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Experimental study on the Hydrological Performance of a Permeable Pavement

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Abstract: Permeable pavements play an essential role in urban drainage systems, making them the subject of great interest to both researchers and practitioners. However, previous studies have demonstrated a significant degree of uncertainty regarding both the hydrological performance and the maintenance requirements of this type of pavement. Within this context, the presented research involved the construction of a one metre square surface area of permeable pavement and a laboratory rainfall simulator to investigate the influence of rainfall intensity on the hydrologic response of permeable pavements. The design of the permeable pavement complied with the SuDS Manual guidance and British Standards (BS 7533-13:2009). The laboratory test programme was designed to investigate the influence of rainfall intensity on the hydrologic response of permeable pavements. The results demonstrate that the hydrologic performance varied according to rainfall intensity. The total volume of discharge from the permeable pavement ranged between 8% to 60% of the inflow. More than 40% of the total rainfall from all rain events was temporarily detained within the structure. Permeable pavement design optimisation has therefore been tested in the study. The SuDS Manual guidance has been found to meet current optimisation requirements.

Keywords: permeable pavement, hydrological performance, laboratory simulation experiment; rainfall simulator; outflow, SuDS

1. Introduction

Sustainable urban drainage systems (SuDS) exist in a variety of forms, including permeable pavements. Thekey benefits of this type of pavement include run-off reduction, improved groundwater recharge, and ultimately reduced pollution (USEPA, 1999). As such, permeable pavements are a key SuDS measure employed both to attenuate surface runoff in urban areas(Pratt et al., 1989, Schluter and Jefferies, 2002, Dawson, 2008) and to filter urban stormwater pollutants(Hatt et al., 2007, Siriwardene et al., 2007, Beecham et al., 2012).

Permeable pavements reduce runoff volumesand peak runoff rates by enabling rainwater to infiltrate through the system.Previous research has demonstrated that the runoff from permeable pavementsis significantly less than that from conventional pavements, and is comparable to urban greenfield runoff(Bond et al., 1999, Andersen et al., 1999, Dreelin et al., 2006, Gilbert and Clasusen, 2006,Ball and Rankin, 2010, Fassman et al., 2010).

Pratt et al. (1989, 1995) studied the performance of a full-scale permeable pavement car park (pavement depth 300-400 mm) at Nottingham Trent University. In the study, impervious partitions separated the base of the car park into four sections, which were then filled with different materials. The results indicated that the average discharge from the different surfaces were 37% for gravel, 34% for blast furnace slag, 47% for granite, and 45% for limestone. Thus, the lowest runoff was created by the blast furnace slag, which was explained by its shape, which results in a void space of 48% and a consequent increase in potential storage for storm water.

Pratt et al. (1989, 1995) observations were confirmed by a field study carried out by Abbott and Comino Mateos (2003). They investigated the in-situ hydraulic performance of a 480mm deep permeable pavement system, which consisted of 80 mm of block paving and 50 mm of bedding course and 350 mm of sub-grade. Their results clearly indicated the attenuating effect of the pavement; 67% of rainfall was percolated through the pavement and the initiation of runoff was delayed between 5 minutes to two hours. The volume of discharge was similar to that noted by Pratt et al. (1989,1995), but the start delay was longer due to the sub-base materials used.

A comparative study was carried out by Collins et al. (2008), to examine the performance of four types of permeable pavements (depths up to 500 mm) relative to a standard asphalt pavement. The study confirmed average percent runoff volume reductions of 36-67%, and average peak flow reductions of 60-77%. Although hydrological performance differences did exist among the different types of permeable pavement, these were minor in comparison with the total improvements over asphalt (Collins et al., 2008).

Palla et al. (2015) conducted a recent laboratory study investigating the hydrological response of a permeable pavement when subjected to different rainfall intensities and slopes. The study examined two types of pervious pavements: a 210mm deep concrete cell (CC)and a 190mm deep pervious brick (PB), with two filter layers made of recycled glass aggregate and a mixture of gravel and coarse sand. The hydrological response was analysed by calculating the discharge coefficients for each pavement, which were then defined in the form of the ratio between the discharge volume and the inflow volume, measured at the end of the rainfall event and corresponding to 15 minutes of constant rainfall intensity. The results of the study confirmed that no surface runoff occurred in any of the tests. The discharge coefficients for CC and PB ranged between 0.55-0.75 during events of high rainfall intensity (98 mm/h in 15 minutes), and 0.01-0.12 during events of low rainfall intensity (17 mm/h in duration 15 min). The results also indicated that higher drainage results wereassociated with higher slopes, and that recycled aggregate is a valid option to replace sand and gravel in permeable pavements (Palla et al., 2015).

