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An Evaluation of Enhanced Geotextile Layer in Permeable Pavement to Improve Stormwater Infiltration and Attenuation

ABSTRACT

This paper reports on an evaluation of the properties of a novel structure known as OASIS® which was designed at Coventry University as an enhancement of the commercially available geotextiles when incorporated in the Permeable Pavement System. The impact on the hydraulic behaviour of a PPS was analyzed through the study of infiltration rate, throughout the PPS and time required to reach the steady-state stage behaviour of the water within the PPS, under extreme rainfall intensities of 100 mm/hr, 200 mm/hr and 400 mm/hr, corresponding to a 100-year return period rainfall over duration of 15 minutes in different parts of the world. The result indicated that the novel structure provides an extra benefit when incorporated in PPS, delaying peak flow of a rainfall event by retaining and storing great volumes of water within its structure. These additional benefits are especially important under extreme rainfall events.

KEYWORDS

Infiltration behaviour, Permeable Paving, SuDS, Stormwater, Geotextile

INTRODUCTION

Sustainable Drainage Systems (SuDS) are designed to achieve three important elements of stormwater management such as quantity - by controlling runoff at source point and implementing stormwater techniques to reduce flooding problems. Quality - by reducing pollutants within runoff introducing a treatment train and amenity- based on biodiversity issues, social equity, environmental protection and prudent use of natural resources (Woods-Ballard et al. 2007).

Permeable or Pervious pavements systems (PPS) are an important part of SuDS techniques that are most used in parking lots and pedestrian walkways as a sustainable and effective replacement for impervious surfaces (Newman et al. 2004; Collins et al. 2006) due to their high infiltration capacity (Sañudo-Fontaneda et al. 2013). The ability of PPS to control drainage at source, treat pollutants in stormwater and provide added benefits which include: water harvesting (Nnadi, 2009), renewable energy (Coupe and Nnadi 2007) and mitigation of thermally enriched stormwater (Wardynski et al. 2012), makes them an important approach to sustainability. PPS's efficiency as a tool for source control is due to its capability to infiltrate stormwater into hard surfaces and gradually attenuate it into the soil or a drainage outlet (Newman et al. 2003). The PPS have been shown by previous studies to be capable of removing most stormwater pollutants especially hydrocarbons through filtration, sorption and biodegradation (Coupe 2004; Brattebo and Booth 2004; Newman et al. 2006; Gomez-Ullate et al. 2010).

Historically, the design of urban drainage systems have been driven at different time periods by different objectives and influenced by climate, topography, geology, engineering and construction capabilities, scientific knowledge, societal values, religious beliefs, etc (Burian and Edwards 2002). It has been established that the design of the PPS affects its performance as a sustainable drainage system (Pratt et al. 2002). The design of PPS with a geotextile installed below the laying course supporting concrete block pavers is probably the most popular one in the UK (Newman et al. 2011) and often consists of the natural stone aggregates base layer which serves both as a load bearing layer and a water storage reservoir. Sometimes the base layer is separated from sub-base by geotextile material (Pratt 1995, Brattebo and Booth 2004). Numerous studies have shown that the geotextile material is an important component of the PPS design which is effective in stormwater pollutant retention (e.g. by filtering out heavy metals and adsorbing hydrocarbons) and serves as the site for biodegradation process within the system (Pratt, 1995; Bond, 1999; Coupe 2004; Culleton et al. 2005; Newman et al. 2006; Nnadi 2009; Gomez-Ullate et al. 2010) and hence must be incorporated in the design in order not to compromise the efficiency of the system.

Although characteristics and role of most commercially available geotextiles that are readily applicable in the PPS are well recognized, the impact of these materials on hydraulic performance of the systems is not well understood despite evidence that this might have significant impact on their water treatment and storage functions (Nnadi 2009). In characterising a novel geotextile material in 2009, Nnadi (2009) observed that the if the PPS are to be used efficiently for water recycling without compromising on filtration and attenuation properties, the availability of a geotextile structure which has the capability to sustain or enhance the hydraulic properties of the system is essential.

