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Composite Barrier Systems for Climate Adaptation

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Abstract. Composite barrier systems, which are two-layer systems of materials (fine-grained material overlying coarse-grained material) of contrasting hydraulic properties, can be used to mitigate the effects of climate change in urban areas, including flooding and shrink swell deformation. Here, a series of experiments were carried out to test a range of materials, including 20-30 mm gravel, recycled crushed concrete, topsoil, and topsoil amended with water treatment residual (WTR). The consideration of waste products here aims to improve the sustainability of composite barrier systems for climate adaptation. The results indicate that WTR-amended topsoil is suitable for use as a fine-grained material in composite barrier systems owing to its enhanced water retention properties. However, while crushed concrete can be used in the coarse-grained layer to form a capillary barrier when the system is dry, once breakthrough has occurred, transmission of water through the barrier is quicker than in composite barriers with 20-30 mm gravel. As such, 20-30 mm gravel is recommended for use in the coarse-grained layer. Two large-scale, outdoor lysimeters were set-up using the recommendations derived from the column experiments. The lysimeter experiments were subjected to a series of simulated rainfall events to enable initial interpretations of composite barrier performance.

1 Introduction

Shrink-swell behaviour of clay soils adversely affects the serviceability of buried geo-infrastructure such as pipes and foundations. Increased seasonality is an anticipated effect of climate change in temperate regions [1] so the magnitude of wetting and drying cycles that result in shrink-swell behaviour will increase. Such issues of increased seasonality are particularly important for clay soils as clay undergoes significant swelling and shrinkage with changes in moisture content, reducing strength [2] and resulting in deformation [3]. Indeed, in the UK, during drought years in the 1990s, over £1.6 billion of damage was caused to infrastructure assets as a result of shrink-swell movement in clays [4]. Additionally, urban flooding is likely to increase owing to increased intensity and duration of rainfall events.

Vegetated composite barrier systems offer a means of mitigating these impacts of climate change. A composite barrier is a two-layer system of materials of contrasting hydraulic properties; a fine-grained layer for water retention, overlaying a coarse-grained capillary break layer that prevents water infiltration into underlying soil. Under dry conditions, rainwater is retained in the fine-grained layer. During intense rainfall, vertical infiltration of soil water may occur (breakthrough). This behaviour is illustrated in Figure 1. Composite barriers therefore reduce surface runoff to prevent flooding in extreme weather events and minimise the amplitude of water content variation in underlying soils which lead to shrink-swell behaviour.

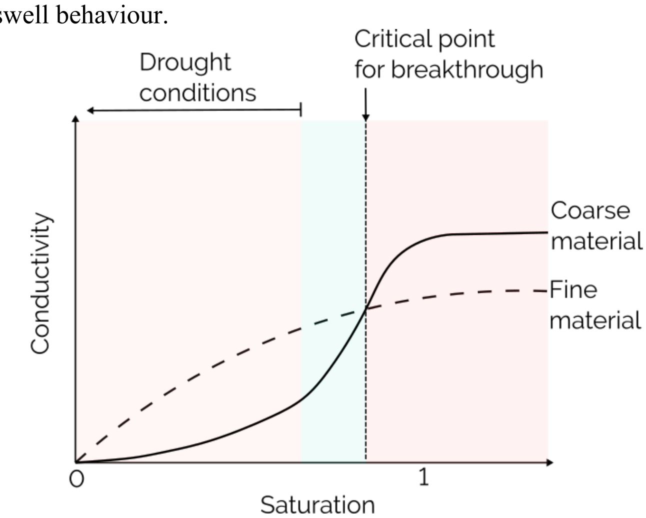

Fig 1. Relationship between hydraulic conductivity and soil saturation for coarse- and fine-grained material.

Typically, composite barrier systems are used in semi-arid settings as waste repository covers, including nuclear waste, to prevent infiltration of water and therefore to reduce soil contamination from waste leachate (e.g., [5]). However, climate adaptation control barriers also provide an opportunity to protect geo-

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infrastructure, including shallow foundations, retaining walls, and buried utilities, supporting Sustainable Drainage Systems (SuDS). This technology can be used to mitigate against flood risk in urban settings and enable adaptation to a changing climate, as it decouples the performance of the underlying infrastructure from infiltration rate and moisture content distribution [6]. The use of composite barriers in temperate areas has been little-studied, and so there is a need for further research into material types that can be used to maintain a capillary barrier under high-intensity rainfall events.

