Experimental Infiltration Tests on Existing Permeable Pavement Surfaces

Research Paper

Experimental infiltration tests on existing permeable pavement surfaces†

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Abstract

This study describes a field investigation that compares water infiltration rates of eight permeable parking lots located in Rimini City, Italy. In the experiment a single ring infiltrometer test was used to analyze the influence of the surface type, filling material, location in the parking stall, pavement age and antecedent dry weather days on the infiltration capacity of the pavements. The results show that the permeability values are mostly affected by the position of the ring in the parking lot, filling material and surface type rather than by the antecedent dry weather time and pavement age. The surface infiltration rate of the eight pavements ranges between a minimum of 123 mm/h (site 6, permeable interlocking concrete paver, 2005) and a maximum of 20 137 mm/h (site 4, concrete grid paver, 2005), exceeding the 97.2 mm/h minimum design infiltration rate required by selected European authorities. The results also show that compaction decreases the infiltration rate. Therefore, the study could be useful in setting the standard test procedure to evaluate the performance of permeable pavements over time in the Mediterranean climate.

Keywords: Parking lots, Permeability, Single ring infiltrometer, Sustainable urban drainage systems

Abbreviations: CGP, concrete grid paver; **PG**, plastic grid; **PICP**, permeable interlocking concrete paver; **SIR**, surface infiltration rate

Introduction

The stormwater drainage systems in most cities in the developed world rely on pipe network systems. Traditional systems capture stormwater runoff, and subsequently distribute the runoff to nearby watercourses or sewer systems. However, several of these systems have become ineffective and inefficient [1] because of different causes such as the aging of the sewer network, increase in impervious urban surfaces and the increase in rainfall intensity caused by climate change. Consequently, during the last few decades, a substantial increase in urban flooding has been observed. Furthermore, traditional systems are usually expensive [2, 3].

Instead of focusing on ‘end of pipe’ solutions (detention/retention tanks), which capture and delay the stormwater when the capacity of the sewer network has been exceeded, a sustainable drainage system must prevent the entry of stormwater into the sewage systems. This prevention could result from the use of ‘green technologies’ that collect, store, treat, redistribute and/or recycle water. The terms “best management practices”, “sustainable urban drainage strategies”, “low impact development”, “water sensitive urban design”, and “green infrastructures” refer to similar concepts. Examples of these technologies are green roofs, filter strips, wetlands, detention ponds, sedimentation basins and permeable pavements.

A permeable pavement is a pavement surface composed of structural units with void areas filled with pervious materials such as soil, gravel or grass. Permeable pavement systems, as described by other authors, e.g. [2], are suitable for a wide variety of residential, commercial and industrial applications. However, these pavements are confined to light duty vehicles and infrequent usage, even though the bearing capabilities of these systems allow a much wider range of usage.

Research studies have shown that permeable pavements have many potential benefits such as the reduction of runoff volumes [4--8], limitation of peak flows [2, 9, 10], recharge of groundwater [7, 11] and prevention of water pollution [6, 12, 13], because the infiltration of water through the pavement layers traps pollutants [10, 14]. In addition, many permeable pavements have a high albedo (light reflectivity) [15], reduced runoff temperature [16], and improved aesthetics. Permeable pavements are able to achieve these benefits by allowing water to pass through the surface layer and being temporarily collected in underlying aggregate storage layers. This water is then either released back into the storm drain system through underdrains, allowed to infiltrate into the underlying soil, or a combination of both. A small fraction of runoff will evaporate or evapo-transpirate. Recently, Mullaney et al. [8] highlighted that permeable pavements do not require any increase in land area, a substantial benefit. The use of pervious pavements is among the best management practices recommended by the Environmental Protection Agency, and by other agencies and geotechnical engineers across the USA, for the management of stormwater runoff on a regional and local basis. This pavement technology creates a more efficient land use by eliminating the need for retention ponds, swales, and other stormwater management devices [17].

Currently, multiple pervious materials are available to suite the different needs of paved surfaces. Permeable pavements are especially suitable in courtyards, open spaces, alleys, pedestrian and cycling paths, driveways, access roads, parking lots, slope stabilization and erosion control [2, 8].

