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Evaluation of surface infiltration rate of permeable block pavements using single-ring infiltrometer

Eunku Lee, Jaehun Ahn*, Hyun-Suk Shin

Department of Civil and Environmental Engineering, Pusan National University, Busan 46241, Korea, email: jahn@pusan.ac.kr (J. Ahn)

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ABSTRACT

The increase in urban flooding has been attributed to the change in stormwater pattern due to climate change as well as the increased impervious coverage following rapid urbanization. The permeable block pavement is one of most widely accepted Green Infrastructure and Low Impact Development facilities for runoff mitigation in urban area where land is generally covered with pavement roads and parking lots. To assess the applicability of single-ring infiltrometer to permeable block pavements, the permeable block pavements with two different joint filler materials constructed in Korea Green Infrastructure and Low Impact Development Center were selected and tested using 300 mm single-ring infiltrometer based on ASTM C 1701. The second measurement sequentially taken after the first measurement gave smaller infiltration rate than the first with few exceptions, because the suction in the system is lost while taking the first measurement. No meaningful dependency of infiltration rate on spatial variation of measurement locations was found from the data. The number of crossing joints or the pattern of blocks tested within the infiltrometer was found to be one of governing factors. One should carefully choose the test domain and pattern contained within the infiltrometer to estimate the infiltration rate which represents the entire domain of block pavements. The infiltration rate of the pavement with coarse filler (Ø 4–8 mm) was about three times the infiltration of the system with finer filler (Ø 2 mm). However, when coarse filler is used, the construction should carefully be conducted as coarse fillers are harder to be uniformly installed into the joint gap with finite width.

Keywords: Surface infiltration rate; Permeable block pavement; Green infrastructure; Low impact development; Single-ring infiltrometer

1. Introduction

The increase in urban flooding has been attributed to the change in stormwater pattern due to climate change as well as the increased impervious coverage following rapid urbanization. Traditional management practices such as increasing the capacity of existing storm sewer system and raising river banks may not be the best solution as they are often accompanied by huge construction and cost [1]; there may be possibly more natural and smaller but still effective solutions. As such, recently, the concept of Green Infrastructure (GI) and Low Impact Development (LID) is well accepted and widely implemented. GI and LID refer to a design philosophy and concept which emphasizes the use of natural infiltration into soils and infrastructures allowing more natural circulation of water that resembles water cycle of pre-development stage [2–5]. Among other concepts and techniques of LID, the permeable block pavement is one of most widely accepted concept in urban area where land is generally covered with pavement roads and parking lots.

The concept of the permeable pavements is not new; for example, in the United States, the permeable pavements were studied since 1970s [6]. In case of block pavements, product licensing and manufacturing groups in the United States invested in research and published the results [6–8] and their work is now finally implemented in a manual from the Interlocking Concrete Pavement Institute [6,9]. In Korea,

* Corresponding author.

the history of the permeable pavement is not as long, but the application of permeable pavements is getting widely accepted recently. For example, in 2014, Seoul Metropolitan City, the capital city of Korea, revised the regulations on rainwater management, and expanded the applicability of permeable pavements [10].

Single- and double-ring infiltrometers are often used to evaluate surface infiltration rate of permeable pavements [11,12]. A research group in North Carolina State University started to use double-ring infiltrometer to measure surface infiltration rate of Concrete Grid Pavers and Permeable Interlocking Concrete Pavers [11], but then this research group moved to a single-ring infiltrometer, because the infiltration rates of permeable pavements are so high that double-ring infiltrometer often requires too much volume of water to maintain hydraulic heads within the rings [12]. In attempt to investigate surface infiltration of permeable pavements, Peter et al. [13] developed a rainfall simulator that can create synthetic rainfall; they recorded the time when surface runoff occurs to estimate the surface infiltration of permeable pavements. Winston et al. [14] measured surface infiltration rate of permeable pavement using single-ring infiltrometer in order to assess different maintenance techniques to prevent degradation of infiltration due to clogging of permeable block and asphalt pavements.

In hydraulic and hydrologic design of LID facilities including permeable pavements, the surface infiltration of the systems should be evaluated first. In addition, the surface infiltration rate is a good indicator for the maintenance of permeable pavements against clogging [12]. However, there have been attempts and efforts to develop reasonable methods to evaluate surface infiltration of permeable pavements as described, but no single method works consistently for different types of permeable pavements. For example, even single-ring infiltrometer, which is one of most widely used equipment, may not provide a proper value of infiltration rate when the value is very high, because it gets very hard to maintain the water head specified in the test procedure [12].