OASIS® is a novel structure developed at Coventry University which has the potential of being a replacement or an additional enhancement of the regular commercially available geotextiles when incorporated in the PPS. OASIS phenolic foam is a material that is highly porous and absorbs all water that it interacts with up to saturation. Heat compressed random mat geotextiles composed of polypropylene fibres with a polyethylene sheath are commonly used in permeable paving. These geotextiles are hydrophobic oleophiliic. The structure reported in this paper holds back water to a much greater degree than geotextile and residence time of water is extended. The internal structure of is such that there is a large internal surface area in addition to the water retention. Geotextiles only have a top surface onto which to retain water, trap pollutants and grow a biofilm for bioremediation. Furthermore,Its three dimensional structure is capable of storage of a great volume of water inside as it is presented in this paper and can also give an extra benefit in the delay of the time needed to reach the peak flow in a rainfall event. The Oasis is presented as a structure because in order to maximise the water retention and it has an increased depth relative to that of the geotextile (geotextile is approximately 0.5 mm in depth).

The aim of this study is to investigate the impact of this novel structure on the hydraulic properties of the PPS. This is analysed through the study of the infiltration rates, the time needed by water to infiltrate throughout the PPS and to reach the steady-state stage behaviour of the water within the PPS, under extreme rainfall intensities. Graphs of the infiltration behaviour of PPS are presented in this paper, showing an important added hydraulic benefit when using the material.

1 EXPERIMENTAL METHODOLOGY

1.1 Scheme of the test rigs

In order to determine water retention and attenuation properties of OASIS® in a model PPS, three sets of three replicated PPS test rigs were constructed according to the specifications stated in Nnadi (2009) with 100mm paving blocks, 50mm bedding layer and 350mm sub-base. Three of them with a 13 mm and other three with 20 mm OASIS® structure placed between the sub-base and bedding layer, where geotextile materials are normally incorporated in PPS (OASIS® rigs). The other three were replicated control test rigs set up without geotextile structure or OASIS® (CONTROL rigs). Also, 2mm diameter drainage pipe was installed in a hole made at the base of each test model as shown in Figure 1. Surface occupied by OASIS® layer within the PPS structure showed in Figure 1 was approximately 0.060 m^2.

1.2 Rainfall intensity analysis

Intensity-Duration-Frequency (IDF) curves of twenty-two cities around the world were analyzed in order to select three rainfall intensities to check the hydraulic behaviour of PPS under extreme rainfall conditions, corresponding to a 100-year return period rainfall over duration of 15 minutes. Duration of the rainfall was selected based on preliminary tests carried out over CONTROL rigs in which at least 10 minutes passed to reach the steady-state stage under different rainfall intensities. The selected duration provided a good parameter for measurement and comparison between control and rigs with OASIS® studied in terms of attenuation which was measured through the number of rainfall events required to reach the steady-state stage.

It was observed that there are at least three different zones of rainfall intensities as shown in Figure 2. These are represented by three dotted lines on 100 mm/hr, 200 mm/hr and 400 mm/hr, respectively (Figure 2). Rainfall intensities of many cities around the world fall within each dotted line. For instance, rainfall intensities in cities such as London (UK) (Sanderson 2010), Santander (Spain) (Cué Pérez et al. 2006), Vancouver (Canada) (Environment Canada 2013), Wellington (New Zealand) (UNESCO 2008), Los Angeles and San Francisco (USA) (NOAA 2013) can be approximately simulated using 100 mm/hr. In the case of cities such as Barcelona (Spain) (Casas Castillo 2005), Onitsha (Nigeria) (Oyebande 1982), Hanoi (Vietnam) (UNESCO 2008), Nagoya (Japan) (UNESCO 2008), Daegu (Korea) (UNESCO 2008), Guatemala City (Guatemala) (INSIVUMEH 2004), Islas Marshall and Honolulu (USA) (NOAA 2013) could be represented by a rainfall intensity of 200 mm/hr, while cities such as Acapulco (Mexico) reach up to 300 mm/hr (Campos-Aranda 2010). Finally, a rainfall intensity of 400 mm/hr could be considered as the top line of rainfall intensity values around the world (e.g. Yongchun (China) and Dagupan (Philippines) (UNESCO 2008)), exceptions being Australia whose cities such as Brisbane usually exceeds 2,000 mm/hr (UNESCO 2008) of rainfall intensity.