Despite their proven ability to attenuate surface runoff, there remains a lack of detailed understanding of the hydrological performance of permeable pavements, and there are consequently no firm design guidelines to assist designers and other stormwater professionals (Mullaney and Lucke, 2014). Thus, the research reported herein has been designed to define the hydrological performance of permeable paving in detail by relating it to rainfall characteristics and soil moisture content.

2. Methods

2.1 Experimental apparatus

One square metre of permeable pavement was built as a 1:1 scale model in a laboratory environment. The pavement rig was made of strong watertight polypropylene walls within a welded steel frame. The dimensions of the pavement rig were 1000 mm x 1000 mm x 1600 mm, with one side made of Perspex to allow visual inspection of the subsurface material as shown in Figure 1. The Priora pavement was designed in accordance with Marshalls' standard specifications(Marshalls, 2013), and the design methodology followed the technical design guidelines provided by the SuDS Manual CIRIA C697 (Woods-Ballard et al., 2007) and British Standard 7533-13:2009(BSI, 2009).

The permeable pavement comprised of Priorablock paving (80 mm in depth), a bedding layer course sediment (50 mm), sub-base (depth of 350 mm) and a sub-grade layer (depth of 300 mm). The design permeability of Priora blocks (200mm long x 100mm wide x 80 mm deep)is18750 l/ha.sec (6750 l/m^2.h)(Marshalls, 2013). The interlocking face on the paver was designed to create space between the bricks which allows storm water to infiltrate to the underlying surface.

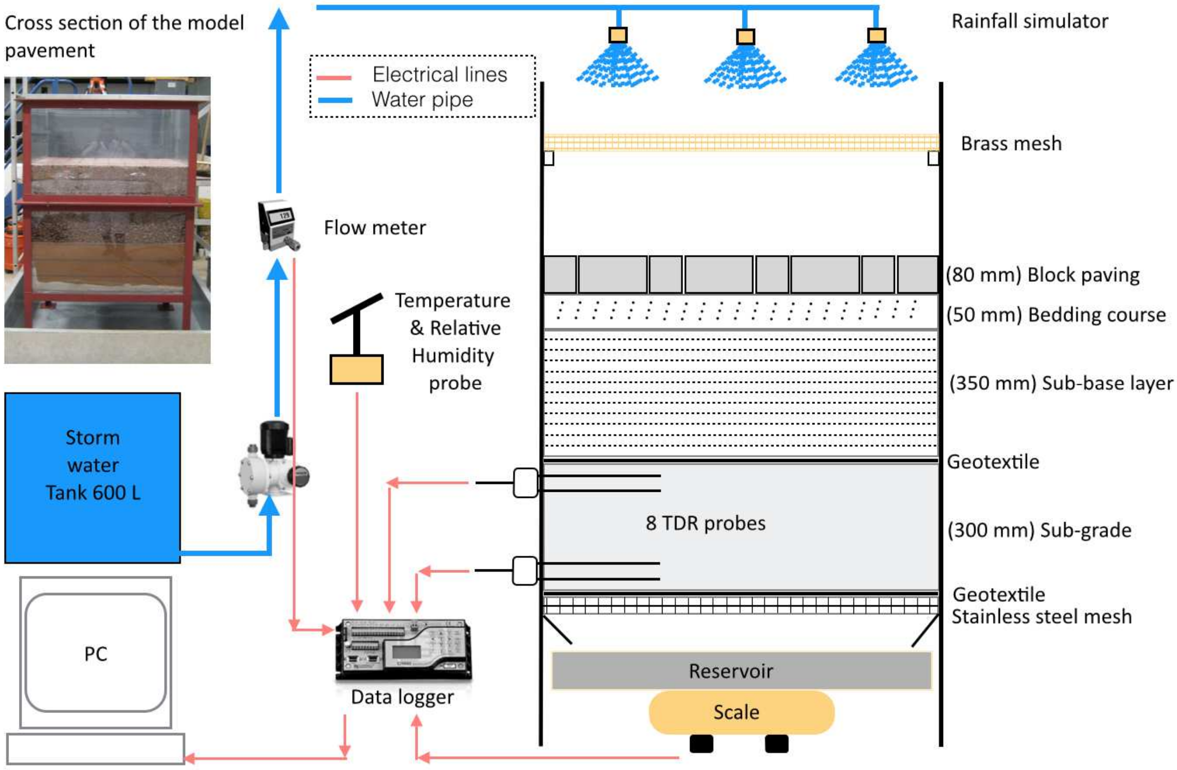

Figure 1: Layout of permeable pavement design used in the laboratory model.

