Long-term hydraulic performance of stormwater infiltration systems – a field survey

Performances hydrauliques à long terme de systèmes d'infiltration des eaux pluviales - une enquête de terrain

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RÉSUMÉ

Cet article examine les facteurs influençant la performance hydraulique à long terme de certains systèmes d'infiltration des eaux pluviales (noue et deux types de revêtements perméables) à Växjö, dans le sud de la Suède. Les capacités d'infiltration de 9 revêtements perméables et de 2 sites de noue, tous d'âges différents allant de 1 an à 14 ans, ont été mesurées en utilisant des infiltromètres à double anneau. Les sites étaient constitués de noues (2), de pavés en béton autobloquants avec joints en gravier (2), de grilles en béton remplis au gravier (3), ou de grilles en béton enherbés (4). Les résultats de cette étude ont montré que le comportement à long terme de la capacité d'infiltration repose largement sur le type et l'âge du système et sur le type de remplissage des joints (gravier ou herbe). De plus, l'étude a montré que les grilles en béton enherbés âgés de 11 ans présentaient la capacité d'infiltration la plus élevée (4,80 ± 2,46 mm/min), tandis que les noues âgées de 9 et 14 ans présentaient la capacité d'infiltration la plus faible (0,10 ± 0,00 mm/min).

ABSTRACT

This paper examined the factors influencing the long-term hydraulic performance of some stormwater infiltration systems (swale and two types of permeable pavements) in Växjö, southern Sweden. The infiltration capacities of 9 permeable pavements and 2 swales sites, all with different ages ranging from 1 year to 14 years, were measured using replicate double ring infiltrometers. The sites were either constructed of swale (2), interlocking concrete pavers (ICP) filled with gravel (2), concrete grid pavers (CGP) filled with gravel (3), or concrete grid pavers (CGP) filled with grass (4). The results of this study showed that the long-term behaviour of the infiltration capacity relies largely on the type and age of the system and the type of joint filling (gravel and grass). Furthermore, the study showed that the 11 year old concrete grid pavers filled with grass had the highest infiltration capacity (4.80 ± 2.46 mm/min), whilst the 9 and 14 year old swales had the lowest infiltration capacity (0.10 ± 0.00 mm/min).

KEYWORDS

Clogging, Concrete grid paver, Infiltration capacity, Long-term performance, Permeable pavements

1 INTRODUCTION

Urban stormwater is of concern due to the high peak flows and large volumes caused by reduced permeable surfaces in cities as well as contamination with e.g. sediments, nutrients, heavy metals and hydrocarbons from a wide range of sources (Ellis and Marsalek, 1996). Thus, urban stormwater discharges imply issues such as flooding risks, erosive flows into watercourses and pollutant discharge into the environment (Walsh, 2000). One strategy that addresses these concerns is the implementation of concepts such as water sensitive urban design (WSUD).

Within WSUD, one option to reduce the detrimental impacts of urban stormwater discharges is a reduction of impermeable surfaces, by the use of stormwater infiltration systems using permeable pavements or infiltration swales (Dietz, 2007). By enabling *in situ* stormwater infiltration, they have the ability to efficiently control runoff volumes and flows and thus reduce or avoid downstream flooding as well as remove pollutants (Bean et al., 2007; Collins et al., 2008; Scholz and Grabowiecki, 2007). Yong et al. (2011) found that permeable pavements can direct as much as 70% to 80% of annual rainfall to recharge groundwater levels.

However, despite their benefits, implementation of infiltration systems and permeable pavements is often hindered by concerns regarding their effective life-span, the related maintenance needs and (in colder regions) their winter performance (Dietz, 2007; Lindsey et al., 1992). The main threat to the long-term hydraulic performance of stormwater infiltration systems is their tendency to become clogged due to the accumulation and deposition of sediments on the system surface over time (Borgwardt, 2006; Dietz, 2007). One main reason for clogging is a demonstrable lack of regular maintenance (Lindsey et al., 1992). Balades et al. (1995) showed that coping effectively with this problem requires regular maintenance as a preventive measure to sustain the infiltration capacity of porous pavements.