1.3 Rainfall simulation

A Portable Laboratory Rainmaker (PLR) was designed, constructed and calibrated for this study (Figure 3) to simulate high rainfall intensities between 50 mm/hr and 450 mm/hr, based on previous experience of Fernandez-Barrera et al. (2008) at University of Cantabria. The PLR demonstrated correct performance, simulating high rainfall intensities for storm duration below 30 minutes, especially with storm duration between 1 minute and 15 minutes which are the most common for extreme rainfall events.

However, a significant loss about 20% in the rainfall intensity simulated in the tests with the PLR was observed when the rainfall event last more than 30 minutes, which was the case of some tests undertaken with the OASIS® rigs. To correct this negative effect, PLR was replaced in this study by using other methodology consistent in simulating the rainfall intensities adding a specific volume of water every minute, distributing it over the entire surface of the PPS rig using a graduated container: 75 ml/minute, 150 ml/minute and 300 ml/minute were added to the rigs simulating the PLR performance, corresponding with rainfall intensities of 100, 200 and 400 mm/hr, respectively. Another graduated container was used to measure water outflow during the test through the drainage pipe installed in the base of the test rigs.

Tests had different durations in OASIS® rigs, which depended on the initial infiltration time, corresponding with the moment in which the water outflow through the drainage pipe started; time to reach the steady-state stage, corresponding with the moment in which the water outflow through the drainage pipe is constant; and the final infiltration time, corresponding with the moment in which the water outflow per minute is near zero. 24 hours after of each test, a measure of the total water infiltrated is measured in order to obtain total water storage by OASIS®. So, tests were divided into two different stages. Firstly, the time needed to reach the moment in which the water started to outflow through the drainage pipe. Secondly, time needed to reach the steady-state stage. The addition of these two stages gives the total duration of the rainfall event during the test and then, the number of consecutive rainfall events of 15 minutes simulated during the tests.

As explained in Section 2.2., rainfall events of 15 minutes were simulated in every CONTROL rig with different intensities. This time period was considered as being enough to analyze the infiltration behaviour in this type of PPS structure and allow for the comparison with OASIS® tests.

The analysis of the results is divided into two parts: (1) analysis and discussion of the infiltration behaviour of the three sets of PPS studied in this investigation with the aim to compare both behaviours (with and without OASIS®), and secondly (2), results of detailed investigation of the performance of OASIS® was provided since it is a novel product in order to give a complete description about the way in which it works within a PPS under extreme rainfall conditions.

2 RESULTS AND DISCUSSION

2.1 Infiltration behaviour of PPS and comparison

Three rainfall events were simulated during 15 minutes at 100, 200 and 400 mm/hr intensity over three exactly replicates of CONTROL rigs, obtaining the following infiltration behaviour as showed in Figure 4 (a). Infiltration started almost instantaneously through the CONTROL structure (Table 1), showed no extra retention property as it can be seen in Figure 4 (a). It was observed in these experiments that water needs 10 minutes from the beginning of the rainfall event to reach the steady-state stage in its infiltration behaviour within this type of PPS structure (Figure 1), independent on the intensity of the rainfall. Some authors such as Davies et al. (2002), Rodriguez-Hernandez et al. (2012) and Sañudo-Fontaneda et al. (2013) suggested 10 minutes as the time needed to reach steady-state stage, but there has not been any experimental demonstration of it.

In the case of the PPS models with 1.3 cm and 2.0 cm OASIS® layer, the infiltration behaviour followed the way presented below in Figure 4 (b) and (c), respectively. Duration of the tests carried out with different thickness of OASIS® layer and different rainfall intensities are presented below in Table 1. Results obtained showed high levels of peak flow attenuation, with absorption of water by OASIS® of 100%, 50% and 20% corresponding with 100, 200 and 400 mm/hr intensities, respectively, with 1.3cm thickness, and 100%, 75% and 38% with 2.0 cm.

As it can be seen in Figure 4 (b) and (c), the infiltration through the 1.3 cm OASIS® layer started near 14 minutes, 8 minutes and 3 minutes, while it lasted 20 minutes, 11 minutes and 6 minutes in the case of 2.0cm OASIS® layer, under rainfall intensities of 100 mm/hr, 200 mm/hr and 400 mm/hr, respectively. This means that the 1.3 cm OASIS® layer is capable of absorbing at least one entire rainfall event of 100 mm/hr, as it can be seen in Table 1.

