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ABSTRACT

Pervious concrete pavements have good drainage capabilities; however, storm water runoff during extreme events can cause the pores clogging in permeable pavement. This study aims to preliminarily reveal the mechanism of sediment clogging in the pores of the pervious concrete pavement under storm water runoff. An innovative continuous permeability measurement system combined with the electrical conductivity measurement is developed. Laboratory simulation tests are conducted with this system to demonstrate the effects of four factors on the permeability reduction. The tests indicate that the pore clogging process generally includes three phases, i.e. quick clogging, temporary mitigation of clogging and progressive clogging. The clogging is more prone to occur in specimens with large porosity. Meanwhile, the variation of electrical conductivity of pervious concrete can accurately reflect the clogging process of pervious concrete. A rapid clogging model has been developed and validated. Research results obtained are important in optimising the design and evaluation of pervious concrete pavement.

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Pervious concrete pavement; storm water runoff; clogging; permeability; pore structure

1. Introduction

Portland cement pervious concrete has a large number of interconnected pores within the aggregate skeleton. Generally, the porosity of pervious concrete is between 15 and 25%, and the initial permeability is typically between 2 and 6 mm/s but can be as high as 10 mm/s (Tennis *et al.* 2004, Montes *et al.* 2005). However for the pervious concrete pavement, the solid matter suspended in storm water runoff can get into the pervious surface, and lead to a gradual reduction in the permeability (Yong *et al.* 2008). This reduction in permeability decreases the service life of pervious concrete pavement (Tan *et al.* 2003). Porous concrete was susceptible to clogging within the first three years (Scholz and Grabowiecki 2007). Chopra *et al.* (2010) compared the pavement cleaning method and found that pressure washing was much more effective than vacuum sweeping for completely clogged cores.

The permeability reduction of porous systems may be caused by two kinds of siltation processes, i.e. a slow siltation process with the continuing or cyclic deposition of small quantities of sediments, and a rapid siltation process triggered by a sudden slump or landslide (Reiser *et al.* 1989). Many studies on slow siltation process i.e. clogging due to long-term deposition of particles or clogging phenomena based on cycle tests, have been reported (Reddi *et al.* 2005, Haselbach *et al.* 2006, Neithalath *et al.* 2006, Deo *et al.* 2010, Kayhanian *et al.* 2012). Kayhanian *et al.* (2012) assessed clogging of pervious concrete pavements in parking lots using the falling head method with NCAT device in the field. In order to evaluate the contribution of pore towards the clogging susceptibility, Deo *et al.* (2010) developed a falling head permeability cell to measure cycling simulation of clogging.

Storm water runoff during extreme events can bring about significant reduction of permeability of the pervious concrete pavement. For example on 21 July 2012, an extreme storm hit the city of Beijing, the average urban rainfall achieved 200 mm during the period of 1 h. The heavy rainfall triggered flash flooding and landslides, fine and coarse sand were carried to the surface of pavement, and there was a large water depth and runoff flow velocity on the pavement surface. Thus, a quantitative relationship that models the rapid clogging process is needed. This study focuses on the simulation of catastrophic clogging caused by these extreme events. A clogging simulation system combined with permeability and electrical conductivity continuous measurement of pervious concrete is developed. Laboratory simulation tests are conducted with this system to demonstrate the effects of porosity of pervious concrete, sediment size, depth of free surface flow, storm water runoff velocity on the permeability reduction. A preliminary rapid clogging model is derived based on the test results.

2. Development of real-time simulation system of pore clogging process

Existing testing apparatuses of concrete permeability cannot continuously measure the change of permeability of the specimens during the process of clogging. In this study, a device is