The main objective of this study is to assess the applicability of single-ring infiltrometer to permeable block pavements. As such, the permeable block pavements with two different joint filler materials constructed in Korea GI-LID Center were selected and their surface infiltration rates were evaluated using single-ring infiltrometer, one of most widely used infiltrometer for permeable pavements.

2. Permeable pavement testbed

2.1. Overview of research center

Korea GI-LID Center (Fig. 1) opened in June 2016 after about 2 years of construction under support of Korea Agency for Infrastructure Technology Advancement funded by Ministry of Land, Infrastructure and Transport. The center is a research complex with laboratory and testbed facilities located at Yangsan campus of Pusan National University, and has a total area of 4,204 m^2. The laboratory is equipped with experimental apparatus that can evaluate hydraulic/hydrologic, structural, and environmental aspects of LID facilities in material or model scale. The testbed has various types of LID facilities in real scale well equipped with monitoring sensors and systems. Examples of LID facility testbeds are permeable pavement parking lots, permeable pavement roads, retention and detention ponds, plant boxes, etc.

Fig. 1. Korea Green Infrastructure and Low Impact Development Center at Yangsan campus, Pusan National University.

2.2. Permeable block pavement testbed

"Permeable block pavement" is a literal translation of the term widely used in public and private sectors in Korea [15]. Permeable block pavements can be categorized into two: (1) a self-permeable block that has pores in the block itself and allows infiltration through the block, and (2) a joint permeable block which allows infiltration through joints only. It is noted that the terms "permeable interlocking concrete pavement" and "concrete block permeable pavements" are often used in the United States, and the United Kingdom, respectively [16,17].

The permeable parking lot testbeds were constructed for about 4 months in 2015. Each parking unit is made of a concrete cell (or box) filled with permeable base and subbase materials and permeable surface layer, so that the amount of stormwater infiltrated, stored and drained out the cell can be monitored and analyzed thoroughly. The dimension of each concrete cell is 2.5 × 10.85 × 0.9 m that meets the minimum requirement of parking lot size in Korea (2.3 × 5.0 m) [18]. Fig. 2 shows the permeable block pavements during and after construction, where BF and BC mean permeable block pavements with fine and coarse joint filler materials, respectively. The same kind of joint permeable blocks, which are 8-mm thick, were installed for both pavements BF and BC. The permeable block pavement BF has block, joint filler (Ø 1.5–2.5 mm), bedding (Ø 4–8 mm), and base (Ø 13 and 25 mm mixed, and Ø 25 mm) with sand filter in the cell. On the other hand, the permeable block pavement BC includes block, joint filler (Ø 4–8 mm), bedding (Ø 4–8 mm), and base (Ø 25 mm, and Ø 65 mm) in the structure. To ensure separation between materials, for both pavements, geotextiles were installed under bedding and Ø 25 mm aggregate layers. The surfaces of both pavements have longitudinal slopes of (1.2%) to allow drainage of stormwater toward monitoring systems. The grid reinforcement in the base layer is to provide better resistance; the effect of the grid on the surface infiltration is assumed to be negligible as it has a lattice structure with much void. The details on the cross section of pavements are presented in Fig. 3.

