil types in need of drainage in Ireland. Clay-textured soil is used in this study as a worst case scenario, as it has the smallest particle sizes and therefore the greatest potential to block a drain envelope when placed on top of a drainage system envelope.

4.1). An additional aggregate was used in the experiments (Aggregate 1 in Table 4.1), which satisfied the aggregate selection criteria for a clay-textured soil as defined by the Soil Conservation Service (SCS, 1988). This allowed for comparison with an idealised aggregate.

Table 4.1 Aggregate envelope data indicating the aggregate type and their size distribution.

Aggregate number	**Aggregate type**	**D_{15} - D_{75}[1] (mm)**
1	River-run gravel	0.7 - 3
2	Limestone	2 - 10
3	Limestone	10 - 14
4	River-run gravel	11-17.5
5	River-run gravel	15.5 - 19
6	River-run gravel	22 - 30
7	River-run gravel	22 - 75
8	Limestone	34 - 47
9	Limestone	42 - 62

[1] D_{75} – D_{15} indicates estimated 75% and 15% passing size.

4.2.2 Hydraulic performance of aggregate ranges

In total, 27 units (Figure 4.1), each 0.57 m in diameter and 0.93 m deep, were constructed and replicated at n = 3 for each aggregate size examined. Each unit consisted of three components: clay-textured soil, an aggregate treatment, and a drainpipe (a standard 80 mm corrugated pipe with perforations 2 mm × 15 mm in size) discharging to a collection tank. A 0.08 m diameter drainpipe was located 0.15

m from the bottom of the tank. In order to obtain reproducibility and determine aggregate suitability based on the soil textural component, dry milled soil (<2 mm) was filled to a depth of 0.02 m at the bottom of the tank, which was overlain by 0.21 m of the chosen aggregate (to the top of the drainpipe), and compacted using a tamping device (0.3 m diameter round base with a 5 kg weight dropped from a height of 0.6 m) in order to ensure no settlement around the drainpipe occurred during the experiment. An additional 0.15 m of aggregate was added over the drainpipe, and tamping was repeated. Finally, the aggregate was overlain by a 0.15-m-deep layer of soil, compacted (in incremental layers) to a wet density of 964.6 kg m^{-3}. The edges of each layer of soil were pressed against the walls of the container by hand to ensure no by-pass flow occurred during the experiment. Nylon straps were added to the tank to prevent bulging at the soil layer, and paraffin wax was applied at the edges of the top layer to prevent by-pass flow.

Each unit was filled with potable water to a height of 0.4 m above the soil surface, which remained constant over the duration of the experiment (using an overflow pipe). In order to prevent damage to the top layer of soil during the initial flow of water into the tank, an aluminium tray (0.2 × 0.2 × 0.05 m) was used to disperse the water. This tray was subsequently removed once a constant head was achieved. The units were routinely monitored for discharge rate and sediment loss over a total experimental duration of 38 days. In order to normalise data, units are expressed as L m^{-1} of pipe cumulatively (0.08 m dia.). Sediment loss was measured in accordance with standard methods (BS, 2005). The sediment loss concentrations were multiplied by the discharge rate to estimate the total sediment loss (g m^{-1} of drainpipe) daily and cumulatively. At the end of the experiment, all the sediment that had settled in the drainpipe was collected and weighed, and the experimental units were destructively sampled. The topsoil layer and a 0.05 m layer of aggregate were discarded. Samples of the remaining envelope material from directly above the pipe were then taken. All of the fine material (<2 mm) was washed from the gravel and subsequently dried and weighed, with the results expressed in g of soil.

In this study, “failure” of the envelope was defined, after Stuyt et al. (2005), as when the soil structure was observed to collapse or when there was excessive movement of soil through the envelope material within the first 24 hr of operation.

The hydraulic performance was assessed on the ability of the drain setup to discharge at least 0.54 mm hr^{-1} (mean intensity of rainfall across 7 sites during a high rainfall period; Tuohy et al., 2018), and the filter performance was assessed by the amount of sediment settled in the drainpipe during the experiment; this should be <25% of the total volume of the drainpipe in order to ensure an excessive reduction in discharge does not occur (Vlotman et al., 2020).

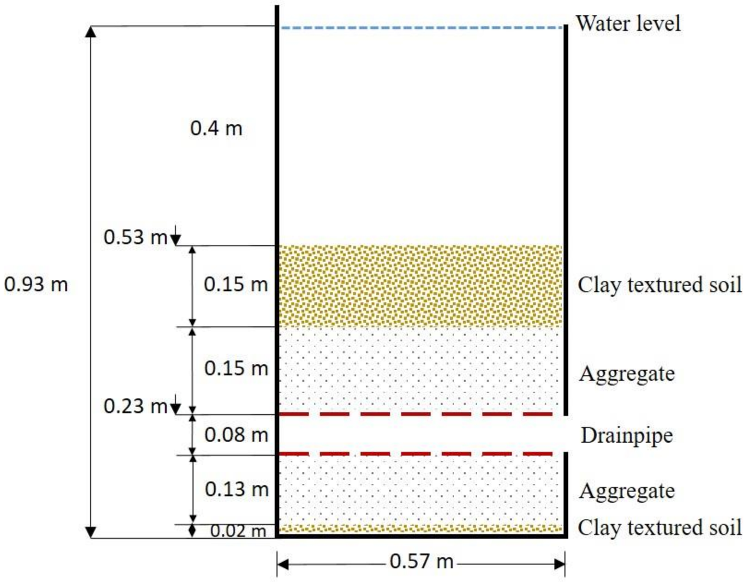

Figure 4.1 Laboratory unit setup showing flow through the system and depth profile.

4.2.3 Statistical analysis

Statistical analysis was carried out using SAS 9.4 (SAS Institute Inc., Cary, NC, USA). A univariate analysis of the data was conducted to determine normality. The data were shown to be non-normally distributed. Following this, the effects of envelope function in relation to daily drainpipe discharge rate and daily drainpipe sediment loss across 9 aggregate distributions were measured using the PROC MIXED procedure (REML – estimation method; profile – residual variance method; model-based – fixed effects SE method; and residual – degrees of freedom method) with repeated measures where time was a factor (T = 10, 19, and 38). Statistical significance was assumed at a value of $P < 0.05$.

4.3 Results

Aggregates 6, 7, 8, and 9 were deemed to have met the criteria for failure within the first 24 hr of starting the experiment. Aggregates 1 to 5 achieved the hydraulic and filter performance criteria for the entire 38-day experimental period. Over the course of the experiment, the cumulative discharge from the five aggregates ranged from 17751 to 27542 L m^{-1} of pipe. The cumulative sediment losses ranged from 13 to 62 g m^{-1} of pipe.

4.3.1 Hydraulic discharge and sediment loss performance

The majority of discharge (67% average) across all treatments occurred within the initial 14-day period of the experiment (Figure 4.2). On day 38, the five aggregates had an average daily difference of 0.74 mm hr^{-1} between the highest and lowest discharges. The lowest discharge was observed from Aggregate 5 on day 38, where a discharge rate of 1.3 mm hr^{-1} was observed (Figure 4.3). Most of the sediment loss occurred within the first 8 days of the experiment: Aggregate 1 lost 34 g m^{-1} of pipe (55% of the total loss) within this time period, followed by Aggregates 4 (67%), 3 (68%), and 5 (82%) (Figure 4.4).

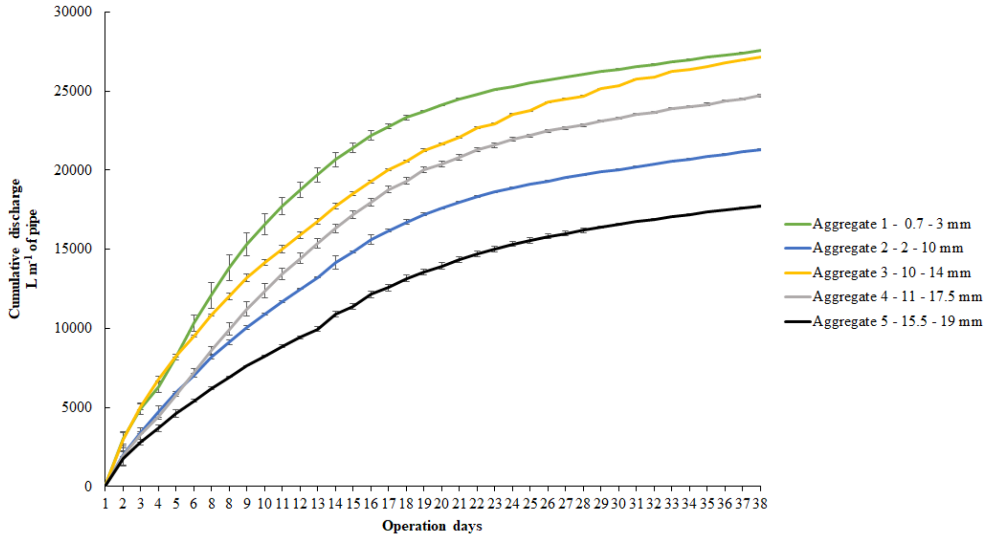

Figure 4.2 Cumulative average discharge rate (error bars indicate the standard deviation). Discharge data for Aggregates 6, 7, 8, and 9 were not obtained, as they met criteria for failure within the first 24 hrs of operation.

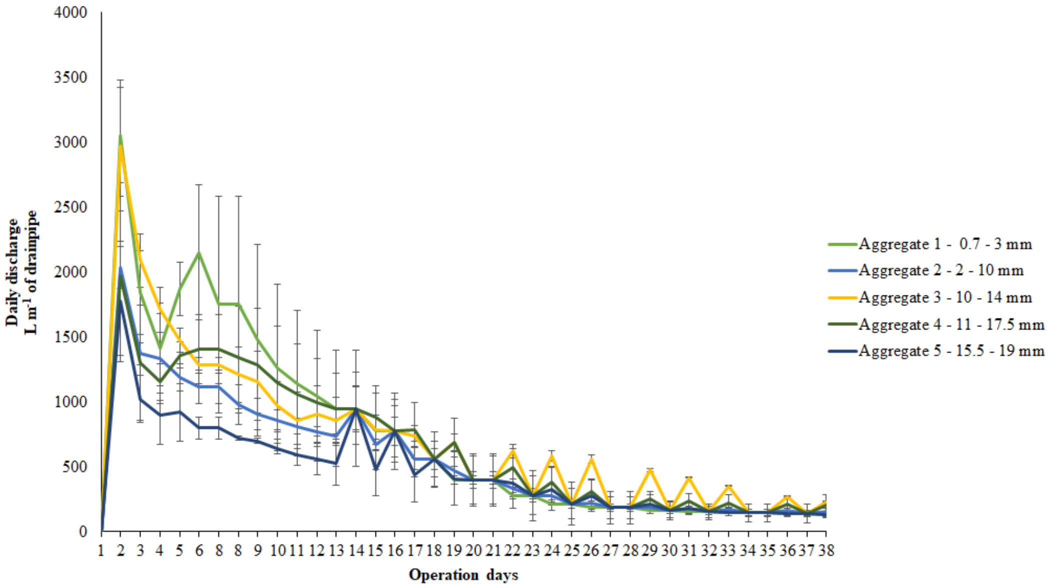

Figure 4.3 Daily discharge rate (error bars indicate the standard deviation). Discharge data for Aggregates 6, 7, 8, and 9 were not obtained, as they met criteria for failure within the first 24 hrs of operation.

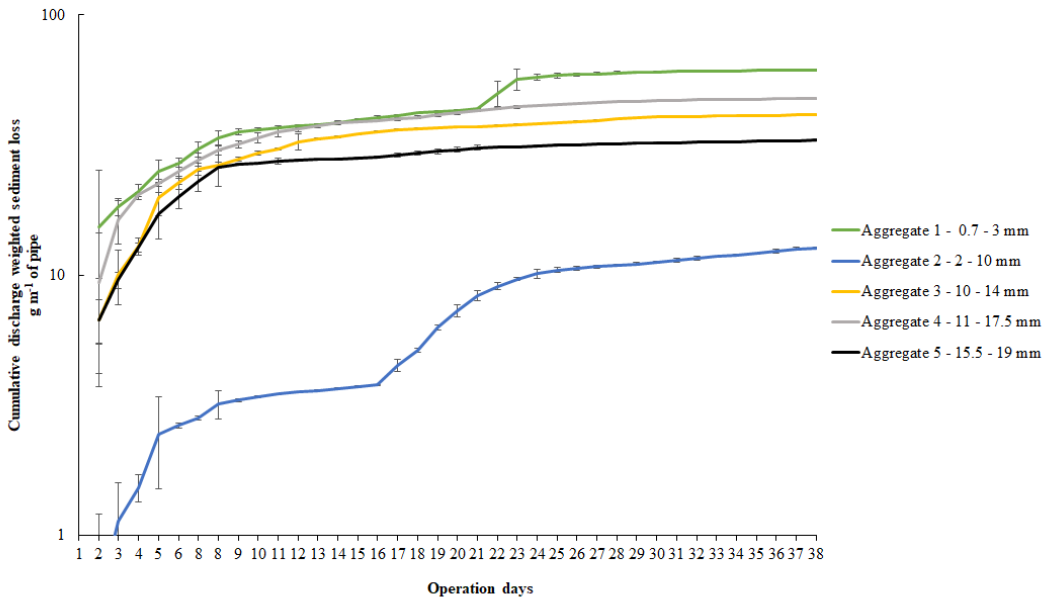

Figure 4.4 Cumulative discharge weighted sediment loss (error bars indicate the standard deviation). Sediment loss data for Aggregates 6, 7, 8, and 9 were not obtained, as they met criteria for failure within the first 24 hrs of operation.

4.3.2 Envelope and pipe sedimentation

Sampling of the envelope after completion of the experiment (Figure 4.5a) indicated that Aggregate 1 had the lowest incursion of soil into the envelope (640 g), while the worst performing aggregate was Aggregate 3 (5699 g). Three other aggregates had soil incursions ranging between 3406 g (Aggregate 2) and 4251 g (Aggregate 4). Figure 4.5b shows the amount of sediment deposited in the pipe after the end of the experiment. Values ranged from 0.54 g m^{-1} of pipe (Aggregate 1) to 1.31 g m^{-1} of pipe (Aggregate 4). The amount of sediment settled within the pipe was insufficient to reduce the drainpipe volume by 25% across any of the treatments, so therefore it was judged to pass the sediment function criterion.

4.3.3 Data aggregation for aggregate selection

In order to determine the suitability of the aggregates across the three factors of discharge, sediment loss, and pipe-envelope sedimentation, a ranking system was developed. Table 4.2 shows the overall suitability of each aggregate range. Results showed that aggregates >19 mm in size, while cost-effective, are not suitable for use as drainage envelopes due to their early failure. Aggregates in the 0.7–19 mm range performed favourably from both hydraulic and filter performance perspectives and are deemed suitable.

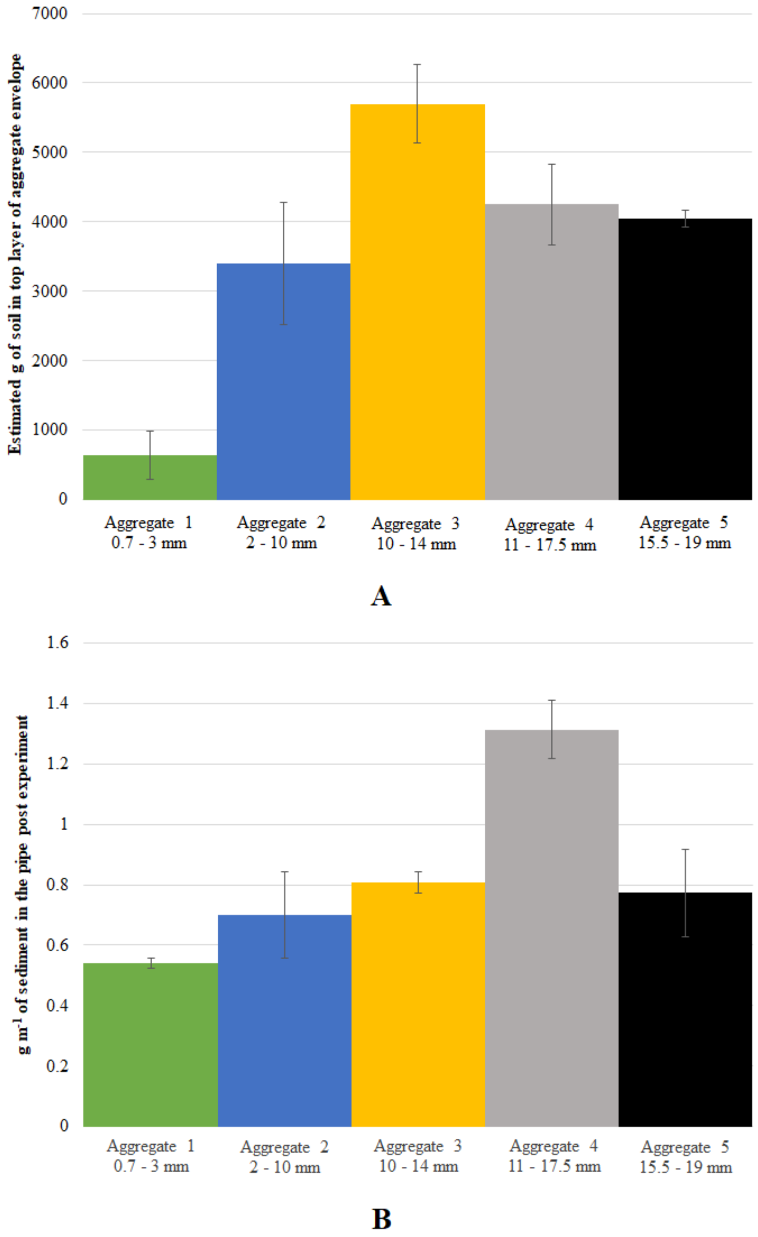

Figure 4.5 Estimated g of soil in the top 0.15 m of aggregate (A) and g m-1 of sediment per length of pipe (B) (error bars indicate the mean and standard deviation. Values (A) exclude the quantity of fine material (<2 mm) already within the aggregate). Data for aggregates 6, 7, 8, and 9 were not obtained as they met criteria for failure within the first 24 hr of operation.

Table 4.2 Aggregate-grade suitability for use with clay-textured soils, based on discharge and filter performance.

Aggregate Number and PSD (D_{15}–D_{75}) (mm)	**% of aggregate material <2 mm (g kg^{-1} of aggregate)**	**Discharge**	**Filter[1]**	**Cost: €/t (ex-pit ex VAT)**	**Discharge and filter performance**	**Overall cost and performance[2]**
Aggregate 1 (0.7–3)	7.2	✓	✓	15.00	Suitable	Sub-optimal
Aggregate 2 (2–10)	9.6	✓	✓	13.00	Suitable	Sub-optimal
Aggregate 3 (10–14)	0.1	✓	✓	11.00	Suitable	Optimal
Aggregate 4 (11–17.5)	1.6	✓	✓	10.00	Suitable	Optimal
Aggregate 5 (15.5–19)	2.0	✓	✓	10.00	Suitable	Optimal
Aggregate 6 (22–30)	2.6	X	X	10.00	Not suitable	N/A
Aggregate 7 (25–75)	0.6	X	X	8.41	Not suitable	N/A
Aggregate 8 (34–47)	1.9	X	X	8.87	Not suitable	N/A
Aggregate 9 (42–62)	13.0	X	X	8.87	Not suitable	N/A

[1] The heading ‘Filter’ has the combined analysis of envelope sedimentation, pipe sedimentation, and sediment loss through the drainpipe.

[2] Aggregates not suitable based on the ‘Discharge and filter performance’ assessment, are not assessed on ‘Overall cost and performance’ and are denoted N/A

4.4 Discussion

4.4.1 Hydraulic and filter performance

Aggregates 6, 7, 8, and 9 were deemed to have met the criteria for failure, which occurred within the first 24 hr of starting the experiment and are considered unsuitable for use. The ability of the envelope to hold back sediment in the unstructured clay-textured soil (similar to trench backfill) was compromised above an aggregate size of 20 mm, resulting in soil incursion into the envelope (Dierickx, 1993). The envelope should function initially during the settlement period to prevent excessive incursion of sediment into the aggregate envelope and provide a filter function. Therefore, a balance between the hydraulic and filter performance of the envelope is needed initially during settlement. These findings have the following implications: larger aggregate sizes (> 20 mm), when used as envelope material, enable backfill topsoil to pass through the stone envelope and into the drainpipe during the settlement period. Some of this sediment will remain in the aggregate envelope, reducing permeability, and may be available to be mobilised over time. The most commonly used aggregate sizes in Ireland are 50 mm and 20–40 mm, respectively (Byrne et al., 2022). The Teagasc Drainage Manual (Teagasc, 2022) recommends an aggregate size in the 10 to 40 mm range, with optimum performance in the 10 to 20 mm range. Based on these findings (pending field trials), aggregates larger than 20 mm in size should not be recommended in the future. The remaining discussion will relate to Aggregate 1 to 5 only.

