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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.

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

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 (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 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 largescale 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 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) (Figure 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) (Figure 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}) (Figure 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 (Figure 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).

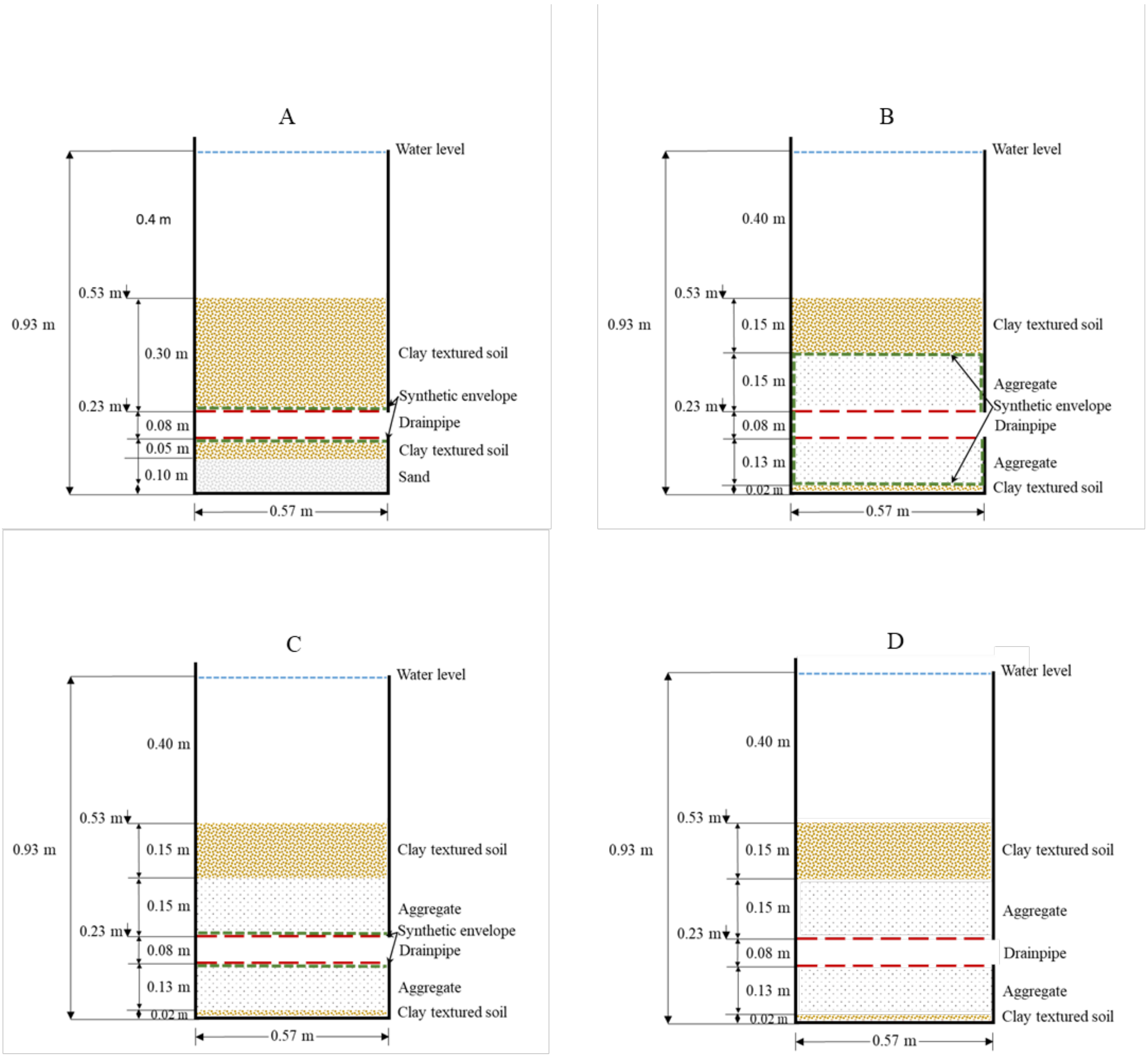

Figure 1. Laboratory unit design for the synthetic envelope, aggregate (2 –10 mm), and clay-textured soil combination with depth profiles indicating: (a) the non-woven geotextile or filter sock (Treatments 1 and 2, respectively); (b) the non-woven geotextile wrapped around the aggregate envelope (Treatment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

In Treatments 1 and 2 (Figure 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 (Figure 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 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) – 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 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

Figure 2 shows the cumulative discharge of five treatments over the total study duration of 31 days (the daily discharge is shown in Figure S4). 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 criterion of 16745 L m^{-1}. Cumulative discharge was highest in filter sock + aggregate (Treatment 4) and non-woven geotextile + aggregate (Treatment 3), with 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 criterion.

