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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.

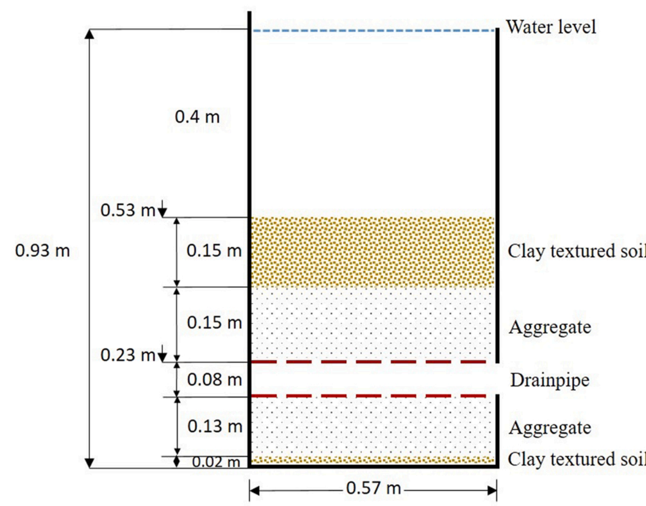

Fig. 1. Laboratory unit setup showing flow through the system and depth profile.

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

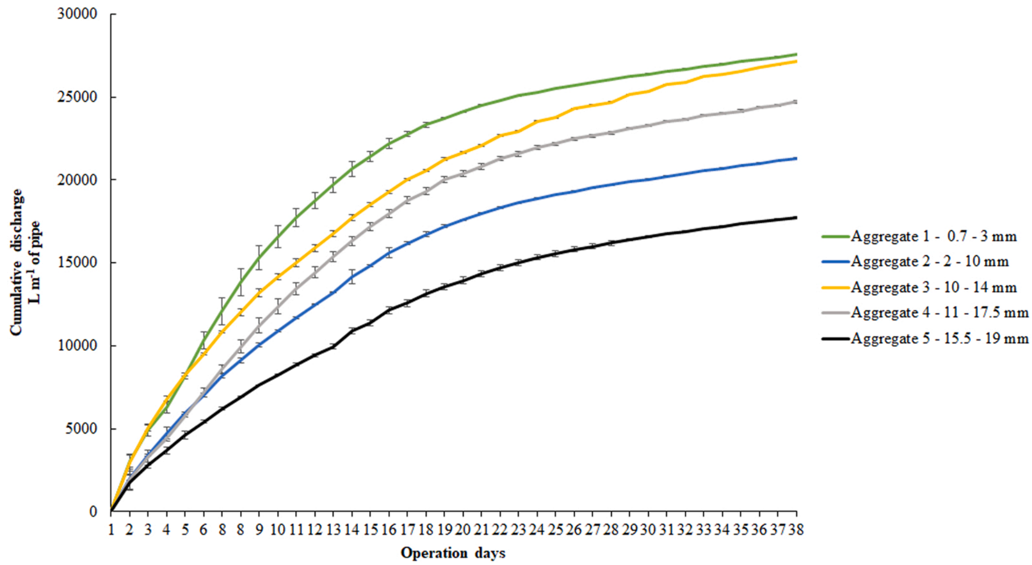

Fig. 2. Cumulative average discharge rate (error bars indicate the standard deviation). Discharge data for Aggregates 6, 7, 8 and 9 were not obtained, as they had met criteria for failure within the first 24 hrs of operation.