Due to the stable nature of clay-textured soils in-situ, incursion of sediment into the envelope is considered low-risk in the long term. However, the potential for blocking during the initial period of settlement is the major risk associated with the introduction of trench backfill before equilibrium within the soil is achieved (Vlotman et al., 1993). Where an envelope prevents excessive incursion of sediment in clay-textured soils, the envelope should then function to maximise the hydraulic performance of the entire system. ADHB (2018) and Teagasc (2022) recommend the use of permeable backfill, even in consolidated clay-textured soils, to maintain the permeability in the drain trench and maintain an increased effective radius, even as the permeability of the trench backfill reduces over time. Bahceci et al. (2018) have suggested that stable clay soils do not need an envelope (Stuyt et al., 2005; Vlotman et al., 2020), but in Turkey, for example, aggregate envelopes are used to improve the hydraulic conditions around the pipe in clay-textured soils. All five aggregates (Aggregate 1 to 5) prevented excessive sediment incursion, so the focus of in-situ field research should be to increase the effective radius in the stable clay soils once settlement has occurred. As Aggregate 1 to 5 exceeded the hydraulic performance criterion of 0.54 mm hr^{-1}, they are suitable from a hydraulic performance perspective and are recommended for in-situ field trials. Discharge appeared to be inversely related to aggregate size, with larger discharges being measured in the smaller aggregate sizes and smaller discharges measured in the larger aggregate sizes (exception: Aggregate 2)[3]

Unlike the discharge measurements, there was no relationship between aggregate size and sediment loss. All five aggregates performed effectively to limit sediment incursion into the envelope and the drainpipe and were deemed suitable based on the filter performance criterion (25% reduction in drainpipe capacity), but Aggregate 1 (0.7–3 mm) lost the most amount of sediment through the drainpipe (Figure 4.4). This can be assumed to be fine material lost from the envelope itself (<2 mm) and may be attributed to the envelope material being lost through the 2 × 15 mm drainpipe perforations. This shows the importance of selecting a granular material based on both the base soil and the drainpipe perforations (Dierickx, 1993). Aggregate 1 was selected to meet the SCS (1988) criterion but was not fully suitable for the drainpipe perforations commonly used. Although it performed effectively as an envelope, some washing of the envelope material into and through the drainpipe at this gradation occurred and should be expected when using 2 × 15 mm drainage perforations. With this loss of fine material from the envelope itself, Aggregate 1 still performed effectively as a filter, and the sediment lost into the drainpipe was not in large enough quantities to violate the filter performance criterion (25% reduction).

4.5 Conclusion

Overall, aggregates ranging in size from 0.7 to 19 mm performed adequately in terms of hydraulic and filter performance and were deemed suitable for subsequent

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[3] This relationship can be attributed to slower sediment incursion into the envelope, maintaining a larger hydraulic radius and flow of water into the drainpipe.

in-situ field trials. The results showed that increasing aggregate size resulted in decreased hydraulic performance. The lowest amount of soil in the pipe and in the envelope at the end of the experimental period was observed in Aggregate 1 (0.7–3 mm), and cumulative discharge rates were aligned with initial sediment incursion rates at the start of the experimental period. When the cost of the aggregate material is also considered, aggregates in the lower range are 18 to 50% more expensive than aggregates in the higher range, which would be optimal from a performance and cost point of view. Contractors and landowners should provisionally source aggregates in these ranges for better performance and lifespan outcomes.

4.6 Acknowledgements

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Chapter 5 – Investigating the suitability of synthetic envelopes as an alternative or complement to stone aggregate in clay-textured soils in Ireland

The aim of this chapter was to test, in a laboratory setting, the hydraulic conductivity and filter performance of four synthetic envelope treatments, and compare those treatments against an ideal aggregate size, identified in Chapter 4, for their suitability for use. The relative costs of the treatments were compared against the aggregate treatment to identify the overall suitability based on both cost and performance.

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Investigating the suitability of synthetic envelopes as an alternative or complement to stone aggregate in clay-textured soils in Ireland

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Abstract

In Ireland, agricultural landscapes dominated by high rainfall and poorly drained soils have high densities of in-field pipe drains surrounded by stone aggregate envelopes. Unlike other countries, there is limited availability and use of synthetic envelopes, and no data exist about their suitability and efficacy in clay-textured soils. Indeed, both aggregate and synthetic envelope-based designs have been implemented without knowledge of their suitability or efficacy. Available synthetic envelopes have two configurations: pre-wrapped loose materials and pre-wrapped geotextiles (woven, non-woven, and knitted, with the knitted being the most common in the U.S. and Canada). In total, five configurations (referred to in this paper as 'treatments') were examined in this study with a view to ranking them from performance and cost perspectives. The treatments were: a 0.8-mm-thick needle-punched, non-woven geotextile or a 2-mm-thick knitted filter sock wrapped around the drainpipe, with no aggregate (Treatments 1 and 2, respectively); a 0.8-mm-thick needle-punched, non-woven geotextile wrapped around 2–10 mm (D_{10}–D_{90}) stone aggregate (Treatment 3); a 2-mm-thick knitted filter sock wrapped around a drainpipe surrounded by 2 to 10 mm diameter stone aggregate (0.15 m above pipe, 0.13 m below pipe) (Treatment 4); and a 2 to 10 mm stone aggregate alone (0.15 m above pipe, 0.13 m below pipe) (Treatment 5). The hydraulic and filter performance of Treatments 1 to 4 were compared with Treatment 5. Treatments 3 and 4 were assessed to determine if they improved hydraulic and filter

performance over Treatment 5. Using cumulative discharge and cumulative flow weighted sediment loss (total suspended solids: TSS) as indicators of performance, geotextiles performed poorly from discharge and TSS perspectives. The discharge for Treatment 1 and Treatment 2 was below the discharge observed from the stone aggregate, and cumulative TSS losses were 636% and 709% higher (Treatment 1 and 2, respectively). The discharge from Treatments 3 and 4 was 67% and 134% higher than the stone aggregate, but this produced an increase in cumulative sediment losses. Treatment 5 performed effectively, with a discharge that was higher than that observed in the geotextile treatments (Treatments 1 and 2) but lower than that observed in Treatments 3 and 4. The use of these treatments, either alone or in combination with stone aggregate, is not recommended in the clay-textured soil tested, from both performance and cost perspectives. Therefore, this study recommends that stone aggregates in the optimal size range should be used as drain envelope material in similar textured soils in Ireland.

5.1 Introduction

The hydraulic conductivity and filtration capacity of a land drainage system depend on many factors, such as matching an appropriate type and sized envelope material with soil texture. Envelope material normally comprises either stone aggregates or synthetic materials. Byrne et al. (2022a) conducted a survey on the availability and suitability of the currently available stone aggregates in the Republic of Ireland (henceforth Ireland). The study found that the majority of stone aggregate sizes did not meet the current guidelines (which recommend an aggregate size in the 10–40 mm range; Teagasc, 2022). When established filter design criteria were applied to the available aggregate sizes, many of the aggregate grades in use were too large for clay-textured ("heavy") soils and were therefore unsuitable for use. A subsequent study (Byrne et al., 2022b) found that only aggregates in the 0.7-to-19-mm-size range performed adequately in a clay-textured soil from both filtration and hydraulic perspectives. When the cost of the aggregate material was also considered, aggregates in the lower size range (0.7–10 mm) were 18 to 50% more expensive than aggregates in the higher size range (10–19 mm).

Synthetic envelopes are commonly used worldwide and have replaced aggregates in many instances due to their relatively low cost compared to aggregate materials, which, even if competitively priced, have higher transportation and associated fuel costs during installation (Vlotman et al., 2020). They are commonly used in unconsolidated soils to prevent the movement of sediment into the drainpipe (El-Sadany Salem et al., 1995). Conversely, field drains in consolidated soils with a clay content greater than 25% do not require a filtering envelope (Vlotman et al., 2020). Synthetic envelopes are classified into two main categories: Prewrapped Loose Materials (PLMs) and Geotextiles (Stuyt and Dierickx, 2006). PLMs contain permeable structures consisting of loose, randomly orientated yarns, fibres, filaments, grains, granules, or beads, surrounding a corrugated drainpipe and retained in place by appropriate netting and/or twines. PLMs are usually installed in non-cohesive soils where soils have less than 25 to 30% clay and less than 40% silt. In the Netherlands, thicker PLMs are preferred in both cohesive and non-cohesive soils (Stuyt et al., 2005; Vlotman et al., 2020). Geotextiles are planar, permeable, synthetic textile materials that may be woven, non-woven, or knitted, and are prewrapped around a drainpipe (Stuyt et al., 2005). Geotextiles have been installed in large-scale land drainage systems in countries such as Canada, France, the United Kingdom, and the United States of America (Stuyt et al., 2005). Ghane (2022) showed the benefits of using a knitted geotextile sock for increasing the effective radius (the effective radius of the drain is the radius of an imaginary drainpipe with a completely open wall (Skaggs, 1978)), which in the field theoretically increases drain spacing. Subsequent work has verified this in sand-tank experiments (Ghane et al., 2022).

Located within the temperate climate zone for agricultural drainage conditions, the main principles of land drainage design in Ireland are to exploit soil layers with relatively high permeability by installing a groundwater drainage system or, where such a layer is not present, to implement a suitable shallow drainage system (Tuohy et al., 2016; Teagasc, 2022). In many countries, such as Ireland, the adoption of synthetic envelopes such as geotextiles in drainage systems is slow due to a combination of limited availability of drainage-specific geotextiles (which are mainly used in construction and civil works), unknown suitability in clay-textured soils, and historical (and continued) usage of aggregate as a drainage envelope (which can be used in both shallow and groundwater drainage systems). Although no data exist to show their suitability under Ireland-specific conditions (i.e., hydraulic conductivity, filter performance versus cost), and in clay-textured soils, these materials are still being installed on farms due to their relatively cheaper cost compared to aggregate envelopes. Double envelopes (envelopes comprising both a geotextile envelope and an aggregate envelope, in any configuration) are being used by farmers to improve drain envelope efficiency. The use of double-envelope systems in agricultural drainage has been influenced by their use in highway and construction drainage systems (TNZ, 2003; TII, 2015; Typargeosynthetics, 2012).

The objectives of this laboratory study were to compare (1) the hydraulic conductivity and filter performance of two synthetic envelopes (non-woven geotextile and filter sock); two synthetic envelopes used in combination with a stone aggregate; and an optimally functioning stone aggregate; and (2) the cost of synthetic envelopes and aggregate, to develop a performance-based cost index of drainage envelopes. These results will enable a direct comparison between the suitability (performance and cost) of geotextile envelopes and stone aggregates in a clay-textured soil and will assess if geotextile envelopes help enhance the function of an aggregate envelope.

5.2 Materials and methods

5.2.1 Soil, synthetic envelope and stone aggregate

A clay-textured soil was collected from the Teagasc Solohead Research Farm (latitude 52° 51' N; 08° 21' W; altitude 95 m a.s.l.). It was dried for 24 hr at 110 ºC and sieved to pass a 2 mm sieve grade. The textural class was determined using ASTM (2021): 7%, silt 37%, clay 56% (clay texture). The synthetic envelope materials were a: (1) 0.8-mm-thick needle-punched, non-woven geotextile (Thrace Synthetics S8NW, [Offaly, Ireland]) with a characteristic opening size (O_{90}) of 100 µm (± 30) (O_{90}/d_{90} - 0.5; O_{90} of the geotextile fabric indicates that 90% of the pores within the geotextile are smaller than the O_{90} value, and d_{90} is the soil particle diameter for which 90% of the soil particles are smaller (Elzoghby et al., 2021)). The average water flow velocity (permeability) of the non-woven geotextile is 130 (±39) mm sec^{-1} (manufacturer specification; EN ISO 11058:2019) (Appendix C, Figure S5.1); and (2) a 2 mm thick knitted polyester filter sock (Wetzel Technische Netze, [Löwenberger Land, Germany]) with an O_{90} of 150–200 µm (O_{90}/d_{90} – 3 to

4) and an average water flow velocity (permeability) of 400 mm sec^{-1} (manufacturer specification; EN ISO 11058:2019) (Appendix C, Figure S5.2). The geotextile properties are based on information received from the manufacturers. There is a limited selection of synthetic envelopes available within Ireland, and the selection of treatments was dictated by the availability of these geotextile envelopes. The stone aggregate was chipped limestone with a gradation of 2–10 mm (D_{15}–D_{75}) (Appendix C, Figure S5.3), and its selection was based on the results of a previous study (Byrne et al., 2022b). The drainpipe used was a 70 mm inside diameter, single wall corrugated pipe (80 mm outside diameter) (Floplast Ltd., Ireland). The perforations are in a 2 × 2 offset pattern and are 2 mm ´ 15 mm in size.

5.2.2 Experimental design

Experimental units comprised a 0.93 m deep x 0.57 m diameter reinforced plastic container (Figure 5.1). In total, five study configurations (referred to in this paper as ‘treatments’) were used. These were: a non-woven geotextile or a filter sock wrapped around the drainpipe, with no aggregate (Treatments 1 and 2, respectively), a non-woven geotextile wrapped around stone aggregate (hereafter: non-woven geotextile + aggregate; Treatment 3), a filter sock wrapped around a drainpipe surrounded by stone aggregate (hereafter: filter sock + aggregate; Treatment 4), and a stone aggregate alone (Treatment 5).

In Treatments 1 and 2 (Figure 5.1a), a 0.1 m deep layer of sand, compacted using a tamping device (0.3 m diameter round base with a 5 kg weight, dropped from a height of 0.6 m) was overlain by a 0.05 m deep layer of clay-textured soil (dry milled soil <2 mm). A non-woven geotextile (Treatment 1), or filter sock (Treatment 2), was prewrapped directly around the drainpipe. A 0.08 m deep layer of soil, compacted into two equal layers, was added around the drainpipe. Finally, a 0.3 m deep layer of soil, compacted in six equal layers to a wet density of 964.6 kg m^{-3}, was added. The edges of each layer of soil were pressed against the walls of the container by hand to ensure no by-pass flow occurred during the experiment. Treatments 3, 4, and 5 (Figure 5.1b, c, and d, respectively) contained clay-textured soil filled to a depth of 0.02 m, overlain by 0.21 m of aggregate (2 to 10 mm; D_{15}-D_{75}). The top of the drainpipe was installed 0.23 m from the bottom, followed by

0.15 m of aggregate over the drainpipe, and, finally, a 0.15 m-deep layer of soil. In these study configurations, a non-woven geotextile fully surrounded the aggregate (Treatment 3), a filter sock was prewrapped around the drainpipe (Treatment 4), or only aggregate was used (Treatment 5).

Each treatment was conducted over a 31-day period. All units were overlain by 0.4 m of water. In order to prevent damage to the top layer of soil during the initial flow of water into the tank, an aluminium tray (0.2 x 0.2 x 0.05 m) was used to disperse the water. This tray was subsequently removed once a constant head was achieved. All experimental units were strengthened by nylon straps, and paraffin wax was applied at the edges of the topsoil layer to prevent by-pass flow. The following measurements were made discharge of water through the drainpipe outlet (an indicator of the hydraulic conductivity functionality of the envelope), expressed as L m^{-1} of drainpipe (0.08 m dia), and total suspended solids (TSS) (to determine the filter functionality of the envelope), measured in accordance with BS872 (BSI, 2005). In order to estimate total sediment loss (g L m^{-1} of drainpipe) daily and cumulatively, TSS concentrations were multiplied by the discharge rate.

The discharge performance criterion was assessed by direct comparison with the performance of 15.5–19 mm diameter aggregate, identified by Byrne et al. (2022b) to have the lowest cumulative discharge in a study comparing the discharges of aggregates ranging in size from 0.7 to 62 mm. That study had an identical configuration to Treatment 5 (aggregate only) in the current study and also contained the same clay-textured soil. In order to compare the discharge of both the current study and that of Byrne et al. (2022b), the cumulative discharges from the five configurations of the current study by day 31 were compared to Byrne et al. (2022b) – 16745 L m^{-1}. Similarly, the filter performance was compared to aggregates with a size ranging from 0.7 to 3 mm, which were found by Byrne et al. (2002b) to have the worst filtration performance of aggregates ranging in size from 0.7 to 62 mm. A similar comparison of both studies was conducted, with a target cumulative TSS of 61 g m^{-1} by day 31 being identified.

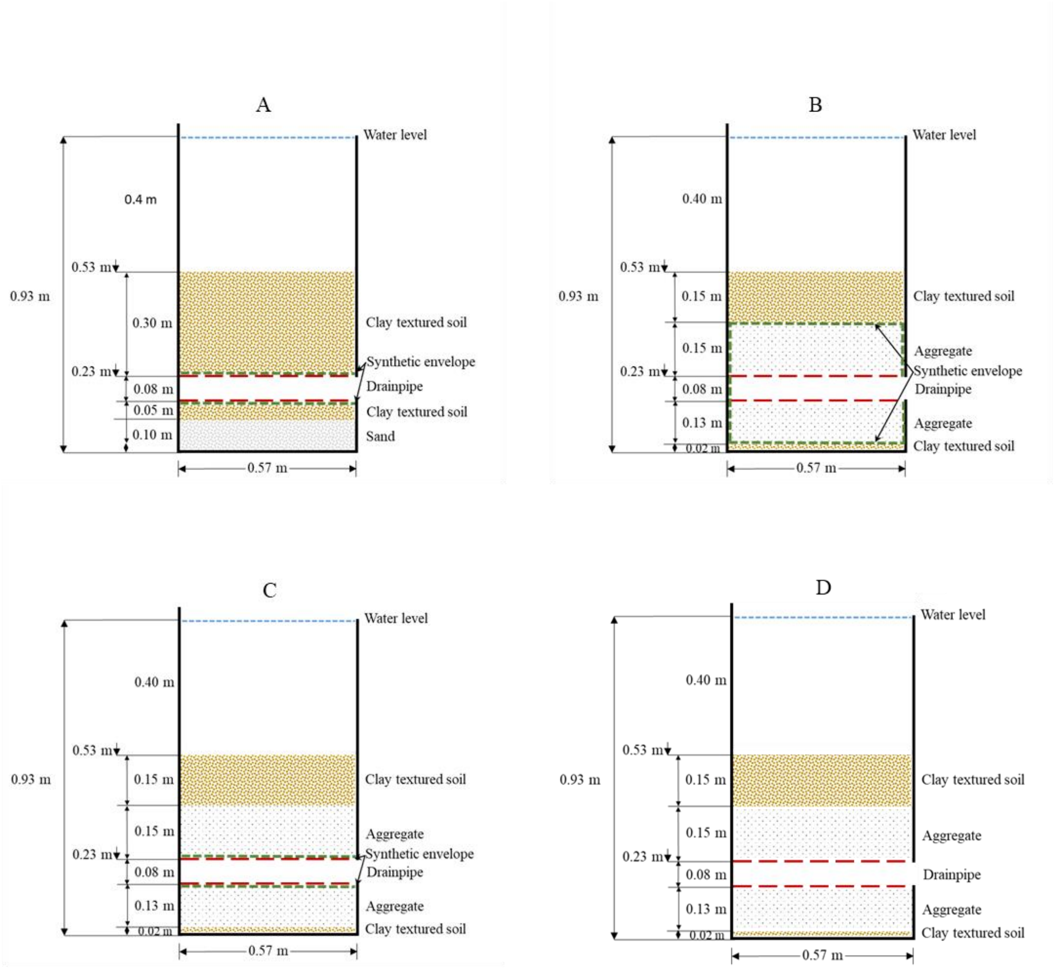

Figure 5.1 Laboratory unit design for the synthetic envelope, aggregate (2–10 mm), and clay-textured soil combination with depth profiles indicating: (a) the non-woven geotextile or filter sock (Treatments 1 and 2, respectively); (b) the non-woven geotextile wrapped around the aggregate envelope (Treatment 3); (c) a filter sock prewrapped around the drainpipe (Treatment 4); and (d) a 2 to 10 mm aggregate installed around the drainpipe (Treatment 5).

5.2.3 Envelope material ranking

To determine the cost effectiveness of these treatments, the cost was expressed as € m^{-1} of drainpipe. The cost of all aggregate ranges available in Ireland (Byrne et al., 2022b) was modified from € T^{-1} (tonne) to an estimated € m^{-1} (assuming a 0.3 x 0.35 m trench (W × H) and an estimated aggregate density of 1500 kg m^{-3} (0.16 T m^{-1} of gravel)) to compare cost effectiveness across all aggregates and synthetic treatments. Under the ‘discharge and sedimentation performance’ category, treatments were either suitable or unsuitable based on their passing or failing the discharge and/or sedimentation criteria. Assessing treatments in ‘overall cost and performance' category, treatments with suitable performance characteristics were optimal or sub-optimal for use. If treatments do not have favourable performance characteristics, they are substandard. The cost data obtained were amalgamated from Byrne et al. (2019) and Byrne et al. (2022b).

5.2.4 Statistical analysis

Statistical analysis was carried out using SAS 9.4 (SAS Institute Inc., Cary, NC, USA). A univariate analysis of the data was conducted to determine normality. The data were shown to be non-normally distributed. The effects of envelope function on discharge and sediment loss across 5 treatments were measured using the PROC MIXED procedure with repeated measures where time was a factor (T = 10, 20, and 31). Statistical significance was assumed at a value of $P < 0.05$.

5.3 Results

5.3.1 Hydraulic performance

Figure 5.2 shows the discharge of five treatments over the total study duration of 31 days. Cumulative discharge rates ranged from 5918 L m^{-1} to 47282 L m^{-1}. All treatments, with the exception of Treatment 2, exceeded the discharge criteria of 16745 L m^{-1}. Cumulative discharge was highest in filter sock + aggregate (Treatment 4) and non-woven geotextile + aggregate (Treatment 3) (47282 and 33783 L m^{-1}, respectively). Treatment 5 and Treatment 1 had similar cumulative discharge levels (20229 and 19131 L m^{-1}, respectively). The lowest cumulative discharge was observed with the filter sock treatment (Treatment 2; 5918 L m^{-1}), failing to meet the discharge criteria.

