STORMWATER RUNOFF TREATMENT AND INFILTRATION VIA SILICA-SAND BASED PERVIOUS PAVERS

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ABSTRACT

Stormwater runoff samples were collected from a roadway in Beijing and were analysed for turbidity, pH, TSS, TDS, COD, TP, TN, as well as metals Pb, Al, Zn, Fe, Cd, and Mn. The results showed that runoff pollutant concentrations were relatively high. TSS, Zn, Fe, and Al concentrations exceeded the benchmark values set by USEPA, indicating a high level of concern about impairing receiving water quality and the need for pollution prevention measures. Also, most pollutant concentrations exceeded the those in Nationwide Urban Runoff Program (NURP) study. The collected runoff samples were treated through two bench-scale facilities composed of sand-based pervious bricks, subbase materials, and two types of 500mm-thick subsoils. The infiltration capacity of the brick is above 0.025 cm/s, and good water retention and recharge properties was achieved with the help of subbase and subsoils. On the other hand, the average removal of TSS, TP, and TN reached 81.8%, 64.1%, and 64.4%, respectively. The average removal rates of Pb, Al, Zn, Fe, and Cd also reached 50%-99.2%. The sand-based pervious brick is featured with micron-level pores. The paver system significantly reduced stormwater runoff pollutant concentrations and good removal rates were acheived comparing to many pervious pavers with larger pores.

KEYWORDS

Stormwater Runoff Treatment; Recharge Water Quantity and Quality; Sand-based Pervious Materials; Pervious Paver.

1. INTRODUCTION

Rapid urbanization caused a series of water-related problems such as stormwater pollution and deterioration of the water environment. Many scholars in China have conducted studies on stormwater runoff quality (such as SS, TN, TP, COD, heavy metals, and dissolved organic matter) in different cities and many exceedances to surface water standards have been found [1][2][3].

Large-scale stormwater runoff sampling and quality analysis have been conducted in the United States for more than 40 years. Some well-known studies include the National Urban Runoff

Program (NURP) by US Federal Environmental Protection Agency (USEPA); Urban Stormwater Database by the U.S. Geological Survey; The International BMP Database by American Society of Civil Engineers; and the National Stormwater Quality Database by the University of Alabama

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[4]. Among these, NURP is the first comprehensive national urban runoff study, with 2,300 rainfall events in 28 cities covered. It is also an important basis for stormwater regulations [5].

The Benchmark Value is based in large part on EPA's aquatic life water quality criteria and some are from the NURP study. The Benchmark Values are not discharge limitations, but they are meant to be used as indicators of how well a site’s stormwater is managed. It is used to determine whether stormwater pollution prevention measures are successfully implemented [6].

Pervious pavement systems can effectively reduce pollutant concentrations through interception, filtration, and adsorption [7]. Due to differences in pore sizes, material wettability, permeability, etc., pollutant removal rates vary [7][8]. Fletcher et al. [8] summarized the TSS, TN, TP, and metals (Pb, Cu, Cd, Zn, Ni) removal via pervious pavements at 80%, 65%, 60%, and 75% respectively. Qin [9] studied the pollutant reduction effect of pervious brick paving structures. The removal rates on SS, COD, TP, and TN were 69.85%, 52.10%, 64.77%, and 36.39%, respectively.

Some pervious materials with micron-level pores generally showed better filtering potential than materials with millimetre-level pores. Yao [10] concluded that sand-based permeable bricks with micron-level pores can effectively reduce stormwater runoff pollution, and SS removal performance is better than that of pervious concrete, especially for particles larger than 100~600μm.

In this study, bench-scale pervious paver systems were constructed and tested under laboratory conditions. Stormwater runoff samples from a busy roadway were collected and were used to simulate the infiltration process. The objective of the study is to better understand the quality and quantity characteristics of water through the micron-level pore paver system.