Column experiments are commonly used in composite barrier research (e.g., [7-16]). Previous studies have used column experiments to investigate the influence of rainfall patterns [9, 16], and barrier geometry [13, 15] on capillary barrier performance. Typical column experiments involve rainfall simulation (e.g., [13]) or subjection to natural climatic conditions (e.g., [14]), and measurements of drainage volume at the base of the column (e.g., [13]) and surface runoff at the top of the column (e.g.,[14]). Measurements of matric suction (e.g., [7, 8, 13]) and volumetric moisture content throughout the soil column is also typical (e.g., [8, 13, 14]).

Here, factors affecting the performance of composite barriers under extreme rainfall events are investigated through a series of column experiments, and an optimum design for composite barrier systems is proposed.

2 Methodology

2.1. Column experiments

Column experiments were carried out in the laboratory to test a range of material types including crushed concrete, gravel, topsoil, and Water Treatment Residual (WTR), a waste product from water treatment, in order to assess the use of these materials for use in composite barrier systems. Three experiments were carried out to test these materials, as set out in Table 1. The soil water retention curves (SWRCs) for the fine-grained materials are shown in Figure 2.

Table 1. Materials used in each column experiment.

Test	Materials
A	200 mm gravel, 300 mm topsoil
B	200 mm crushed concrete, 300 mm topsoil
C	200 mm gravel, 300 mm WTR 5% amended topsoil

The apparatus used to test the capillary barriers is shown in Figure 3. A 110 mm diameter, 1000 mm long pipe was used for each experiment. Breakthrough volumes and timings were measured in KIPP004 tipping bucket flow gauges [17] at the base of each column, as shown. Experiments were each subjected to three simulated rainfall events, one day apart. In line with the Environment Agency guidance for the design of drainage systems, a 1 in 100-year +45% storm was selected as the simulated rainfall event: 34 ml of water was added every 15 minutes over 6 hours. The topsoil, or WTR-amended topsoil, used in each experiment was dry for the initial test to ensure a capillary barrier was formed due to the contrasting hydraulic properties of the fine- and coarse-grained materials in the composite barrier systems (Figure 1).

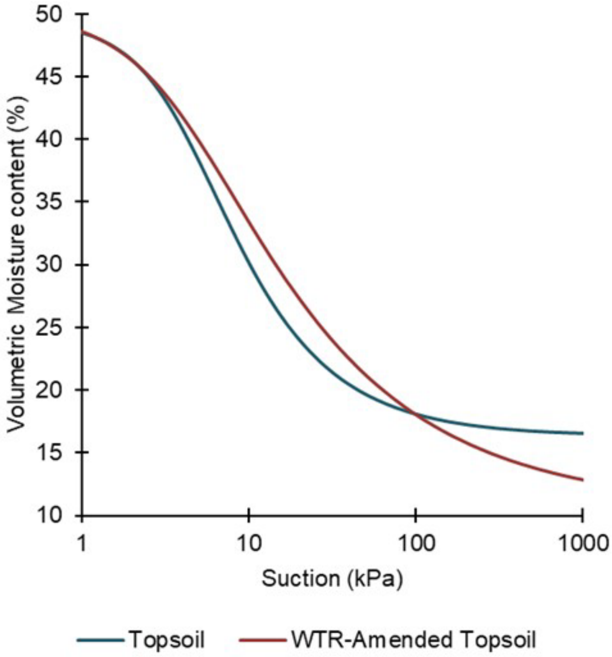

Fig. 2. SWRCs for the topsoil and amended topsoil (5% WTR) used in the column experiments.

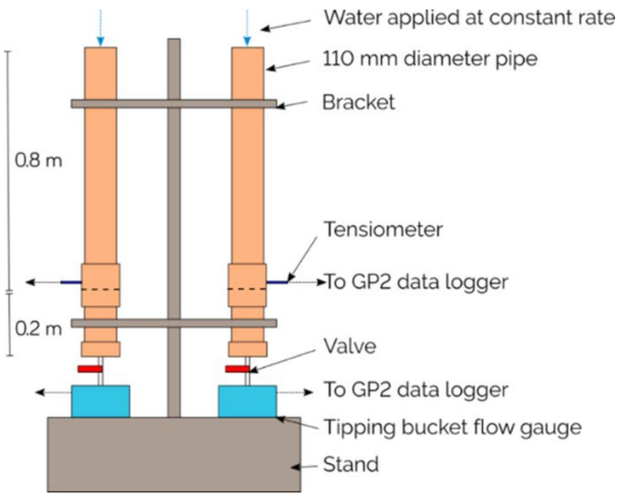

Fig. 3. Set-up of column experiments.

