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Sediment transport and pore clogging of a porous pavement under surface runoff

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Drainage capacity of pervious concrete pavements will be greatly decreased once the pores become clogged. In this study, the mechanism of sediment clogging in the pores of the pervious concrete pavement under surface runoff is preliminarily revealed. Based on the modified permeability measurement system, a series of laboratory simulation tests are conducted to demonstrate the effects of porosity of pervious concrete, sediment size, depth of free surface flow, storm water runoff velocity on the permeability reduction due to clogging of the porous pavement. Within the scope of this study, the clogging is observed to more easily occur for specimens with large porosity, for well-graded sand as the clogging materials and large storm water depth. Horizontal runoffs has little influence on the final clogging ratio.

Keywords: porous pavement; clogging; sediment transport; surface runoff

1. Introduction

Portland cement pervious concrete, also referred to as porous concrete, is a relatively newer kind of concrete that is a mixture of Portland cement, uniform coarse aggregate, with either a small amount of or without fine aggregate, and water. Generally, the porosity of pervious concrete is between 15% and 25%, and the permeability is typically about 2 ∼ 6 mm/s, up to 10 mm/s (Montes, Valavala, & Haselbach, 2005; Tennis, Leming, & Akers, 2004). The primary benefit offered by pervious concretes is their ability to transport large volumes of water through the material structure, thus reducing or eliminating problems associated with storm-water runoff. Other environmental benefits of this material include the ability to reduce tire–pavement interaction noise, limiting the amounts of pollutants entering the groundwater, and reducing urban heat island effects.

Although there have been significant progresses in the conventional pavement diseases area (Hou, Wang, Yue, Pauli, & Sun, 2014; Hou, Yue, et al., 2014), the detailed research in the previous pavement diseases is still rare. Clogging is the most serious disease that restricts the application of pervious pavement. The suspended solid matter such as dirt, fine sand, and debris contained by the influx of storm water can get into the pervious surface, and lead to a gradual reduction in the permeability of pervious concretes pavements (Nielsen, 2007; Siriwardene, Deletic, & Fletcher, 2007; Tan, Fwa, & Han, 2003).

Many studies on clogging due to long-term deposition of particles or clogging phenomena based on cycle tests have been reported (Deo, Sumanasooriya, & Neithalath, 2010; Haselbach, Valavala, & Montes, 2006; Kayhanian, Anderson, Harvey, Jones, & Muhunthan, 2012; Neithalath, Weiss, & Olek, 2006; Reddi, Ming, Hajra, & Lee, 2000). Kayhanian et al. (2012)

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assessed clogging of pervious concrete pavements in parking lots using the falling head method with National Center for Asphalt Technology device in the field. Haselbach et al. (2006) studied both theoretically and experimentally runoff on a permeable concrete block. A relation between the permeability of the sand-clogged pervious concrete block system, the porosity of the block near the surface and the permeability of the sand was established theoretically as an effective permeability equation for sand-clogged pervious concrete and verified experimentally in the flume experiments for the conditions tested with high rainfall intensities. Numerical simulation of the sediment transport and retention over porous region has also received considerable attention in recent years (Deo et al., 2010; Hou, Huang, Sun, & Guo, 2016; Hou, Sun, et al., 2016; Reddi et al., 2000).

Extreme rainfall weather events occur more and more frequently, which can bring about significant reduction of permeability of the pervious concrete pavement. The heavy rainfall may triggers flash flooding and landslides (Reiser, Ramey, & Wesche, 1989), a lot of fine and coarse sand may be carried to the surface of pavement, and the drainage system may be paralysed, so there could be a large water depth and runoff flow velocity over the pavement surface. This study focuses on the simulation of rapid clogging caused by these rain events, in which the pervious pavement is saturated and covered by a certain depth of free surface runoff. A series of laboratory simulation tests are conducted to demonstrate the effects of porosity of pervious concrete, sediment size, depth of free surface flow, storm water runoff velocity on the clogging of the porous pavement.