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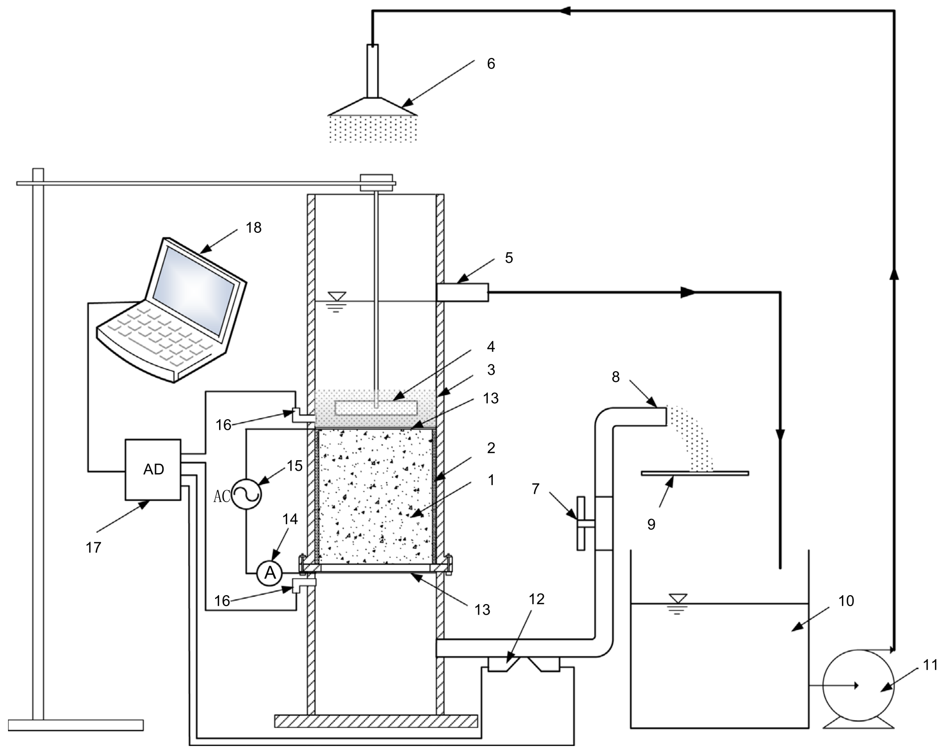

1. Pervious concrete sample; 2. Petroleum jelly and rubber cushion; 3. Plexiglass sleeve; 4. horizontal runoff maker (impeller); 5. Overflow (height changeable); 6. Sprinkler; 7. Valve; 8. Outflow; 9. Filter; 10. Water container; 11. Pump; 12. ultrasonic wave flow meter; 13. wire netting; 14. Current meter; 15. alternate current power source; 16. Pressure sensor; 17. Data acquisition system; 18. PC.

Figure 1. Schematic of the clogging simulation system.

developed. The main structure is shown as Figure 1. Its functions mainly are: (1) to avoid leakage on the pervious concrete specimen sidewalls during tests by using waterproof daub and flexible rubber cushion (Cui *et al.* 2015); (2) to continuously record the changing processes of the permeability and the electrical resistivity of specimen in clogging process; and (3) to simulate the horizontal storm water runoff on the pervious concrete pavement.

As shown in Figure 1, two water pressure sensors and an ultrasonic velocity meter are installed to continuously record the changing of permeability in clogging process through an A/D (Analog to Digital) converter. The head loss between the upper and bottom surfaces of the specimen can be acquired by the water pressure sensors and the seepage velocity can be acquired through the ultrasonic velocity meter. The permeability is calculated by the method presented by Cui *et al.* (2015).

Electrical resistivity has already been used to characterise the porosity concrete (Zhang *et al.* 2014). The electrical resistivity is also employed to characterise the clogging process of pervious concrete in this study. In order to form an electric circuit in the saturated pervious concrete specimen, 10% salt water (the density is 1.070 g/cm^3) is used as the circulating fluid. As this study mainly focuses on millimeter scale sand particles, the influences of ionic strength of the permeating fluid on permeability reduction can be ignored (Hajra *et al.* 2002). As shown in Figure 1, two copper meshes (13) are placed on both sides of the specimen as the electrodes are connected to an alternating current power (15) of 12 V. The current and power changes in the specimen are continuously measured by a multimeter (14) connected to the computer (18) via an A/D converter (17), therefore the electrical resistivity of pervious concrete specimen can be calculated as follows (Zhang *et al.* 2014):

$$\rho = \frac{W}{A^2}\frac{S}{L} \quad (1)$$

where ρ is electrical resistivity; W is power; A is current; S is area of cross section of the specimen; L is length of the specimen.

The horizontal pavement is more easily clogged than sloped pavement. Thus, a simplification is made in this experimental simulation and only horizontal pavement is studied. As shown in Figure 1, water is evenly sprayed over the specimen (1) using a sprinkler (6) 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) during one simulation case. A horizontal flow maker (impeller, (4)) 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.