To analyse the influence of pavement type on runoff quality and quantity, Day et al. (1981) examined three types of concrete grid pavers and found that the type of pavement is one of the key factors that has a significant impact on the reduction of runoff quantities by 50 to 80%. Booth and Leavitt (1999) examined the hydrologic performance of four types of permeable pavement (interlocking concrete pavement - ICP - filled with gravel, concrete grid pavers - CGP - filled with grass, plastic grid pavers filled with grass and plastic grid pavers filled with gravel) after six years of daily usage. All the pavements showed no surface runoff; the authors observed that if the pavement is filled with clean sand and grass, then it is less susceptible to clogging over time. Borgwardt (2006) found that the type of joint filling material influenced the infiltration capacity. Studies have indicated that vegetation can reduce or slow down clogging of infiltration systems (Gonzalez-Merchana et al. 2012). To test the long-term hydraulic performance of different types of porous pavements and the importance of vegetation on the infiltration capacity compared to non-vegetated systems, different types of infiltration systems of different ages and designs (including vegetated and non-vegetated systems) were evaluated in the field in Växjö, southern Sweden.

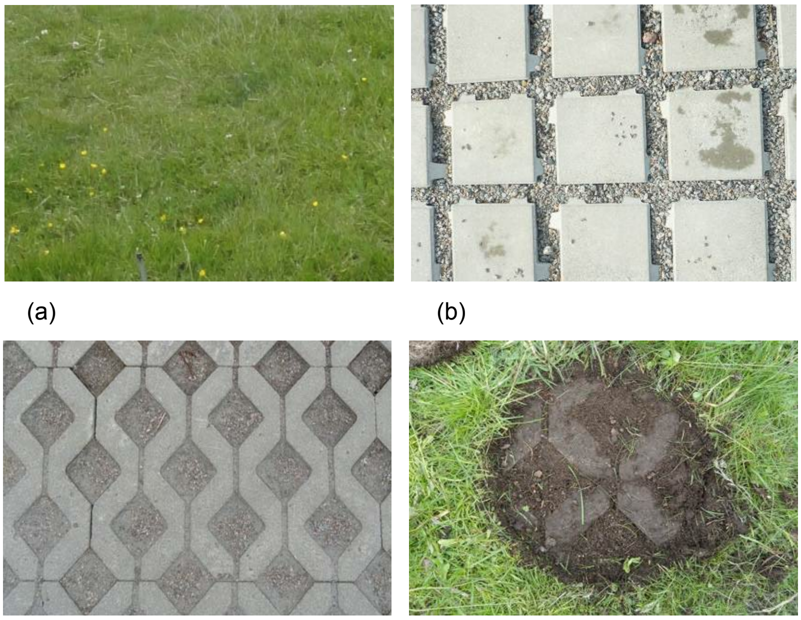
2 MATERIALS AND METHODS

2.1 Site description

Infiltration capacity measurements were conducted at twelve stormwater infiltration sites in Växjö, Sweden. All the sites are located along residential streets in Växjö, southern Sweden, with the exception of one, which is located next to a forest (1 year old ICP filled with gravel, see below).

- Two infiltration swales: constructed in 1998 and 2003; the swales' widths are approx. 1 m and 2 m (Fig. 1a).
- Two sites paved with interlocking concrete pavers (ICP) filled with gravel: constructed in 2006 and 2011; the pavements' widths are approx. 0.55 m and 0.7 m (Fig. 1b, 2).
- Three sites paved with concrete grid pavers (CGP) filled with gravel: 40% open surface area; constructed in 2002, 2004 and 2005; the pavements' widths are approx. 2 m, 2 m and 2.4 m (Fig. 1c).
- Four sites paved with concrete grid pavers (CGP) filled with grass: 40% open surface area; constructed in 1998, 1999, 2001 and 2002; the pavements' widths are approx. 2 m for 4 sites (Fig. 1d, 2).