The bedding course layer was formed of 6mm d_{50} washed aggregate, and a sub-base comprised of 20mm d_{50}washed aggregate.The grading of the fine and coarse aggregates was tested using a sieve analysis, and construction undertaken in accordance with BS EN 13242, 2002 (BSI, 2002), and found to be within the particle size distribution recommendations stated in the design guidelines (see Figure 2).

The sub-grade was filled with clean sand, uniformly graded in accordance with the British soil classification system for engineering purposes BS 5930:1981 (BSI, 1981), with a particle size distribution d_{50} of 0.2mm. The sub-grade layer was built up by placing sieved sand in three layers, to achieve the required compaction according to the Proctor test BS 1377-4:1990(BSI, 1990). In conjunction with staggered layering, the sand was prepared using a known sand to water volume ratio to ensure it met the design moisture content within the model structure.

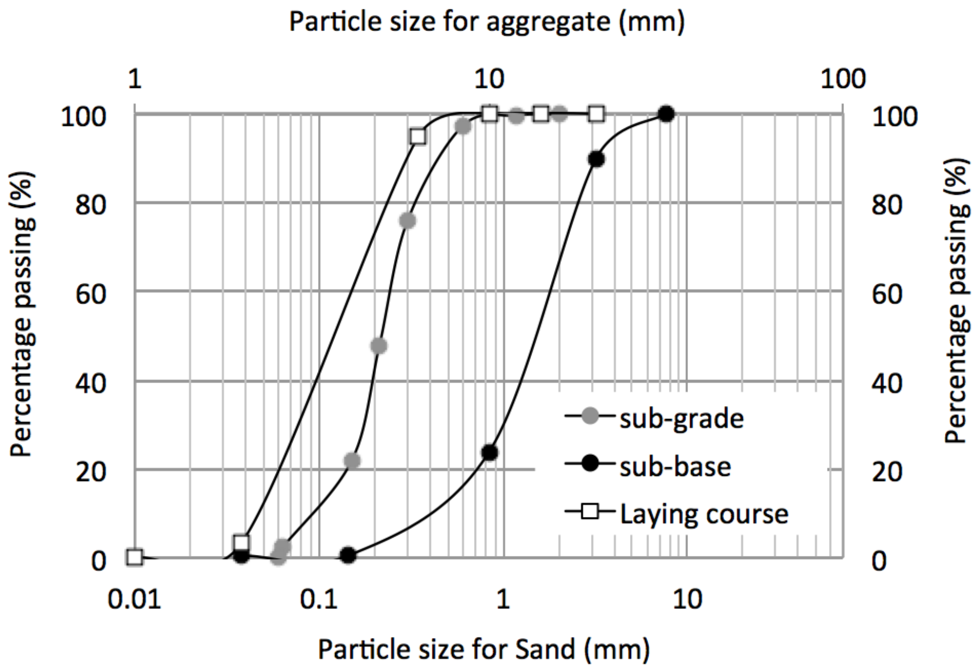

Figure 2: The particle size distribution curves for bedding course (6 mm aggregate), sub-base (20 mm aggregate), and sub-grade (sand).

A geotextile was used in two locations in the pavement structure (Figure 1). One layer was placed between the coarse aggregate and sand to prevent migration of the sand into the course aggregate layer(USEPA, 1999), and another was placed under the sand, to prevent loss of subgrade materials within the outflow.

The rainfall simulator was designed to deliver water into the system in a manner that provided control of the rain volume, intensity and duration. In order to achieve the necessary rainfall droplet size and intensity, water was pumped throughstainless steel spray nozzles and discharged onto a brass mesh located above the pavement. A flow meterwas connected to the main pipe to measure the inflow rate, and outflow was measured by continuously monitoring the weight of water in a container placed beneath the pavement outlet.

Within the sub-grade, data about moisture content data was collected using time domain reflectometry (TDR) probes. The eight moisture content probes were installed within the sub-grade at two depths: in the top layer of the sub-grade (75 mm from surface) and in the lower layer of the sub-grade (225 mm from surface). Finally, a thermistor monitored temperature across a range of -55°C to +70°C.

2.2Experimental procedure

The experimental procedure involved applying three different rainfall intensities/duration combinations, with each combination repeated three times. The sequence, involving three rainfall storms with different duration and intensities, enable the collection of data that can be analysed from different perspectives relative to the pavement design. Each rainfall storm was repeated across three weeks. Typically, simulated rainfall events occurred over a cycle of seven days. Rainfall was simulated, once per day for the first five days (Days 1 to 5), withno rainfall on days 6 and 7. Repetition within a three week period revealed an average trend in the structure's response, as well as in increase in the reliability of the results via repetition.

The rainfall charcaterstics based on Flood Estimation Handbook calculations for return periods of 5,10, and 10 year average recurrence intervals (ARI) at the Heriot Watt University site in Edinburgh which yielded rainfall depths of 6.39, 7.78, and 10.85 mm was applied over periods of 15, 15, and 30 minutes respectively.