3. Test materials and procedure

3.1. *Pervious concrete*

Pervious concrete mixtures are prepared using ordinary Portland cement and coarse aggregates. The size of aggregates

Table 1. Mix proportions of per cubic meter of pervious concrete.

Target porosity (%)	Cement (kg/m^3)	Water (kg/m^3)	Aggregate (kg/m^3)	Water reducer (SS) dosage (%)
15	335	121		
20	262	94	1622	0.8
25	189	68		

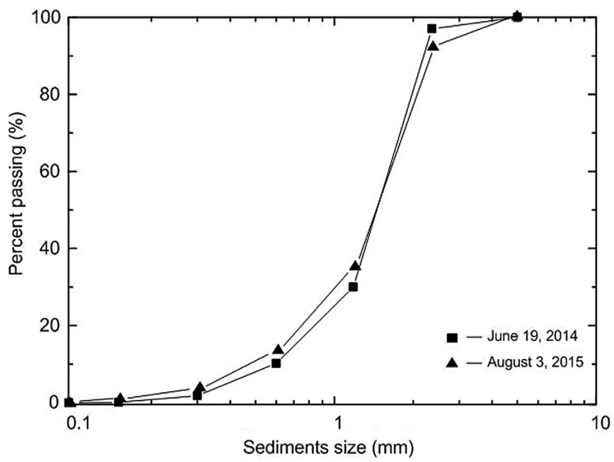

Figure 2. Gradation curves of collected sediments.

Table 2. Compositions of clogging materials.

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

Table 3. Test cases.

Cases	Pervious concrete porosity (%)	Water depth (mm)	Clogging materials	Horizontal flow velocity
1	15	100	Fine	Low
2	20	100	Fine	Low
3	25	100	Fine	Low
4	20	150	Fine	Low
5	20	200	Fine	Low
6	20	100	Coarse	Low
7	20	100	Well-graded	Low
8	20	100	Fine	Medium
9	20	100	Fine	High

is 4.75–9.5 mm, apparent density is 2.665 g/cm^3, stacking density is 1.655 g/cm^3, porosity is 37.89% and crushed value is 8.6%. The pervious concrete mixture is designed for three target porosities (15, 20 and 25%). The mix design method used in this study is presented by Cui *et al.* (2015). The mix proportions of pervious concrete per cubic meter are shown in Table 1. Specimens are cast in the ϕ100 mm × 100 mm cylindrical moulds.

3.2. Clogging materials

In order to analyse the gradation specification for sediments carried by storm water runoff, sediments were collected after storm events on 19 June 2014 and 3 August 2015 at the test site on Lvyou Road in Jinan, China, which has a pervious concrete pavement and is almost horizontal. During the storm events, sediments were washed out from the nearby hills and carried to this road. In Figure 2, the gradation specifications for collected sediments of both events are very close and the size of most sediment is in the range of 0.15–2.36 mm. Therefore, this size range is used to design clogging material mixtures. The clogging materials used in this study were obtained by sieving sand into fine and coarse sizes and the mixture of both sizes. The compositions of three types of clogging materials are listed in Table 2. In the test, 50 g clogging materials are evenly added in 30 s, and the clogging process is recorded. The permeability measurement continues till there is no noticeable change in permeability. After the test, the specimen is taken out, and the sand outside the specimen is collected, dried and sieved to analyse the grading of the sand.

3.3. Test cases

The test cases are shown in Table 3. Three water levels are set to 100, 150 and 200 mm above the upper surface of the specimen 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), 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) 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). For each case, 3 samples are tested, which means totally tested 27 samples for 9 cases.

4. Experimental results and analysis

The mean value of permeability of the specimen 2 min before adding sand is taken as the initial permeability coefficient of pervious concrete. Then the Normalized Permeability (NP) is acquired by dividing the initial permeability, the Normalized Electrical Resistivity (NER) is got with the same method.