In Italy, the use of permeable pavements was introduced during the Roman Empire when large stones with gaps between were used for drainage [18]. Currently, several Italian regional and council laws (as in Bologna City through the R.U.E. (Urban Municipal Regulation), the Autonomous Province of Bolzano or the Province of Rimini) promote this type of pavement because of its hydraulic and environmental benefits. However, despite a steady increase in the number of pervious pavement systems installed in Italy and worldwide, few rules have been established to evaluate and monitor their long-term infiltration performances.

Boogaard et al. [19] underlined that in Europe (in particular, in Holland, Belgium and Germany), pervious pavements are normally designed to demonstrate a minimum infiltration capacity of 270 L/s per ha or 97.2 mm/h. At present, Italian regulations do not recommend any minimum infiltration capacity value other than a standard test procedure for determining the infiltration capacities of these permeable surfaces.

Furthermore, limited literature is available in regard to the permeable pavement behavior over time [19, 20], and few studies analyzed the influence of the antecedent dry weather time or the plastic/concrete grid pavers (CGPs) behavior (as recently highlighted by Mullaney et al. [8]). Therefore, no empirical tests are available for references in scheduling maintenance interventions.

The evident lack of knowledge on the specific infiltration performance results in a consequent scarcity of validated parameters recommendations as well as adequate methods for modelling stormwater runoff and infiltration processes on pavement structures. This can lead to considerable uncertainties in urban drainage computations.

Therefore, the goal of this study was to generate a reliable experimental reference that shows a field analysis of the infiltration process and provides a first set of factors that could determine a reduction in the infiltration capacities of in-service permeable parking lots. The correlation between permeability and factors such as the age of the parking lot, the measurement position and the preceding dry weather before the test have been analyzed.

Materials and methods

1.1 Case study

The case studies include eight permeable pavement surfaces constructed for parking lots (Fig. 1) situated in Rimini City (Emilia Romagna Region, Italy) and in its proximal outskirts.

Rimini is a city of approximately 150 000 inhabitants located at the Adriatic coast. The city has a humid subtropical climate, which is mild with no dry season and is constantly moist. Summers are usually hot and muggy with thunderstorms, and winters are mild with precipitation from mid-latitude cyclones. The average annual temperature is 13.2 °C, and the average total annual precipitation is approximately 702 mm.

Site 1 (Fig. 1a) was installed in 2006 to accommodate the demand generated by the newly constructed adjacent football field. The parking lot, which is 625 m^2, has a capacity for 50 cars. The lot consists of CGPs with open surface voids filled with a mixture of sand (70%) and soil (30%). The voids occupy at least 40% of the total surface area and are filled with spontaneously grown grass.

Site 2 (Fig. 1b), situated in the identical neighborhood, was built in 2007 and serves a residential area in the south-west outskirts of the city. This lot is characterized by a total capacity of 30 cars (surface = 375 m^2), and the traffic volume is moderate. The permeable paving is composed of 5 cm thick honeycomb plastic grids (PG) and filled with a mixture of soil to allow grass growth. These reinforced grids are laid on a mixed sand (70%) and soil (30%) layer of 10 cm, which is separated from the subgrade by a filter fabric and a 30 cm thick gravel reservoir layer.

Site 3 (Fig. 1c), built in 2003, serves a recreational area (park). This lot consists of a surface of 1000 m^2 used by light-duty vehicles. The total parking lot capacity accommodates 80 cars. CGPs compose the parking surface layer, which is 5 cm thick with a slope of <2% to achieve the maximum possible infiltration. The voids that occupy at least 35% of the total surface area are filled with a mixture of gravel and sand. The composition of the reservoir layer and subgrade is unknown.

In 2005, an old traditional asphalt parking lot located close to a small train station was replaced by the parking lot corresponding to site 4 (Fig. 1d). The pavement surface (750 m^2) is composed of concrete grids filled with gravel. For this lot, 8 cm of sand and 10 cm of gravel reside below this layer. The traffic volume of this parking lot (capacity of approximately 60 vehicles) is moderate.