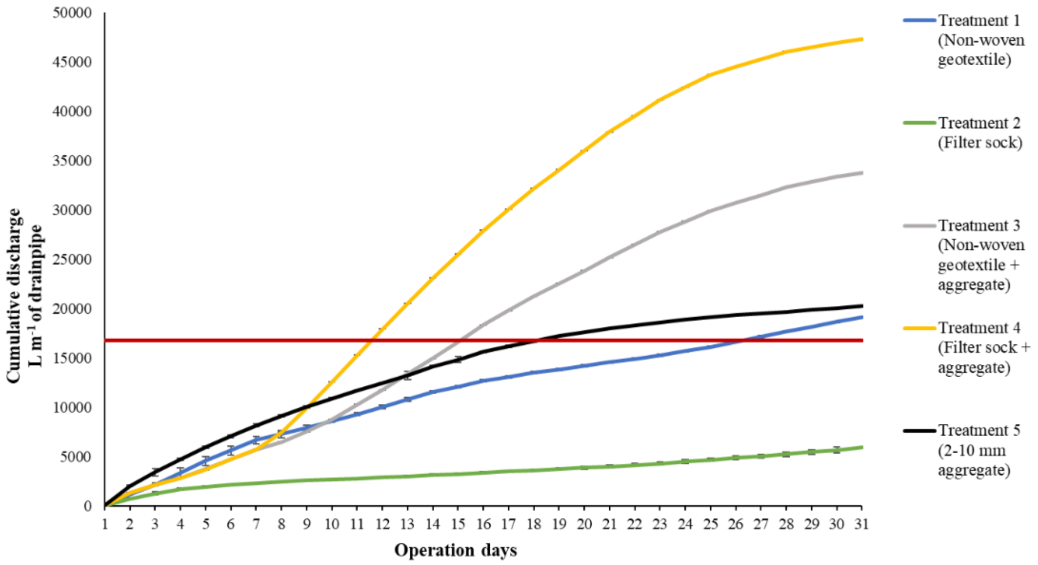

Figure 5.2 Cumulative average discharge rate, with the minimum required discharge allowed under the hydraulic conductivity (discharge) criterion highlighted in red (error bars indicate the standard deviation).

5.3.2 Sediment loss

Only two Treatments (Treatment 3 and 5) met the TSS criterion for effective filtration performance (less than 61 g m^{-1}). TSS losses observed across the treatments ranged from 11 g m^{-1} (Treatment 5; 2–10 mm aggregate) to 89 g m^{-1} (Treatment 2; filter sock) (Figure 5.3). The aggregate (Treatment 5) had the lowest TSS losses of the five treatments (11 g m^{-1}). The highest TSS losses were observed using the filter sock and non-woven geotextile (Treatments 2 and 1) (89 and 81 g m^{-1}, respectively). The majority of the sediment lost for each treatment occurred within 7 days of the start of the experiment: losses during this period, expressed as a percentage of the total sediment loss over the experiment’s duration, ranged from 58% (filter sock + aggregate) to 77% (filter sock). After this time, sediment loss was greatly reduced, potentially due to blocking of the filter during this period[4]

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[4] A wet sieving test to determine the changes in aggregate stability and sediment incursion over this period of time should be conducted in further studies to determine this.

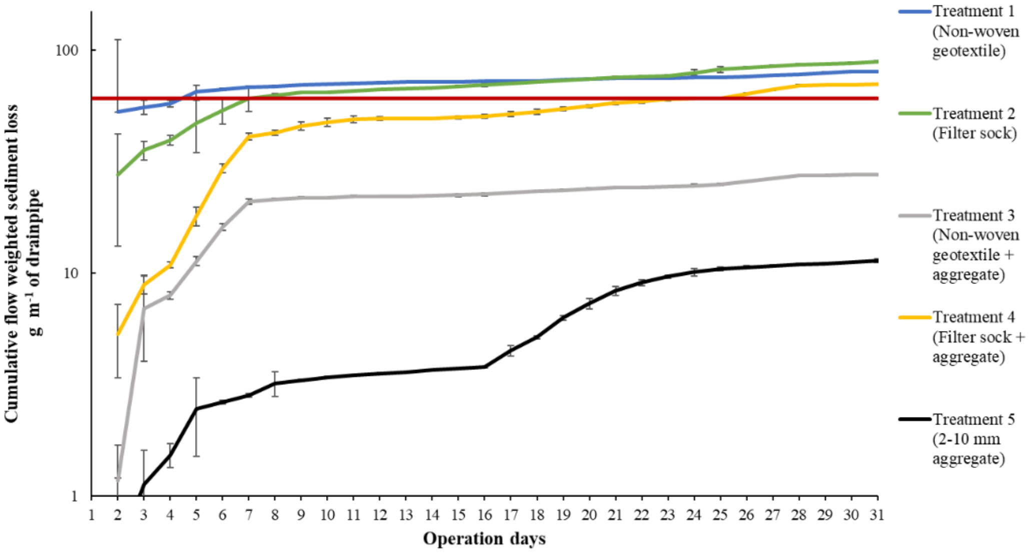

Figure 5.3 Cumulative discharge weighted sediment loss, with the maximum sediment loss allowed under the filter (sedimentation) criterion highlighted in red indicating the worst performing aggregate (Byrne et al., 2022b) (error bars indicate the standard deviation).

5.3.3 Data aggregation and cost analysis for selection

Table 5.1, combining both the performance and cost of materials, indicates that Treatment 5 (2–10 mm aggregate) is optimal for use based on both cost and performance, with the lowest cost where it exceeded both the hydraulic and filter design criteria. The non-woven geotextile + aggregate (Treatment 3) was 42% more costly than aggregate alone and had a 67% increase in discharge and a 155% increase in sediment loss in comparison with the aggregate. Moreover, it performed effectively with regard to the discharge and filter (sedimentation) criteria. The filter sock + aggregate (Treatment 4) performed effectively with regard to the discharge criterion, but it produced TSS above the limit of acceptable sediment losses. The other treatments (Treatment 1 and 2) failed on the filter (sedimentation) criteria, while Treatment 2 was below the limit for discharge criteria and Treatment 1 was above the acceptable limit.

Table 5.1 Synthetic and aggregate envelope suitability for use with clay-textured soils from a discharge, sedimentation, and cost perspective.

Treatments (Aggregate, D_{15}-D_{75} (mm))	**Treatment number**	**Discharge**	**Sedimentation**	**Cost € m^{-1} (ex VAT ex delivery)[1]**	**Discharge and sedimentation performance**	**Overall cost and performance[2]**
Synthetics						
Non-woven geotextile	1	✓	X	0.83	Not suitable	Substandard
Filter sock	2	X	X	1.23	Not suitable	Substandard
Non-woven geotextile + aggregate	3	✓	✓	2.83	Suitable	Sub-optimal
Filter sock + aggregate	4	✓	X	3.23	Not suitable	Substandard

Aggregate						
Aggregate Optimum Range (2–10 mm)	5	✓	✓	2.00	Suitable	Sub-optimal

[1] Cost of aggregates € m^{-1} assumes 0.16 T m^{-1} of aggregate used.

[2] Treatments with suitable performance characteristics were optimal or sub-optimal for use. If treatments were classified as ‘not suitable’ in the discharge and sedimentation performance category, they are considered substandard for the overall assessment. The aggregate optimum range (2–10 mm) is classified as sub-optimal due to its increased cost over other suitable aggregates in the 0.7 to 19 mm range (Byrne et al., 2022b)

5.4 Discussion

5.4.1 Discharge, sedimentation and cost of geotextiles

Based on discharge and TSS losses, both non-woven geotextiles and filter socks should not be used where geotextiles are surrounding the drainpipe in clay-textured soils, as these treatments did not meet both the required minimum discharge rate and sedimentation criteria (Section 5.2.2). No difference in the day of peak flow (indicating hydraulic saturation) (Appendix C, Figure S5.4) was observed between treatments based on differing soil overburden thickness in Figure 5.1. El-Sadany Salem et al. (1995) concluded that thin envelopes were at a higher risk of clogging than voluminous envelopes, while Choudhry et al. (1995) likewise concluded that although a selection of needle-punched, non-woven geotextile envelopes had met the particle-retention criterion in their experiments, the envelopes could not meet the standard of desired blocking, clogging, and hydraulic performance. They concluded that further testing was necessary. Non-woven geotextiles and filter socks had the lowest cost for an envelope on a € m^{-1} basis, but with poor hydraulic and filter performance, these geotextiles are not suitable for use in clay-textured soils. The range of aggregates (0.7–19 mm) identified by Byrne et al. (2022b) is preferred with a clay-textured soil. These aggregates had lower rates of cumulative TSS and greater cumulative discharge rates than the geotextile treatments investigated in the current study.

5.4.2 Discharge, sedimentation and cost of the non-woven geotextile and aggregate combination

The non-woven geotextile + aggregate combination met the criteria for discharge and sedimentation rate, but this combination is not recommended as it still exhibits the same potential risks of clogging as highlighted in Section 5.4.1. Although this treatment method is commonly applied in road drainage systems where a geosynthetic material (typically non-woven geotextile) is placed over the top of the aggregate at the edge of road drainage systems (TNZ, 2003; TII, 2015), the higher discharge rates observed for this treatment may lead to a filter cake formation over time at the interface between the soil and the envelope (Stuyt and Dierickx, 2006) due to higher hydraulic conductivity rates. This is backed up by the higher sediment transmission observed for this treatment in comparison to the aggregate treatment.

Additionally, Elzoghby et al. (2021) found that although the non-woven geotextiles (Typar SF27 and Typar SF20) used indicated effective filtration of soil particles, five times more fine soil particles than the original soil were found at the geotextile-soil interface. This highlights the importance of considering the O_{90} of both the geotextile material and soil size distribution (Stuyt and Dierickx, 2006). In the current study, a 42% increase in cost per metre (for the non-woven geotextile + aggregate) yielded only a 67% increase in cumulative discharge at day 31. The potential filter cake development at the soil-envelope interface after installation and the small increase in discharge do not currently justify the use of this combined treatment.

5.4.3 Discharge, sedimentation and cost of the filter sock and aggregate combination

The filter sock + aggregate drain envelope is considered unsuitable for use based on failing the sedimentation criterion. The highest discharge rates were also observed for this treatment. This treatment is thought to limit blocking of the envelope system by reducing hydraulic gradients and movement into the envelope, thereby allowing it to function effectively for longer. Swihart (2000) found that the use of a geotextile sock around the drainpipe combined with a sand envelope produced a discharge 3 to 12 times higher than tests conducted without the geotextile sock (analogous to the filter sock + 2-10 mm aggregate combination). The high discharge rates observed in this experiment and a larger O_{90} size (150–200 µm) of the filter sock help to limit the blocking of the filter while aiding increased hydraulic performance. These higher discharge rates caused greater sediment transmission, which may potentially block the drainpipe quicker than at lower discharge rates. The 62% increase in cost per metre (for the filter sock and aggregate treatment compared to the aggregate treatment) yielded a potential 134% increase in cumulative discharge at day 31, but the factors discussed above may potentially mitigate these increases over time due to increased sediment transmission and blocking of the aggregate envelope and drainpipe. Until further research is carried out on this potential combination, the filter sock should not be recommended in combination with an aggregate.

5.4.4 Discharge, sedimentation and cost of the aggregate, and its suitability based on installation methods and availability

The 2 to 10 mm diameter stone aggregate performed more effectively for hydraulic and filter performance than the geotextiles alone. Cumulative TSS levels in the geotextile + aggregate treatment was 143% higher than in the aggregate only treatment, while only a 67% increase in discharge was observed for the geotextile + aggregate treatment over the aggregate alone.

Additionally, it was more cost-effective (in comparison to the geotextile + aggregate treatments) but is still considered sub-optimal based on its increased cost compared to other suitable aggregates in the 10 to 19 mm range that were more suitable based on both cost and performance aspects (Byrne et al., 2022b). The suitability of both aggregates and geotextiles in clay-textured soils has a number of advantages and disadvantages. Although relatively expensive compared to synthetic envelopes, stone aggregate is abundant in Ireland (Byrne et al., 2022a), and the production of aggregate sizes within the current national guidelines (10 to 40 mm, with increased filtration performance evident from 10 to 20 mm aggregates) (Teagasc, 2022) will improve drain envelope performance. Geotextiles or any synthetic envelopes tend to be unsuitable where fine-textured heavy soils dominate and shallow drainage techniques (e.g., sub-soiling, mole drains, and gravel mole drains) are employed (Teagasc, 2022). Such shallow drainage systems are commonly applied in Ireland where no permeable soil layer is present in the soil profile (Teagasc, 2022). Tuohy et al. (2018) highlighted climate trends and predictions of future higher rainfall intensities. This may result in more shallow drainage systems being installed on heavy clay soils where drainage works were previously not justified due to increased rainfall intensity, waterlogging, reduced yields, and low soil bearing capacity. This will require the continued use of shallow drainage systems and necessitate the use of stone aggregate in most situations.

This study will help inform the selection of geotextiles used in clay-textured soils and additionally provide information on possible future synthetic materials that become available on the Irish market for installation in subsurface drainage systems, but each synthetic envelope will still have to be tested due to the varying physical properties (Palmeira and Gardoni, 2002).

5.5 Conclusion

The results showed that locally available non-woven and knitted sock geotextiles alone did not function as well as 2 to 10 mm diameter stone aggregate and were unsuitable for the tested clay-textured soils in Ireland. The selection of suitable geotextiles was limited by local availability. Both double envelope synthetic envelope treatments performed effectively from a performance perspective but are currently uneconomical. Further drain envelope efficiency would be achieved from greater adoption of aggregates in the 0.7 to 19 mm range by farmers and contractors and greater production of this aggregate range in quarries around the country. Future research on thicker synthetic envelopes (with similar performance functionality to aggregates) to aid in reducing the cost of drainage works may be required, but the current availability of these envelope types locally is unknown.

5.6 Acknowledgements

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Chapter 6 Conclusions and Recommendations

6.1 Overview and context

The initial hypothesis of this study was that the stone aggregate sizes in use as drainage envelope materials in Ireland were much larger than recommended under the current national guidelines or established filter design criteria for drainage envelopes. A need was identified to establish guidelines for a range of materials suitable for clay-textured soils in Ireland. Chapter 3 developed a database classifying the distribution, type, popularity, size and availability of aggregates in quarries throughout Ireland. The key findings of Chapter 3 were that in many regions across Ireland, aggregates larger than the current national recommended guidelines (10 – 40 mm) are used in agricultural drainage envelopes. This will likely cause problems with the ability of the envelope to filter any soil material and potentially may affect the lifespan of the drain system.

The objectives of Chapter 4 and Chapter 5 were to assess, in laboratory experiments, the hydraulic and filter performance, and associated cost, of a range of aggregate gradations (identified in Chapter 3) and geotextile envelopes in clay-textured mineral soils. This allowed a comparison to be made between geotextile envelopes and stone aggregates, considering performance and cost. The findings of Chapter 4 were that only aggregates in the 0.7 to 19 mm range are suitable for use in clay-textured soils. Discharge was inversely related to aggregate size, with larger discharges being measured in the smaller aggregate sizes and smaller discharges measured in the larger aggregate sizes. For all aggregates examined, discharge was greatest at the start of the experiment before reducing over time. The findings of Chapter 5 were that non-woven geotextiles and filter socks should not be used where geotextiles surround the drainpipe in clay-textured soils, as these treatments did not meet both the required minimum discharge rate and sedimentation criteria. The use of geotextile + aggregate combinations were not recommended, because they posed a potential risk of clogging. Additionally, the cost of the geotextile + aggregate combination was not justified based on the increased performance observed over the aggregate alone.

It is important to note that while the continued use of stone aggregate in clay-textured soils is recommended, it is necessary to conduct in situ field experiments to determine their suitability using various installation techniques and based on a range of hydrological conditions. The same applies to the geotextile materials examined in this study.

6.2 Conclusions

The main conclusions of this study are:

- The sizes of aggregates currently in use in Ireland are larger than what is specified by the current national guidelines (10 to 40 mm). In addition, they do not conform to established design criteria for drainage systems, which specify a smaller aggregate size than what is currently in use. Further research is needed to investigate the efficacy of materials currently in use in Irish drainage systems and to identify suitably sized aggregates for Irish mineral soils.
- The method used by quarries in identifying aggregates by a single aggregate size ("Q size") or a Q size within a specified grading range, does not give a fair reflection of the true gradation of aggregate being sold by quarries. This approach causes confusion regarding the aggregate being used by the drainage contractor or farmer. To remove confusion, a standardisation of quarry aggregate specifications based on their grading range (D_{90}–D_{10}) is required. This allows the selection of a suitable aggregate range based on current national guidelines (10 to 40 mm) or by applying established aggregate filter design criteria.
- Aggregates ranging in size from 0.7 to 19 mm performed adequately in terms of hydraulic and filter performance in laboratory trials. The results showed that increasing aggregate size resulted in decreased hydraulic performance. The lowest amount of soil in the pipe and in the envelope at the end of the experimental period was observed in an aggregate ranging in size from 0.7–3 mm. When the cost of the aggregate material is considered, aggregates in the lower range are 18 to 50 % more expensive than aggregates in the higher range, which would be optimal from performance and cost perspectives.
- Locally available non-woven and knitted sock geotextiles alone did not function as well as 2 to 10 mm stone aggregate and were unsuitable for Irish

clay-textured soils. The selection of suitable geotextiles was limited by local availability. Both double envelope synthetic envelope treatments performed effectively but are currently uneconomical. Further drain envelope efficiency would be achieved from adoption of aggregates in the 0.7 to 19 mm range by farmers and contractors and greater production of this aggregate range in quarries around the country.

6.3 Limitations

- The laboratory tests conducted in this study are stress tests comparing envelopes under controlled laboratory conditions. The results cannot be directly translated to field conditions and are subject to field testing.
- The mechanisms of the envelope-soil and envelope-pipe interactions were not studied but may provide useful information on why some envelopes get blocked and others do not.
- The laboratory tests conducted used only a clay textured soil, but clay loam textured soils are also commonly drained in Ireland. Experiments should be conducted on this soil texture to determine envelope suitability.

6.4 Recommendations

The main recommendations from this thesis are:

- Limestone is the most abundant rock type available in Ireland. Limestone from quarries should be tested to determine their vulnerability to chemical precipitation of calcium carbonate under rainwater and acidic soil conditions, as precipitation of calcium carbonate has the potential to block both envelope systems and drainpipes.
- Quarry aggregate should be standardised based on their grading range (D_{90}–D_{10}) across all quarries. This would eliminate confusion over the size of aggregate being used by the drainage contractor or farmer when purchasing drainage aggregate in the future. It is advised that this recommendation would be disseminated by Teagasc to the quarries directly.
- Laboratory experiments, like those described in this thesis, could be used as a quick screening method to determine the suitability of new geotextile

materials that become available in the Irish market before, they are used in the field.

- Further research should be conducted in the field, with the envelope materials considered optimal based on the laboratory experiments conducted in this thesis. This would allow their selection and assessment for use based on the field conditions and installation methods used.
- Clay-textured soils are predominantly drained in Ireland, but laboratory tests, like those described in this thesis, could be conducted to determine the suitability of stone aggregates and geotextiles in different textured, poorly drained, Irish soil types. Drainage of these poorly drained soil types will play a large role in Irish agriculture meeting their climate change targets.
- A series of parallel flow permeameter tests could be conducted to observe the physical processes of particle passage and envelope clogging involved in the soil-envelope interaction for several geotextile and aggregate envelopes.
- Field experiments should be conducted with aggregates and geotextiles to determine groundwater levels and discharge in the field.
- Envelopes should be examined to determine their suitability for use in soils with high iron contents, which are susceptible to iron ochre deposition. Additionally, methods to reduce or remove iron ochre deposition in drainage systems should be examined.
- Drainpipes act as pathways for the discharge of nitrogen (and less so phosphorus) to open drains and subsequently stream and river systems, which can have a number of effects on the ecosystem of these water bodies. Envelope materials should be examined to determine their nutrient attenuation capacity.

Appendix A

Appendix: Additional survey information on indicative aggregate costs

Cost survey

From the survey carried out in December 2018. The survey sought information on lithology (limestone, sandstone, mixed, or other); 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). Where three sizes were specified, information on the cost of this aggregate gradation was collected. The costs of the materials are quoted per tonne, excluding haulage and VAT.

Aggregate costs based on lithology and region

Table S3.1 outlines the prices for average sizes by region. They vary with rock type, size, quantity purchased, delivery distance, and the intensity of grading and washing conducted, and are only provided as an indicative cost of aggregate in Ireland. On average, a 50 mm stone costs €8.87. This can vary anywhere from €5.50 to €12.50. The average cost for a 20 mm, 20-40 mm, and 20-50 mm stone is €10.00. The larger 75 mm and 100 mm stones are cheaper at €8.41 on average, with the smaller 10 mm, 12 mm, and 14 mm stones costing around €9. Larger aggregate sizes generally have lower end costs due to less material processing required and these sizes being less popular for use in the construction and road building industries. The cost of most sizes in Munster was more expensive than those in Connaught or Leinster.