3. Results and discussion

3.1 Moisture content and Atmospheric condition

Analysis of the moisture content data demonstrated the extended period necessary to allow the 300 mm sub-grade to dry. This period may correlate with the climatic conditions surrounding the pavement area. Figure 3 a,b shows the profile of the air temperature, surface temperature, and relative humidity over the experiment's duration. The average atmospheric temperature over three months was at 23.5˚C (SD 1.5˚C), with a relative humidity of 33.6% (SD 4.8%).

The difference in temperature was approximately 9.5 °C throughout the period of the experiment, which is no more than one would expect in the field, and is hence considered not to be a significant factor. Relative humidity was notably variable within this time. However, this data shows the average air and surface temperatures during the experimental period were relatively constant. Therefore, for the purposes of this study it is safe to assume that the evaporation rate during the experiment period remained constant.

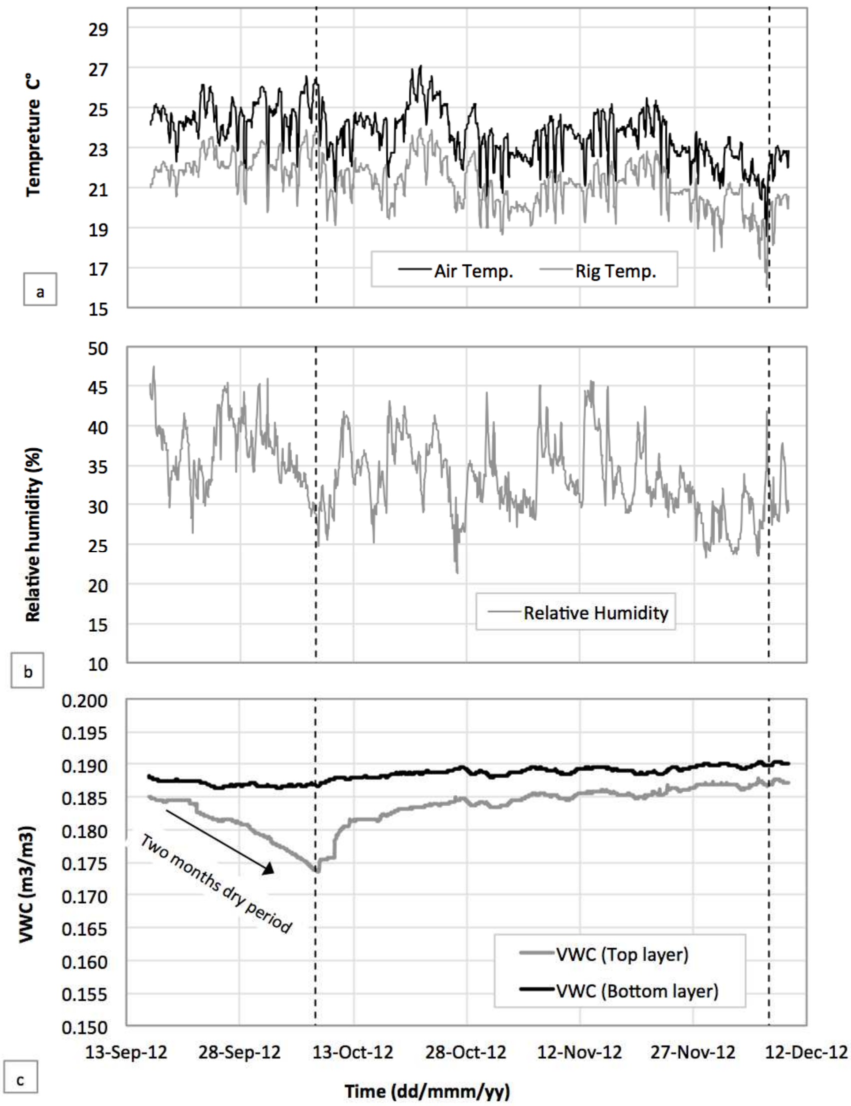

Figure 3: Showing (a) air and surface rig temperature, (b) relative humidity, (c) analysis of the change in VWC levels during the course of the experiment

3.2. The initial condition of the sub-grade

Volumetric water content (VWC) was measuredusing a TDR probe (Figure 1) at two different depths in the subgrade. The results for VWC (Figure 3c)show that VWC responded to a rainfall event on 8th of October 2012, and that the VWC level increased markedly as a consequence. The sub-grade was found to be relatively dry during this rainfall event, explaining the lack of discharge during the first and second rain events. The study's results confirm that rainfall response is associated with sub-grade conditions.