2. MATERIALS AND EXPERIMENTAL SETUPS

Experiments were conducted mainly in two bench-scale boxes (912 x 462 X 1190mm) made of glass, which is shown in Figure 1. The pervious bricks, base layers, and subsoil layers were built following the typical field application procedure to simulate the real-world conditions.

Figure 1. Experiment setups - photo (L) and conceptual illustration(R)

2.1. Sand-Based Pervious Brick

The pervious brick used in this study is based on an innovative pervious material made of silica sand [11]. The brick is featured with micron-level pores averaging about 50-100µm in diameter. Figure 2 shows photos of the brick, an SEM image of the pores, and a typical project application.

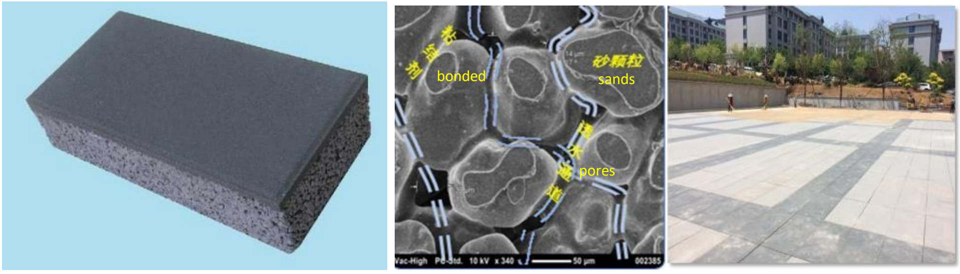


Fig 2. Silica sand-based pervious brick with micron-level pores. The brick (L), SEM photo (M), and typical applications

The experiment boxes were carefully size to install one full piece of pervious brick (900mm×450mm×100mm) in each. The porosity of the brick is 22.5%, and the infiltration rate is above 0.025 cm/s. In this study, the infiltration rate of the brick is higher than the simulated rainfall intensity, and water was fully infiltrated through the system.

2.2. Subbase layers

The subbase layers (Layer #2 - #5 as shown in Figure 1) under the brick, from top to bottom, are 30mm thick of coarse sand, 150mm pervious concrete, and 200mm gravel, respectively [12].

2.3. Subsoil

Under the pervious paver and the subbase is 500mm of subsoil (Layer #6 in Figure 1). Soil A used in Box A (GPS coordinates: 40°21'28"N; 116°48'21"E, 1 m below grade) and Soil B used in Box B (GPS coordinates 40°23'02"N; 116°47'22"E, 0 m below grade) are both classified as Sand per USDA

(See Figure 3) [13]. They are similar in particle sizes with a major difference that Soil B, obtained from the ground surface, contains visible root residues, as shown in Figure 4.

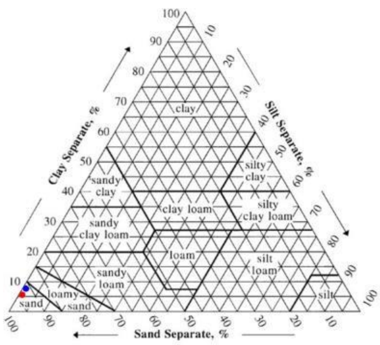


Figure 3. USDA soil classification (blue: Soil A& red: Soil B)

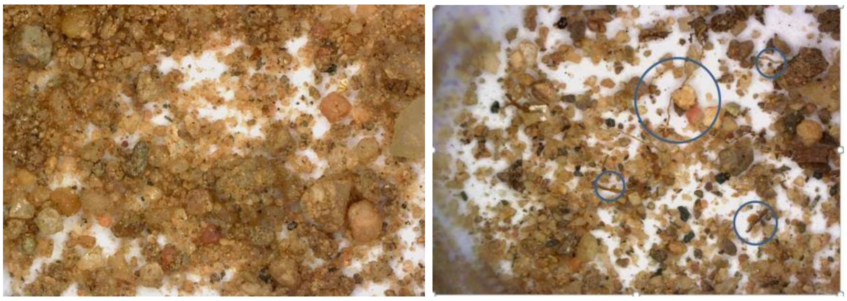


Figure 4. Soil A and B microscope images – blue cycles highlighting root residues

2.4. Bottom and Outlet

Pre-washed gravels wrapped with Geotextile were used below the subbase materials. Embedded perforated tubes were used to collect and divert effluent samples through holes at the bottom.