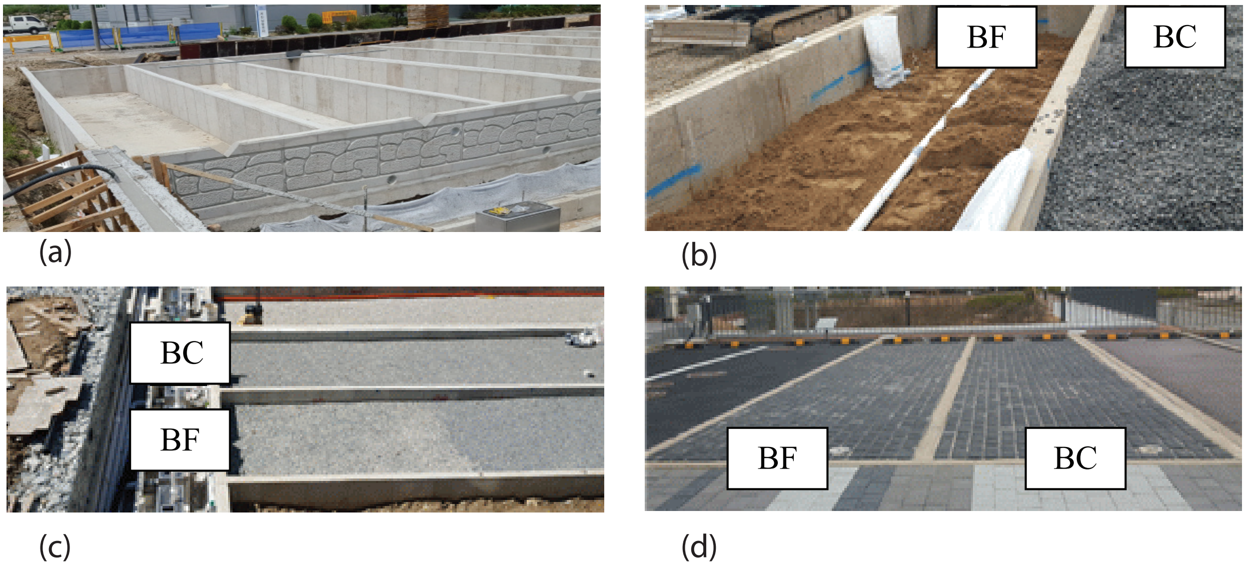


Fig. 2. Permeable block pavement testbed at Korea GI-LID Center: (a) concrete cells at the parking lot testbed, (b) base layer under construction, (c) constructed bedding layer, and (d) permeable block pavements after construction.

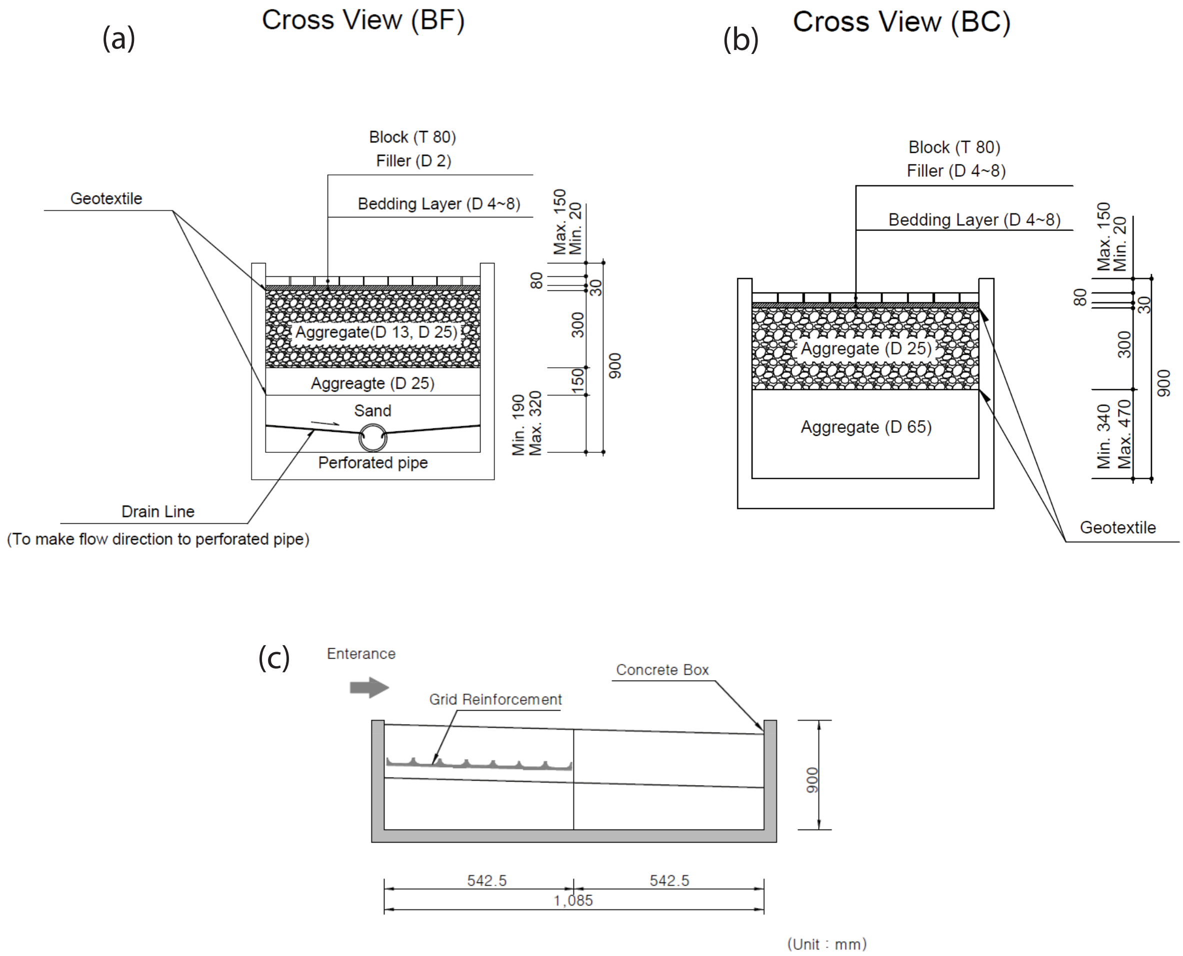


Fig. 3. Cross section of permeable block parking lots: (a) BF cross section, (b) BC cross section, and (c) side section.