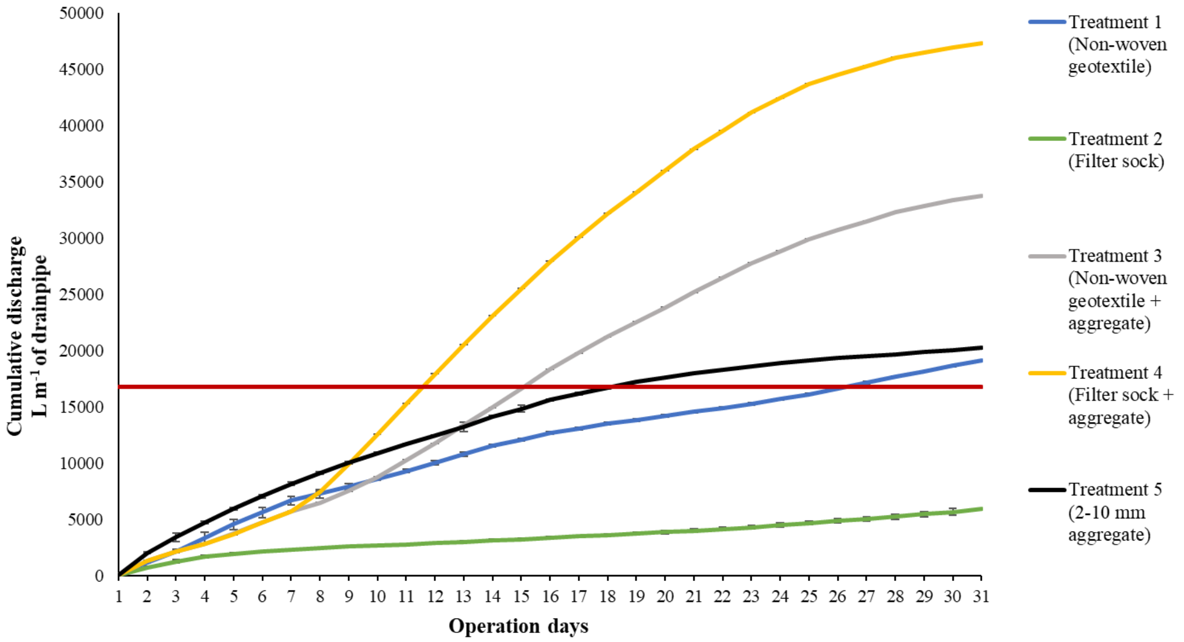

Figure 2. Cumulative average discharge rate, with the minimum required discharge allowed under the hydraulic conductivity (discharge) criterion highlighted in red (error bars indicate the standard deviation).

3.2. Sediment loss

Only two treatments (Treatment 3 and 5) met the cumulative TSS criterion for effective filtration performance (less than 61 g m^{-1}). Cumulative TSS losses (daily flow weighted sediment loss is shown in Figure 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) (Figure 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.

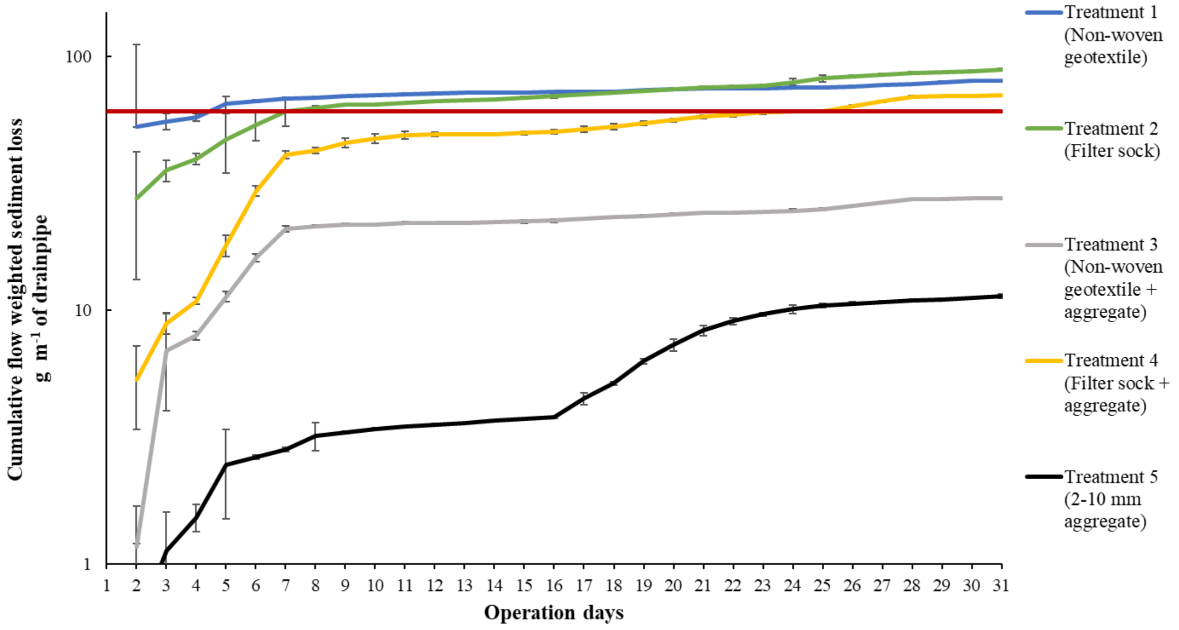

Figure 3. Cumulative discharge weighted sediment loss, with the maximum sediment loss allowed under the filter (sedimentation) criterion highlighted in red (error bars indicate the standard deviation).

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.

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. 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) (Figure S4) was observed between treatments based on differing soil overburden thickness in Figure 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.

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.

Acknowledgements

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Appendix A. Supplementary material

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”

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