3. METHODOLOGY

3.1. Stormwater Runoff (inlet sample)

Stormwater runoff samples (approximately 200 litters each) were collected in the autumn of 2019 and spring of 2020 from a major roadway in Miyun Economic Development Zone of Beijing (GPS coordinates: 40°21'31"N, 116°48'28"E). Samples were analysed and later used to simulate rainfall in the laboratory.

3.2. Rainfall Simulation and Infiltrated Water Sample (outlet sample)

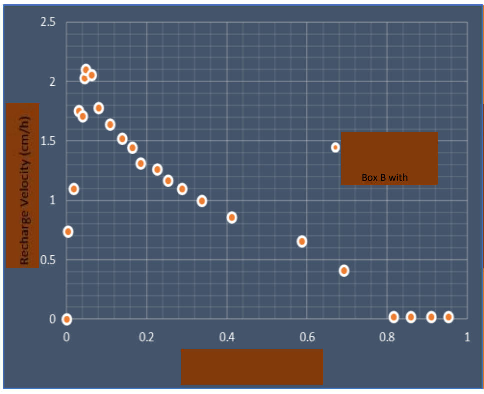
Two infiltration experiments were completed. Experiment 1, using runoff sample 1 collected in the fall of 2019, were completed under saturated subsoil condition; while Experiment 2, using runoff sample 2 collected in spring of 2020, were completed under dry subsoil conditions. During the experiments, runoff samples were evenly sprinkled on the surface of the sand-based bricks. Table 1 describes the equivalent rainfall intensity and duration of the simulated rainfall events.

The infiltrated water samples were collected at the outlets of the boxes. Flow rates were also measured and recorded using the bucket and stopwatch method.

4. RESULTS

4.1. Infiltration and Recharge Water Quantity

Figures 5 to 8 are the effluent flow at the outfalls during Experiments 1 and 2.



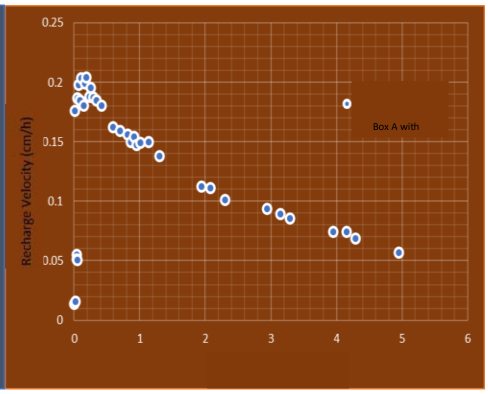
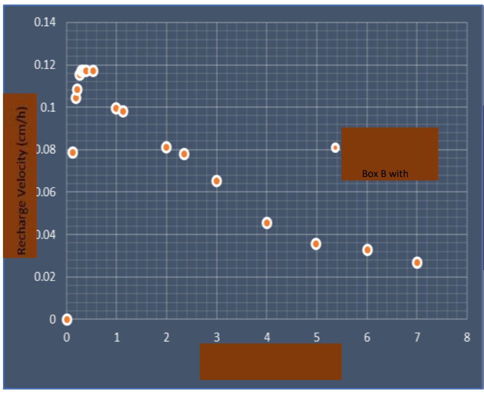


Figure 5. Infiltration Experiment 1, Box A   Figure 6. Infiltration Experiment 1, Box B