3. Infiltration test

3.1. Test method

ASTM C 1701 [19] and ASTM D 3385 [20], which utilize the single- and double-ring infiltrometers, are widely used standard test methods for evaluation of surface infiltration rate. ASTM D 3385 is proposed for soil materials which may have the infiltration rate of 10^{-5}–10^{-1} mm/s, and may not be well applied for permeable pavements whose infiltration rate is generally higher than 10^{-1} mm/s. ASTM C 1701 was originally proposed for in-place pervious concrete, but has been applied to other types of permeable pavements as well including block pavements [16,12,14,21].

To evaluate surface infiltration rate of permeable pavements based on ASTM C 1701, one should first clean the surface of the pavement by brushing off trash, debris, and other non-seated materials. Then apply plumbers putty around the bottom edge of the single-ring and place it onto the pavement surface creating a watertight seal. After setting the single-ring, pre-wetting is conducted by using 3.6 kg of water while heads are maintained between 10 and 15 mm, and then the amount of elapsed time is recorded. If elapsed time is less than 30 s during pre-wetting, 18 kg of water is needed, otherwise 3.6 kg of water is used to identify surface infiltration rates. Surface infiltration rate may be evaluated twice, but the second measurement should be made no later than 5 min after the first measurement.

When the water volume V is applied into a single-ring with diameter D for time t to complete infiltration, the surface infiltration rate I can be estimated as follows [22]:

$$I = \frac{1\times 10^{6}\times V}{\pi \times \left(\frac{D}{2}\right)^{2}\times t}, \tag{1}$$

which is an identical equation in ASTM C 1701 presented in terms of the water mass M, and a conversion factor F (F = 4,583,666,000 mm^3 s/kg h),

$$I = \frac{F\times M}{D^{2}\times t\times 60}. \tag{2}$$

3.2. Infiltration rate on bedding layer

This study considers two permeable block pavements with different sizes of joint fillers, but then these two systems do not have the same layers below the surface layer as shown in Fig. 3; it was necessary to evaluate the effect of different layer structures on infiltration of the systems. As such the infiltration rates were evaluated on the bedding layers of two different systems after removing the blocks [22]. The rates of infiltration on the bedding layers of BF and BC pavements were evaluated to be 13.6 and 13.5 mm/s, respectively, therefore practically identical. Considering that the particle size of bedding layer material is D 4–8 mm, the results compare well with infiltration rate of the aggregate of similar size, 6.35 mm, presented in Table 1 [6]. The surface infiltration rates measured on the blocks, presented in Table 2, are much smaller than the infiltration on the bedding layer, 13.5 mm/s; it was postulated that the surface infiltrations of the joint permeable block pavements investigated were governed by the block and joint filler not by the layers below.

Table 1
Infiltration rate of aggregates under saturated condition (after Ferguson [6]

Aggregate size (mm)	Surface infiltration rate (mm/s)
25.4	352.8
12.7	105.8
6.35	17.6

4. Surface infiltration on permeable block pavement

Series of surface infiltration tests were conducted on two joint permeable block pavements, and the test cases and results are summarized in Table 2. Tests I, II, and IV were conducted at two different locations on each pavements BF and BC on the dates specified, and the antecedent days of no rainfall were 12, 41, and 7, respectively. For these three tests, the locations of surface infiltration measurement were not the same each time, but two locations apart in longitudinal direction were selected for each test (Fig. 4(a)). The Arabic number in test number represents the location of the measurement in tests I, II and IV (See Table 2 and Fig. 4(a)). In test III, the surface infiltration measurements were taken at eight different locations on each pavement (Fig. 4(b)) to see if there is any tendency in special distribution of surface infiltration measurement. For this test case, antecedent dry days was 8. The Arabic number in test number matches the measurement location in test V as well (See Table 2 and Fig. 4(b)). Finally, test V was designed and conducted to see if the patterns of block contained in the infiltrometer affect the surface infiltration measured. For all the test cases, the antecedent dry days was at least 3. Considering very high porosity and permeability of permeable base materials used, it is reasonable to assume that the effect of precedent rainfall event is negligible for test V. The filler and bedding materials in the surface layer may not be as highly permeable, but the pre-wetting resets the effect of precedent rainfall in this thin layer. In fact, ASTM C 1701 recommends that a test be conducted at least 24 h after rainfall, and all the test cases conducted here meet this requirement.