In each experiment, a geotextile was placed at the boundary between the coarse-grained material and the fine-grained material to prevent wash-through of fines over the course of the experiment, such that the hydraulic contrast could be maintained. This is shown in Figure 4.

Fig. 4. Example of a column experiment showing the boundary between the coarse- and fine-grained materials.

2.2. Large-scale lysimeter experiments

Informed by the results of the column experiments, a large-scale (2 m x 1 m x 4.5 m), outdoor lysimeter experiment was constructed at the National Green Infrastructure Facility (NGIF), Newcastle-upon-Tyne UK, to test the performance of composite barriers under natural weather conditions (Figure 5). This work will provide insight into engineered soil-plant-atmosphere interactions and their influence on the performance of barriers using differing geometries under a range of typical and extreme weather conditions, ultimately informing recommendations for the construction of urban composite barrier systems.

The lysimeter is fabricated from stainless steel and timber-clad to fit within the urban landscape (Figure 6). A geotextile was installed at the boundary between the coarse- and fine-grained layers to prevent wash-through of fines into the coarse-grained layer and to maintain the required contrasting hydraulic behaviour. A fibreglass liner installed in the lysimeter separates the barrier into two equally sized cells. In each compartment, the thickness of the water retention layer is varied such that the impact of geometry on the effectiveness of composite barriers can be assessed: A 0.6 m retention layer with large water-holding capacity will be compared with a more cost-effective 0.3 m retention layer. The drainage layer in each case was kept a constant thickness of 0.2 m. Each barrier was planted with a biodiverse mixture of native flora, including species adapted to wet conditions (*Lotus pedunculatus, Deschampsia cespitosa, Geum rivale*) and species adapted to dry conditions (*Lotus corniculatus, Festuca ovina, Daucus carota*). Besides the aesthetic and biodiverse appeal of such a community, it is intended that this range of species will provide maximum evapotranspiration throughout the year [18].

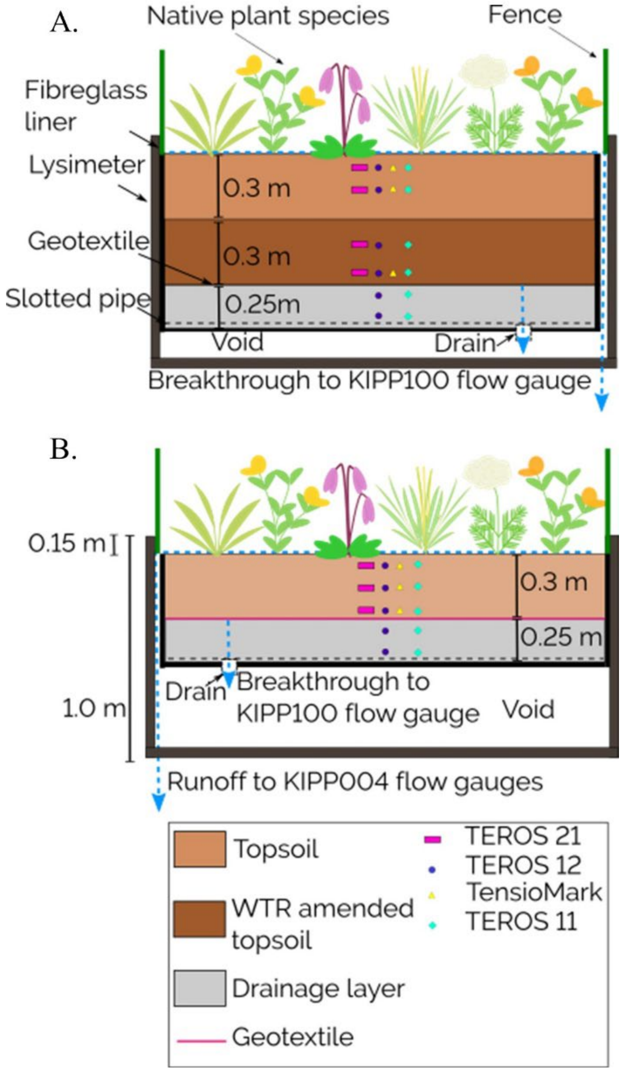

Fig 5. Set-up of lysimeter experiments: A) deep lysimeter with 200 mm gravel, 300 mm WTR-amended topsoil, and 300 mm topsoil, and B) 200 mm gravel, and 300 mm topsoil.