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

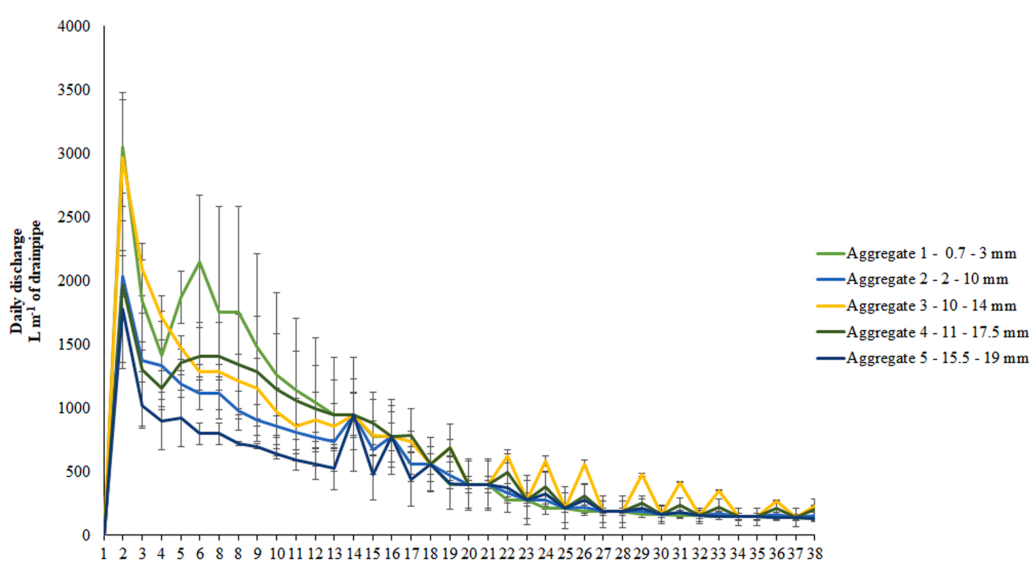

Fig. 3. Daily discharge rate (error bars indicate the standard deviation). Discharge data for Aggregates 6, 7, 8 and 9 were not obtained, as they had met criteria for failure within the first 24 hrs of operation.

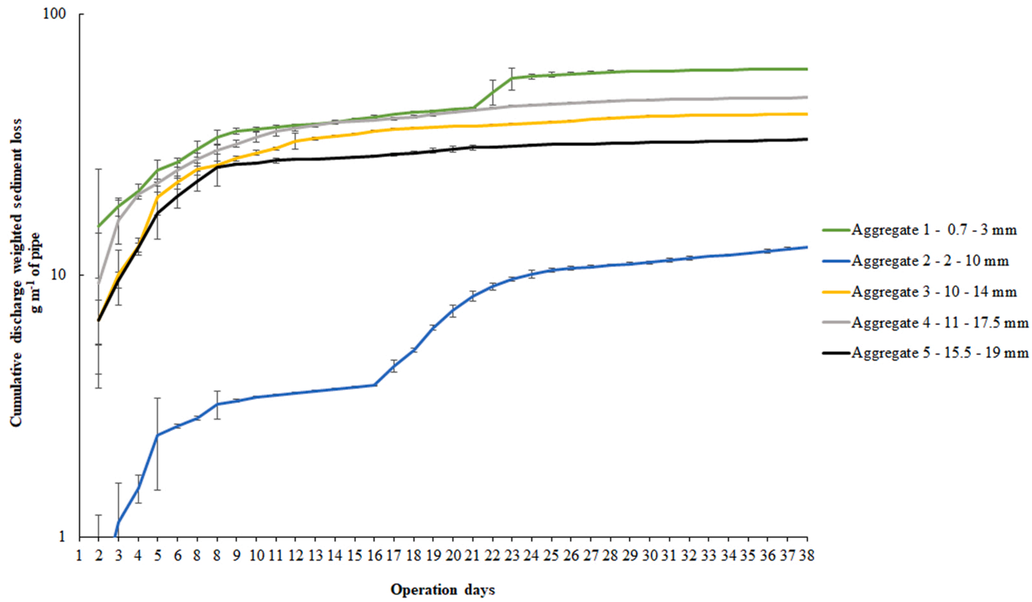

Fig. 4. Cumulative discharge weighted sediment loss (error bars indicate the standard deviation). Sediment loss data for Aggregates 6, 7, 8 and 9 were not obtained, as they had met criteria for failure within the first 24 hrs of operation.