4.1. Effect of measurement order and location

A general trend found over the entire data is that the second measurement of surface infiltration rate is consistently smaller than the first measurement as given in Table 2. When infiltration occurs on unsaturated media, the rate of infiltration is influenced by the suction in soils. After the first infiltration, the aggregates, especially small particles such as bedding and joint filler materials, will become moister loosing suction developed, which will decrease the infiltration rate measured. However, the first and second measurements are not significantly different; making average of the two measurements, as suggested in ASTM C 1701 would still be reasonable.

In test III, the surface infiltrations were measured at eight locations distributed over each pavement (Fig. 4(b)), but no meaningful dependency of infiltration rate on

Table 2
Surface infiltration rate of permeable block pavements

Test no.	Date in 2016	Antecedent dry period (d)	Surface infiltration rate (mm/s)						Remark
			BF			BC			
			First	Second	Average	First	Second	Average	
I-1	15 July	12	0.99	0.84	0.91	3.47	3.39	3.43	Measured at 2 locations
I-2			0.89	0.77	0.83	1.01	0.94	0.97	Measured at 2 locations
II-1	25 August	41	1.15	0.97	1.06	3.51	3.53	3.52	Measured at 2 locations
II-2			0.31	0.27	0.29	1.27	1.27	1.27	Measured at 2 locations
III-1	10 September	3	1.35	1.51	1.43	2.16	1.90	2.03	Measured at 8 locations
III-2			0.72	0.64	0.68	2.68	2.53	2.61	Measured at 8 locations
III-3			1.03	0.93	0.98	2.57	2.35	2.46	Measured at 8 locations
III-4			1.50	1.46	1.48	3.69	3.49	3.59	Measured at 8 locations
III-5			0.71	0.72	0.71	1.53	1.57	1.55	Measured at 8 locations
III-6			0.64	0.62	0.63	2.91	2.54	2.73	Measured at 8 locations
III-7			0.93	0.83	0.88	2.38	2.28	2.33	Measured at 8 locations
III-8			1.10	1.03	1.07	3.64	3.63	3.64	Measured at 8 locations
IV-1	24 September	7	0.93	0.83	0.88	2.59	1.87	2.23	Measured at 2 locations
IV-2			1.11	0.98	1.04	2.30	2.56	2.43	Measured at 2 locations
V-1	14 October	7	0.70	0.62	0.66	1.27	1.10	1.18	4 Cross joints
V-2			0.66	0.60	0.63	2.10	1.99	2.05	4 Cross joints
V-3			0.76	0.70	0.73	2.10	2.12	2.11	4 Cross joints
V-4			1.12	1.07	1.09	3.36	3.30	3.33	8 Cross joints
V-5			1.10	1.11	1.10	3.82	3.55	3.69	8 Cross joints
V-6			1.21	1.13	1.17	2.95	2.46	2.71	8 Cross joints

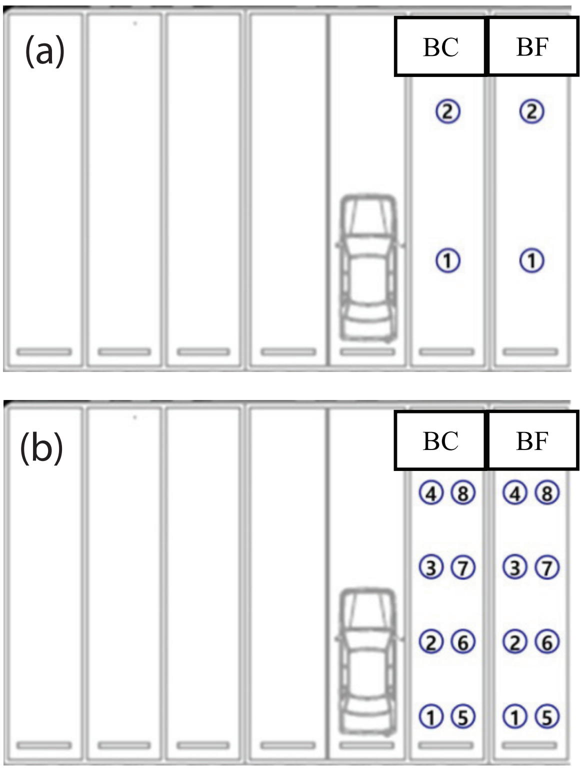


Fig. 4. Locations of surface infiltration measurements: (a) Tests I, II, and IV, and (b) Test III.

spatial variation of measurement locations was found from the data.