Table S3.2 shows the breakdown of stone types for the three main rock types. When divided by lithology, the most expensive is gravel, followed by sandstone and limestone, respectively. Gravel, generally used as a drainage stone, is usually more expensive due to the lower abundance of natural gravel quarries and its suitable application for various drainage purposes. Gravel quarries in Ireland are abundant but are mainly located within the centre of the country. While sandstone is mainly available within the Munster region, it is usually more expensive than limestone due to it being a harder-wearing stone that is not susceptible to breakdown physically or chemically. Limestone, being the cheapest aggregate type, is available throughout Ireland, and its abundance makes it a cheaper aggregate type to buy.

Care must be taken when selecting a limestone aggregate, as certain limestone types have a high percentage of calcium carbonate, which makes them susceptible to chemical breakdown, and the chemical precipitate (calcite) can bind the stone together and in turn reduce its porosity (Stuyt et al., 2005).

Appendix: Supplementary Figures and Tables for Chapter 3

Figure S3.1 A selection of Q20 mm aggregates of different lithologies.

Table S3.1 Aggregate cost by region.

Aggregate 'Q' size (mm)[1]	**Munster**	**Connaught**	**Leinster**
10	**-**	**-**	**€9**
12	**-**	**-**	**€9**
14	**-**	**-**	**€9**
20	**€10**	**€9**	**€10**
50	**€9.42**	**€8.36**	**€8.14**
75	**€8.20**	**€8.86**	**-**
100	**€8.20**	**€8.86**	**-**

20 – 40	**€11**	**€9**	**€9**
20 - 50	**€11**	**€9**	**€9**

[1] The ‘Q’ size indicates an approximate size of the aggregate as specified by the quarry. This can either be given as a gradation (20-40 mm) or a single size (50 mm).

Table S3.2 Aggregate cost by type.

Aggregate ‘Q’ size (mm)	Gravel	Sandstone	Limestone
10	**€10.16**	**-**	**€8**
20	**€10**	**-**	**€9.50**
50	**€10.13**	**€9.30**	**€8.11**
75	**-**	**€10**	**€8.57**
100	**€10**	**€7.75**	**€8.10**
20-40	**€9**	**€9.50**	**€6.50**
20-50	**€10**	**€9**	**€11.50**

[1] The ‘Q’ size indicates an approximate size of the aggregate as specified by the quarry. This can either be given as a gradation (20-40 mm) or a single size (50 mm).

Appendix B

Appendix: Supplementary Figures for Chapter 4 indicating the flow of water through the experimental units and the daily flow weighted sediment loss.

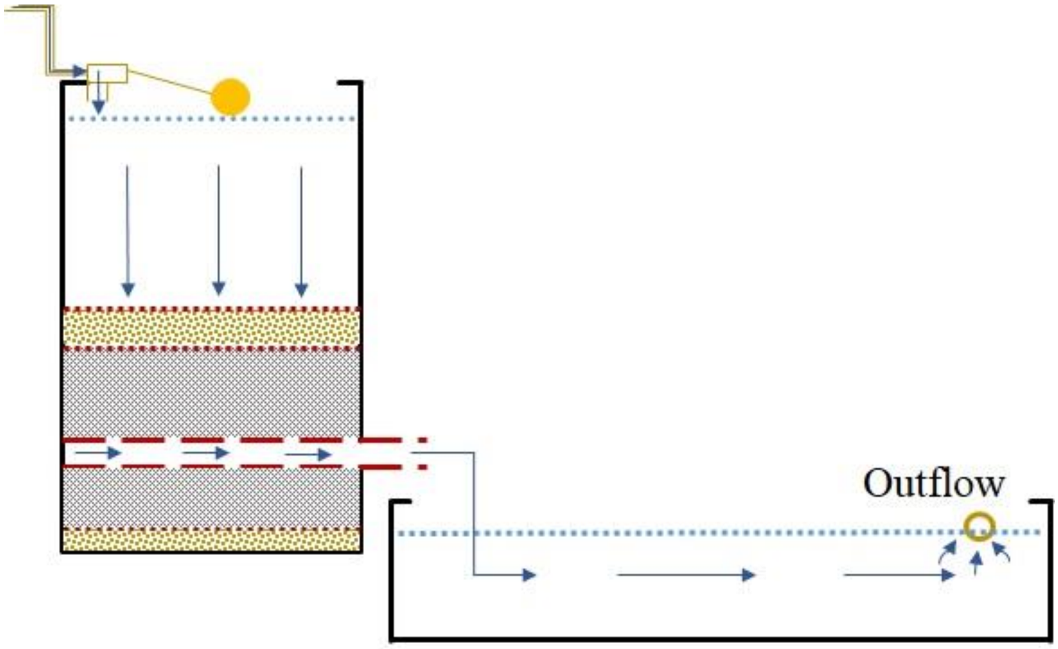

Figure S4.1 Flow pathway of water through the experimental unit.

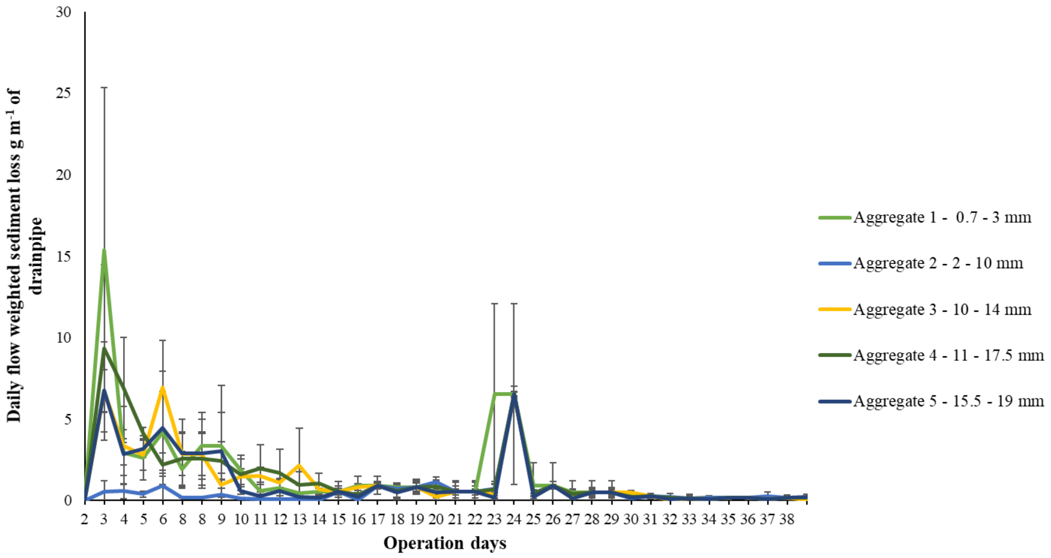

Figure S4.2 Daily flow weighted sediment loss g m^{-1} of drainpipe, showing sediment loss during the initial settlement period of the soil.

Appendix: Soil layer development experiments

An experiment was carried out to determine an appropriate soil thickness in the experimental units in order to limit "failure" of the envelope in this study (when the soil structure was observed to collapse or when there was excessive movement of soil through the envelope material within the first 24 hours of operation; Stuyt et al., 2005). The aim of this experiment was to determine a suitable thickness of soil for use in experimental units (used in Section 4.2) that would provide no break in the surface layer (indicating excessive movement of soil) while enabling the maximum flow rate possible. The experiment used three different soil thicknesses of 10, 15, and 20 cm, tested in conjunction with an 11 to 17.5 mm diameter aggregate (D_{15}-D_{75}). Figure S4.3 shows the flow rate of water through the trial unit over a period of 10 days. The flow rate through the different layers was greatest in the 15 cm layer. The lowest flow was observed in the 10 cm and 20 cm layers, respectively. On day 3, 16.00 hr, a break in the surface of the soil layer was observed in the 10 cm layer (Figure S4.4). After this time, an associated increase in flow was observed, linked to the direct flow through this broken layer of soil. Because of this, the 10 cm soil layer was considered too thin for use. The 15 cm soil layer was accepted for use based on flow rate, workability, and enabling finer sediment to wash through the envelope without compromising the structural stability of the soil layer, resulting in failure of the unit.

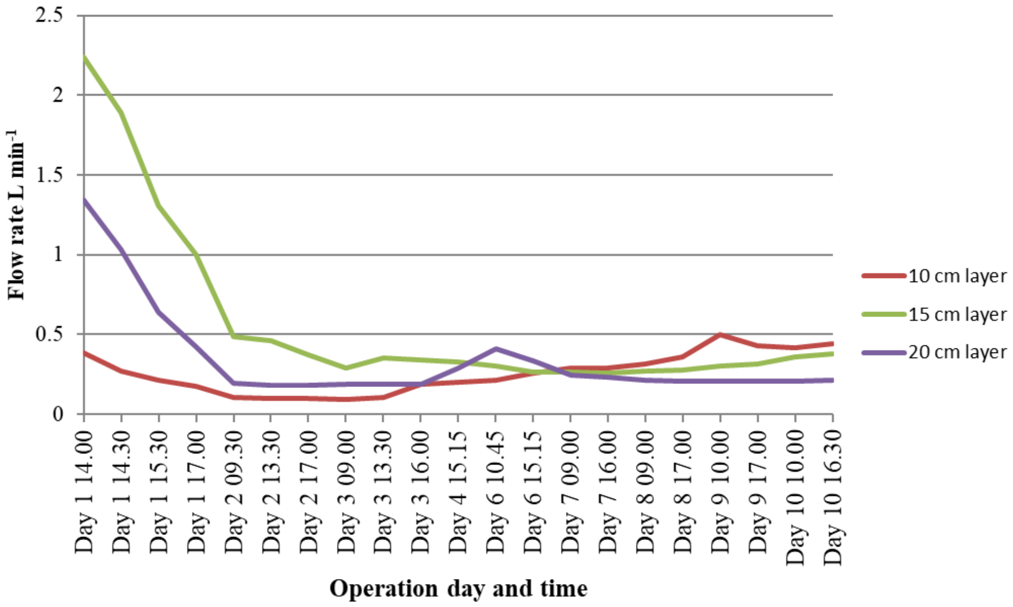

Figure S4.3 Flow rate of water through the drainpipe under three soil thicknesses.

A break in the surface of the 10 cm soil layer was observed on Day 3 16.00 hr (see Figure S4.4.).

Figure S4.4 Break in the 10 cm soil layer observed on Day 3 16.00 hr.

Appendix C

Supplementary material: Supplementary figures and tables for Byrne et al. (2022) "Investigating the suitability of synthetic envelopes as an alternative or complement to stone aggregate in clay-textured soils in Ireland"

Figure S5.1 Needle punched non-woven geotextile with a characteristic opening size (O_{90}) of 100 µm (± 30).

Figure S5.2 Knitted polyester filter sock with an O_{90} of 150 – 200 µm.

Figure S5.3 Chipped limestone with a gradation of 2-10 mm (D_{15}-D_{75}).

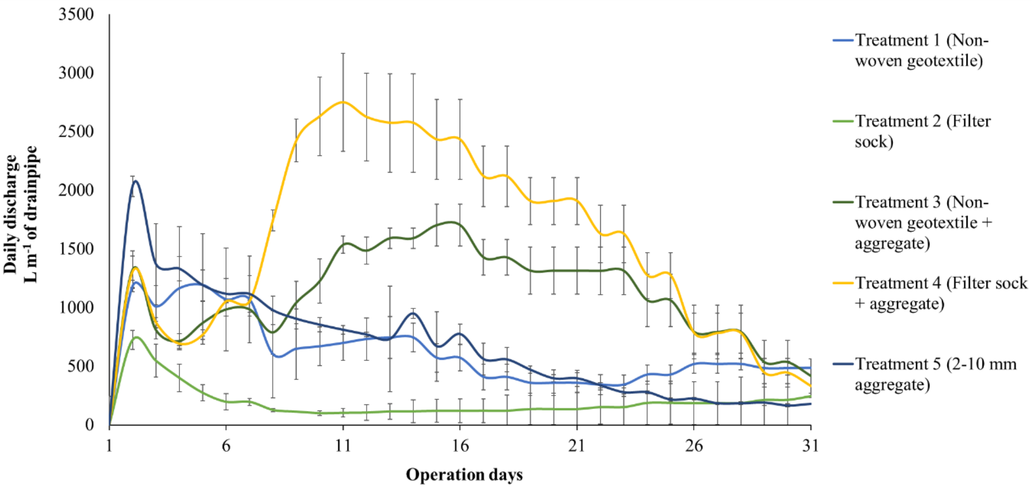

Figure S5.4 Daily discharge L m^{-1} of drainpipe.

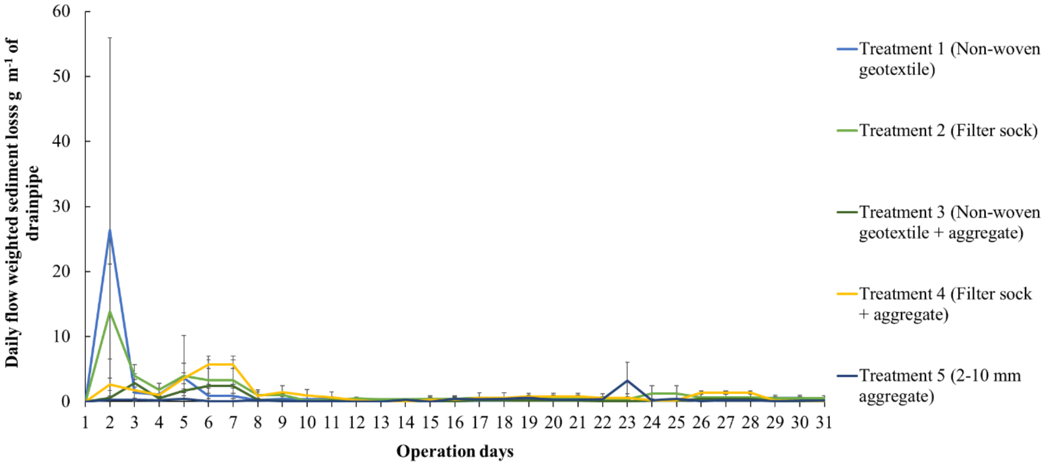

Figure S5.5 Daily flow weighted sediment loss g m^{-1} of drainpipe.

Appendix D

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Irish Journal of Agricultural and Food Research

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.

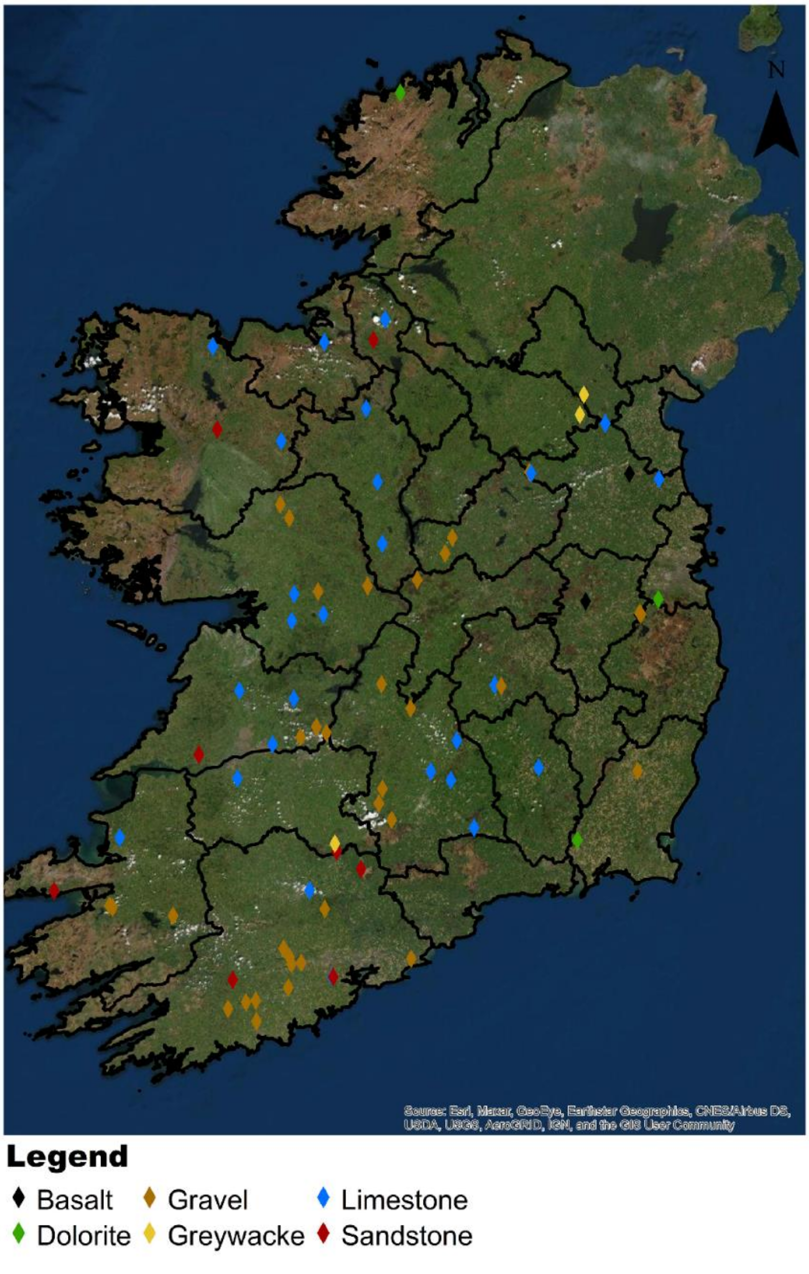
Sample collection and characterisation

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



Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

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

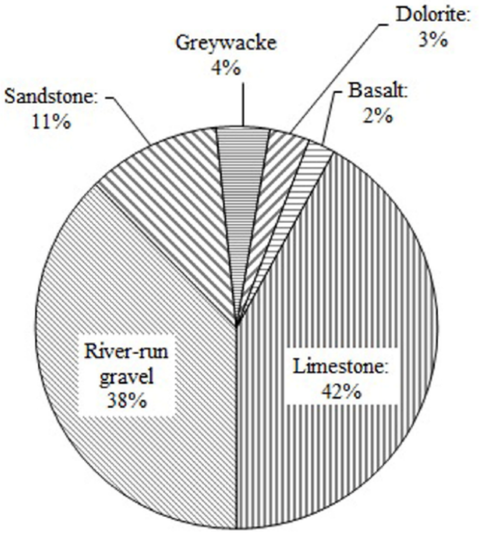


Figure 2. The most common quarry types in Ireland, by lithology (n = 100).

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

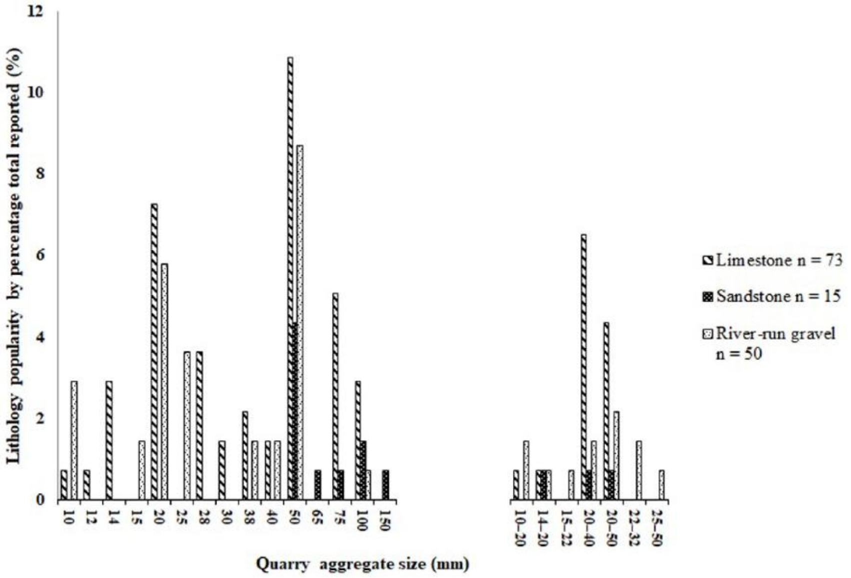


Figure 4. The most popular aggregate Q sizes (indicative sizes as reported by quarries, left: single size and right: grading band) for land drainage from quarries surveyed by lithology (n = 138).

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

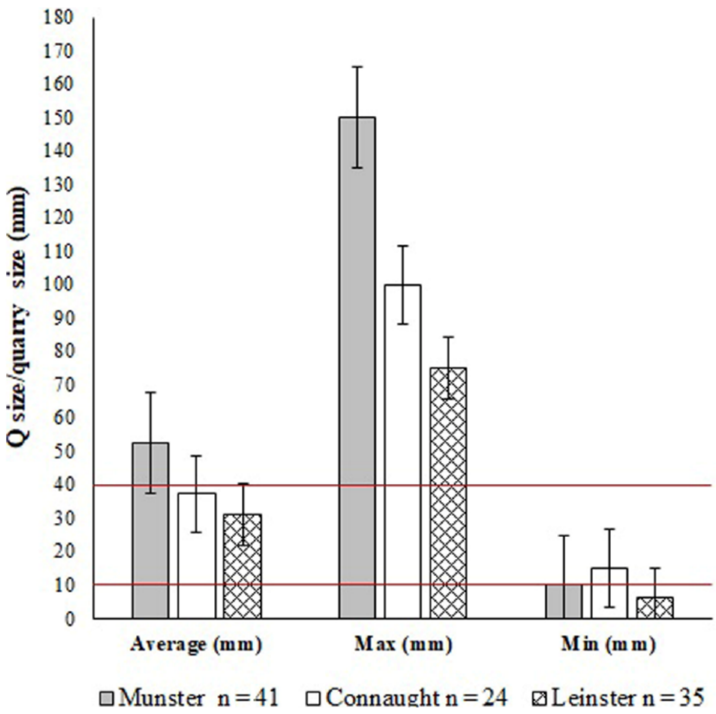


Figure 5. The average (mean of the mean), minimum (mean of the minimum) and maximum (mean of the maximum) Q sizes (inclusive of all lithologies) within each province based on survey data collected. The recommended size range of 10–40 mm from Teagasc (2013) is highlighted in red.