Site 5 (Fig 1e) is a PG paver with 95% open surfaces filled with soil. This 250 m^2 lot was built in 2005 and serves a commercial/residential area.

Site 6 (Fig. 1f) with a total surface of 1950 m^2 holds 155 vehicles. This lot is located in a residential/recreational area in the southern outskirts of the city. The lot was built in 2005 with a surface layer of permeable interlocking concrete slabs with wide joints and apertures. The voids, occupying at least 10% of the total surface, are filled with sand.

Sites 7 (Fig 1g) and 8 (Fig 1h) were built in 2006 and 2010, respectively, to provide parking space for the daily needs of a company; these lots are consequently empty at night. The design package of both parking lots is identical: 8 cm thick CGPs with at least 40% of voids and a 22 cm thick drainage layer between the surface layer and the subgrade. The filling material is a mixture of sand and soil. The voids of site 7, unlike site 8, also contain dense vegetation.

Table 1 summarizes the properties of the different sites. For each site, the maintenance procedures are managed by a public company, and the maintenance plan depends on the surface layer type: no maintenance is provided to parking lots covered by PGs (sites 2 and 5) or with concrete grids filled with gravel (site 4 and 3). Grass trimming is provided every 15 days from April to October to those parking lots with concrete grids filled with soil (sites 1, 7 and 8). Permeable interlocking concrete pavers receive the most complete maintenance because they receive a vacuum sweeping twice a month to prevent clogging (site 6).

The objectives of this study are to (i) measure the infiltration rate of the eight parking lots using a single ring infiltrometer procedure and (ii) determine the correlation between a set of factors and the surface infiltration rate. The factors analyzed are: a) position of the ring on the parking stall, b) surface type and filling material, c) age, and d) antecedent dry weather days.

1.2 Surface infiltration test

The hydrological performance of permeable pavement systems is usually determined using a surface infiltration test. This test generally measures the infiltration rate of water through a particular section of the pavement surface. Whereas a variety of infiltration test procedures have been used, most approaches are based on a type of modified single or double-ring infiltrometer tests [19--23].

This study investigates the field infiltration rate using a single ring infiltrometer test, which is a modified version of ASTM D 3385 (the standard test method for infiltration rate in field soils using double-ring infiltrometer as a basis to measure infiltration rates) [24]. Because of difficulties in maintaining the hydraulic head during high infiltration rates, a modified test known as a “surface inundation test” [20] has been used. At least nine tests were run at each monitoring site, following a procedure similar to that suggested by Bean et al. [20]. On parking lot site 5, only three tests were performed because of the poor maintenance condition and the continuous presence of cars occupying the stalls. The experimental equipment was composed of a plastic ring, a bucket, water and sealing material. The single ring infiltrometer consisted of one transparent Plexiglas cylinder with an adhered centimeter scale to measure the water level (Fig. 2a). The cylinder had an inner diameter of 300 mm, coinciding with the usual diameter of the inner ring employed in the double infiltrometer test.

The main problem encountered with the infiltrometer test was that the ring was unable to penetrate the concrete surface and displayed leaks when the infiltration test is performed on soil [25]. Therefore, the ring must be sealed against the pavement surface using a waterproof sealant; in this study, bentonite was used to seal the edge between the ring and the pavement (Fig. 2b).

Using a 16-L bucket, the water was quickly poured into the Plexiglas cylinder. The time was recorded starting when the water was infiltrating from a stable point on the scale, without waves. The time was then recorded every 30--60 s until the cylinder was empty.

This test was not as accurate or precise as the double-ring-infiltrometer test (ASTM D 3385-03) [24], because the surface inundation test did not prevent the horizontal migration of water once the water entered the soil media. However, as suggested by Boogaard et al. [19] and Bean et al. [20], this method is valid for quantifying a fast and high surface infiltration rate, as in the studied parking lots. The simplicity, minimal-time required, non-destructive testing and cost effectiveness of the procedure were additional benefits of this method.