2. Experimental programme

2.1. *Modified permeability test device*

In this study, a simulation system is developed, as shown in Figure 1.

The permeability is acquired by the Darcy's law, as Equation (1) shows. However, since the petroleum jelly is used to daub the sample sidewall to seal the open pores on the surface for the modified developed device, the effective cross section is smaller than that of the specimen. The effective area can be calculated as Equation (2) shows:

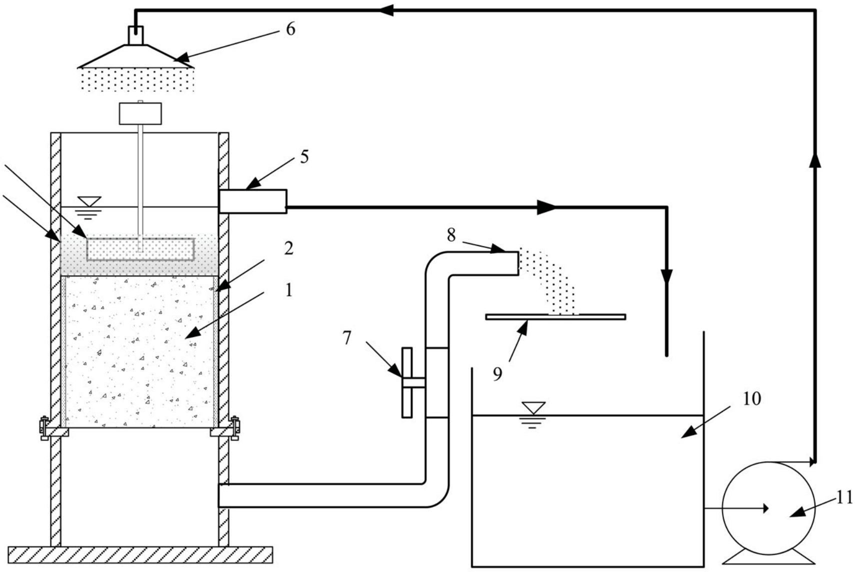
$$k = \frac{QL}{A\Delta h}, \tag{1}$$

$$A_{ef} = A - \frac{V_V}{L}, \tag{2}$$

where k is the permeability; Q is the flow rate; L is the length of the specimen; Δh is the head loss; A is the specimen area; A_{ef} is the effective area of cross section of the specimen; V_V is the volume of petroleum jelly daubed on the specimen.

A simplification is made in this experimental simulation, only horizontal pavement is studied, because the horizontal pavement is more easily clogged than sloped pavement. Another reason to apply this simplification is that both the surface layer and sub-base of pervious concrete pavement is made up by materials with very high permeability, and compared with horizontal seepage, the vertical seepage is predominant.

In the test, water is evenly sprayed over the specimen (1 in Figure 1) using a sprinkler (6 in Figure 1) in order to simulate the rainfall, the depth of water is used to simulate the depth of storm runoff, and the water depth keeps constant by an overflow (5 in Figure 1) during one simulation case. An impeller (4 in Figure 1) promoted by micro motor is installed to form the horizontal runoff. The impeller is made by a flat metal sheet with the length of 60 mm, and the distance the between bottom of impeller and the surface of the specimen is 10 mm.



1. Pervious concrete sample; 2. Petroleum jelly and rubber cushion; 3. Plexiglass sleeve; 4. Impeller; 5. Overflow (height changeable); 6. Sprinkler; 7. Valve; 8. Outflow; 9. Filter; 10. Water container; 11. Pump.

Figure 1. Schematic of the simulation system.

Table 1. Coarse aggregate physical indexes.