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

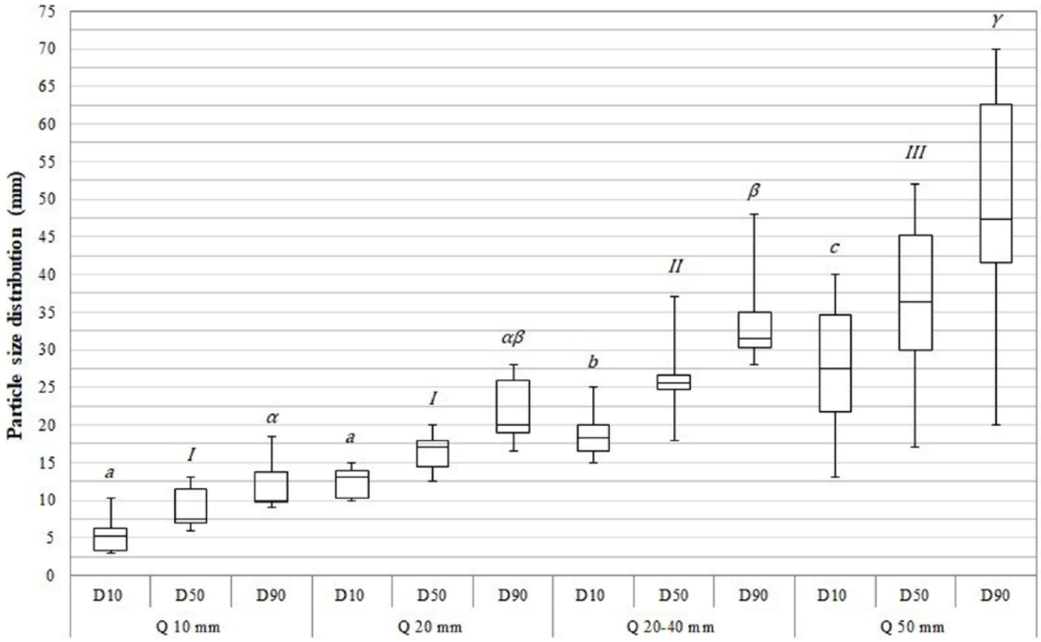


Figure 6. Q sizes, representing an approximation of the size of aggregate in mm as specified by the quarry, showing estimated 10%, 50% and 90% passing (D_{10}, D_{50} and D_{90}) figures indicating labelling variation across different quarries. Means with the same symbol are not significantly different 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.

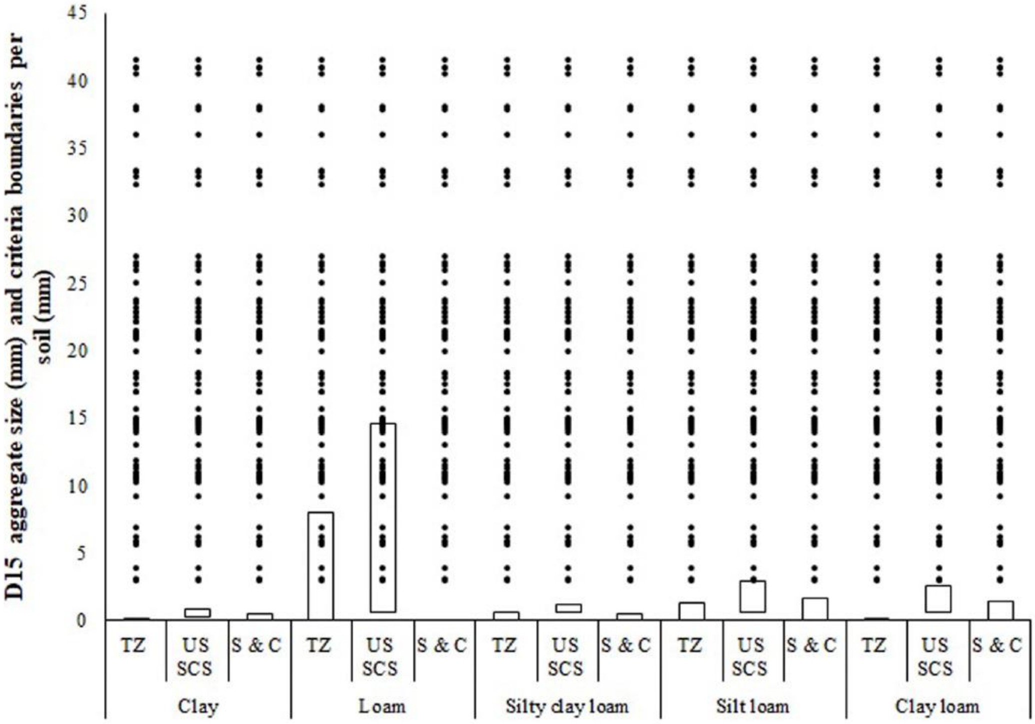


Figure 7. Recommended aggregate size using three filter design criteria (Terzaghi's [Terzaghi & Peck, 1961] ["TZ"]; US Soil Conservation Service [SCS, 1988] ["US SCS"]; Filters for Silts and Clays [Sherard *et al.*, 1984] ["S & C"]) applied to five soil textures, showing the suitability of 74 gravels 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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Investigating the suitability of synthetic envelopes as an alternative or complement to stone aggregate in clay-textured soils in Ireland

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ABSTRACT

In Ireland, agricultural landscapes dominated by high rainfall and poorly drained soils have high densities of in-field pipe drains surrounded by stone aggregate envelopes. Unlike other countries, there is limited availability and use of synthetic envelopes, and no data exist about their suitability and efficacy in clay-textured soils. Indeed, both aggregate and synthetic envelope based designs have been implemented without knowledge of their suitability or efficacy. Available synthetic envelopes have two configurations: pre-wrapped loose materials and pre-wrapped geotextiles (woven, non-woven, and knitted, with the knitted being the most common in the U.S. and Canada). In total, five configurations (referred to in this paper as 'treatments') were examined in this study with a view to ranking them from performance and cost perspectives. The treatments were: a 0.8-mm-thick needle-punched, non-woven geotextile or a 2-mm-thick knitted filter sock wrapped around the drainpipe, with no aggregate (Treatments 1 and 2, respectively); a 0.8-mm-thick needle-punched, non-woven geotextile wrapped around 2–10 mm (D_{10}–D_{90}) stone aggregate (Treatment 3); a 2-mm-thick knitted filter sock wrapped around a drainpipe surrounded by 2-to-10-mm-diameter stone aggregate (0.15 m above pipe, 0.13 m below pipe) (Treatment 4); and a 2-to-10-mm stone aggregate alone (0.15 m above pipe, 0.13 m below pipe) (Treatment 5). The hydraulic and filter performance of Treatments 1 to 4 were compared with Treatment 5. Treatments 3 and 4 were assessed to determine if they improved hydraulic conductivity and filter performance over Treatment 5. Using cumulative discharge and cumulative flow weighted sediment loss (total suspended solids: TSS) as indicators of performance, geotextiles performed poorly from discharge and TSS perspectives. The discharge for Treatment 1 and Treatment 2 was below the discharge observed from the stone aggregate, and cumulative TSS losses were 636% and 709% higher (Treatment 1 and 2, respectively). The discharge from Treatments 3 and 4 was 67% and 134% higher than the stone aggregate, but this produced an increase in cumulative sediment losses. Treatment 5 performed effectively, with a discharge that was higher than that observed in the geotextile treatments (Treatments 1 and 2) but lower than that observed in Treatments 3 and 4. The use of these treatments, either alone or in combination with stone aggregate, is not recommended in the clay-textured soil tested, from both performance and cost perspectives. Therefore, this study recommends that stone aggregates in the optimal size range should be used as drain envelope material in similar textured soils in Ireland.

1. Introduction

The hydraulic conductivity and filtration capacity of a land drainage system depend on many factors, such as matching an appropriate type and sized envelope material with soil texture. Envelope material normally comprises either stone aggregates or synthetic materials. Byrne et al. (2022a) conducted a survey on the availability and suitability of the currently available stone aggregates in the Republic of Ireland (henceforth Ireland). The study found that the majority of stone aggregate sizes did not meet the current guidelines (which recommend an aggregate size in the 10–40 mm range; Teagasc., 2022). When established filter design criteria were applied to the available aggregate sizes, many of the aggregate grades in use were too large for clay-textured ("heavy") soils and were therefore unsuitable for use. A subsequent study (Byrne et al., 2022b) found that only aggregates in the 0.7-to-19-mm-size range performed adequately in a clay-textured soil from both

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filtration and hydraulic perspectives. When the cost of the aggregate material was also considered, aggregates in the lower size range (0.7–10 mm) were 18 to 50% more expensive than aggregates in the higher size range (10–19 mm).

Synthetic envelopes are commonly used worldwide and have replaced aggregates in many instances due to their relatively low cost compared to aggregate materials, which, even if competitively priced, have higher transportation and associated fuel costs during installation (Stuyt et al., 2005). They are commonly used in unconsolidated soils to prevent the movement of sediment into the drainpipe (El-Sadany Salem et al., 1995). Conversely, field drains in consolidated soils with a clay content >25% do not require a filtering envelope (Vlotman et al., 2020). Synthetic envelopes are classified into two main categories: Prewrapped Loose Materials (PLMs) and Geotextiles (Stuyt and Dierickx, 2006). PLMs contain permeable structures consisting of loose, randomly orientated yarns, fibres, filaments, grains, granules, or beads, surrounding a corrugated drainpipe and retained in place by appropriate netting and/or twines. PLMs are usually installed in non-cohesive soils where soils have <25 to 30% clay and <40% silt. In the Netherlands, thicker PLMs are preferred in both cohesive and non-cohesive soils (Stuyt et al., 2005; Vlotman et al., 2020). Geotextiles are planar, permeable, synthetic textile materials that may be woven, non-woven, or knitted, and are prewrapped around a drainpipe (Stuyt et al., 2005). Geotextiles have been installed in large-scale land drainage systems in countries such as Canada, France, the United Kingdom, and the United States of America (Stuyt et al., 2005). Ghane (2022) showed the benefits of using a knitted geotextile sock for increasing the effective radius (the effective radius of the drain is the radius of an imaginary drain pipe with a completely open wall (Skaggs, 1978)), which in the field theoretically increases drain spacing. Subsequent work has verified this in sand-tank experiments (Ghane et al., 2022).

Located within the temperate climate zone for agricultural drainage conditions, the main principles of land drainage design in Ireland are to exploit soil layers with relatively high permeability by installing a groundwater drainage system or, where such a layer is not present, to implement a suitable shallow drainage system (Tuohy et al., 2016; Teagasc., 2022). In many countries, such as Ireland, the adoption of synthetic envelopes such as geotextiles in drainage systems is slow due to a combination of limited availability of drainage-specific geotextiles (which are mainly used in construction and civil works), unknown suitability in clay-textured soils, and historical (and continued) usage of aggregate as a drainage envelope (which can be used in both shallow and groundwater drainage systems). Although no data exist to show their suitability under Ireland-specific conditions (i.e., hydraulic conductivity, filter performance versus cost), and in clay-textured soils, these materials are still being installed on farms. Double envelopes (envelopes comprising both a geotextile envelope and an aggregate envelope, in any configuration) are being used by farmers to improve drain envelope efficiency. The use of double-envelope systems in agricultural drainage has been influenced by their use in highway and construction drainage systems (TNZ, 2003; TII, 2015; Typargeosynthetics, 2012).

The objectives of this laboratory study were to compare (1) the hydraulic conductivity and filter performance of two synthetic envelopes (non-woven geotextile and filter sock); two synthetic envelopes used in combination with a stone aggregate; and an optimally functioning stone aggregate; and (2) the cost of synthetic envelopes and aggregate, to develop a performance-based cost index of drainage envelopes. These results will enable a direct comparison between the suitability (performance and cost) of geotextile envelopes and stone aggregates in a clay-textured soil and will assess if geotextile envelopes help enhance the function of an aggregate envelope.

2. Materials and methods

2.1. Soil, synthetic envelope and stone aggregate

A clay-textured soil was collected from the Teagasc Solohead Research Farm (latitude 52° 51′ N; 08° 21′ W; altitude 95 m a.s.l.). It was dried for 24 h at 110 °C and sieved to pass a 2 mm sieve grade. The textural class was determined using ASTM (2021): 7%, silt 37%, clay 56% (clay texture). The synthetic envelope materials were a: (1) 0.8-mm-thick needle-punched, non-woven geotextile (Thrace Synthetics S8NW, [Offaly, Ireland]) with a characteristic opening size (O_{90}) of 100 μm (± 30) (O_{90}/d_{90}–0.5; O_{90} of the geotextile fabric indicates that 90% of the pores within the geotextile are smaller than the O_{90} value, and d_{90} is the soil particle diameter for which 90% of the soil particles are smaller (Elzoghby et al., 2021)). The average water flow velocity (permeability) of the non-woven geotextile is 130 (±39) mm *sec*$^{-1}$ (manufacturer specification; EN ISO 11058, 2019) (Fig. S1); and (2) a 2-mm-thick knitted polyester filter sock (Wetzel Technische Netze, [Löwenberger Land, Germany]) with an O_{90} of 150–200 μm (O_{90}/d_{90}–3 to 4) and an average water flow velocity (permeability) of 400 mm sec^{-1} (manufacturer specification; EN ISO 11058, 2019) (Fig. S2). The geotextile properties are based on information received from the manufacturers. There is a limited selection of synthetic envelopes available within Ireland, and the selection of treatments was dictated by the availability of these geotextile envelopes. The stone aggregate was chipped limestone with a gradation of 2–10 mm (D_{15}–D_{75}) (Fig. S3), and its selection was based on the results of a previous study (Byrne et al., 2022b). The drainpipe used was a 70 mm inside diameter, single wall corrugated pipe (80 mm outside diameter) (Floplast Ltd., Ireland). The perforations are in a 2 × 2 offset pattern and are 2 mm × 15 mm in size.

2.2. Experimental design

Experimental units comprised a 0.93-m-deep x 0.57-m-diameter reinforced plastic container (Fig. 1). In total, five study configurations (referred to in this paper as 'treatments') were used. These were: a non-woven geotextile or a filter sock wrapped around the drainpipe with no aggregate (Treatments 1 and 2, respectively); a non-woven geotextile wrapped around stone aggregate (hereafter: non-woven geotextile + aggregate; Treatment 3); a filter sock wrapped around a drainpipe surrounded by stone aggregate (hereafter: filter sock + aggregate; Treatment 4); and a stone aggregate alone (Treatment 5).

In Treatments 1 and 2 (Fig. 1a), a 0.1-m-deep layer of sand, compacted using a tamping device (0.3-m-diameter round base with a 5-kg weight, dropped from a height of 0.6 m). The purpose of the sand layer was to reduce the saturation time due to an increased soil overburden in Treatments 1 and 2, in comparison to Treatments 3, 4 and 5. The sand layer was overlain by a 0.05-m-deep layer of clay-textured soil (dry milled soil <2 mm). A non-woven geotextile (Treatment 1) or filter sock (Treatment 2) was prewrapped directly around the drainpipe. A 0.08-m-deep layer of soil, compacted into two equal layers, was added around the drainpipe. Finally, a 0.3-m-deep layer of soil, compacted in six equal layers to a wet density of 964.6 kg m^{-3}, was added. The edges of each layer of soil were pressed against the walls of the container by hand to ensure no by-pass flow occurred during the experiment.

Treatments 3, 4 and 5 (Fig. 1b, c and d, respectively) contained clay-textured soil filled to a depth of 0.02 m, overlain by 0.21 m of aggregate (2–10 mm; D_{15}–D_{75}). The top of the drainpipe was installed 0.23 m from the bottom, followed by 0.15 m of aggregate over the drainpipe, and, finally, a 0.15-m-deep layer of soil. In these study configurations, a non-woven geotextile fully surrounded the aggregate (Treatment 3), a filter sock was prewrapped around the drainpipe (Treatment 4), or only aggregate was used (Treatment 5).

Each treatment was conducted over a 31-day period. All units were overlain by 0.4 m of potable water. In order to prevent damage to the top layer of soil during the initial flow of water into the tank, an aluminium

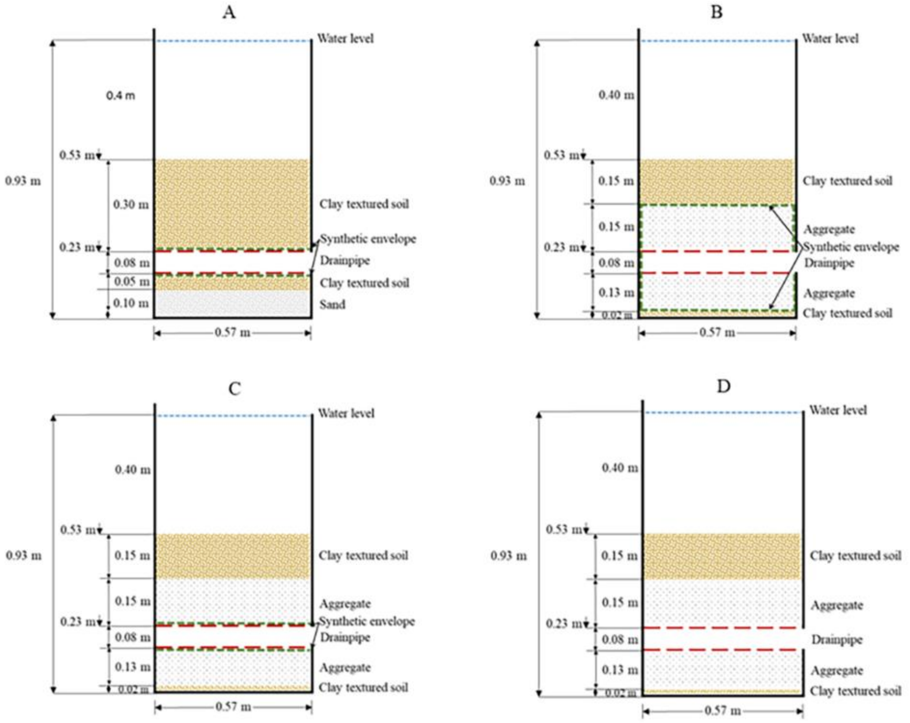

Fig. 1. Laboratory unit design for the synthetic envelope, aggregate (2–10 mm), and clay-textured soil combination with depth profiles indicating: (a) the non-woven geotextile or filter sock (Treatments 1 and 2, respectively); (b) the non-woven geotextile wrapped around the aggregate envelope (Treatment 3); (c) a filter sock prewrapped around the drainpipe (Treatment 4); and (d) a 2-to-10-mm aggregate installed around the drainpipe (Treatment 5).

tray (0.2 × 0.2 × 0.05 m) was used to disperse the water. This tray was subsequently removed once a constant head was achieved. All experimental units were strengthened by nylon straps, and paraffin wax was applied at the edges of the top soil layer to prevent by-pass flow.

The following measurements were made: discharge of water through the drainpipe outlet (an indicator of the hydraulic conductivity functionality of the envelope), expressed as L m^{-1} of drainpipe (0.08-m-diameter), and cumulative flow-weighted sediment loss (henceforth total suspended solids: TSS) (to determine the filter functionality of the envelope), measured in accordance with BS872 (BSI, 2005). In order to estimate total sediment loss (g L m^{-1} of drainpipe) daily and cumulatively, TSS concentrations were multiplied by the discharge rate.

The hydraulic conductivity (discharge) performance criterion was assessed by direct comparison with the performance of 15.5-to-19-mm-diameter stone aggregate, identified by Byrne et al. (2022b) to have the lowest cumulative discharge in a study comparing the discharges of aggregates ranging in size from 0.7 to 62 mm. That study had an identical configuration to Treatment 5 (aggregate only) in the current study and also contained the same clay-textured soil. In order to compare the discharge of both the current study and that of Byrne et al. (2022b), the cumulative discharges from the five configurations of the current study by day 31 were compared to Byrne et al. (2022b) – 16,745 L m^{-1}.

Similarly, the filter performance was compared to aggregates with a size ranging from 0.7 to 3 mm, which were found by Byrne et al. (2022b) to have the worst filtration performance of aggregates ranging in size from 0.7 to 62 mm. A similar comparison of both studies was conducted, with a maximum cumulative TSS of 61 g m^{-1} by day 31 being identified.