3.3 Hydrology performance

In total, 43 rainfall event simulations were applied to the permeable pavement rig. Figure 4 illustrates the volumes of rainfall and the outflow during the course of the experiment. It shows that the pavement discharged the lowest volume of runoff on Day 1. Although the VWC level in the sub-grade increased, this occurred because the moisture content of the upper layers decreased during days 6 and 7 due to infiltration. Thus, during the simulation on Day 1, the structure of the permeable pavement and the underlying material had a higher absorption rate when compared with Days2-5. After the consecutive rain events, the permeable paving and underlying material became more saturated; reaching maximum saturation by day 5, as shown in Figure 4. The retention volume decreased within the upper layers of the structure over days 6 and 7 due to the lack of rainfall. This behaviour occurred weekly during the experiment, thus illustrating a cyclical, rainfall driven pattern.

The storage volume (the balance between rainfall and outflow) is plotted in Figure 4. It can be seen that the pavement performed well, generally retaining rainfall within the structure. However, this was not the case for Rainfall Intensity 3, where the pavement discharged more rainfall than either during or after Rainfall Intensities 1 and 2. The increase in outflow is attributable to the increase in VWC level over time and the fact that the duration of the rainfall event for Rainfall Intensity 3 was longer than for Rainfall Intensities1 or 2. Overall, the available storage within the pavement structure provided a consistent volume over all three rainfall intensities during wet conditions (Day 2 to 5). It can be concluded that the pavement structure was capable of providing a significantly larger storage volume than that required to mitigate hydrologic Rainfall Intensities1, 2, and 3 according to published SuDS design standards.

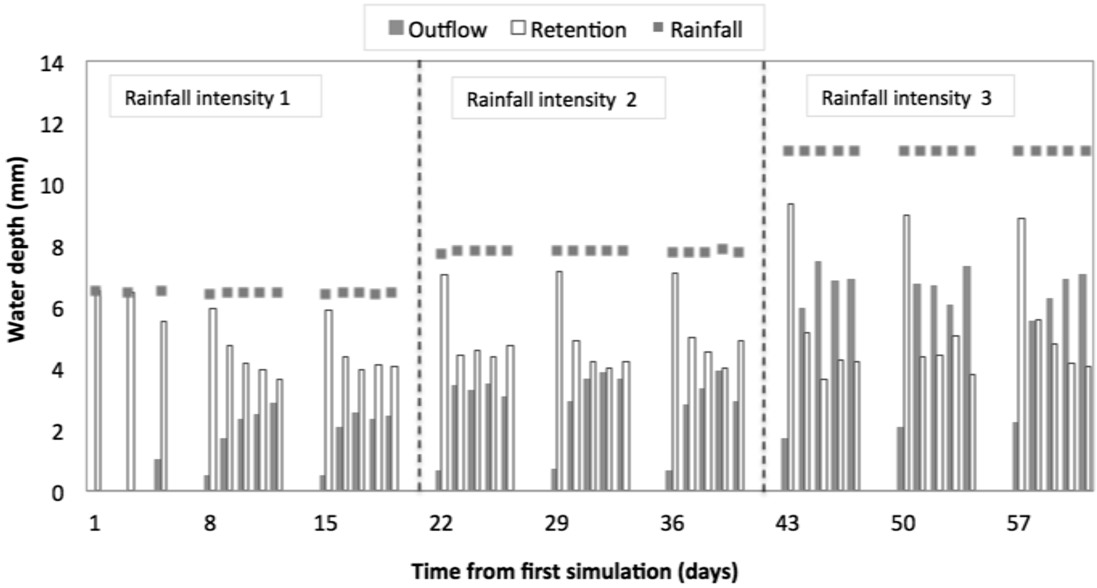

Figure 4: Analysis of rainfall and outflow volumes during the course of the experiment.

3.3.1 Hydrograph

Figures 5a, 5cand 5e illustrate typical hydrographs and Figures 5b, 5d and 5f show the cumulative flow hydrograph for Rainfall Intensities1, 2, and 3. It is apparent from the shape of the curves in Figures 5a, 5b, 5c and 5d that cumulative flow and flow rate specific outflows follow trends for Rainfall Intensity 1 and 2. The hydrologic performance for Rainfall Intensities 1 and 2 are comparable (p=0.92) although the difference in inflow rates between Rainfall Intensity 1 and 2 is up to 5mm/hr. This illustrates that increasing the intensity of the rainfall above 25mm/h without increasing the rainfall duration causes an increase in rainfall attenuation within the pavement structure.

Figures 5e and 5f represent Rainfall Intensity 3, and show a different response in terms of the outflow rates than that seen in Rainfall Intensities1 and 2. Outflow during and after rainfall event 3 is higher than for either Rainfall Intensities 1 or 2. Figures 5c to 5f illustrate that increasing the rainfall duration results in an increase in the outflow and therefore anincrease in rainfall attenuation within the pavement structure.