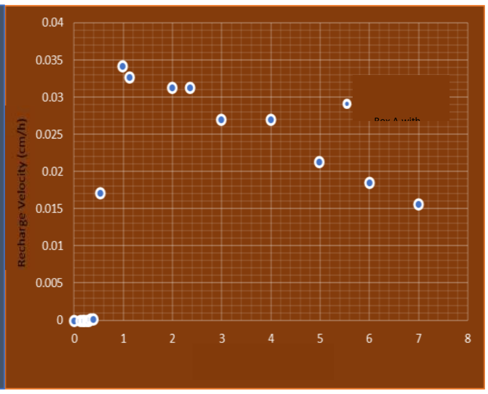


Figure 7. Infiltration Experiment 2, Box A   Figure 8. Infiltration Experiment 2, Box B

During Experiment 1, The effluent lag time of Box A and Box B was 3 hours and 1 hour, respectively. The peak flow reduction rates were 99.2% and 91.5%, respectively. During Experiment 2, The lag time of Box A is about one day, which is 2.5 times that of Box B. Also similar to Experiment 1, the peak infiltration flow from Box A is about one-fifth of Soil B, showing better retention by Soil A. Table 2 summarised the major water quantity-related results of the two infiltration experiments.

Table 1. Summary of Infiltration Test Results (Quantity)

	Infiltration Experiment 1 using Event 1 sample, saturated subsoil		**Infiltration Experiment 2 using Event 1 sample, dry subsoil**	
	Soil A	Soil B	Soil A	Soil B
Duration of simulated rainfall	40min		135min	
Simulated rainfall intensity	253mm/h		105 mm/h	
Simulated rainfall depth	190mm		237mm	
Lag time of peak flow	0.15d	0.05d	1d	0.4d
Peak flowrate reduction	99.2%	91.5%	99.7%	98.8%
Time of 50% flow attenuation	2.1d	0.25d	6.5d	3.5d

Comparing Experiments 1 and 2, the initial water content has a significant impact on infiltration. This is in line with the Green-Ampt infiltration equation. Saturated water in the pores has assisted in pulling down water above, thus has a positive impact on the infiltration. Comparing infiltration rates of Boxes A and B, the root residues in Soil B have a positive impact on the infiltration rates. This observation is similar to the research conducted by Wang et al.,[14] in which the steady infiltration rates of the soil with plant roots were 2~5.23 times higher.

4.2. Stormwater Runoff Quality

Constituent concentrations in the stormwater runoff samples were analysed and summarized in Table 2.

Table 2. Stormwater Runoff Quantity

Constituents	Event 1	Event 2	USEPA Benchmark value	Bench- mark values exceedance ①	USEPA NURP EMC	Compare to Mean of EMC③
TSS/ (mg/L)	173	1255	100	1 of 2	141～224	Higher
COD/(mg/L)	76	272	120	1 of 2	73～92	Higher
TP/(mg/L)	0.2	1.1	2	0 of 2	0.37～ 0.47	Higher
TN/(mg/L)	12.7	2.4	—②	—	1.62～ 2.12	Higher
pH	7.39	7.21	6.0～9.0	0 of 2	-	-
Pb/(mg/L)	0.042	0.1	0.0816	1 of 2	0.161～ 0.204	Lower
Zn/(mg/L)	0.664	1.23	0.117	2 of 2	0.179～ 0.226	Higher
Fe/(mg/L)	7.74	39.8	1	2 of 2	—	—
Cd/(mg/L)	0.0012	ND	0.0021	0 of 2	—	—
Mn/(mg/L)	0.19	0.87	1	0 of 2	—	—
Al/(mg/L)	6.06	29.4	0.75	2 of 2	—	—

Note ①: High risk refers to the concentration of pollutants in both samples exceeding the USEPA benchmark value; Medium risk refers to one sample exceeded the benchmark value; Low risk refers to neither. Note ②: USEPA has established a benchmark value of nitrate + nitrite nitrogen based on NURP EMC. There is no benchmark value for total nitrogen. Note ③: Comparing to the average value of the EMC range published by NURP study.

Compared with EPA Benchmark Values and NURP studies, most constituent concentrations in the runoff were relatively high, especially TSS, COD, Zn, Fe, and Al. Watershed management and stormwater runoff treatment are highly recommended to avoid negative impacts on the environment.