Also, time to reach the OASIS® saturation point (steady-state stage) from the beginning of the infiltration seems to be independent from the thickness of the OASIS® layer, considering values showed in Figure 4 (14 minutes, 17 minutes and 19 minutes corresponding with 100, 200 and 400 mm/hr, respectively). It could depend more on the rainfall intensity, but more tests are necessary with more thicknesses and rainfall intensities to demonstrate this point.

2.2 OASIS® Performance Zones

OASIS® showed at least three different performance zones regarding with its infiltration behaviour as it can be seen in Figure 5. Firstly, there is an absorption zone (A) in which OASIS® works as an absorption body, absorbing all water from the rainfall event till the initial infiltration time detailed in Figure 4 and Table 1. Secondly, it can be shown that there is an intermediate absorption and infiltration zone (B), in which OASIS® was locally saturated of water. This fact allows the beginning of the infiltration, but OASIS® continued absorbing water from the rainfall event until the complete saturation of the OASIS® layer. The moment in which the steady-state stage starts marks the beginning of the third zone (zone C) called infiltration zone because OASIS® was infiltrating all the water from the rainfall through itself and working like the CONTROL models (Figure 4).

The volume of water store in the OASIS® PPS structure was measured through the difference between the water used in the test to simulate the rainfall event and the water which flowed out through the drainage pipe in the bottom part of the test rig, taking the last measure of infiltrated water 24 hours after the simulation of the rainfall event (Table 2). The amount of water absorbed by CONTROL rigs was also measured through the same method. In this case, the value was constant, independently on the rainfall intensity and its value was 0.3 L. Therefore, this value must be subtracting from the values obtained in Table 2 for total water storage in OASIS® to reach the real water storage capacity of the OASIS®.

Based on previous argumentation, values of water storage in OASIS® layer showed in Table 2 and the OASIS® surface (0.060m^2) used in the test rigs, the total water storage capacity of this new product was obtained, taking into account the influence of the rest of the PPS layers presented in structure showed in Figure 1. For instance, water storage capacity of 1.3 cm OASIS® layer is 19.07

L/m² (17.17 L/m² in zone A), while for 2.0 cm OASIS® layer is 32.75 L/m² (27.17 L/m² in zone A). Therefore, the percentage of water stored in OASIS® layer in zone A (absorption) is 90.0% in the case of 1.3 cm of thickness, while 83.0% was obtained in the case of 2.0 cm of thickness. Taking into account the influence of all layers within the OASIS® PPS structure, the percentage of water absorbed before the beginning of the infiltration was 71.5%, being independent on the thickness of the OASIS®. However, it was observed as shown in Table 2 that an increase of 0.7cm in the thickness of the OASIS® layer can produce an increase of 37% in the OASIS® total storage capacity. Finally, Figure 5 can be used as a brief guide by technicians to understand how the OASIS® works in the PPS during storm events.

3 CONCLUSIONS

1. Water infiltrates almost instantaneously through PPS without geotextile or OASIS®, showing zero extra benefits as regards delay of the peak flow. In this case, water flowing through the PPS needs 10 minutes to reach the steady-state stage, independent of the intensity of the rainfall event.

2. OASIS® layer in PPS provided high levels of peak flow attenuation, absorbing 100%, 50% and 20% of 15 minutes of 100, 200 and 400 mm/hr, respectively, with 1.3cm thickness, and 100%, 75% and 38% with 2.0 cm.

3. Total storage capacity of OASIS® was 19.07 L/m² with 1.3cm thickness and 32.75 L/m² with 2.0 cm thickness.

An increase of almost 1cm in the OASIS® layer thickness produced an increase of 37% in the water volume which can be stored the system.

4. OASIS® provided an extra benefit in comparison with usual PPS, delaying peak flow of a rainfall event by retaining and storing water within its structure, being especially relevant under extreme rainfalls.

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Figure 1. Scheme of the CONTROL and OASIS® rigs.

Figure 2. Rainfall intensity values in mm/hr, corresponding to a 100-year return period rainfall over duration of 15 minutes in twenty-two cities around the world.

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