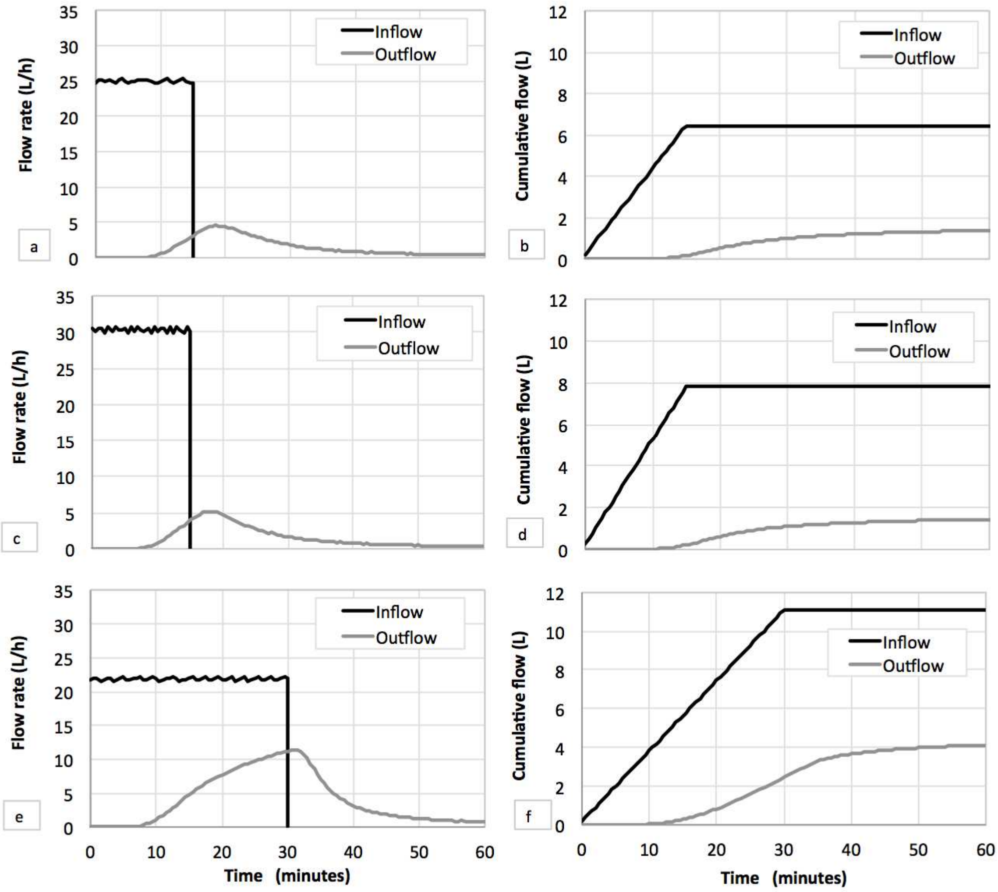

Figure 5: Average typical and cumulative hydrograph related to rainfall intensity, (a – b) Rainfall Intensity 1, (c – d) Rainfall Intensity 2, and (e –f) Rainfall Intensity 3.

3.3.2 Outflow rate

Figures 6a, 6b and 6c illustrate the outflow rate during Day2-5conditions across Rainfall Intensities1, 2, and 3 (respectively). The peak discharge occurred only after the rainfall stopped, indicating that there is a lag time between rainfall event peak and peak outflow from the permeable pavement. The occurrence of this lag between the inflow and outflow peaks also suggests the pavement has not reached saturation point and could accommodate a larger rain event (in terms of intensity and duration) than Rainfall Intensities 1, 2 or 3. The peak discharge measured was 5.8, 6.5, and 15 L/m^2.h for Rainfall Intensities 1, 2 and 3 respectively. Despite a high level of subgrade permeability (218 mm/h), the average delay before the outflow began was approximately 8 minutes during Day2-5conditions. The duration of the outflow events varied between 0.86 and 7.43 hours. It became apparent that the outflow duration for all rainfall events was significantly longer than the rainfall duration,thereby demonstrating the high attenuation rate of the permeable pavement.