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

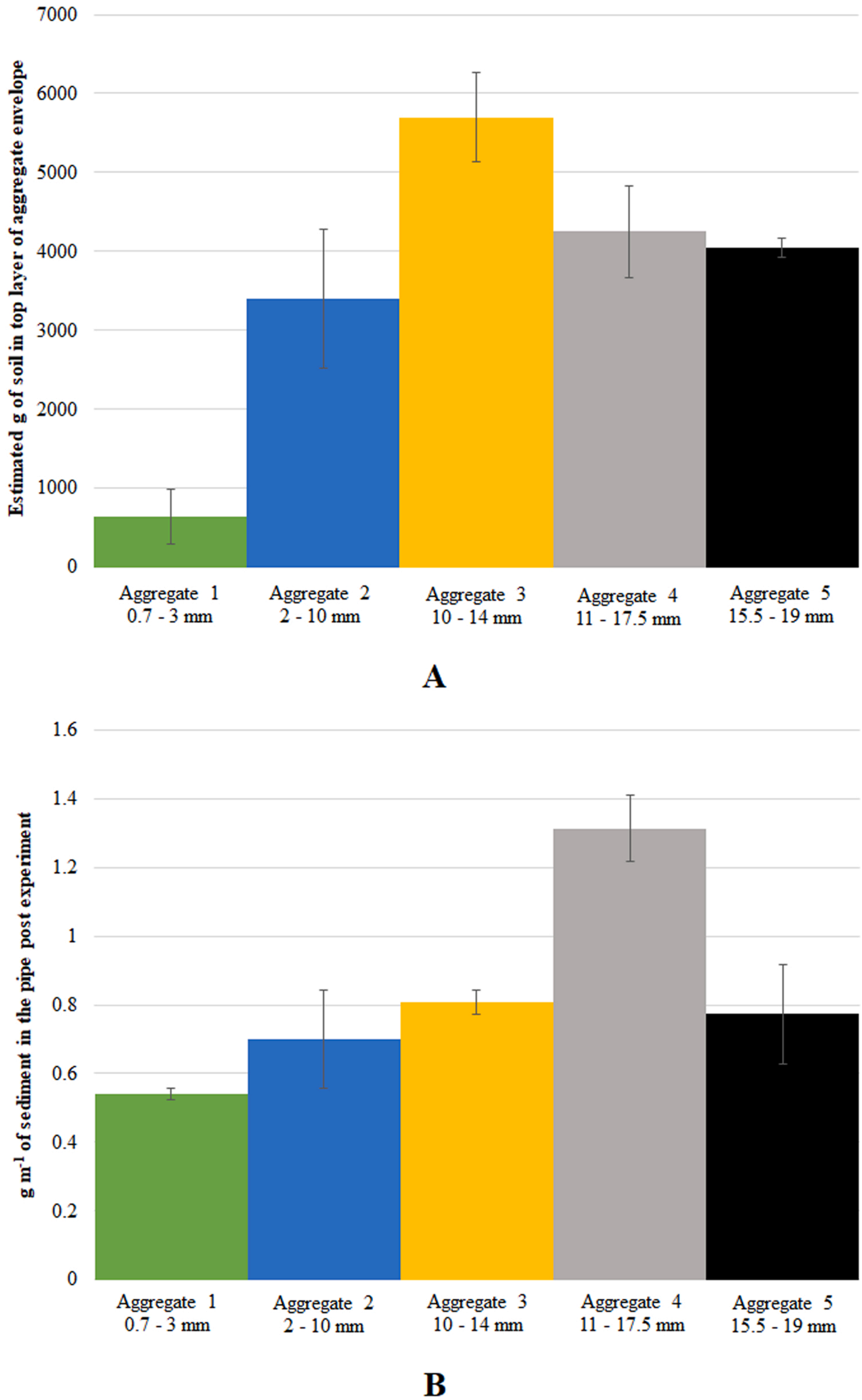

Fig. 5. Estimated g of soil in the top 0.15 m of aggregate (A) and g m^{-1} of sediment per length of pipe (B) (Error bars indicate the mean and standard deviation. Values (A) exclude the quantity of fine material (<2 mm) already within the aggregate). Data for aggregates 6, 7, 8 and 9 were not obtained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