- One reference site paved with ICP filled with gravel: construction was completed immediately before the measurements.



(a) (b)

(c) (d)

Figure 1. (a) Swale; (b) ICP filled with gravel; (c) CGP filled with gravel; (d) CGP filled with grass

The residential streets (approx. width: 5 m) drained by the infiltration systems were constructed using conventional asphalts, cambered towards the infiltration systems; thus, all stormwater from the streets was discharged into the infiltration systems. All streets had little traffic; they were not used as through roads (except the street with the infiltration swale constructed in 2003). During winter, sand mixed with road salt is applied to the streets regularly (depending on weather conditions) and then removed using a mechanical sweeper. No regular maintenance to ensure adequate infiltration capacity was carried out.

Figure 2. Views of two of the sites: infiltration system with vegetated CGP (left) and ICP filled with gravel (right)

2.2 Infiltration measurements

Double ring infiltrometers were used to measure the infiltration capacity. Each test included measurements with three replicate infiltrometer sets that were placed on the infiltration system surface. The infiltrometer sets were sealed to the pavement surface with plumber’s putty, with the exception of the swale where the infiltrometers were driven into the surface with a rubber mallet. The outer ring was then partially filled with water to check the seal; any leaks were stopped. Then both rings were filled with water to a depth of approximately 7 – 10 cm. The initial water level in the inner ring was recorded at time zero and then the water level was logged every 2 – 10 minutes, depending on the infiltration rate. The tests were completed when the infiltration rate stayed constant or almost reached zero. During the measurements, the water level in both rings was maintained at a near constant level (± 5 cm).

The above described method could not be utilised at the reference site since its infiltration capacity was far too high to maintain a standing water level in the rings. To collect data at that site, a certain amount of water (10 L) was poured into the inner ring and the time recorded for the water to completely infiltrate the system.

2.3 Data analysis

To determine if the factors “type of system” (CGP, ICP and grassed swale), “age” and “type of joint filling” (gravel and grass) significantly influenced the hydraulic performance, a n-way analysis of variance was performed using a Univariate GLM.. All statistical tests and plots were computed using SPSS® 20 and the significance level was $\alpha = 0.05$.

To investigate the practical function of the infiltration systems, we determined which design of rainfall (cf. SWWA, 2011) could be infiltrated. Thus, the required infiltration capacities of the systems to handle a selected design storm event (without any overflow of stormwater) were calculated using the rational equation (SWWA, 2011):

$$Q = A^{*}\varphi^{*}i \qquad (1)$$

Where: Q = Flow rate (l/min); A = Contributing area (m^2); φ = Runoff coefficient (dimensionless); i = Rainfall intensity (l/min*m^2 or mm/min)

Since the infiltration systems are sited adjacent to impervious catchments (asphalt covered streets, Fig. 2), they receive both surface runoff from the street as well as direct rainfall onto the infiltration system. Thus the inflow passing to the infiltration system is the sum of the flow rate directly to the system and from the surrounding area.

3 RESULT AND DISCUSSION

The mean infiltration capacities of the tested infiltration systems were all between practically zero and 4.8 ± 2.5 mm/min. The reference site (ICP filled with gravel) had a much higher infiltration capacity (313 ± 61 mm/min); thus, as expected, substantial clogging was observed at all sites. Results from infiltration capacity measurements at the eleven sites are summarised in Table 1 and shown in Figure 3.

All the selected sites are located in residential streets with the exception of one located next to a forest (ICP filled with gravel, 1 year old); they represented different conditions with regard to age, winter application and maintenance.