4.3. Recharge Water Quality

Table 3 summarizes the effluent water quality.

Table 3. Characteristics of Recharge Water Quality

Parameter	Experiment 1		Experiment 2		USEPA Bench Mark Value	Benchmark Value Exceedance ②
	Box A Effluent	Box B Effluent	Box A Effluent	Box B Effluent		
TSS/(mg/L)	33	39	100	291	100	1 of 4
COD/(mg/L)	89	95	65	341	120	1 of 4
TP/(mg/L)	0.04	0.16	0.25	0.23	2	0 of 4
TN/(mg/L)	4.99	7.3	0.81	0.29	- ①	-
pH	7.97	8.39	7.51	8.02	6.0-9.0	0 of 4
Pb/(mg/L)	0.007	0.011	ND	ND	0.0816	0 of 4
Zn/(mg/L)	0.014	0.015	0.041	0.047	0.117	0 of 4
Fe/(mg/L)	0.13	0.36	0.38	14.4	1	1 of 4
Cd/(mg/L)	0.047	0.0006	ND	ND	0.0021	0 of 4
Mn/(mg/L)	0.02	0.19	0.74	19.2	1	1 of 4
Al/(mg/L)	0.047	0.066	1.79	1.90	0.75	2 of 4

①：USEPA has established a benchmark value of nitrate + nitrite nitrogen based on NURP EMC. There is no benchmark value for total nitrogen. ②: Comparing individual outfall samples in each experiment with USEPA benchmark values.

The water quality of the effluents collected at the outfalls, which can be considered as simulated recharge water, is much better than that of the stormwater runoff. Thanks to the removal by the micron-level pores of the pervious brick and the subsoil, only a few constituent concentrations exceeded the USEPA Benchmark Values.

In these experiments, 500mm of subsoil was installed and highly contaminated runoff samples were used. The recharge quality can be better when thicker subsoil presents. This is in line with design suggestions that the bottom of the recharge facility should be at least 1m higher than groundwater level [15].

4.4. Removal rates

The removal rates through the experiment setups are summarized in Table 4. Removal rates in general, are higher than many previous studies [8][9].

Table 4. Removal through the Pervious Brick System

	Experiment 1		Experiment 1	
	Box A	Box B	Box A	Box B
Turbidity	94.0%	92.4%	99.9%	94.7%
TSS	80.9%	77.5%	92.0%	76.8%
COD	-17% ①	-25% ①	76.3%	-25% ①
TP	80.0%	20.0%	77.3%	79.1%
TN	60.7%	42.5%	66.3%	87.9%
Pb	83.3%	73.8%	50% ②	50% ②
Zn	97.9%	97.7%	96.7%	96.2%
Fe	98.3%	95.3%	99.0%	63.8%
Cd	91.7%	50.0%	- ③	- ③
Al	99.2%	98.9%	93.9%	93.5%

Note: ①: constituents in effluent increased. ②: not detected in the effluent. half of the detection limit was used in calculation. ③: not detected in both influent and effluent.

5. CONCLUSIONS

The sand-based brick performed well in stormwater runoff treatment and infiltration. The system tested, which includes the pervious brick, subbase, and 500mm of subsoil, demonstrated a lag time from 0.15 to 1 day, and the peak infiltration flow rates were reduced by 91.5% to 99.7%, comparing to the inflow. The recharge process lasted from 1 day to several days. Stormwater runoff samples collected from the road in an industrial park in Beijing showed high risks on pollution potential. However, the water quality of the recharge improved significantly thanks to the micro-level pores of the bricks and the subsoils. The pavement system is efficient in removing pollutants, and the average removal of TSS, TP, and TN were 81.8%, 64.1%, and 64.4%, respectively. The removal rates of Pb, Al, Zn, Fe, Cd also reached 50%-99.2%. Additional studies with different subsoil under different rainfall patterns are suggested in the future to further study the recharge quantity and quality through the system.

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