Primary statistics of infiltration rate data from tests I, II, III, and IV is summarized in Table 3. For both pavements BF and BC, the infiltration data is highly scattered, which, however, is not due to the spatial location of measurement as already observed from the results of test III. As such, to find the reason of high scatter in infiltration data, the pattern of blocks contained in the infiltrometer was investigated.

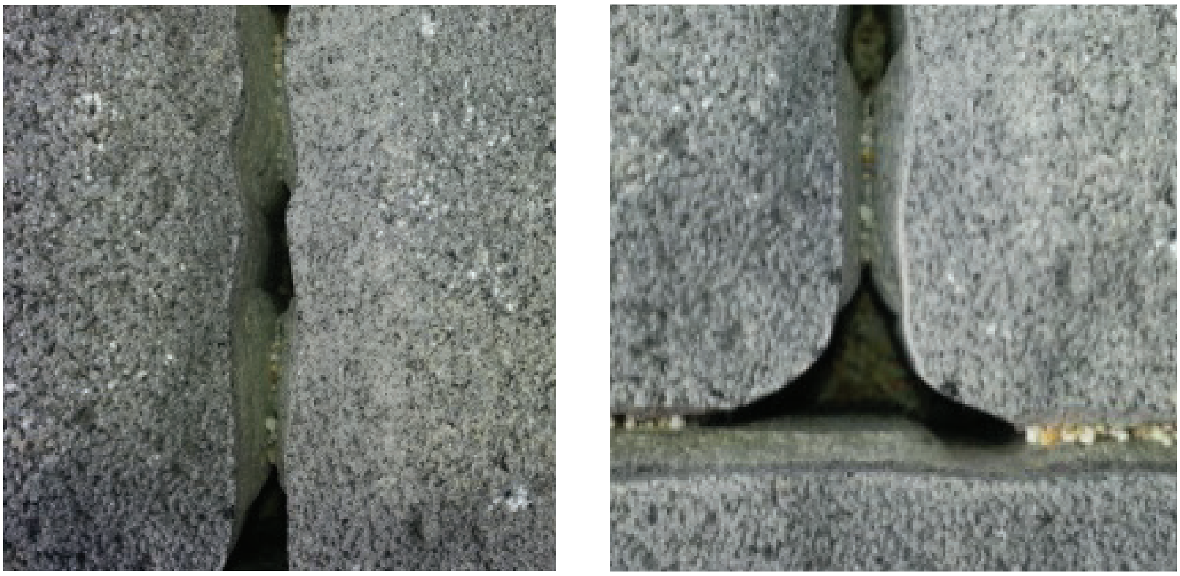
4.2. *Effect of block pattern contained in infiltrometer*

The dimensions of blocks vary depending on manufacturers in Korea, but most widely used one for parking lots and roads has planar dimension of around 200 × 100 mm. As such, the patterns of block contained in an infiltrometer with 300 mm diameter are not same or consistent, but may differ every time the measurement is taken. Blocks meet making linear or crossing joint as presented in Fig. 5, and for the blocks tested the crossing joint has wider opening than the linear joint; the number of crossing joint involved in the test may be a factor that influences the results. In case of the permeable block pavements tested, the number of crossing joints that can be contained within the single-ring with 300 mm diameter varies from 4 to 8. Therefore, in test V, the infiltrations of permeable block pavements were evaluated containing either four or eight crossing joints in the infiltrometer. The infiltrometer setups actually used for measurements are presented in Fig. 6. The results of test V are summarized in Table 2 and plotted in Fig. 7. Tests V-1, V-2, and V-3 were conducted with four crossing joints contained in the single-ring (Fig. 6(a)); tests V-4, V-5, and V-6 with eight crossing joints (Fig. 6(b)). The statistical values of the results are presented in Table 4. As shown in Table 2 and Fig. 7, the results of the second measurements are consistently smaller than the first ones, which attributes to the decrease in suction for the second measurement. There actually are a few exceptions, but this may be due to operational error during the tests or limit of the test method itself. In the standard test method (ASTM C 1701, 2009), the water head should be maintained 10–15 mm above the pavement surface, but it is not always easy to maintain the water level within these bounds, not to mention 10–15 mm is not exactly a consistent boundary condition.