Analysis of the data showed that the factors “the type and age of system and type of joint filling (gravel and grass)” have a statistically significant effect on the long-term hydraulic performance of infiltration systems at a confidence level of 95% (A univariate GLM; p-value < 0.05, R2 (adjusted) = 0.78). The highest mean infiltration capacity was measured for an 11 year old CGP with grass (4.80 ± 2.46 mm/min). In contrast, the lowest mean infiltration capacity was found for both swales (0.10 ± 0.00 mm/min). The presence of grass in CGP appears to increase the infiltration capacity compared to CGP filled with gravel (p-value = 0.01); despite their higher age, the grassed CGP had a clearly higher infiltration capacity than the non-vegetated system. Testing four types of aggregates used in the joint filling (crushed gravel 2 – 5 mm, crushed gravel 1 – 3 mm, mixed gravel and sand 0 – 5 mm, sand 0 – 2 mm), Borgwardt (2006) observed a correlation between the hydraulic performance and the aggregate material used in the joint filling where the coarser materials exhibited a higher infiltration than the other types.

The results for the two ICP with gravel are inconsistent. Despite its higher age, the 6 year old system had a higher infiltration capacity (4.00 ± 0.00 mm/min) whilst the 1 year old system had an infiltration capacity of only 1.80 ± 0.00 mm/min. This may be due to the locations of the two pavements: the older one is located along a residential street whilst the newer system is located next to a forest. Visual inspection revealed large amounts of organic material (leaves, litter etc.) on the system which may have caused clogging. These results are in line with the findings of Bean et al. (2004) who reported that if permeable pavements are placed away from disturbed soils, this has a significant effect on hydraulic performance. They found the average infiltration rate of ICP filled with gravel was 333 mm/min while the ICP sites near disturbed soils with fines was 10 mm/min.

Although the ICP filled with gravel has a lower open surface area than the CGP filled with gravel, the measured infiltration capacity at the ICPs was higher than CGPs, possibly as a result of different ages. However, based on the limited data set in this study, we cannot determine if this is a general trend or if this, for example, depends on the different ages of the systems. However, a similar trend was shown by Bean et al. (2004), who compared the performance of 16 CGPs filled with sand and 11 ICPs filled with gravel, ranging in age from six months to 20 years. Similar to the results of this study, the ICP had a significantly higher infiltration capacity than the CGP for the reason mentioned above.

Table 1. Mean infiltration capacity ± standard deviation (n=3) for all sampling sites

Infiltration System Type	Joint Filling Type	Age (Years)	Infiltration Capacity (mm/min)
Swale	Grass	14	0.10 ± 0.00
Swale	Grass	9	0.10 ± 0.00
ICP	Gravel	6	4.00 ± 0.00
ICP	Gravel	1	1.80 ± 0.00
CGP	Gravel	10	0.13 ± 0.06
CGP	Gravel	8	1.53 ± 0.23
CGP	Gravel	7	0.30 ± 0.00
CGP	Grass	14	2.50 ± 0.30
CGP	Grass	13	1.67 ± 0.23
CGP	Grass	11	4.80 ± 2.46
CGP	Grass	10	1.80 ± 0.70