Particle size (mm)	Apparent density (g/cm^3)	Stacking density (g/cm^3)	Porosity (%)	Crushed value (%)
4.75 ~ 9.5	2.665	1.655	37.89	8.6

2.2. *Pervious concrete*

The physical indexes of aggregates used in pervious concrete mixtures are listed in Table 1. The pervious concrete mixture is designed for three target porosities, that is, 15%, 20% and 25%. The mix design method used in this study is presented in authors' previous study (Cui et al., 2015). Specimens were cast in the ϕ100 mm × 100 mm cylindrical moulds. For each case nine specimens were prepared and porosity was measured after standard curing. Only three specimens for each case which best fits to the target porosities are used in this experimental study.

2.3. *Clogging materials*

The clogging materials used in this study were fine and coarse sizes and the mixture of both sizes. The compositions of three types of clogging materials are listed in Table 2.

2.4. *Experimental procedure*

(1) The specimen is pre-saturated in water for 24 h, then it is taken out, wiped, and the side is daubed with petroleum jelly and then covered with a flexible rubber cushion (2 in Figure 1). Then specimens are installed in the Plexiglass sleeve (3 in Figure 1), and the mounting bolts are screwed.

Table 2. Grading of clogging materials.

Particle size fraction (mm)	Fine sand (%)	Coarse sand (%)	Full grading sand (%)
1.18–2.36	0	45.8	32.4
0.6–1.18	0	54.2	38.2
0.3–0.6	77.6	0	22.8
0.15–0.3	22.4	0	6.6

Table 3. Test cases.

Cases	Pervious concrete porosity (%)	Water depth (mm)	Clogging materials	Reynolds number of horizontal flow
1	15	100	Fine	800
2	20	100	Fine	800
3	25	100	Fine	800
4	20	150	Fine	800
5	20	200	Fine	800
6	20	100	Coarse	800
7	20	100	Well-graded	800
8	20	100	Fine	4700
9	20	100	Fine	14100

(2) The outlet tap (7 in Figure 1) is turned off, and then the circulating fluid is sprayed evenly into the sleeve. When the water depth is achieved to the required level and no bubbles appear from the specimen, the tap is turned on, thus a constant hydraulic head is applied to form a steady flow. Outflow rate is measured, and the initial permeability is acquired.
(3) 50 g clogging materials (sands) are evenly added in 30 s. The permeability is measured for several times till there is no noticeable change in permeability.
(4) After the test, the specimen is taken out, and the sand outside the specimen is collected, dried in the oven and sieved to analyse the grading of the sand.
(5) Change the parameters, including porosity of pervious concrete, sediment size, depth of free surface flow, storm water runoff velocity, etc., and repeat the steps 1–4.

2.5. *Parameters of the study*

Table 3 presents the parameters used in this study. Three water levels above the upper surface of the specimen are used to simulate the different storm water depth. Three horizontal rotate velocities of impeller are used to study the effect of storm water runoff velocity on clogging, which are 5 r/min (low rotate velocity, which is equivalent to a maximum of runoff velocity of 0.016 m/s and average runoff velocity of 0.008 m/s, the Reynolds number is 800), 30 r/min (medium rotate velocity, which is equivalent to a maximum of runoff velocity of 0.094 m/s and average runoff velocity of 0.047 m/s, the Reynolds number is 4700) and 90 r/min (high rotate velocity, which is equivalent to a maximum runoff velocity of 0.283 m/s and average runoff velocity of 0.141 m/s, the Reynolds number is 14100). Three kinds of clogging materials are used to evaluate the effect of size of clogging material on clogging. For each case, three samples are tested.

3. Experimental results and analysis

The mean value of permeability of the specimen 2 min before adding sand was taken as the initial permeability coefficient of pervious concrete. The permeability of clogged specimen can be obtained when there is no noticeable change in permeability, as the average value of permeability between 16 and 20 min after adding sand, then the normalised permeability was acquired by dividing the initial permeability. Change of permeability 20 min after adding sand are shown in Table 4.