As highlighted by Lucke et al. [26], the infiltration capacity decreases with increasing average daily traffic counts. To understand the influence of the position of the ring in the parking space and the relative surface infiltration rate, the testing measurements were realized in three different positions, as illustrated in Fig. 2c. The assumption was that the three positions coincide with the respective position of the left rear tire (A), the middle of the parking spot (B), and the right front tire (C).

1.3 Data analysis

Following the data collection, the water levels inside the cylinder (mm) were plotted as a function of time (h)) for each surface infiltration test. Figure 3 shows a plotter sample of select ring infiltration measurements performed during three different tests in this case for site 7. The linear regression of all data points determined the best fitting line between the two monitored variables.

The infiltration rate is equivalent to the maximum-steady state or average incremental infiltration velocity. Therefore, the absolute value of the regression line slope for each test was considered as the surface infiltration rate (SIR) of the permeable surface [20]. All data points were included in the regression analysis.

SIRs were occasionally variable during the identical test as a result of variable hydraulic heads, as observed in Fig. 3. However, the coefficients of determination (R^2), for water depth versus time equivalents for all sites, were predominantly >0.82, and the majority exceeded 0.99, indicating minimal variability in the infiltration rates.

For each test, the permeability values matched the percent of pervious pavement surface, namely the void areas between the pavement blocks. This result was calculated through a photo-analysis as previously performed [19].

Results and discussion

Infiltration tests were performed from September 2012 to October 2013. The field investigations determined the permeability values for each parking lot.

This section of the paper discusses the following topics: (1) the influence of the position of the ring in the parking stall, (2) the correlation between the percentage of the permeable area in the sample and the permeability values, and (3) the influence of other parameters such as filling material, antecedent dry weather days and site age.

The statistical summary results of all tested sections are presented in Tab. 2. SIR values for each position (A, B, C) are obtained by averaging the results of all samples for that position. In particular, Tab. 2 shows the number of measurements and the hydrologic response of the parking lots in terms of the minimum, median, maximum and average SIR.

The influence of the position of the sample during the experiment was analyzed. All monitored parking stalls have approximately a uniform size of 12.5 m^2. As shown in Fig. 2, three positions were identified to determine areas of the stall characterized by different traffic conditions.

The permeability value shown in Fig. 4 was obtained by calculating the ratio between the average SIR for each position and the average SIR for the parking lot. The permeability is equal to 1 when the permeability for that position coincides with the average permeability of the considered parking lot.

Figure 4 shows that tests performed in positions B and C are characterized by higher values of permeability than those measured in correspondence to position A. This higher permeability is likely because this position is more influenced by vehicular traffic. The repeated transition of the wheels during the parking phases determines a greater compaction of the soil and, consequently, a lower permeability value.

As suggested by Bean et al. [20], to eliminate the influence of the test location, the overall SIR for each site was determined by averaging the results from different tests and positions. The average values ranged between a minimum of 123 mm/h for site 6 and a maximum of 20 137 mm/h for site 4. Boogaard et al. [19] indicated that the minimum rate required by the European authorities after an established number of years in service is 97.2 mm/h. Between three and eleven years of service, all sites tested must display infiltration rates exceeding those required by the European regulation.

Despite companies provide the average percentage of open surface area for each m^2 of product, the real percentage of permeable area depends on the position of the cylinder, and therefore this may affect the infiltration value. Through the photo-analysis test procedure, the percentage of permeable area contained in each sample was calculated. As shown in Tab. 3, the permeable area was matched with the permeability value and surface type. Generally, without considering the surface type, larger permeable areas result in higher SIR. Notably, site 6 is characterized by a lower percent of voids (11%) and by a lower mean permeability value (123 mm/h). However, this relationship was not found in the results of the tests performed on sites 2 and 5. Despite having only 3% impermeable surface, the SIR values of PG were similar to those obtained by the other parking lots. This similarity could be because of the minor compressive strength of the system grid/soil that in the long term produces a greater soil compaction and a lower infiltration capacity.