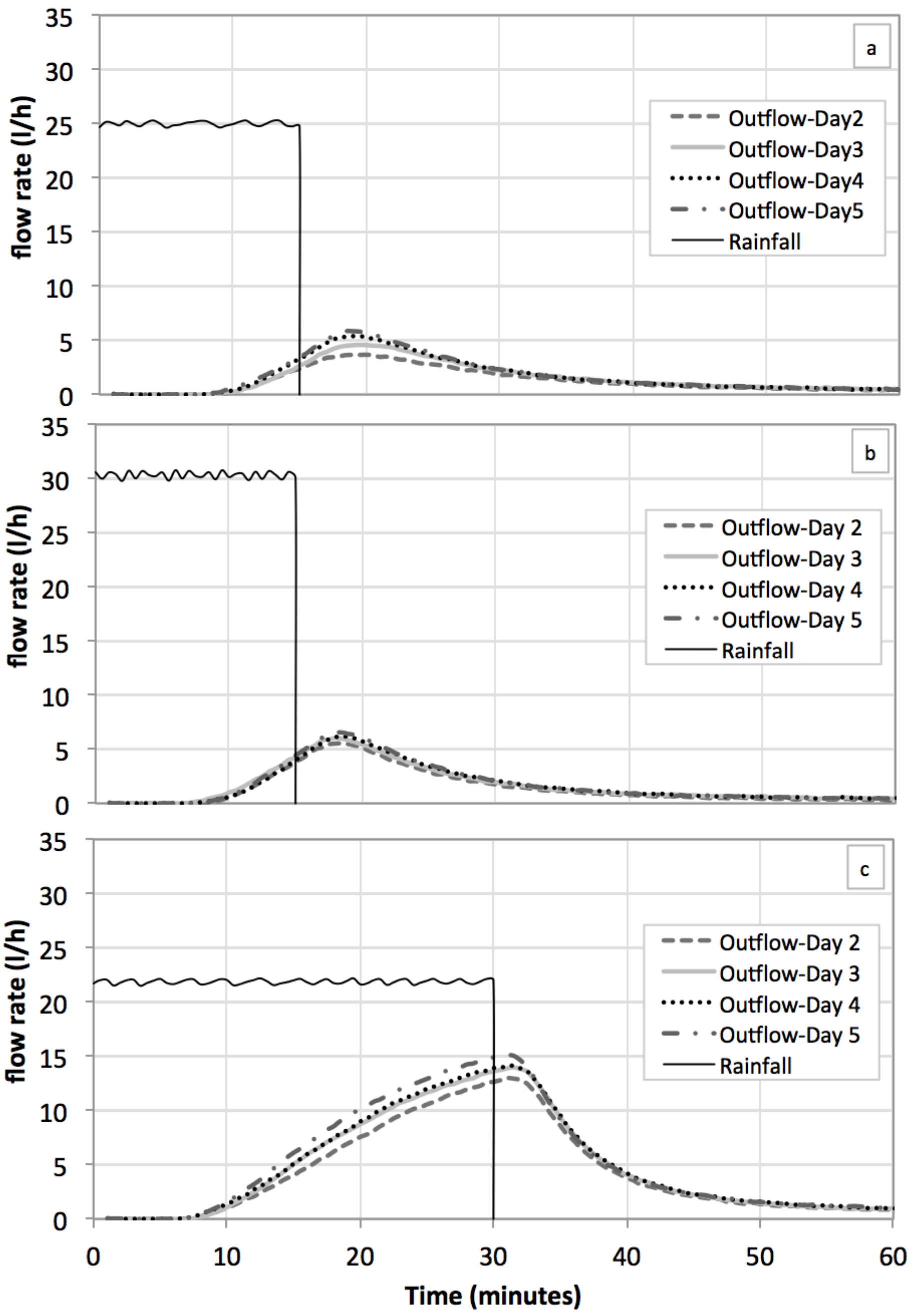

Figure 6: Outflow rate during Day2-5 conditions and related to rainfall intensity: (a) RainfallIntensity 1, (b) RainfallIntensity 2, and (c) RainfallIntensity 3.

3.3.3 Outflow volume

The average outflow for Rainfall Intensities1, 2 and 3 were analysed, and are presented in Table 1. The amount of water drained from the pavement ranged between 7.78% and 59.94% of rainfall volume. These results are similar to those reported by Abbott et al (2003), who stated a range of 30-120% of rainfall, with an average value of 67%.

Table 1: Outflow amount**,** outflow duration, and start delay asrelated to rainfall intensity and pavement conditions

Rainfall Intensity No.	**Pavement Condition**	**Average Rainfall (L)**	**Average Outflow (L)**	**Average Outflow (%)***	**Average Outflow Duration (hours)**	**Average Start Delay (minutes)**
1	Day-1	6.45 (0.08)	0.50 (0.02)	7.78	0.86 (0.09)	10.40 (0.35)
	Day2-5	6.45 (0.01)	2.33 (0.33)	36.18	5.64 (1.09)	7.60 (0.52)
2	Day-1	7.78 (0.05)	0.67 (0.02)	8.56	0.85 (0.03)	10.20 (0.19)
	Day2-5	7.83 (0.03)	3.34 (0.37)	42.65	5.90 (1.24)	8.10 (0.46)
3	Day-1	11.07 (0.01)	1.99 (0.25)	18.02	1.87 (0.22)	10.20 (0.35)
	Day2-5	11.06 (0.04)	6.63 (0.58)	59.94	7.43 (0.91)	7.80 (0.44)
* Average volume discharged as a percentage of total rainfall volume (%) ( ) standard deviation						