In the results of test V, for a constant number of crossing joints in the infiltrometer, whether it is four or eight, the standard deviations of the results are about 0.05 mm/s for the BF pavement and 0.5 mm/s for BC, both of which are far less than the standard deviations of the results with no consideration of number of crossing joints in Table 3. The number of crossing joints or the pattern of blocks tested within the infiltrometer can be one of governing factors of

Table 3
Statistical results of surface infiltration rate from tests I, II, III, and IV (mm/s)

Pavement	Surface infiltration rate (mm/s)			
	Average	Minimum	Maximum	Standard deviation
BF	0.92	0.29	1.48	0.31
BC	2.49	0.97	3.64	0.86



(a) (b)

Fig. 5. Type of permeable block joint: (a) linear joint and (b) crossing joint.

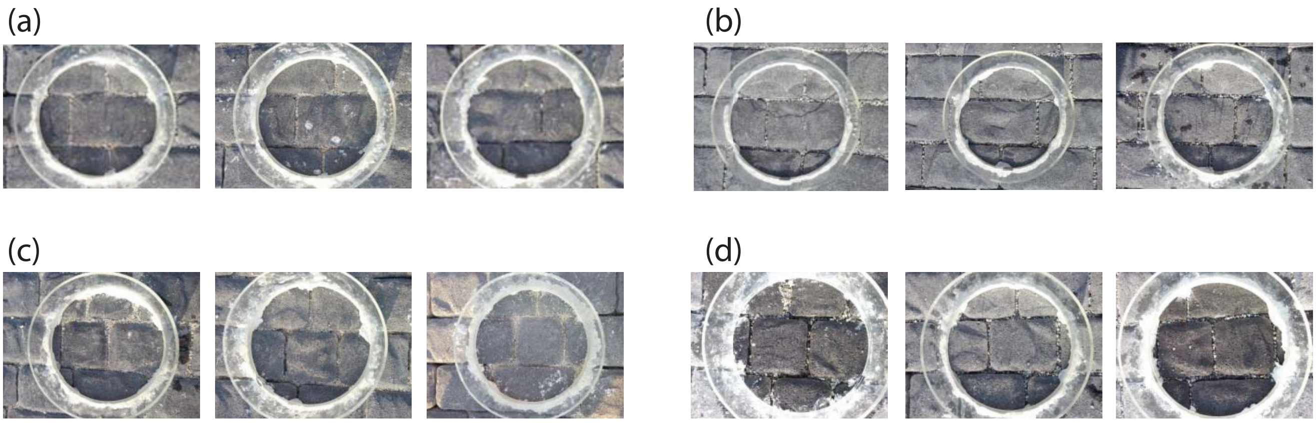


Fig. 6. Block patterns contained in infiltrometer for test V: (a) four crossing joints on BF, (b) four crossing joints on BC, (c) eight crossing joints on BF, and (d) eight crossing joints on BC.