Sites with open surface areas ranging from 35 to 54% of the total area display distinct permeability performance values. These differences cannot be explained by differences in surface types or maintenance procedures because these are approximately identical. The substantial dissimilarity between these parking lots results from the filling material. Sites 3 and 4 (where the filling material is homogeneous with a diameter ranging between 4 and 14 mm) are characterized by the highest average SIR of 10 574 and 20 137 mm/h, respectively. These values support the findings of Mullaney et al. [8], which indicated that the infiltration rate of a pervious pavement in a good working status ranges from 130 mm/h to several thousand.

Boogard et al. [19] studied the effect of the permeable pavement age on infiltration. They concluded that despite a decreasing infiltration capacity with pavement age, the performance of the clogged permeable pavement systems was still generally acceptable, even after many years of service. This performance results from a combination of evolving construction practices, evolving maintenance practices, and gradual clogging by sediment.

In this study, the age of the permeable lots (at the time of the tests) ranged between three years (site 8) and eleven years (site 5). By grouping the parking lots by surface type and voids distribution, the following can be concluded: the PG pavements at sites 5 and 2 appeared to ensure a good average permeability, despite their age and absence of maintenance. The SIR of the CGP parking lot (sites 1, 3, 4, 7, 8) was independent of age because the most recent parking lot had the lowest SIR in this group. This independence may result from the grain size of the filling aggregate, the different environmental conditions and perhaps different clogging phenomena, all playing a role in the SIR performance. The influence of the maintenance procedures could be excluded, because a high void ratio with no maintenance still displays a good SIR (as for sites 5 and 2).

Table 4 reports the summary statistics for all permeability measurements for different weather conditions and in particular: the mean average SIR, the antecedent dry weather days, the recorded rainfall (mm) during the last precipitation event and the day of the test. Overall, several sites presented an increase in the infiltration rate with a higher dry weather period, and no regular correlation between dry weather days and SIR was noted. This lack of a relationship may result from the different soil moisture contents, different intensity peaks during the previous rainfall event, and different clogging situations because of the wash-off.

Conclusion

This study reports the results of field investigations conducted in Italy on eight permeable parking lots. The hydrologic performance of the parking lots has been determined using a surface inundation test [19], which is a simple and affordable procedure, well suited for high infiltration rates. This study did not determine the improvement in water quality for permeable pavements, but other studies have shown that the infiltration of water through pavement layers traps pollutants [8, 10, 14].

The experimental tests determined (for all monitored sites) the surface infiltration rate, which describes the ease with which water can move through the soil pore spaces or fractures. The values for the permeability ranged between a minimum of 123 mm/h (site 6, PICP, 2005) and a maximum SIR of 20 137 mm/h (site 4, CGP, 2005).

This study demonstrates that the SIR is strongly influenced by the position of the testing ring on the parking stall (Fig. 4). In particular, the infiltration capacity appeared to increase when the location has a lower compaction rate (Fig. 4, position B and C), and decreased (Fig. 4, position A) when the area is subject to a higher vehicular traffic, which produces a greater compaction.

In agreement with other studies, the SIR appeared to decrease with pavement age for several parking lots. However, this parameter did not strongly influence SIR, and site 4 (CGP, 2005), which had the highest SIR, is not the most recently built. Similarly, higher antecedent dry weather days seemed to determine a slight increase in the SIR value, but the relationship between those parameters and the previous rainfall event requires further research. The open surface area is important, but did not drive the change in the SIR performance.

In addition to the position of the ring on the stall, the grain size distribution of the filling material (larger appears to be better) was found to be the key parameter for improving the hydrological performance of a permeable parking lot.

The main result of the study is that the SIR is higher when the compaction is lower because of the lower vehicular traffic and/or the higher grain size and homogeneous distribution of the filling material (gravel or similar).

This study can assist authorities responsible for issuing technical regulations in finding a simple, cheap and reliable test procedure. Moreover, the experiments have shown the influence of several factors on the permeability and increased the availability of field data on this topic.

The authors have declared no conflict of interest.