2.3. *Envelope material ranking*

To determine the cost effectiveness of these treatments, the cost was expressed as € m^{-1} of drainpipe. The cost of all aggregate ranges available in Ireland (Byrne et al., 2022b) was modified from € T^{-1} (tonne) to an estimated € m^{-1} (assuming a 0.3 × 0.35 m trench (W × H) and an estimated aggregate density of 1500 kg m^{-3} (0.16 T m^{-1} of gravel)) to compare cost effectiveness across all aggregates and synthetic treatments. Under the 'discharge and sedimentation performance' category, treatments were either suitable or unsuitable based on them passing or failing the discharge and/or sedimentation criteria. Assessing treatments in 'overall cost and performance' category, treatments with suitable performance characteristics were optimal or sub-optimal for use based on cost, once they had passed on their performance suitability. The cost data obtained was amalgamated from Byrne et al. (2019) and Byrne et al. (2022b).

2.4. *Statistical analysis*

Statistical analysis was carried out using SAS 9.4 (SAS Institute Inc., Cary, NC, USA). A univariate analysis of the data was conducted to determine normality. The data were shown to be non-normally distributed. The effects of envelope function on discharge and sediment loss across 5 treatments were measured using the PROC MIXED procedure with repeated measures where time was a factor ($T = 10$, 20, and 31). Statistical significance was assumed at a value of $P < 0.05$.

3. Results

3.1. Hydraulic performance

Fig. 2 shows the cumulative discharge of five treatments over the total study duration of 31 days (the daily discharge is shown in Fig. S4). Cumulative discharge rates ranged from 5918 L m^{-1} to 47,282 L m^{-1}. All treatments, with the exception of Treatment 2, exceeded the discharge criterion of 16,745 L m^{-1}. Cumulative discharge was highest in filter sock + aggregate (Treatment 4) and non-woven geotextile + aggregate (Treatment 3), with 47,282 and 33,783 L m^{-1}, respectively. Treatment 5 and Treatment 1 had similar cumulative discharge levels (20,229 and 19,131 L m^{-1}, respectively). The lowest cumulative discharge was observed with the filter sock treatment (Treatment 2; 5918 L m^{-1}), failing to meet the discharge criterion.

3.2. Sediment loss

Only two treatments (Treatment 3 and 5) met the cumulative TSS criterion for effective filtration performance (<61 g m^{-1}). Cumulative TSS losses (daily flow weighted sediment loss is shown in Fig. S5) observed across the treatments ranged from 11 g m^{-1} (Treatment 5; 2–10 mm aggregate) to 89 g m^{-1} (Treatment 2; filter sock) (Fig. 3). The aggregate (Treatment 5) had the lowest cumulative TSS losses of the five treatments (11 g m^{-1}). The highest cumulative TSS losses were observed using the non-woven geotextile and filter sock (Treatments 1 and 2) (81 and 89 g m^{-1}, respectively). The majority of the sediment lost for each treatment occurred within 7 days of the start of the experiment; losses during this period, expressed as a percentage of the total sediment loss over the experiment duration, ranged from 58% (filter sock + aggregate) to 77% (filter sock). After this period, sediment loss was greatly reduced and equilibrium was established.

3.3. Data aggregation and cost analysis for selection

Table 1, combining both the performance and cost of materials, indicates that Treatment 5 (2–10 mm aggregate) is sub-optimal for use based on both cost and performance, with the lowest cost where it exceeded both the hydraulic and filter design criteria. The non-woven geotextile + aggregate (Treatment 3) was 42% more costly than aggregate alone, and had a 67% increase in discharge and a 155% increase in sediment loss in comparison with the aggregate. Moreover, it performed effectively with regard to the hydraulic conductivity (discharge) and filter (sedimentation) criteria. The filter sock + aggregate (Treatment 4) performed effectively with regard to the hydraulic conductivity (discharge) criterion, but they produced cumulative TSS above the limit of acceptable sediment losses. The other treatments (Treatment 1 and 2) failed on the filter (sedimentation) criteria, while Treatment 2 was below the limit for hydraulic conductivity (discharge) and Treatment 1 was above the acceptable limit.

4. Discussion

4.1. Discharge, sedimentation and cost of geotextiles

Based on discharge and TSS losses, both non-woven geotextiles and filter socks should not be used where geotextiles are surrounding the drainpipe in clay-textured soils, as these treatments did not meet both the required minimum discharge rate and sedimentation criteria (Section 2.2.). No difference in the day of peak flow (indicating hydraulic saturation) (Fig. S4) was observed between treatments based on differing soil overburden thickness in Fig. 1. El-Sadany Salem et al. (1995) concluded that thin envelopes were at a higher risk of clogging than voluminous envelopes, while Choudhry et al. (1995) likewise concluded that although a selection of needle-punched, non-woven geotextile envelopes had met the particle-retention criterion in their experiments, the envelopes could not meet the standard of desired blocking, clogging, and hydraulic performance. They concluded that further testing was necessary. Non-woven geotextiles and filter socks had the lowest cost for an envelope on a € m^{-1} basis, but with poor hydraulic conductivity and filter performance, these geotextiles are not suitable for use in clay-textured soils. The range of aggregates (0.7–19 mm) identified by Byrne et al. (2022b) is preferred with a clay-textured soil. These aggregates had lower rates of cumulative TSS and greater cumulative discharge rates than the geotextile treatments investigated in the current study.

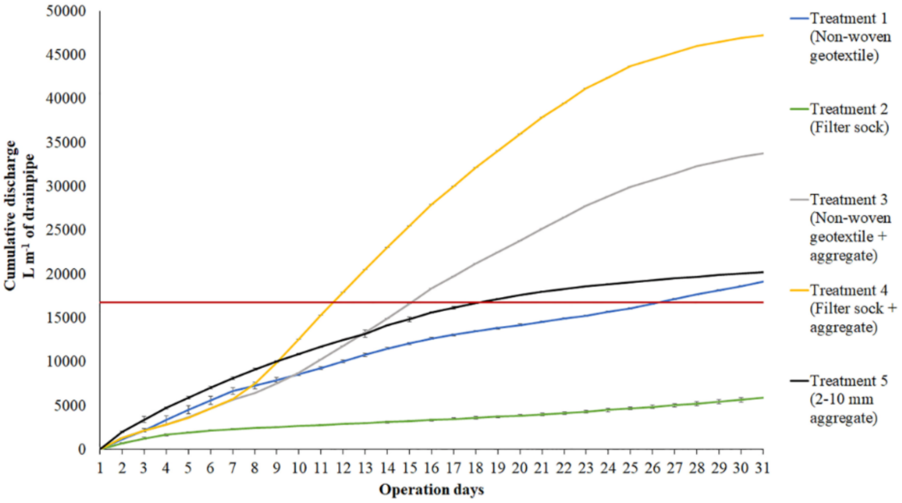

Fig. 2. Cumulative average discharge rate, with the minimum required discharge allowed under the hydraulic conductivity (discharge) criterion highlighted in red (error bars indicate the standard deviation).

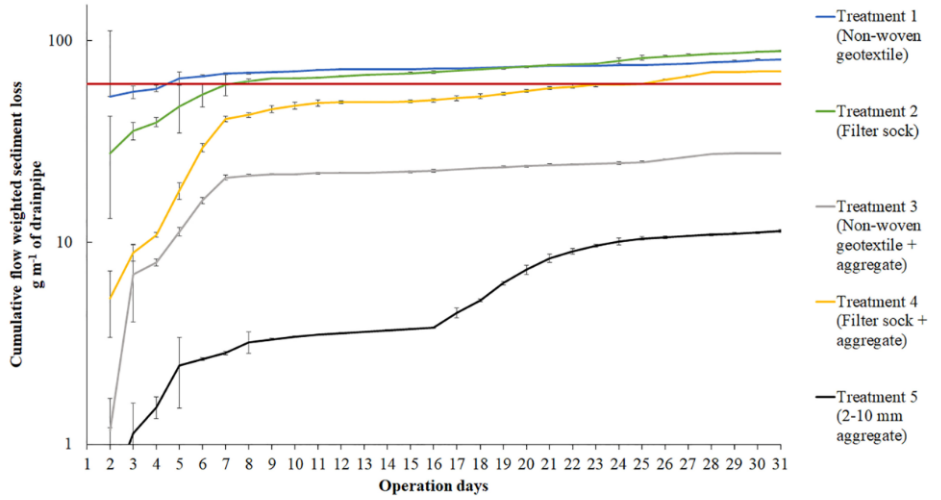

Fig. 3. Cumulative discharge weighted sediment loss, with the maximum sediment loss allowed under the filter (sedimentation) criterion highlighted in red (error bars indicate the standard deviation).

Table 1
Synthetic and aggregate envelope suitability for use with clay-textured soils from a discharge, sedimentation, and cost perspective.

Treatments (Aggregate, D_{15}–D_{75} (mm))	Treatment number	Discharge	Sedimentation	Cost € m^{-1} (ex VAT ex delivery)[1]	Discharge and sedimentation performance	Overall cost and performance[2]
Synthetics						
Non-woven geotextile	1	✓	X	0.83	Not suitable	Substandard
Filter sock	2	X	X	1.23	Not suitable	Substandard
Non-woven geotextile + aggregate	3	✓	✓	2.83	Suitable	Sub-optimal
Filter sock + aggregate	4	✓	X	3.23	Not suitable	Substandard
Aggregate						
Aggregate Optimum Range (2–10 mm)	5	✓	✓	2.00	Suitable	Sub-optimal

[1] Cost of aggregates € m^{-1} assumes 0.16 T m^{-1} of aggregate used.

[2] Treatments with suitable performance characteristics were optimal or sub-optimal for use. If treatments were classified as 'not suitable' in the discharge and sedimentation performance category, they are considered substandard for the overall assessment. The aggregate optimum range (2–10 mm) is classified as sub-optimal due to its increased cost over other suitable aggregates in the 0.7-to-19-mm range (Byrne et al., 2022b).

4.2. Discharge, sedimentation and cost of the non-woven geotextile and aggregate combination

The non-woven geotextile + aggregate combination met the criteria for discharge and sedimentation rate, but this combination is not recommended as it still exhibits the same potential risks of clogging as highlighted in Section 4.1. Although this treatment method is commonly applied in road drainage systems where a geosynthetic material (typically non-woven geotextile) is placed over the top of the aggregate at the edge of road drainage systems (TNZ, 2003; TII, 2015), the higher discharge rates observed for this treatment may lead to a filter cake formation over time at the interface between the soil and the envelope (Stuyt and Dierickx, 2006) due to higher hydraulic conductivity rates. This is backed up by the higher sediment transmission observed for this treatment in comparison to the aggregate treatment. Additionally, Elzoghby et al. (2021) found that although the non-woven geotextiles (Typar SF27 and Typar SF20) used indicated effective filtration of soil particles, five times more fine soil particles than the original soil were found at the geotextile-soil interface. This highlights the importance of considering the O_{90} of both the geotextile material and soil size distribution (Stuyt and Dierickx, 2006). In the current study, a 42% increase in cost per metre (for the non-woven geotextile + aggregate) yielded only a 67% increase in cumulative discharge at day 31. The potential filter cake development at the soil-envelope interface after installation and the small increase in discharge do not currently justify the use of this combined treatment.

4.3. Discharge, sedimentation and cost of the filter sock and aggregate combination

The filter sock + aggregate combination is considered unsuitable for use based on failing the sedimentation criterion. The highest discharge rates were observed for this treatment, which has been shown to increase discharge rates (similarly to the geotextile + aggregate treatment). Swihart (2000) found that the use of a geotextile sock around the drainpipe combined with a sand envelope produced a discharge 3 to 12 times higher than tests conducted without the geotextile sock (analogous to the filter sock + aggregate combination used in the current study). The high discharge rates observed in this experiment and the larger O_{90} size (150–200 μm) of the filter sock help to limit the blocking of the filter while aiding increased hydraulic conductivity. These higher discharge rates cause greater sediment transmission, which may potentially block the drainpipe quicker than at lower discharge rates. The 62% increase in cost per metre (for the filter sock and aggregate treatment compared to the aggregate treatment) yielded a potential 134% increase in cumulative discharge at day 31, but the factors discussed above may potentially mitigate these increases over time due to increased sediment transmission and blocking of the aggregate envelope and drainpipe. Until further research is carried out on this potential combination, the filter sock should not be recommended in combination with an aggregate.

4.4. Discharge, sedimentation, and cost of the aggregate and its suitability based on installation methods and availability

The 2-to-10-mm-diameter stone aggregate performed more effectively for hydraulic and filter performance than the geotextiles alone. Cumulative TSS levels in the geotextile + aggregate treatment were 143% higher than in the aggregate only treatment, while only a 67% increase in discharge was observed for the geotextile + aggregate treatment over the aggregate alone.

Additionally, it was more cost-effective (in comparison to the geotextile + aggregate treatments), but is still considered sub-optimal based on its increased cost compared to other suitable aggregates in the 10 to 19 mm range that were more suitable based on both cost and performance aspects (Byrne et al., 2022b). The suitability of both aggregates and geotextiles in clay-textured soils has a number of advantages and disadvantages. Although relatively expensive compared to synthetic envelopes, stone aggregate is abundant in Ireland (Byrne et al., 2022a), and the production of aggregate sizes within the current national guidelines (10 to 40 mm, with increased filtration performance evident from 10 to 20 mm aggregates) (Teagasc., 2022) will improve drain envelope performance. This study will help inform the selection of geotextiles used in clay-textured soils and additionally provide information on possible future synthetic materials that become available on the Irish market for installation in subsurface drainage systems, but each synthetic envelope will still have to be tested due to the varying physical properties (Palmeira and Gardoni, 2002).

Geotextiles or any synthetic envelopes tend to be unsuitable where fine textured heavy soils dominate and shallow drainage techniques (e.g. sub-soiling, mole drains, and gravel mole drains) are employed (Teagasc., 2022). Such shallow drainage systems are commonly applied in Ireland where no permeable soil layer is present in the soil profile (Teagasc., 2022). Tuohy et al. (2018) highlighted climate trends and predictions of future higher rainfall intensities. This may lead to increased installation of shallow drainage systems on heavy clay soils where drainage works weren't previously justified due to increased rainfall intensity, waterlogging, reduced yields, and low soil bearing capacity. This will require the continued use of shallow drainage systems and necessitate the use of stone aggregate in most situations.

5. Conclusions

The results showed that locally available non-woven and knitted sock geotextiles alone did not function as well as 2-to-10-mm-diameter stone aggregate and were unsuitable for the tested clay-textured soils in Ireland. The selection of suitable geotextiles was limited by local availability. Both double envelope synthetic envelope treatments performed effectively from a performance perspective, but are currently uneconomical. Further drain envelope efficiency would be achieved from greater adoption of aggregates in the 0.7 to 19 mm range by farmers and contractors, and greater production of this aggregate range in quarries around the country. Future research on thicker synthetic envelopes (with similar performance functionality to aggregates) to aid in reducing the cost of drainage works may be required, but the current availability of these envelope types locally is unknown.

Declaration of Competing Interest

None.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geodrs.2022.e00598.

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Assessment of the hydraulic and filter performance of different drainage stone aggregates to elucidate an optimum size range for use in clay-textured soils

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ABSTRACT

On poorly drained grassland farms in Ireland, stone aggregates remain the only in-field drain envelope material used by contractors. A variety of aggregate sizes and lithologies are currently in use, but their performance in clay-textured mineral soils is unknown. In practice, this may result in ad-hoc system performance and a varied lifespan due to sediment ingress. The aim of this study was to evaluate the hydraulic and filter performance of a range of aggregate gradations in clay-textured mineral soils. Nine aggregates (three replicates of each) were examined in laboratory units containing clay-textured soil, with a perforated drainpipe surrounded by an aggregate envelope ranging in size from 0.7 to 62 mm and a constant 0.4 m head of water above the soil surface. To determine the hydraulic performance of the envelope, the discharge rate of water through the drainage pipe outlet was measured over 38 days. To determine the filter performance, sediment loss, sediment settlement in the drainpipe, and ingress of sediment into the envelope were measured. The results indicated that only aggregates in the 0.7–19 mm size range performed adequately from both the hydraulic and filter perspectives and were deemed suitable for use with a clay-textured soil. Discharge appeared to be inversely related to aggregate size, with larger discharges being measured in the smaller aggregate sizes and smaller discharges measured in the larger aggregate sizes (exception: Aggregate 2). For all aggregates examined, discharge was greatest at the start of the experiment before reducing over time. When the cost of the aggregate material is also considered, aggregates in the lower size range are 18–50% more expensive than aggregates in the higher size range. Aggregates with particle sizes ranging from 0.7–19 mm are recommended for in situ field testing in clay-textured soils.

1. Introduction

Agricultural land drainage plays a key role in supporting food production on poorly drained soils (Tuohy et al., 2018; Castellano et al., 2019). A typical contemporary land drainage system comprises a network of subsurface drains, each consisting of perforated pipes wrapped in an envelope material (Stuyt et al., 2005; Teagasc, 2022). The key to efficient and consistent hydraulic and filter performance is an appropriate type and size of envelope material to surround the drainage pipe (Yannopoulos et al., 2020). The drain envelope must offer proficiency in a number of functions, such as protecting the drainpipe from excessive sedimentation and reducing water entry resistance around the pipe and surrounding soil. An envelope with a higher hydraulic conductivity than the surrounding soil reduces the entrance resistance (resistance of approach flow) into the pipe so that no hydraulic pressure will build up in the surrounding soil (Stuyt et al., 2005; Vlotman et al., 2020). In theory, the entrance resistance of a drainage system is a material constant, but in practice it may be seriously reduced due to particle deposits at the soil-envelope interface or in the envelope. The entrance resistance of a drainage system depends on soil texture and evolves with time (Dierickx, 1993).

Aggregates such as river-run gravel or crushed stone are commonly used in temperate climates with moderate to heavy (lower hydraulic conductivity) soil textures to keep the water table below a depth of 0.45 m in order to maximise grass growth and trafficability (Teagasc, 2022). They improve the hydraulic conductivity around the drainage pipe,

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reduce the entrance resistance, protect and support the pipe, and prevent the ingress of sediment (Vlotman et al., 2020). The antecedence of their use is due to a combination of factors, such as the scale and system of farming undertaken, the type of drainage system, the abundance of mineral aggregate, and the historical use of aggregate for drainage (Byrne et al., 2022). Typical aggregate sizes used in different regions range from 0.2 to 4.0 mm in Finland (Luoko, 2020), 5–50 mm in the United Kingdom (AHDB, 2018), and 10–40 mm is recommended in Ireland (Teagasc, 2022).

Byrne et al. (2022) conducted a review of the availability of aggregate throughout Ireland. Eighty-six quarries across Ireland were surveyed, which classified the distribution, type, popularity, size, and availability of aggregates for land drainage systems. The average size of the aggregate available was 41 mm. The most commonly used sizes ranged from 2 to 62 mm, representing the vast majority of aggregate sizes available throughout Ireland. This study found that the most commonly used aggregate size is unsuitable for the majority of moderate to "heavy" (lower hydraulic conductivity) soil types encountered. Using 74 aggregates characterised in the study, three filter design criteria (SCS, 1988; Sherard et al., 1984; Terzaghi and Peck, 1961) were applied to five soil types (clay, clay loam, loam, silty clay loam, and silt loam). Only 31% met the SCS (1988) criterion and 11% met the Terzaghi and Peck (1961) criterion for a loam soil texture (the Sherard et al., 1984 design criterion was not applicable for this soil texture). The study concluded that there was a need for guidelines for aggregates based on both the hydraulic and filter performance of the drainage envelope in moderate to lower hydraulic conductivity soil types. Currently, the recommended 10–40 mm aggregate sizes are based on field observations (Teagasc, 2022), but no data exist on their applicability and suitability in clay-textured soils. These recommendations are primarily based on filtration recommendations, and although clay-textured soils have a higher structural strength after settlement, they may be needed to provide temporary filtering functions. It has been suggested that soil with a clay content of > 30% does not need an envelope around a drainpipe (Stuyt et al., 2005; Vlotman et al., 2020). However, the use of an aggregate envelope increases drain spacing by increasing the effective radius of the drainpipe and provides other additional benefits, such as a conduit of flow in shallow drainage systems where mole ploughs and sub-soilers have a direct connection to the drainpipe through the aggregate envelope. Therefore, there is a need to identify if hydraulic conductivity and effective radius can be maximised based on choosing a more suitable aggregate size, along with providing initial filtering capabilities.

Laboratory evaluation of an envelope system is useful as a simple and easily reproducible method for evaluating various envelope materials and scenarios at a low cost (Dierickx, 1989). It is also useful to test the functional properties of drain envelopes, such as their ability to retain soil particles and prevent invasion of soil particles into the envelope; the blocking or immediate reduction of hydraulic conductivity of an envelope in contact with soil; and the decrease in hydraulic conductivity of an envelope over time due to particle accumulation or if the envelope material is too fine (El-Sadany Salem et al., 1995).

In the current study, the range of aggregate gradations from 0.7 to 62 mm in size (representing the most commonly available aggregate sizes throughout Ireland (2–62 mm), and a 0.7–3 mm aggregate (satisfying the SCS, 1988 criterion) were tested in laboratory units to identify a subset of optimal aggregate ranges for use in clay-textured soils, which should subsequently be tested in situ in the field. The overall objective of this study was to evaluate the hydraulic and filter performance of a range of aggregate gradations in clay-textured mineral soils. To achieve this objective, the experiments aimed to: (1) assess the hydraulic and (2) filter performance of commonly used gravel aggregates as envelope materials for use in clay-textured soils; and (3) rank the aggregates based on their hydraulic and filter performance and cost for use in clay-textured soils.