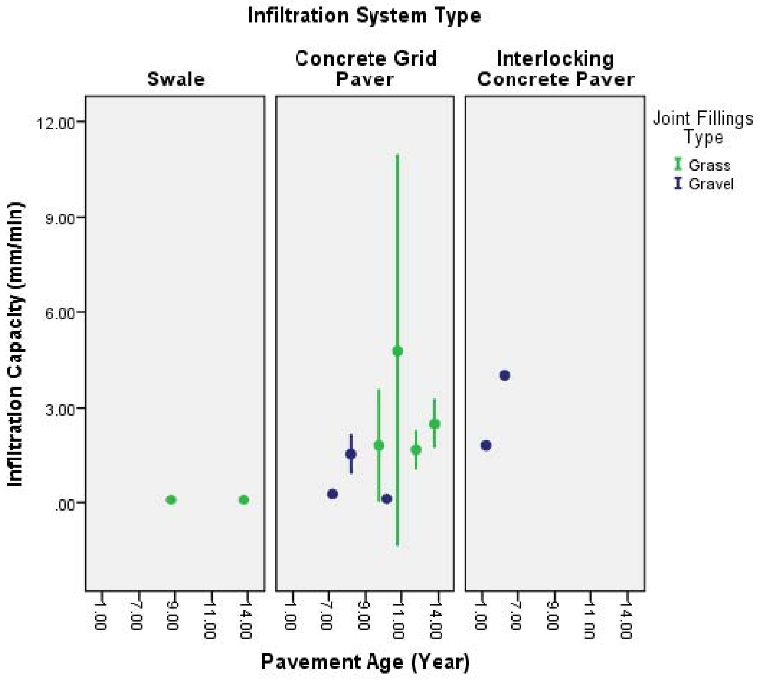


Figure 3. Interval plots of infiltration capacity for all sampling sites with the 95% confidence interval

The results of the infiltration capacities were compared with design rainfall intensities recommended for use with the design of stormwater facilities in Sweden, for durations between 0 and 120 min and average return intervals (ARI) between 1 and 100 years (SWWA, 2011). The comparison reveals the level of precipitation that the infiltration systems can still infiltrate, despite their decreased performance. A 100 year ARI and 5 minutes duration have been adopted as the largest storm event; the rainfall intensity is 4.0 mm/min (SWWA, 2011). Only the 11 year old CGP with grass can still infiltrate 50% of this rainfall event, compared to (1 – 26%) in other systems. In the case of a rainfall event with 100 ARI and 30 minutes duration, the rainfall intensity is 1.5 mm/min. Table 2 shows the calculated flow rates that would occur from each system and the surrounding streets using the rational formula mentioned above. This comparison shows that the 11 year old CGP with grass can completely infiltrate this rainfall event whilst in the other systems, 2 – 70% of this rainfall event could be handled. The infiltration capacities of the swales and the 10 year old CGP with gravel are reduced to an unacceptable level so, therefore, these systems need maintenance to recover their hydraulic potential because they would not be adequate to accommodate such rainfall events. The reduction in the performance of these systems is due to a complete lack of maintenance measures; thus all the systems need regular maintenance to sustain the long-term hydraulic performance and to counteract clogging.

Table 2. Flow rates for a 100 year average return intervals (ARI) and 30 minutes duration

Infiltration System Type	Joint Filling Type	Infiltration Capacity (l/min)	Flow from the system and the surrounding street (l/min)	Percentage Reduction %
Swale	Grass	0.10	6.80	2
Swale	Grass	0.20	6.22	3
ICP	Gravel	2.20	6.22	35
ICP	Gravel	1.26	6.24	20
CGP	Gravel	0.26	7.11	4
CGP	Gravel	3.06	7.11	43
CGP	Gravel	0.72	7.35	10
CGP	Grass	5.00	7.11	70
CGP	Grass	3.34	7.11	50
CGP	Grass	9.60	7.11	135
CGP	Grass	3.60	7.11	51

4 CONCLUSION

The objectives of this paper were to examine the infiltration capacity of different systems and to determine the factors influencing the long-term hydraulic performance of 11 infiltration systems sites with different pavement ages ranging from 1 year to 14 years. The results of this study show that:

- The hydraulic performance was statistically highly influenced by the type and age of the systems and type of joint filling (at a confidence level of 95%).
- The CGP filled with grass had a higher infiltration capacity than the CGP filled with gravel and the other types of infiltration system.
- The presence of grass in permeable pavements showed to provide the best infiltration capacities.
- The swales exhibited a lower infiltration capacity than other types and were completely clogged.
- Although some of the infiltration systems were still capable of infiltrating, their infiltration capacities were far below initial values compared to the reference site.

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