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Fig. 1: Monitored permeable parking lots

Fig. 2: Single infiltration ring: a) Taped scale in cm, b) bentonite sealing used to waterproof the lateral infiltration of water in the soil, c) positions of the ring during the tests.

Fig. 3: Sample graph of single ring infiltrometer test data and regression lines.

Fig. 4: Correlation between the position of the ring in the stall and permeability. Positions correspond to: left rear tire (A); middle of the parking (B); right front tire (C).

Table 1: Characteristics of each parking lot in the study

Site ID	Surface type	Year of construction	Area (m^2)	Number of stalls	Filling material
1	CGP	2006	625	50	Soil/sand/grass
2	PG	2007	375	30	Soil/sand
3	CGP	2003	100	80	Gravel
4	CGP	2005	750	60	Gravel
5	PG	2002	250	20	Soil/sand
6	PICP	2005	1,950	155	Sand
7	CGP	2006	590	47	Soil/sand/grass
8	CGP	2010	300	24	Soil/sand

Table 2: Statistical summary of SIR for each position and average permeability for the parking lots.

Surface infiltration rate (mm/h)					
Site ID	N	Min	Median	Max	Mean
1-A	6	358	1195	4716	1839
1-B	6	201	800	11 693	3722
1-C	6	244	381	18 031	3676
1 (all)	**18**	**201**	**451**	**18 031**	**3079**
2-A	6	287	587	1191	682
2-B	6	491	1107	1759	1166
2-C	6	526	1110	2771	1510
2 (all)	**18**	**287**	**970**	**2771**	**1119**
3-A	9	92	3929	8663	3437
3-B	8	125	12 563	21 543	12 419
3-C	8	743	19 148	28 837	15 865
3 (all)	**25**	**92**	**8663**	**28 837**	**10 574**
4-A	9	454	5871	15 600	7062
4-B	9	19 264	26 012	58 500	31 044
4-C	9	11 605	18 691	38 400	22 305
4 (all)	**27**	**454**	**18 691**	**58 500**	**20 137**
5-A	3	632	781	1049	821
5-B	N/A	N/A	N/A	N/A	N/A
5-C	N/A	N/A	N/A	N/A	N/A
5 (all)	**3**	**632**	**781**	**1049**	**821**
6-A	3	6	8	9	8
6-B	3	4	11	143	53
6-C	3	149	226	553	309
6 (all)	**9**	**4**	**11**	**553**	**123**
7-A	6	138	237	461	259
7-B	3	642	767	838	749
7-C	5	564	974	1158	918
7 (all)	**14**	**138**	**564**	**1158**	**642**
8-A	2	103	107	174	128
8-B	3	124	181	266	191
8-C	5	86	418	885	423
8 (all)	**10**	**86**	**174**	**885**	**247**

Table 3: Results of the photo-analysis procedure to establish the % of permeable area for each sample.

Average permeable area (%)	Average SIR (mm/h)	Site name	Surface type	Year of construction
11	123	6	PICP	2005
35	10 574	3	CGP	2003
40	3079	1	CGP	2006
41	20 137	4	CGP	2005
44	247	8	CGP	2010
54	642	7	CGP	2006
97	1119	2	PG	2007
97	821	5	PG	2002

Table 4: Summary statistics for all permeability measurements for different weather conditions.

Site ID	ADWD	Rainfall (mm)	Mean daily SIR (mm/h)	Date
1	4	0.6	5,391	07/03/2013
1	11	0.6	767	07/03/2013
2	5	0.6	1231	07/04/2013
2	12	0.6	1008	07/04/2013
3	0.5	7	8812	10/12/2013
3	2	0.2	7213	07/01/2013
3	2	3.2	14 156	07/16/2013
4	0.5	1.2	20 092	07/12/2013
4	1	1.2	17 161	07/13/2013
4	10	0.6	25 739	07/09/2013
5	3	47.4	820	11/16/2012
6	1	23.5	268	10/31/2012
6	1.0	81.50	8	11/14/2012
6	3.0	6.3	10	11/05/2012
6	5.0	6.3	5	11/07/2012
7	1.0	12.4	529	11/02/2012
7	2.0	47.40	321	11/15/2012
7	25.0	4.8	832	10/26/2012
8	0.5	36.6	576	10/30/2012
8	0.5	12.4	141	11/09/2012
8	2	47.4	117	11/15/2012
8	8	12.4	142	11/02/2012