The outflow data forRainfall Intensities 1, 2 and 3 show that the performance of a permeable pavement can effectively decrease stormwater runoff resulting from rainfall events. Permeable paving is shownto store more than 40% of rainfall and to release it slowly to the underlying soil or subsurface stormwater collection system. Outflow from each rainfall intensity was comparedunder Day1 and Day2-5 conditions. The comparison demonstrated up to a 42% increase in outflow when wetness of the initial paving condition increased. The initial moisture content of a permeable pavement, prior to a rainfall event occurring, is key to its ability to store rainfall. As rainfall intensity increases (with a wet initial condition), the attenuation of rainfall by the permeable pavement structure decreases. The rate of decrease in pavement attenuation for a wet initial condition is 370-400 times greater than that in a dry condition. Furthermore, the increase in rainfall duration, under different initial pavement moisture conditions, results in a 233% attenuation rate increase (Day2-5 compared to Day1 initial conditions).

3.3.4 Outflow duration

The outflow duration is defined as the period of time between the start and the end of the outflow during a single rain event. For this study, the outflow duration was measured continuously over a period of 24 hours. Overall, during the monitoring period of the experiment, 41 outflow durations were analysed (as summarised in Table **1**). During Day1 conditions, the average outflow time was 0.86, 0.85 and1.87 hours for Rainfall Intensities 1, 2, and 3 respectively. In wet conditions (Day 2-5), the average outflow duration was 5.64, 5.9, and 7.43 hours for Rainfall intensities 1, 2, and 3 respectively. Comparing Day1 to Day2-5 conditions, Table 1 illustrates that the initial Day2-5 conditions result in an outflow duration increase of 4.78-5.56hrs, and a 300-600% increase relative to the Day1 initial condition of outflow duration.

3.3.5 Start delay

Start delay is defined as the time required for rainfall to permeate through a pavement structure until it reaches the free drainage point, i.e. when outflow commences. In total, 41 rain events were analysed and the results are summarised in Table 1. As shown, the start delay for relatively wet days at the beginning of the rainfall cycle (Day 1) exceeded 10 minutes (up to 70% into the rainfall duration), and decreased by up to 2.8 minutes when the initial conditions were wet (Days2-5). This result shows that the permeable pavement performs acceptably during relatively wet conditions.

During Day2-5 conditions the start delay was 7.6, 8.1, and 7.8 minutes for Rainfall intensities 1, 2, and 3 respectively. The start of the firstdischarge was 26-50% into the rainfall duration, and the discharge was prolonged after the rainfall stopped. These results are comparable to those reported by Pratt et al.,(1995), who found the start of the first discharge occurred25-50% into rainfall duration. It is apparent that the start delay decreases as the number of rainfall events increases (Days 1 to 5). The decrease in the start delay throughout the rainfall cycle may be explained by the fact that the water retention level in the pavement structure increased over consecutive rainfall events, causing a reduction in the travel time through the thickness of the pavement.

4. Conclusion

One of the important benefits of permeable pavements and other SuDS techniques relates to how much water will be stored during, and then released after a storm. This is a crucial parameter when designing a SuDS device. This paper has presented findings obtained from laboratory experiments that evaluated the performance of one square metre of permeable pavement (and a respective vertical infiltration structure) during different rainfall intensities and durations. The conclusions relevant to the performance of a permeable pavement can be drawn:

- More than 40% of the total rainfall from all the rain events tested were retained within the permeable pavement structure.
- The outflow duration increased by two hours during Day1 conditions, and by 7.4 hours in Day2-5 conditions.
- Rainfall was discharged from the permeable pavement within 7 hours of the rain event commencing, confirming the ability of the pavement to attenuate storm water.
- The response of outflow varied in response to modifications to rainfall duration and pavement condition. Increased rainfall duration and increased initial pavement wetness caused a higher outflow from the pavement structure.

The experiment findings confirm that permeable pavements designed in accordance with the SuDS manual (CIRIA C697) do provide rainfall runoff attenuation. Thus, appropriately designed permeable pavements offer an excellent source of control, by offering the capacity to deal with a variety of storm water types. Thus far, the permeable pavement structure has been examined for hydrology performance. Urban runoff, however, usually incorporated sediment and urban debris;therefore, further research is required to consider permeable pavement functionality and attenuation capacity when sediment is present.

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