3.1. *Influence of pervious concrete porosity*

Three porosities of the specimens are used in the tests, that is, 15%, 20% and 25%, respectively, in order to study the influence of pervious concrete porosity on clogging (cases 1, 2 and 3 in Table 3). As Table 4 shows, specimens with larger porosity (e.g. 25%) are more severely to be clogged. This is because pore size and seepage velocity is larger in specimens with larger porosity, more particles will get into the pore system with seepage flow, thus increasing the possibility of particles clogged at the narrow part of the pathway.

After the tests, the sand outside the specimen is collected, dried and sieved. Sand size distributions before and after tests are shown in Table 5. When the porosity is increased, the mass of sand over the surface of the specimen are found to be smaller. This is because more sand can accumulate inside the specimen with larger porosity. In addition, as the porosity increases, the coarser constituent of sand outside the specimen range from 0.3 to 0.6 mm reduces but the finer sand range from 0.15 to 0.3 mm increases. This suggests that bigger particles are more easily to be clogged in larger porosity specimens while smaller ones are not. According to the research of Deo et al. (2010), there is a certain pore size to particle size ratio range in which the permeability reduction is the maximum.

Table 4. Change of permeability 20 min after adding sand.

Case	Average value of permeability (mm/s)		Normalised permeability
	Initial	20 min later	
1	1.39	1.03	0.74
2	1.72	1.33	0.77
3	3.55	2.27	0.64
4	2.25	1.46	0.65
5	2.86	1.6	0.56
6	2.23	2.15	0.96
7	2.12	1.49	0.70
8	2.17	1.69	0.78
9	1.92	1.58	0.82

Table 5. Size distributions of sand before and after test for different porosities.

Sand size	Sand added		Sand outside the specimens					
			15% porosity (case 1)		20% porosity (case 2)		25% porosity (case 3)	
	Mass (g)	Percentage	Mass (g)	Percentage	Mass (g)	Percentage	Mass (g)	Percentage
0.3–0.6 mm	38.8	77.6	33.6	75.3	31.6	74.9	18.0	74.7
0.15–0.3 mm	11.2	22.4	11.0	24.7	10.6	25.1	6.1	25.3

Table 6. Size distributions of sand before and after test for different water head.

Sand size (mm)	Sand added		Sand outside the specimens					
			100 mm head (case 2)		150 mm head (case 4)		200 mm head (case 5)	
	Mass (g)	Percentage	Mass (g)	Percentage	Mass (g)	Percentage	Mass (g)	Percentage
0.3–0.6	38.8	77.6	31.6	74.9	29.7	75.7	27.4	77.2
0.15–0.3	11.2	22.4	10.6	25.1	9.5	24.3	8.1	22.8

3.2. *Influence of storm water depth*

In order to study the influence of storm water depth on clogging, water head has been changed in the test, ranging from 100, 150 and 200 mm (cases 2, 4 and 5 in Table 3). As Table 4 shows, 20 min after adding sand, the permeabilities become 0.77, 0.65, and 0.56 times of their initial values. Therefore, specimens with larger water head are more easily to be clogged. This is because larger water head causes a larger seepage velocity, more particles get into the pore structure with seepage flow, thus increasing the possibility of particles clogged at the pathway. This indicates that under deeper storm water the pervious concrete pavement is more easily to get clogged.

Table 6 shows the sand size distributions before and after tests under different water head. As the head increases, total mass of the sediments outside the specimens 20 min after adding sand decreases, 0.3–0.6 mm sand constituent increases while 0.15–0.3 mm decreases. That is because a smaller seepage velocity caused by lower water head makes the coarser particles prone to be clogged at the gate of passageway and stop the finer particles getting inside of the specimen. While, a higher water head makes the coarser particles which temporarily clogged easy to shift their positions and restart moving under a larger pressure. As is shown in the table, the component concentration of sand outside the specimen is basically the same as that before tests under the water head of 200 mm.