Data will be acquired from the lysimeter experiment across a two-year monitoring period, during which the composite barriers will be subjected to natural and simulated rainfall events. The lysimeter has been instrumented with volumetric moisture content probes (Teros 12 and EC-5 [17]) and soil suction probes (Teros 21 [17] and TensioMark [19]) positioned at a range of depths below the surface. Runoff and breakthrough are measured using KIPP004 and KIPP100 tipping counter flow gauges [17] as shown in Figure 5.

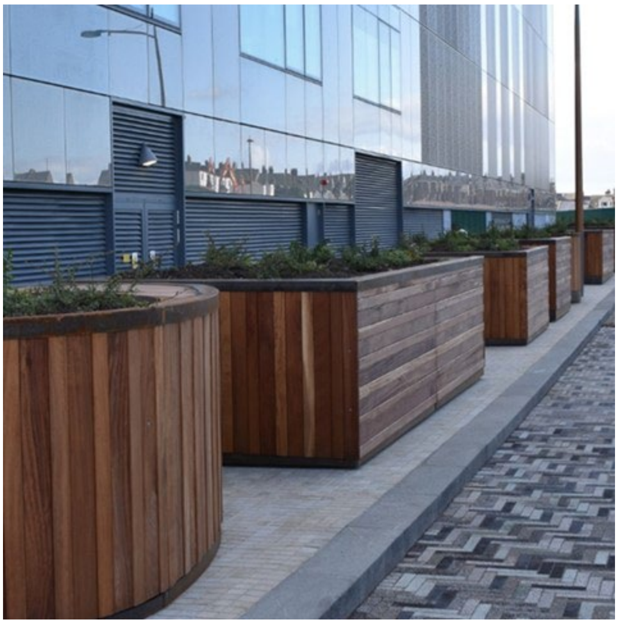

Fig 6. Lysimeters at the National Green Infrastructure Facility (NGIF), Newcastle University, UK.

Variations in each of the measured parameters will be monitored over two years to assess the effectiveness of the composite barrier through varying weather conditions, which will be recorded by an onsite weather station consisting of a WXT536 [20] which provides measurements of wind speed and direction, precipitation, barometric pressure, temperature and relative humidity, as well as a Kalyx-RG rain gauge [20] which provides measurement of precipitation adjacent to, and at the same elevation as the lysimeter. The monitoring data generated by this work will be made available via the NGIF app, accessible here: https://linktr.ee/NGIF_UK.

In addition to long-term monitoring under natural weather conditions, the composite barrier lysimeter experiments have been subjected to simulated rainfall events for comparison with the column experiments presented here. A 2 m x 2 m rainfall simulator comprising of 102 drip nozzles with a 2 L/h outflow rate on a pipe network secured to a steel frame was used to simulate a 1 in 100 year +45% storm with a duration of 1 hour (equivalent to 52 mm of rainfall). Three storm events were simulated, each one week apart. The rainfall simulator is shown in use in Figure 7. The simulated storms were applied under non-vegetated conditions, prior to establishment of the aforementioned mentioned species and ongoing work will investigate the efficiency of root-water uptake to renew conditions that promote composite barrier functionality.

Fig. 7. Rainfall Simulator set-up.

3 Results and Discussion

3.1. Column experiments

Figure 8 shows the results from the three column experiments carried out here: A) 200 mm gravel and 300 mm topsoil, B) 200 mm crushed concrete and 300 mm topsoil, and C) 200 mm gravel and 300 mm WTR-amended topsoil. In all three composite barrier experiments, no breakthrough occurred in the first simulated rainfall event (Run 1), so Figure 7 shows the second and third simulated rainfall events only (Run 2 and Run 3).