Table 1
Aggregate envelope data indicating the aggregate type and their size distribution.

Aggregate number	Aggregate type	D_{15} - D_{75} (mm)[a]
1	River-run gravel	0.7–3
2	Limestone	2–10
3	Limestone	10–14
4	River-run gravel	11–17.5
5	River-run gravel	15.5–19
6	River-run gravel	22–30
7	River-run gravel	22–75
8	Limestone	34–47
9	Limestone	42–62

[a] D_{75} – D_{15} indicates estimated 75% and 15% passing size.

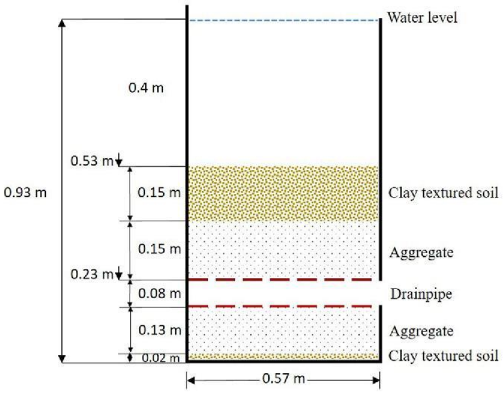

Fig. 1. Laboratory unit setup showing flow through the system and depth profile.

2. Materials and methods

2.1. Soil and stone aggregate selection

A clay-textured soil was collected from the Teagasc Solohead Research Farm (latitude 52° 51' N; 08° 21' W; altitude 95 m a.s.l.) and dried in 2 kg batches for 24 hr at 110 °C then milled to pass a 2 mm sieve grade. The textural class was determined according to ASTM (2021): 7% sand, silt 37%, clay 56% (clay texture). Eight commonly used envelope material aggregates in Ireland were selected (Table 1). An additional aggregate was used in the experiments (Aggregate 1 in Table 1), which satisfied the aggregate selection criteria for a clay-textured soil as defined by the Soil Conservation Service (SCS, 1988). This allowed for comparison with an idealised aggregate.

2.2. Experimental set-up and performance criteria

In total, 27 units (Fig. 1), each 0.57 m in diameter and 0.93 m deep, were constructed and replicated at n = 3 for each aggregate size examined. Each unit consisted of three components: clay-textured soil, an aggregate treatment, and a drainpipe (a standard 80 mm corrugated pipe with perforations 2 mm × 15 mm in size) discharging to a collection tank. A 0.08 m diameter drainpipe was located 0.15 m from the bottom of the tank. In order to obtain reproducibility and determine aggregate suitability based on the soil textural component, dry milled soil (<2 mm) was filled to a depth of 0.02 m at the bottom of the tank, which was overlain by 0.21 m of the chosen aggregate (to the top of the drainpipe), and compacted using a tamping device (0.3 m diameter round base with

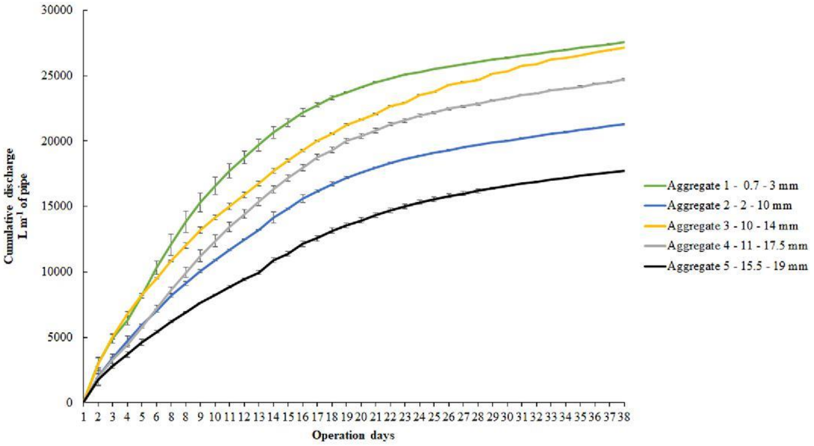

Fig. 2. Cumulative average discharge rate (error bars indicate the standard deviation). Discharge data for Aggregates 6, 7, 8 and 9 were not obtained, as they had met criteria for failure within the first 24 hrs of operation.

a 5 kg weight dropped from a height of 0.6 m) in order to ensure no settlement around the drainpipe occurred during the experiment. An additional 0.15 m of aggregate was added over the drainpipe, and tamping was repeated. Finally, the aggregate was overlain by a 0.15-m-deep layer of soil, compacted (in incremental layers) to a wet density of 964.6 kg m^{-3}. The edges of each layer of soil were pressed against the walls of the container by hand to ensure no by-pass flow occurred during the experiment. Nylon straps were added to the tank to prevent bulging at the soil layer, and paraffin wax was applied at the edges of the top layer to prevent by-pass flow.

Each unit was filled with potable water to a height of 0.4 m above the soil surface, which remained constant over the duration of the experiment (using an overflow pipe). In order to prevent damage to the top layer of soil during the initial flow of water into the tank, an aluminium tray (0.2 × 0.2 × 0.05 m) was used to disperse the water. This tray was subsequently removed once a constant head was achieved.

The units were routinely monitored for discharge rate and sediment loss over a total experimental duration of 38 days. In order to normalise data, units are expressed as L m^{-1} of pipe cumulatively (0.08 m dia.). Sediment loss was measured in accordance with standard methods (BS, 2005). The sediment loss concentrations were multiplied by the discharge rate to estimate the total sediment loss (g m^{-1} of drainpipe) daily and cumulatively. At the end of the experiment, all the sediment that had settled in the drainpipe was collected and weighed, and the experimental units were destructively sampled. The top soil layer and a 0.05 m layer of aggregate were discarded. Samples of the remaining envelope material from directly above the pipe were then taken. All of the fine material (<2 mm) was washed from the gravel and subsequently dried and weighed, with the results expressed in g of soil.

In this study, "failure" of the envelope was defined, after Stuyt et al. (2005), as when the soil structure was observed to collapse or when there was excessive movement of soil through the envelope material within the first 24 hr of operation. The hydraulic performance was assessed on the ability of the drain setup to discharge at least

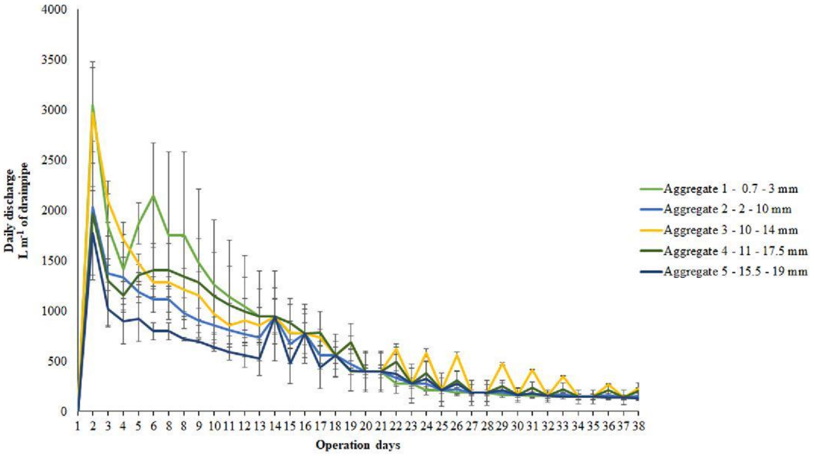

Fig. 3. Daily discharge rate (error bars indicate the standard deviation). Discharge data for Aggregates 6, 7, 8 and 9 were not obtained, as they had met criteria for failure within the first 24 hrs of operation.

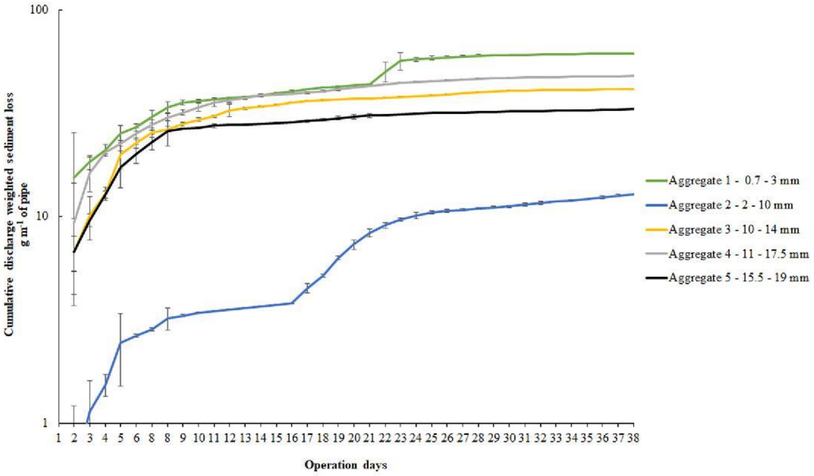

Fig. 4. Cumulative discharge weighted sediment loss (error bars indicate the standard deviation). Sediment loss data for Aggregates 6, 7, 8 and 9 were not obtained, as they had met criteria for failure within the first 24 hrs of operation.

0.54 mm hr^{-1} (mean intensity of rainfall across 7 sites during a high rainfall period; Tuohy et al., 2018), and the filter performance was assessed by the amount of sediment settled in the drainpipe during the experiment; this should be < 25% of the total volume of the drainpipe in order to ensure an excessive reduction in discharge does not occur (Vlotman et al., 2020).

2.3. Statistical analysis

Statistical analysis was carried out using SAS 9.4 (SAS Institute Inc., Cary, NC, USA). A univariate analysis of the data was conducted to determine normality. The data were shown to be non-normally distributed. Following this, the effects of envelope function in relation to daily drainpipe discharge rate and daily drainpipe sediment loss across 9 aggregate distributions were measured using the PROC MIXED procedure (REML – estimation method; profile – residual variance method; model-based – fixed effects SE method; and residual – degrees of freedom method) with repeated measures where time was a factor (T = 10, 19, and 38). Statistical significance was assumed at a value of $P < 0.05$.

3. Results

Aggregates 6, 7, 8, and 9 were deemed to have met the criteria for failure within the first 24 hr of starting the experiment. Aggregates 1–5 achieved the hydraulic and filter performance criteria for the entire 38-day experimental period. The cumulative discharge from the five aggregates over the experiment duration ranged from 17751 to 27542 L m^{-1} of pipe. The cumulative sediment losses ranged from 13 to 62 g m^{-1} of pipe.

3.1. Hydraulic discharge and sediment loss performance

The majority of discharge (67% average) across all treatments occurred within the initial 14-day period of the experiment (Fig. 2). On day 38, the five aggregates had an average daily difference of 0.74 mm hr^{-1} between the highest and lowest discharges. The lowest discharge was observed from Aggregate 5 on day 38, where a discharge rate of 1.3 mm hr^{-1} was observed (Fig. 3). Most of the sediment loss occurred within the first 8 days of the experiment: Aggregate 1 lost 34 g m^{-1} of pipe (55% of the total loss) within this time period, followed by Aggregates 4 (67%), 3 (68%), and 5 (82%) (Fig. 4).

3.2. Envelope and pipe sedimentation

Sampling of the envelope after completion of the experiment (Fig. 5a) indicated that Aggregate 1 had the lowest incursion of soil into the envelope (640 g), while the worst performing aggregate was Aggregate 3 (5699 g). Three other aggregates had soil incursions ranging between 3406 g (Aggregate 2) and 4251 g (Aggregate 4). Fig. 5b shows the amount of sediment deposited in the pipe after the end of the experiment. Values ranged from 0.54 g m^{-1} of pipe (Aggregate 1) to 1.31 g m^{-1} of pipe (Aggregate 4). The amount of sediment settled within the pipe was insufficient to reduce the drainpipe volume by 25% across any of the treatments, so therefore it was judged to pass the sediment function criterion.

3.3. Data aggregation for aggregate selection

In order to determine the suitability of the aggregates across the three factors of discharge, sediment loss, and pipe-envelope sedimentation, a ranking system was developed. Table 2 shows the overall suitability of each aggregate range. Results showed that aggregates > 19 mm in size, while cost-effective, are not suitable for use as drainage envelopes due to their early failure. Aggregates in the 0.7–19 mm range performed favourably from both hydraulic and filter performance perspectives and are deemed suitable.

4. Discussion

4.1. Hydraulic and filter performance

Aggregates 6, 7, 8, and 9 were deemed to have met the criteria for failure, which occurred within the first 24 hr of starting the experiment, and are considered unsuitable for use. The ability of the envelope to hold back sediment in the unstructured clay-textured soil (similar to trench backfill) was compromised above an aggregate size of 20 mm, resulting in soil incursion into the envelope (Dierickx, 1993). The envelope should function initially during the settlement period to prevent excessive incursion of sediment into the aggregate envelope and provide a filter

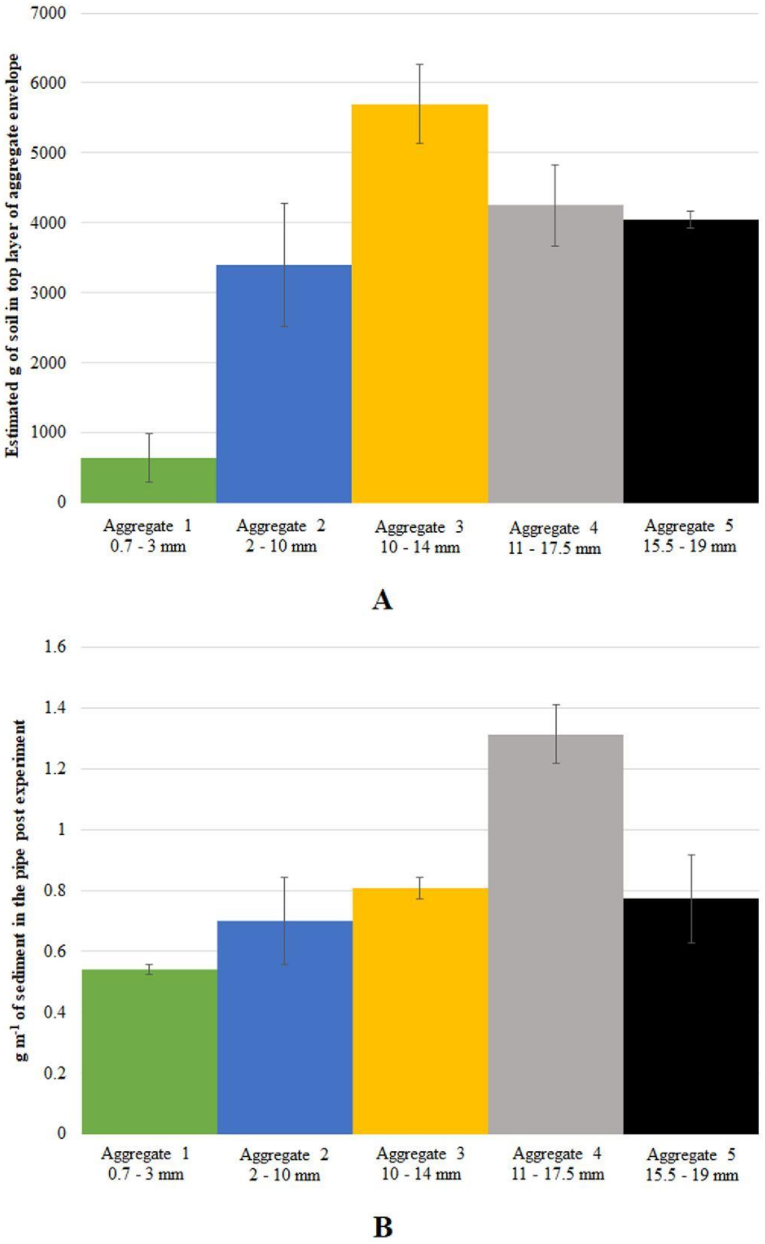

Fig. 5. Estimated g of soil in the top 0.15 m of aggregate (A) and g m^{-1} of sediment per length of pipe (B) (Error bars indicate the mean and standard deviation. Values (A) exclude the quantity of fine material (<2 mm) already within the aggregate). Data for aggregates 6, 7, 8 and 9 were not obtained as they had met criteria for failure within the first 24 hr of operation.

function. Therefore, a balance between the hydraulic and filter performance of the envelope is needed initially during settlement. These findings have the following implications: larger aggregate sizes (>20 mm), when used as envelope material, enable backfill topsoil to pass through the stone envelope and into the drainpipe during the settlement period. Some of this sediment will remain in the aggregate envelope, reducing permeability, and may be available to be mobilised over time. The most commonly used aggregate sizes in Ireland are 50 mm and 20-to-40-mm stone aggregate, respectively (Byrne et al., 2022). The Teagasc Drainage Manual (Teagasc, 2022) recommends an

Table 2
Aggregate grade suitability for use with clay textured soils based on discharge and filter performance.

Aggregate Number and PSD (D_{15} – D_{75}) (mm)	% of aggregate material < 2 mm (g kg^{-1} of aggregate)	Discharge	Filter[a]	Cost €/t (ex pit ex VAT)	Discharge and filter performance	Overall cost and performance[b]
Aggregate 1 (0.7 – 3)	7.2	✓	✓	15.00	Suitable	Sub-optimal
Aggregate 2 (2 – 10)	9.6	✓	✓	13.00	Suitable	Sub-optimal
Aggregate 3 (10 – 14)	0.1	✓	✓	11.00	Suitable	Optimal
Aggregate 4 (11 – 17.5)	1.6	✓	✓	10.00	Suitable	Optimal
Aggregate 5 (15.5 – 19)	2.0	✓	✓	10.00	Suitable	Optimal
Aggregate 6 (22 – 30)	2.6	X	X	10.00	Not suitable	N/A
Aggregate 7 (25 – 75)	0.6	X	X	8.41	Not suitable	N/A
Aggregate 8 (34 – 47)	1.9	X	X	8.87	Not suitable	N/A
Aggregate 9 (42 – 62)	13.0	X	X	8.87	Not suitable	N/A

[a] The heading 'filter' has the combined analysis of envelope sedimentation, pipe sedimentation and sediment loss through the drainpipe.

[b] Aggregates not suitable based on the 'Discharge and filter performance' assessment, are not assessed on 'Overall cost and performance' and is denoted N/A.

aggregate size in the 10–40 mm range, with optimum performance in the 10–20 mm range. Based on these findings (pending field trials), aggregates greater than 20 mm in diameter should not be recommended in the future. Aggregate sizes greater than 20 mm in diameter are more cost-effective, which may deter the use of aggregate sizes less than 20 mm in diameter. Byrne et al. (2023) have conducted a laboratory experiment to determine the suitability of geotextile materials as an alternative or complement to stone aggregate in clay-textured soils, in an effort to reduce drainage system costs. The remaining discussion will relate to Aggregate 1–5 only.

Due to the stable nature of clay-textured soils in situ, incursion of sediment into the envelope is considered low-risk in the long term. However, the potential for blocking during the initial period of settlement is the major risk associated with the introduction of trench backfill before equilibrium within the soil is achieved (Vlotman et al., 1993). Where an envelope prevents excessive incursion of sediment in clay-textured soils, the envelope should then function to maximise the hydraulic performance of the entire system. AHDB (2018) and Teagasc (2022) recommend the use of permeable backfill, even in consolidated clay-textured soils, to maintain the permeability in the drain trench and maintain an increased effective radius, even as the permeability of the trench backfill reduces over time. It is suggested that stable clay soils do not need an envelope (Stuyt et al., 2005; Vlotman et al., 2020), but in Turkey, for example, aggregate envelopes are used to improve the hydraulic conditions around the pipe in clay-textured soils (Bahceci et al., 2018). All five aggregates (Aggregate 1–5) prevented excessive sediment incursion, so the focus of in situ field research should be to increase the effective radius in the stable clay soils once settlement has occurred. As Aggregate 1–5 exceeded the hydraulic performance criterion of 0.54 mm hr^{-1}, they are suitable from a hydraulic performance perspective and are recommended for in situ field trials. Discharge appeared to be inversely related to aggregate size, with larger discharges being measured in the smaller aggregate sizes and smaller discharges measured in the larger aggregate sizes (exception: Aggregate 2).

Unlike the discharge measurements, there was no relationship between aggregate size and sediment loss. All five aggregates performed effectively to limit sediment incursion into the envelope and the drainpipe, and were deemed suitable based on the filter performance criterion (25% reduction in drainpipe capacity), but Aggregate 1 (0.7–3 mm) lost the most amount of sediment through the drainpipe (Fig. 2). This can be assumed to be fine material lost from the envelope itself (<2 mm) and may be attributed to the envelope material being lost through the 2 × 15 mm drainpipe perforations. This shows the importance of selecting a granular material based on both the base soil and the drainpipe perforations (Dierickx, 1993). Aggregate 1 was selected to meet the SCS (1988) criterion but was not fully suitable for the drainpipe perforations commonly used. Although it performed effectively as an envelope, some washing of the envelope material into and through the drainpipe at this gradation occurred and should be expected when using 2 × 15 mm drainage perforations. With this loss of fine material from the envelope itself, Aggregate 1 still performed effectively as a filter, and the sediment lost into the drainpipe was not in large enough quantities to violate the filter performance criterion (25% reduction).