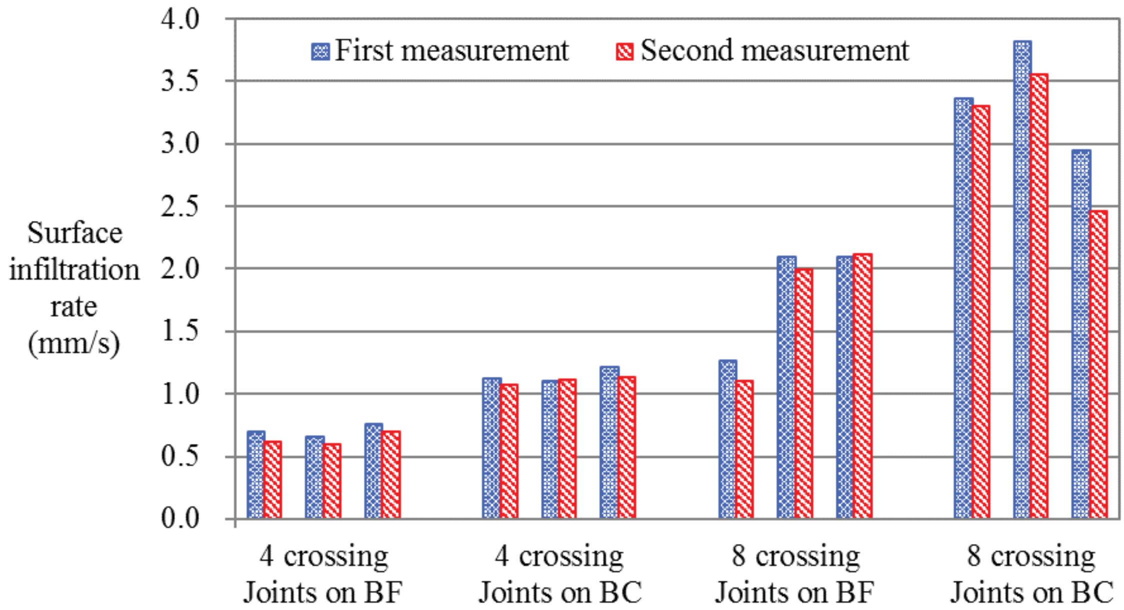


Fig. 7. Surface infiltration rate under four and eight crossing joints setup (test V).

Table 4
Statistical results of surface infiltration rate from test

Pavement	No. of crossing joints	Surface infiltration rate (mm/s)	
		Average	Standard deviation
BF	4	0.67	0.05
	8	1.12	0.04
	4 and 8	0.90	0.25
BC	4	1.78	0.52
	8	3.24	0.50
	4 and 8	2.51	0.92

the infiltration results by ASTM C 1701. Table 3 summarizes 14 tests for the BF and BC pavements each that do not consider the block patterns tested, and Table 4 presents 6 tests for each pavement type which do consider the block patterns in the infiltrometer. It can be found that the average infiltrations of pavement BF and BC in Table 3, 0.92 and 2.49 mm/s, respectively, compare very well with those in Table 4, 0.90 and 2.51 mm/s. Therefore, when estimating the surface infiltration of permeable block pavements, it is very important to control and choose the proper patterns of blocks; it is more important carefully choosing the test domain and pattern contained within the infiltrometer than increasing number of test cases with no proper basis. When the test patterns are properly considered, one can estimate the infiltration rate that represents the entire domain of block pavements, by conducting reasonable number of tests.

4.3. *Effect of size of joint filler material*

From Tables 2, 3, and 4, and Fig. 7, it is quite eminent that the permeable block pavement BC with the joint filler size of Ø 4–8 mm has a larger value of the surface infiltration rate than the BF pavement with the joint filler of Ø 2 mm. Especially when the infiltration on the bedding layer for both BF and BC is practically the same, the size of joint filler would be the only difference embedded in the systems. By looking at the results of better controlled tests, test V in Table 4, it is noted that the average infiltration rate of BC, 2.51 mm/s, is roughly three times that of BF, 0.90 mm/s.

The standard deviation of BC, about 0.50 mm/s, however, is larger than that of BF, about 0.05 mm/s. The size of filler in BC is Ø 4–8 mm and the width of the gap in joints ranges from 6 to 11 mm. Therefore, it is harder to fill uniformly the coarse filler in BC into the gap of joints than to fill fine filler (Ø 2 mm) in BF, which is supported by visual inspection of constructed block systems. Therefore, the larger standard deviation in the BC pavement seems to be attributed to the less uniform installation of coarse fillers.

5. Conclusion

To assess the applicability of single-ring infiltrometer to permeable block pavements, the permeable block pavements with two different joint filler materials constructed in Korea GI-LID Center were selected and tested using 300 mm single-ring infiltrometer based on ASTM C 1701. It was noted that the difference in permeable base materials and precedent dry period considered did not have a meaningful effect on the infiltration rate results.

Most of time, the second measurement sequentially taken after the first measurement gave smaller infiltration rate than the first with few exceptions, because the suction in the system is lost while taking the first measurement. No meaningful dependency of infiltration rate on spatial variation of measurement locations was found from the data.

The number of crossing joints or the pattern of blocks tested within the infiltrometer was found to be one of governing factors of the infiltration results by ASTM C 1701. One should carefully choose the test domain and pattern contained within the infiltrometer, to estimate the infiltration rate that represents the entire domain of block pavements.

When the same blocks were installed, the infiltration rate of the pavement with coarse filler (Ø 4–8 mm) was about three times the infiltration of the system with finer filler (Ø 2 mm). However, when coarse filler is used, the construction should carefully be conducted as coarse fillers are harder to uniformly install into the joint gap with finite width.

Acknowledgments

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Symbols

- I — Infiltration rate, mm/s
- V — Water volume, l
- D — Inside diameter of infiltration ring, mm
- t — Time required for measured amount of water to infiltrate the block surface, s
- F — Conversion factor (4,583,666,000), mm^3s/kg h
- M — Mass of water, kg

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