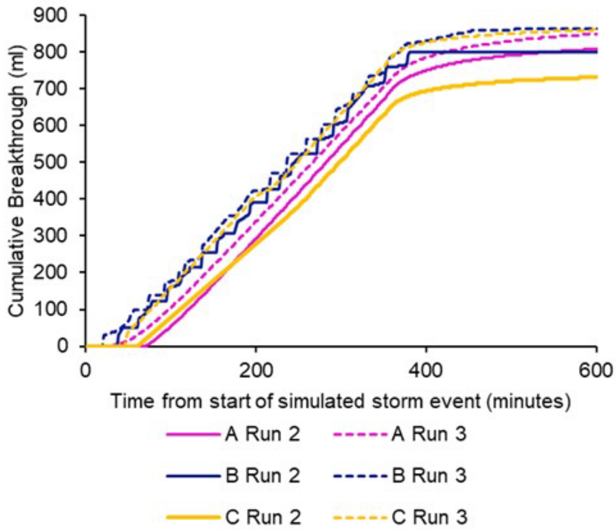

Fig. 8. Cumulative breakthrough in column A and B, showing 3 rainfall events (Run 1 to 3).

Time to breakthrough was longer in the second simulated rainfall event (Run 2) than in the third simulated rainfall event (Run 3) in all cases, owing to drier starting conditions in Run 2 compared with Run 3. On average across all three experiments, breakthrough occurred 24 minutes earlier in Run 3 than in Run 2. Indeed, as in [10], with each subsequent wetting cycle following the first breakthrough, the amount of time to the next breakthrough event decreased, despite controlled rainfall conditions. This is attributed to soil moisture remaining high in the fine-grained layer between cycles. Therefore, this highlights the importance of vegetation for maximising the efficiency of composite barrier systems [15], as root water uptake between wetting events results in drying of the fine-grained layer to increase the hydraulic contrast with the coarse-grained layer to maintain a capillary barrier effect at the boundary. Indeed, a range of native vegetation species were planted on the large-scale lysimeter experiment to maintain optimum function of the experimental composite barrier systems under a range of conditions [18].

The total cumulative breakthrough was lower in Column C (WTR amended topsoil) than in Column A and B (unamended topsoil) in the second rainfall event. This is due to the enhanced water retention characteristics of the WTR-amended topsoil when compared with the unamended topsoil, as indicated by the SWRCs shown in Figure 2. In the third rainfall event (Run 3), the performance of Columns A, B, and C was similar. This is likely to be because the fine-grained material in all three column experiments had reached saturation by the third simulated rainfall event.

Whilst the time to breakthrough and the total cumulative breakthrough in Column B was similar to that of Column A, following Run 1, where a capillary barrier was formed and no breakthrough occurred, the composite barrier with a recycled crushed concrete coarse-grained layer allowed for very fast transmission of water. This is indicated by the fact that the cumulative breakthrough in Runs 2 and 3 increased in rapid, short bursts over the course of the simulated rainfall events, coinciding with the timing of the water additions which occurred once every 15 minutes. This is attributed to the fact that the crushed concrete was more angular than the gravel used in Columns A and C, and so a larger, more connected pore network was formed. As such, as soon as breakthrough occurred in Column B, water was quickly transmitted through the coarse-grained layer and was recorded in the KIPP004 tipping bucket flow gauge. This demonstrates a need for consideration of the effects of sustainable and recycled materials in composite barrier systems. Previous studies indicate that recycled crushed concrete is suitable for use in composite barrier systems [21]. However, the properties of recycled crushed concrete vary greatly between sources, and so the behaviour and effectiveness of composite barriers using crushed concrete will also vary greatly.

3.2. Large-scale lysimeter experiments

Breakthrough in Lysimeter A and Lysimeter B (shown in Figure 5) over the three simulated rainfall events carried out here is shown in Figure 9. Given that the lysimeters are situated outdoors to facilitate long-term monitoring of the effectiveness of capillary barriers under natural weather conditions, natural rainfall that occurred during this time is also shown. At the time of the first simulated rainfall event (24.08.2022), the soil was dry and so the breakthrough volume was smaller in both Lysimeter A and Lysimeter B than in subsequent simulated rainfall events as water was retained in the fine-grained water retention layer of the composite barrier systems.

With the exception of the second simulated rainfall event (31.08.2022), the total breakthrough was greater in Lysimeter B than in Lysimeter A in each event. Given that Lysimeter B consists of a shallower fine-grained layer than Lysimeter A, this indicates that overall, a composite barrier system with a deeper fine-grained layer is more effective for protecting buried geo-infrastructure than a shallower composite barrier system. However, this requires a greater volume of material, and so is less cost-effective than a shallower composite barrier system. As such, a cost-benefit analysis should be carried out before recommendations are made. The long-term monitoring of the lysimeters exposed to natural weather conditions will enable such an analysis to be undertaken.