5. Conclusions

Overall, aggregates ranging in size from 0.7 to 19 mm performed adequately in terms of hydraulic and filter performance, and were deemed suitable for subsequent in situ field trials. The results showed that increasing aggregate size resulted in decreased hydraulic performance. The lowest amount of soil in the pipe and in the envelope at the end of the experimental period was observed in Aggregate 1 (0.7–3 mm), and cumulative discharge rates were aligned with initial sediment incursion rates at the start of the experimental period. When the cost of the aggregate material is also considered, aggregates in the lower range are 18–50% more expensive than aggregates in the higher range, which would be optimal from a performance and cost point of view. Contractors and landowners should provisionally source aggregates in these ranges for better performance and lifespan outcomes.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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The authors acknowledge the assistance of the quarries who provided the materials for this project, and the Walsh Scholarship Programme (grant number: RMIS-0047) for providing the financial assistance that made the research possible.

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Investigating the suitability of geotextile envelopes as an alternative to stone aggregate in clay textured soils in Ireland

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The Key Message

- Geotextiles, in combination with a clay textured soil, did not function as well as an optimum aggregate size (2 – 10 mm ($D_{15} – D_{75}$)).
- A geotextile and aggregate (2 – 10 mm) envelope improved hydraulic conductivity compared to the 2 – 10 mm aggregate alone, but with associated increased sedimentation. The combination was not practical based on cost.
- Stone aggregate in the 0.7 to 19 mm range should be used as the main drain envelope material in clay-textured soils (Byrne et al., 2022).

Objectives

The objectives of this laboratory study were to compare the:

1. Hydraulic conductivity and filter performance of two synthetic envelopes (non-woven geotextile and filter sock): two synthetic envelopes used in combination with a stone aggregate, and an optimally functioning stone aggregate, using an unconsolidated clay-textured soil.
2. Cost of synthetic envelopes and aggregate to develop performance-based cost index of drainage envelopes.

These results will enable a direct comparison between the suitability (performance and cost) of geotextile envelopes and stone aggregates in a clay-textured soil, and assess if geotextile envelopes help to enhance the function of an aggregate envelope.

Materials & Methods

The five treatments were:

1. Non-woven geotextile.
2. Filter sock.
3. Non-woven geotextile and 2–10 mm stone aggregate.
4. Filter sock and 2–10 mm stone aggregate.
5. 2-10 mm optimum stone aggregate.

The following parameters were measured:

1. Flow rate of water through the drainage pipe outlet (an indicator of the hydraulic functionality of the envelope).
2. Total suspended solids (TSS) (to determine the filter functionality of the envelope).

The hydraulic conductivity (discharge) performance criteria were assessed by comparison with the performance of a 15.5-19 mm aggregate. Filter performance were assessed by comparison with the performance of a 0.7-3 mm aggregate (highest cumulative TSS, identified by Byrne et al. (2022)). The discharge and filter criterion is indicated with a red line in Figure 2 and 3.

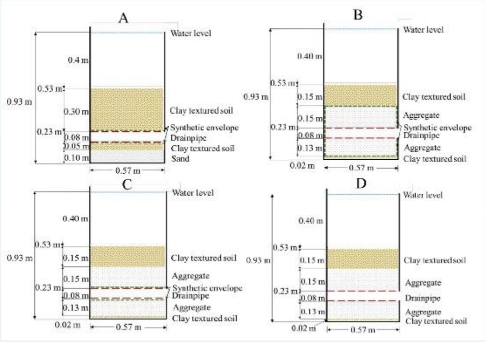

Figure 1. Laboratory unit design for the synthetic envelope, aggregate (2-10 mm) and clay-textured soil combination with depth profiles indicating (a) the non-woven geotextile and filter sock (treatments 1 and 2, respectively) (b) the non woven geotextile wrapped around the aggregate envelope (treatment 3) (c) a filter sock prewrapped around the drainpipe (treatment 4), and (d) a 2-10 mm aggregate installed around the drainpipe (treatment 5). 40 cm head of water maintained at the top of the soil surface (clay textured soil) for 31 days (n=3).

Results

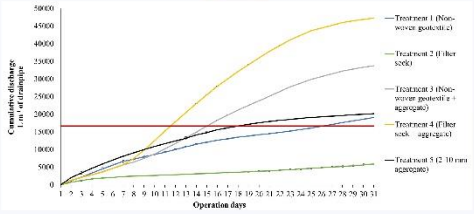

Figure 2. Cumulative average discharge rate, with the minimum required discharge allowed under the hydraulic conductivity criterion highlighted in red (error bars indicate the standard deviation).

Cumulative discharge rates ranged from 5918 L m-1 to 47282 L m-1. All treatments, with the exception of Treatment 2, exceeded the discharge criteria of 16745 L m-1. Cumulative discharge was highest in filter sock + aggregate (Treatment 4) and non-woven geotextile + aggregate (Treatment 3) (47282 and 33783 L m-1, respectively).

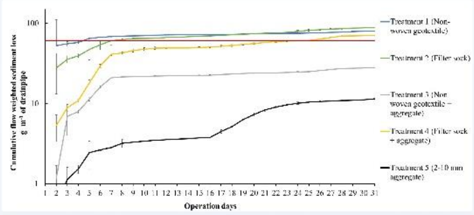

Figure 3. Cumulative discharge weighted sediment loss, with the maximum sediment loss allowed under the filter criterion highlighted in red (error bars indicate the standard deviation).

Only two Treatments (Treatment 3 and 5) met the TSS criterion for effective filtration performance (less than 61 g m^{-1}). Most of the sediment loss occurred within the first 8 days of the experiment. Highest sediment ingress into the envelope was observed in the geotextile treatments.

Conclusion

The results showed that geotextile envelopes (Treatment 1 and 2) did not function as effectively as the 2 to 10 mm aggregate. The aggregate used in combination with the geotextile envelopes (Treatment 3 and 4) performed better from a discharge rate perspective. The higher discharge observed in the geotextile + aggregate combinations indicate that geotextiles could aid in enhancing the discharge rate from a drain, but with associated higher sedimentation rates. Further drain envelope efficiency would be achieved from greater production by quarries, and greater adoption of aggregates from farmers and contractors (Byrne et al., 2022).

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Teagasc
AGRICULTURE AND FOOD DEVELOPMENT AUTHORITY

Aggregate suitability for drainage systems

Dairy Research Ireland
funded by Irish Dairy Farmers

What are the problems currently?

- Aggregates for subsurface drains are mostly bought based on preference and availability.
- The size as specified by the quarries do not give a fair reflection of the true gradation of aggregates being sold.
- The sizes commonly used are larger than what is suitable.

Why is selecting the right size aggregate is important?

- Smaller sized aggregate offers better bedding for protection of the drainpipe.
- Reduced sediment and nutrient loss into drainage ditches.
- Increased lifespan of the drain and improved drainage function.


"50 mm" aggregates from quarries have a visible variance in size

Current drainage research

- Determining a suitable aggregate grade for Irish heavy soils.
- The applicability of geotextiles for use in subsurface drains in Ireland.

Take home messages

- An aggregate grading should always be obtained from the quarry.
- A clean single sized aggregate in the 10 - 20 mm range offers best results in the majority of soils.

Building drainage systems for the future: How drainage material selection plays an important role in optimal system functionality

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1. The Key Message

An aggregate size range from 2 – 10 mm is optimal for a clay textured soil. Aggregates up to 20 mm are acceptable. The cost of aggregates are more expensive in the size lower ranges than the higher ranges. The adoption of aggregates from 0.7 to 20 mm will optimise performance and extend the lifetime of drainage systems in mineral soils.

2. Introduction

On poorly drained farms in Ireland, stone aggregates are the only drainage envelope material used by contractors. An aggregate survey conducted across quarries showed that the most popular drainage aggregate size (50 mm) available in quarries nationally is too large. Such a size is likely to decrease the system performance and lifetime due to sediment ingress. The objectives of this laboratory study were to: a) select a gradation of aggregates suitable for use in clay textured soils, and b) assess the performance of commonly used aggregates based on their hydraulic and filter function.

3. Methods

A bespoke laboratory setup consisting of replicated units containing clay textured soil with a series of aggregates size ranges was created (Figure 1). The treatments were 9 aggregates from 0.7 and 62 mm used in combination with a clay textured soil, replicated three times. Each unit had a 40 cm head of water, which was maintained above the top of the soil surface for 38 days. The following parameters were measured: Discharge rate of water through the drainage pipe outlet as an indicator to determine the hydraulic conductivity functionality of the envelope: Total Suspended Solids to determine the filter functionality of the envelope. Destructive sampling of the envelope after completion of the experiment to determine ingress of sediment into the envelope.

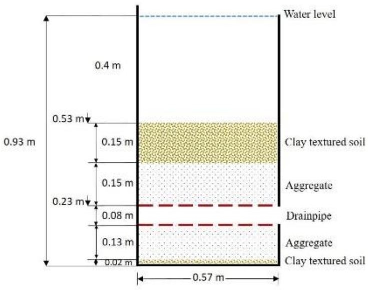

Figure 1. Laboratory unit setup showing flow through the system and depth profile.

4. Results

An aggregate in the 0.7 – 3 mm range preformed best from a discharge rate perspective (Figure 2a). Discharge was inversely related to aggregate size, with larger discharges being measured in the smaller aggregate sizes. For all aggregates examined, discharge was greatest at the start of the experiment, before reducing over time. From a sediment loss perspective, the best performing aggregate was in the 2 – 10 mm range (Figure 2b). Most of the sediment loss occurred within the first 8 days of the experiment. Lowest sediment ingress into the envelope was observed in the 0.7 to 10 mm range.

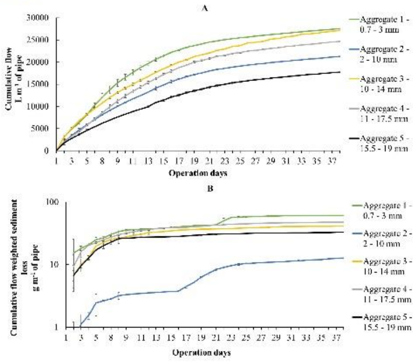

Figure 2. (A) Cumulative average discharge rate and (B) cumulative flow weighted sediment loss (error bars indicate the standard deviation). Discharge and sediment loss data for Aggregates 6, 7, 8 and 9 were not obtained, as they had met criteria for failure within the first 24 hrs of operation.

5. Conclusions

An aggregate size range from 2 – 10 mm is optimal from both filtration and discharge perspectives. for a clay textured soil. However, aggregate sizes up to 20 mm would be acceptable. Aggregates greater than 20 mm in size did not perform effectively and should not be used with a clay textured soil. When the cost of the aggregate material is also considered, aggregates in the lower range (0.7 to 10 mm) are 18 to 50% more expensive than aggregates in the higher range (10 to 20 mm). The higher range would be optimal from a performance and cost point of view. Contractors and landowners should source aggregates in these ranges for better performance and lifespan outcomes.

6. Acknowledgements

I would kindly like to thank the quarries who kindly provided the materials to conduct this project.

How the availability and cost of aggregates across Ireland can influence the selection of poor quality materials for land drainage systems.

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1.Take home message

Aggregates that are uniformly graded, have a low percentage of fine material and are in the 10-40mm range, need to be selected for land drainage systems in order to maximise the functionality and lifespan of a drainage system.

2. Introduction

- Questions remain over which size and type of material to use in drainage systems.
- Available aggregates are highly influenced by geology, cost and local perception.
- The grading and washing of aggregates can change.

3. Materials and Methods

Survey:

- 61 Crushed rock quarries and 32 sand and gravel pits.
- Questions asked on lithology, 3 sizes sold for land drainage and associated cost.
- The results of this survey will be assessed for location (Fig.1), popularity of type (Fig.3) & size and the associated cost (Fig.4).

Fig.1 Location and type of surveyed quarries

PSD & % of fine material:

- 80 samples of drainage stone varying in size and type were collected and subsequently sieved and washed for PSD analysis.
- The weight retained on each sieve were plotted and converted for graphing on a cumulative percentage graph.
- These results were the grouped by size and assessed for a gravel that has a close grading and low percentage of fines.

Fig.2 Various aggregate types and sizes.

4. Survey results

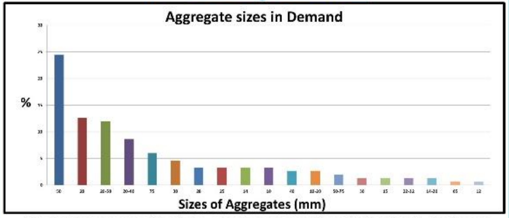


Fig.3 The aggregate sizes most commonly sold for land drainage use.

Aggregate Size	Munster	Connaught	Leinster
50mm	€9.42	€8.36	€8.14
20mm	€10	€9	€10
20-40 & 20-50mm	€11	€9	€9
75 &100mm	€8.20	€8.86	–
10, 12, 14mm	–	–	€9

Fig.4 Cost of aggregate sizes by region.

1. PSD analysis results

- IBAG19028 represented in Fig.5 in black is an ideal gravel where 85% of the material is within a 3mm range and has a low amount of fine material.
- Depending on the sieves used a 20mm gravel can range anywhere on the higher end between 31.5-20mm and on the lower end between 17-5mm.

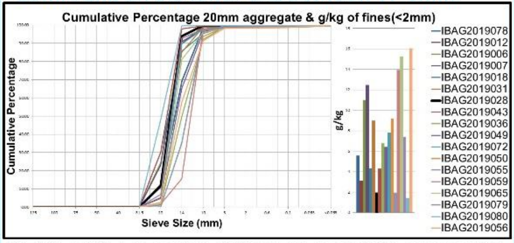
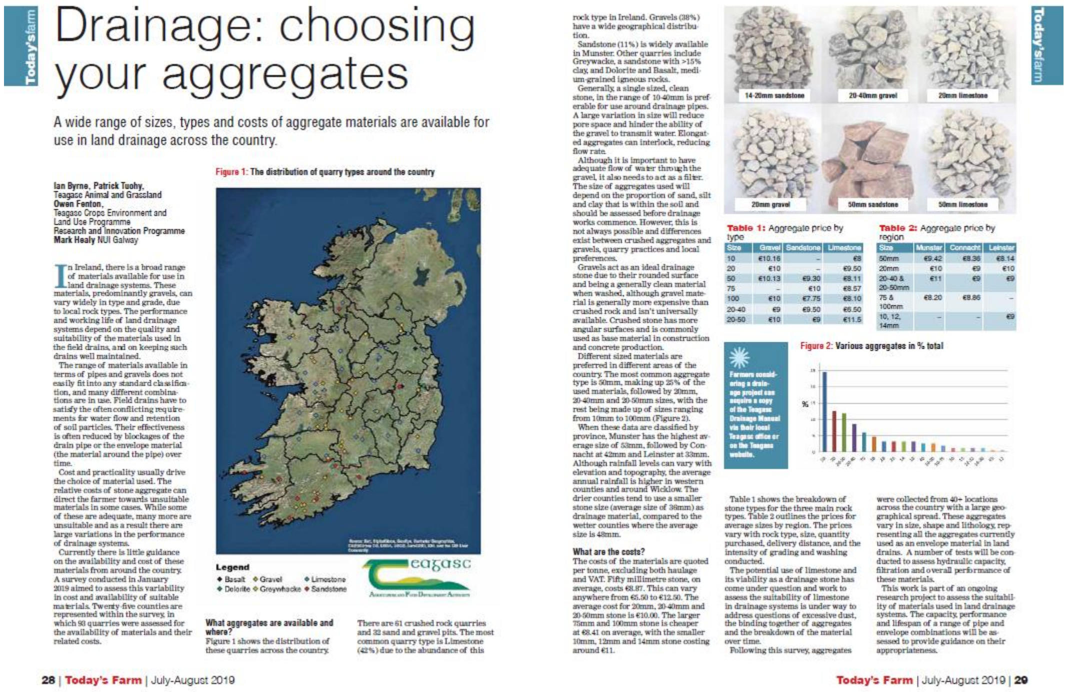


Fig.5 Cumulative percentage of 20mm aggregate & the corresponding g/kg of fines material (<2mm).

5. Conclusions

- Compromising quality for cost can affect the lifespan of you drainage system, an emphasis should be placed on reducing the size of aggregate.
- Aggregates should be closely graded, well washed and in the range of 10-40mm.
- Different grading of the aggregate can have a large effect on the particle size distribution curve. A grading curve should be obtained from the quarry as quoted sizes can vary between quarries.



Today'sfarm

Drainage: choosing your aggregates

A wide range of sizes, types and costs of aggregate materials are available for use in land drainage across the country.

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In Ireland, there is a broad range of materials available for use in land drainage systems. These materials, predominantly gravels, can vary widely in type and grade, due to local rock types. The performance and working life of land drainage systems depend on the quality and suitability of the materials used in the field drains, and on keeping such drains well maintained.

The range of materials available in terms of pipes and gravels does not easily fit into any standard classification, and many different combinations are in use. Field drains have to satisfy the often conflicting requirements for water flow and retention of soil particles. Their effectiveness is often reduced by blockages of the drain pipe or the envelope material (the material around the pipe) over time.

Cost and practicality usually drive the choice of material used. The relative costs of stone aggregate can direct the farmer towards unsuitable materials in some cases. While some of these are adequate, many more are unsuitable and as a result there are large variations in the performance of drainage systems.

Currently there is little guidance on the availability and cost of these materials from around the country. A survey conducted in January 2019 aimed to assess this variability in cost and availability of suitable materials. Twenty-five counties are represented within the survey, in which 93 quarries were assessed for the availability of materials and their related costs.

Figure 1: The distribution of quarry types around the country

Legend
◆ Basalt ◆ Gravel ◆ Limestone
◆ Dolorite ◆ Greywhacke ◆ Sandstone

What aggregates are available and where?

Figure 1 shows the distribution of these quarries across the country.

There are 61 crushed rock quarries and 32 sand and gravel pits. The most common quarry type is Limestone (42%) due to the abundance of this rock type in Ireland. Gravels (38%) have a wide geographical distribution.

Sandstone (11%) is widely available in Munster. Other quarries include Greywacke, a sandstone with >15% clay, and Dolorite and Basalt, medium-grained igneous rocks.

Generally, a single sized, clean stone, in the range of 10-40mm is preferable for use around drainage pipes. A large variation in size will reduce pore space and hinder the ability of the gravel to transmit water. Elongated aggregates can interlock, reducing flow rate.

Although it is important to have adequate flow of water through the gravel, it also needs to act as a filter. The size of aggregates used will depend on the proportion of sand, silt and clay that is within the soil and should be assessed before drainage works commence. However, this is not always possible and differences exist between crushed aggregates and gravels, quarry practices and local preferences.

Gravels act as an ideal drainage stone due to their rounded surface and being a generally clean material when washed, although gravel material is generally more expensive than crushed rock and isn't universally available. Crushed stone has more angular surfaces and is commonly used as base material in construction and concrete production.

Different sized materials are preferred in different areas of the country. The most common aggregate type is 50mm, making up 25% of the used materials, followed by 20mm, 20-40mm and 20-50mm sizes, with the rest being made up of sizes ranging from 10mm to 100mm (Figure 2).

When these data are classified by province, Munster has the highest average size of 53mm, followed by Connacht at 42mm and Leinster at 33mm. Although rainfall levels can vary with elevation and topography, the average annual rainfall is higher in western counties and around Wicklow. The drier counties tend to use a smaller stone size (average size of 36mm) as drainage material, compared to the wetter counties where the average size is 48mm.

What are the costs?

The costs of the materials are quoted per tonne, excluding both haulage and VAT. Fifty millimetre stone, on average, costs €8.87. This can vary anywhere from €5.50 to €12.50. The average cost for 20mm, 20-40mm and 20-50mm stone is €10.00. The larger 75mm and 100mm stone is cheaper at €8.41 on average, with the smaller 10mm, 12mm and 14mm stone costing around €11.

14-20mm sandstone

20-40mm gravel

20mm limestone

20mm gravel

50mm sandstone

50mm limestone

Table 1: Aggregate price by type

Size	Gravel	Sandstone	Limestone
10	€10.16	–	€8
20	€10	–	€9.50
50	€10.13	€9.30	€8.11
75	–	€10	€8.57
100	€10	€7.75	€8.10
20-40	€9	€9.50	€6.50
20-50	€10	€9	€11.5

Table 2: Aggregate price by region

Size	Munster	Connacht	Leinster
50mm	€9.42	€8.36	€8.14
20mm	€10	€9	€10
20-40 & 20-50mm	€11	€9	€9
75 & 100mm	€8.20	€8.86	–
10, 12, 14mm	–	–	€9

Farmers considering a drainage project can acquire a copy of the Teagasc Drainage Manual via their local Teagasc office or on the Teagasc website.

Figure 2: Various aggregates in % total

Table 1 shows the breakdown of stone types for the three main rock types. Table 2 outlines the prices for average sizes by region. The prices vary with rock type, size, quantity purchased, delivery distance, and the intensity of grading and washing conducted.

The potential use of limestone and its viability as a drainage stone has come under question and work to assess the suitability of limestone in drainage systems is under way to address questions of excessive dust, the binding together of aggregates and the breakdown of the material over time.

Following this survey, aggregates were collected from 40+ locations across the country with a large geographical spread. These aggregates vary in size, shape and lithology, representing all the aggregates currently used as an envelope material in land drains. A number of tests will be conducted to assess hydraulic capacity, filtration and overall performance of these materials.

This work is part of an ongoing research project to assess the suitability of materials used in land drainage systems. The capacity, performance and lifespan of a range of pipe and envelope combinations will be assessed to provide guidance on their appropriateness.

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