ADWD, antecedent dry weather days

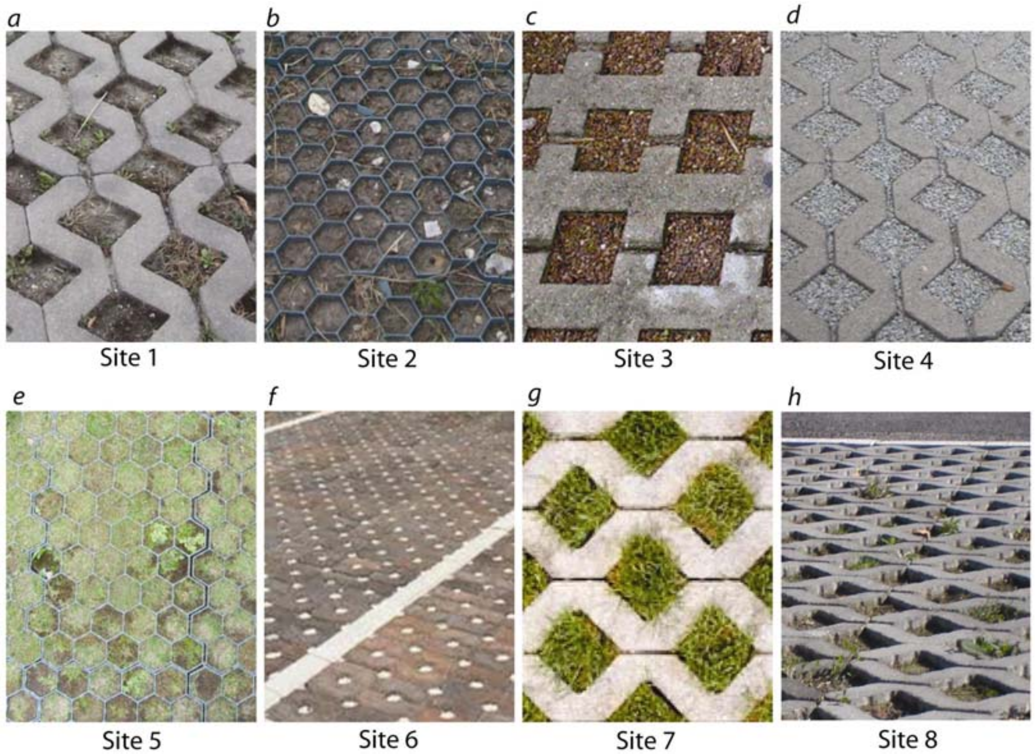


Figure 1

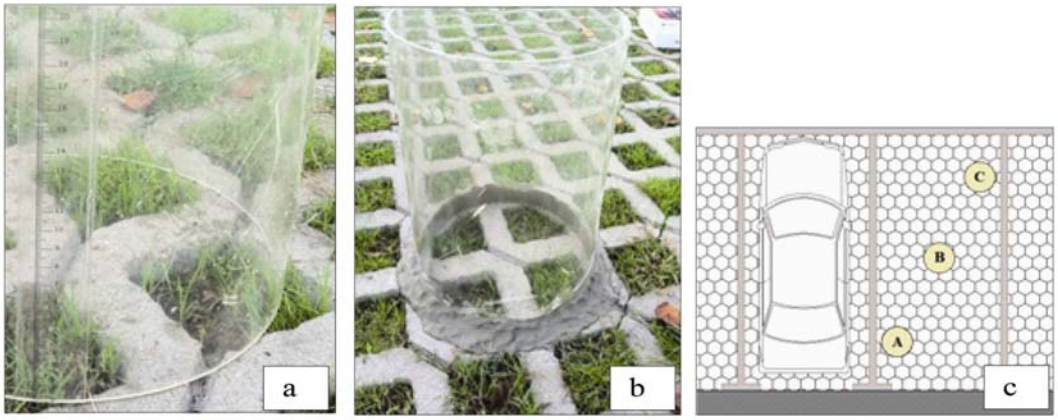
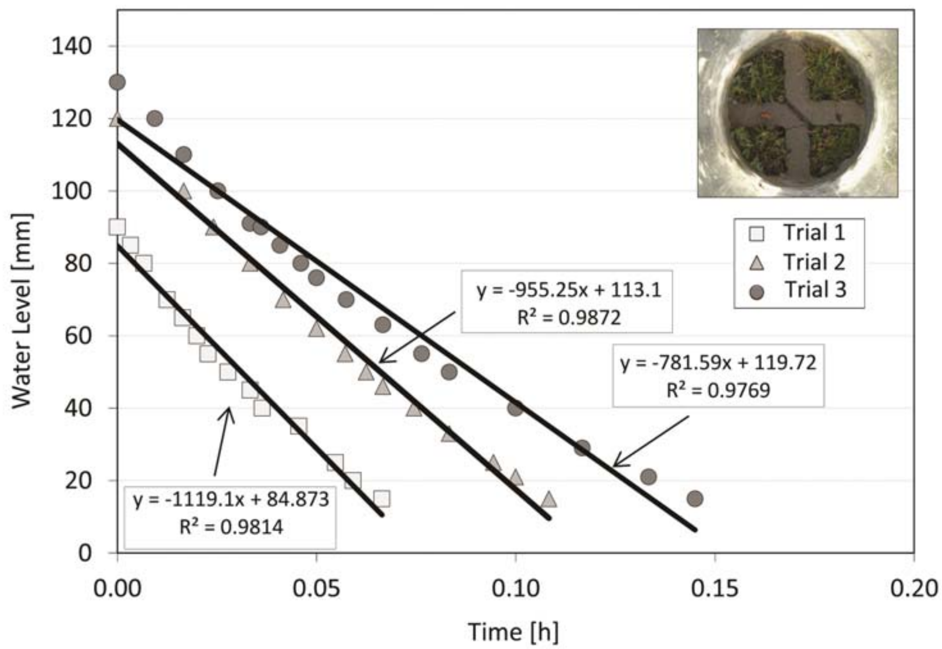


Figure 2



140
120
100
80
60
40
20
0
Water Level [mm]
0.00
0.05
0.10
0.15
0.20
Time [h]
Trial 1
Trial 2
Trial 3
y = -955.25x + 113.1