3.3. *Influence of clogging materials grading*

The grading of clogging materials is changed in the test in order to study on its influence on clogging (cases 2, 6 and 7 in Table 3). Fine, coarse and well-graded sand acted as the clogging materials (Table 2). As Table 4 shows, 20 min after adding sand, the permeabilites become 0.77, 0.96 and 0.70 times of their original values, respectively. Thus, clogging is not obvious in the specimens adding coarser particles and the reduction factor of permeability of specimen adding coarse sand is just 0.96 times of the value before the test. That is because bigger particles are prone to clogging in the pores near the upper surface and hard to access into the specimen, which has little influence on the inner permeability. The permeability of well-graded sand reduces most because the coarser sand blocks the upper pores while the finer sand fills the rest, which makes the permeability plunge. The reduction of permeability of fine sand is also serious. This can be explained by fine sand can easily get into the pore structure of the specimen and clogged at "pore throats", indicating the micro-structure will affect the performance (Hou, Wang, Pauli, & Sun, 2015).

Table 7 shows the sand size distributions before and after tests the sand in different gradings. As Table 7 shows, the specimen with well-graded sand added clogged most. The specimen with coarse sand is clogged least because the proportion of the pore sizes and particles diameter is smaller than the minimum proportion for serious clogging.

Table 7. Size distributions of sand before and after test for sand of different gradings added.

Sand size (mm)	Fine sand (case 2)				Well-graded sand (case 9)				Coarse sand (case 8)			
	Sand added		Sand outside the specimens		Sand added		Sand outside the specimens		Sand added		Sand outside the specimens	
	Mass (g)	Percentage	Mass (g)	Percentage	Mass (g)	Percentage	Mass (g)	Percentage	Mass (g)	Percentage	Mass (g)	Percentage
1.18–2.36	0	0	0	0	16.2	32.4	15.4	40.8	22.9	45.8	21.9	53.9
0.6–1.18	0	0	0	0	19.1	38.2	13.2	35.0	27.1	54.2	25.6	46.1
0.3–0.6	38.8	77.6	31.6	74.9	11.4	22.8	6.6	17.5	0	0	0	0
0.15–0.3	11.2	22.4	10.6	25.1	3.3	6.6	2.5	6.6	0	0	0	0

Table 8. Size distributions of sand before and after test for different horizontal flow velocities.

Sand size (mm)	Sand added		Sand outside the specimens					
			Low speed (case 2)		Medium speed (case 8)		High speed (case 9)	
	Mass (g)	Percentage	Mass (g)	Percentage	Mass (g)	Percentage	Mass (g)	Percentage
0.3–0.6	38.8	77.6	31.6	74.9	30.7	74.2	31.0	74.0
0.15–0.3	11.2	22.4	10.6	25.1	10.7	25.8	10.9	26.0

3.4. *Influence of horizontal runoff*

Rotation speed of impeller was changed in the test in order to study on the influence of horizontal runoff on clogging (cases 2, 8 and 9 in Table 3). Three rotation speeds were used in the test including low speed (5 rpm), medium speed (30 rpm) and high speed (90 rpm). As Table 4 shows, the permeabilities of specimens are 0.77, 0.78 and 0.82 times of their initial values, respectively. The permeabilities are roughly equal after clogging stabilised.

As Table 8 shows, the total mass of the sand outside the specimen remained unchanged as the flow velocities rise. They are 42.2 g, 41.4 g and 41.9 g, respectively. It is also shown in the table that the mass of finer sand outside the specimen increases as the horizontal flow velocities increase. It might be because the finer sediments are carried by the flow and suspend in the water above the specimen while the coarser ones can only roll on the specimen surface and get stuck as they encounter pores.

4. Conclusions

This paper has described a study on fluid-driven sediment transport and retention over pervious concretes pavement with experimental approach. A series of laboratory simulation tests are conducted to analyse the effects of porosity of pervious concrete, pore size, depth of free surface flow, flow velocity on sediment transport and pore clogging of the porous pavement. Within the scope of this study, the clogging is observed to more easily occur in specimens with large porosity, for well-graded sand as the clogging materials and large storm water depth. Horizontal runoffs has little influence on the final clogging ratio.

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