Despite the fact that the natural rainfall events that occurred over the study period considered here were smaller storms than the simulated rainfall events (maximum of 27 mm compared with 52 mm), the breakthrough in both Lysimeters A and B was greater in the natural rainfall events. This is for two main reasons: Firstly, owing to the reduced time between rainfall events in the natural events compared with the simulated rainfall events which were carried out a week apart, the moisture content of the composite barrier systems was higher at the onset of the natural rainfall events (Figure 9), and so less water was retained in the fine-grained retention layer before breakthrough occurred (see Figure 1). Secondly, the simulated rainfall events took place over a short time (1 hour each). In the natural rainfall events, although the total rainfall (mm) was lower than in the simulated events, the storm duration was longer (e.g., 14 hours of rain on 09.09.2022). As such, more of the rainfall was allowed to infiltrate into the soil and less runoff was generated in the natural storm events and therefore, there a greater volume of water exfiltrated from the base of the composite barrier system and was recorded as breakthrough. This demonstrates the importance of antecedent conditions for composite barrier performance and highlights the need to consider different storm characteristics when designing such systems for climate change adaptation.

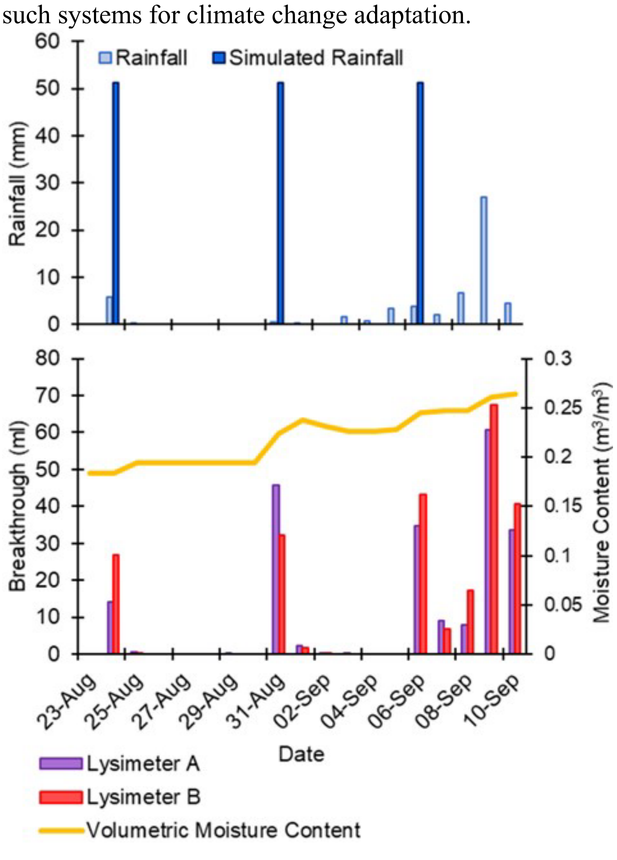

Fig. 9. Breakthrough in Lysimeter A and B, shown alongside rainfall data, including simulated rainfall events and natural rainfall.

4 Conclusions

Composite barrier systems have been shown to be effective for use in reducing surface runoff and protecting buried geo-infrastructure from shrink-swell behaviour in native soils, particularly under dry starting conditions, through a range of soil column and lysimeter experiments presented here. All materials tested were effective as composite barrier systems when starting from dry conditions, but where simulated rainfall events were carried out on soils with a higher starting moisture content (following prior rainfall events), differences in the performance of these composite barrier systems were observed.

Overall, waste products (crushed concrete and WTR) were shown to be as effective as inert materials for use in composite barriers, which will improve the sustainability of composite barrier construction. The addition of WTR to topsoil improved the water retention capacity of the composite barriers tested when compared with composite barriers without amended topsoil, and so it is recommended for use. However, consideration must be given to the variation in the properties of the available materials, as the properties of recycled crushed concrete can vary greatly, affecting the suitability for use in composite barrier systems. Indeed, the composite barrier system comprising of a crushed concrete coarse-grained layer was only effective when starting conditions were dry. Additionally, owing to limitations in the availability of crushed concrete in the size and grading required, it is not recommended for composite barrier construction.

Large-scale experiments are ongoing, and preliminary results (under non-vegetated conditions) indicate that performance improves with increased thickness of the retention layer. The importance of storm characteristics for determining composite barrier performance has also been highlighted and is an area for further research.

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