R² = 0.9872
y = -781.59x + 119.72
R² = 0.9769
y = -1119.1x + 84.873
R² = 0.9814

Figure 3

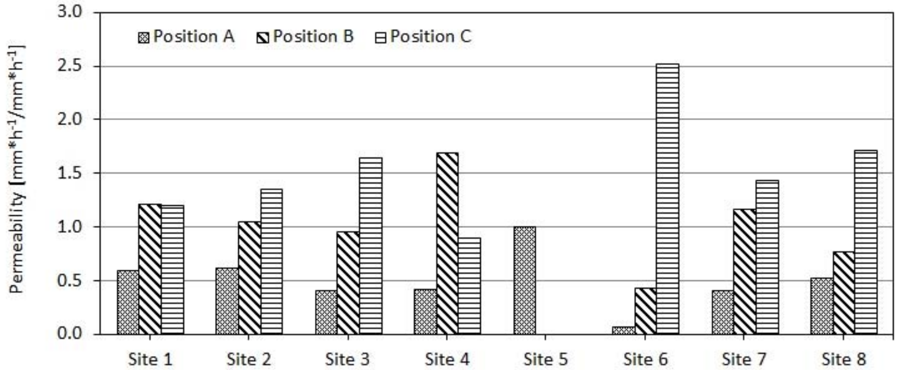

Position A
Position B
Position C
Permeability [mm*h-1/mm*h-1]
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Site 1
Site 2
Site 3
Site 4
Site 5
Site 6
Site 7
Site 8

Figure 4