4.1. Rapid clogging process of pervious concrete

The permeabilities of all cases have the similar development tendency. Taking the Case 1 in Table 3 for instance, the characteristics of time history curve of permeability are illustrated in Figure 3. As the figure shows, permeability reduces sharply after sand added (phase 1) and then slightly rises (phase 2), after that it has a slow decrease (phase 3) and finally gets stabilised. There are two characteristic time points (t_{1-2} and t_{2-3}) on the curve. The first characteristic time t_{1-2} corresponds to the intersection of phase 1 and 2, which implies the time when the fine sands that have entered the pervious concrete begin to escape from the bottom of the specimen. The second characteristic time t_{2-3} corresponds to the intersection of phase 2 and 3, and implies that at this moment less fine sand particles pass through the specimen.

Moveable sand in the specimen is driven by fluid flow, and the sand transport velocity v_s can be approximately obtained through dividing the length of specimen by t_{1-2}. As the Figure 3 shows,

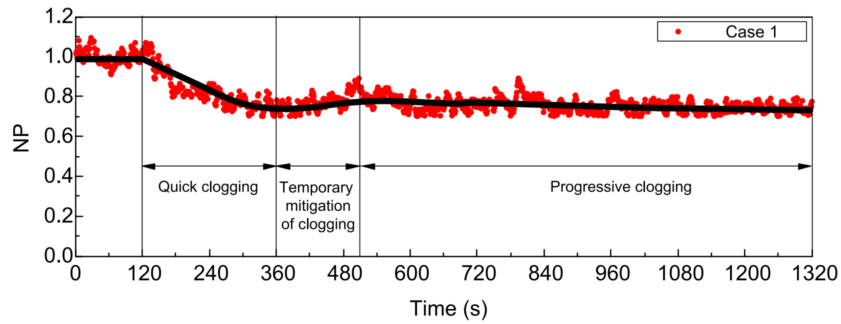

Figure 3. Variation of NP in pore clogging process.

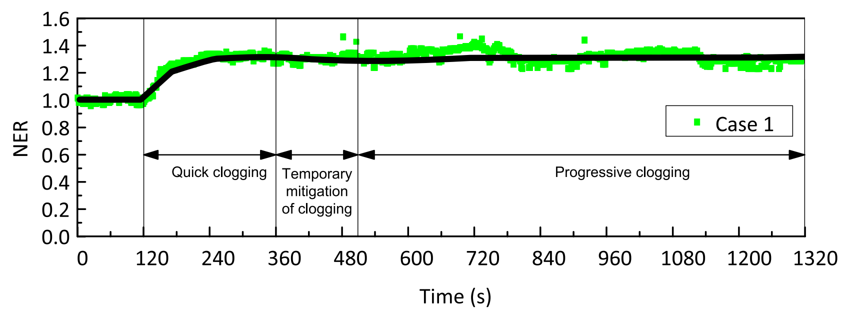

Figure 4. Variation of NER in pore clogging process.

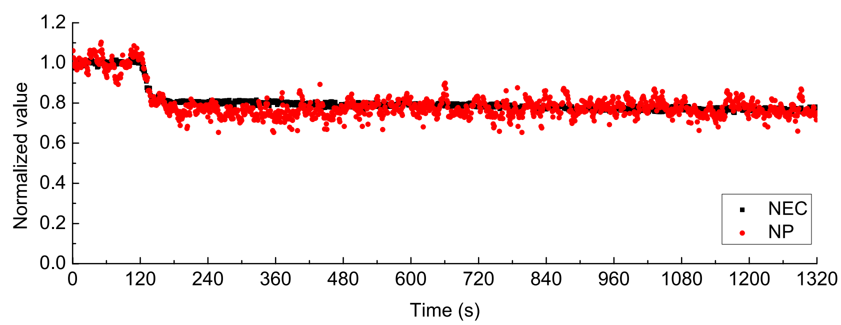

Figure 5. NEC time history and NP time history curves (take Case 2 for example).

in Case 1, t_{1-2} is 240 s, corresponding to the transport velocity v_s of 0.38 mm/s. At the initial time before adding sand, the average velocity of water in the specimen is 2.71 mm/s. It implies that the transport velocity of sand inside the pervious concrete is much lower than the fluid flow, as the transport of sand is prevented by the narrow pore structure of pervious concrete.

Figure 4 shows the NER time history curve of Case 1. As the result shows, the resistivity vs. time curve is opposite to the permeability vs. time curve. The resistivity of pervious concrete rises rapidly after adding sand and then falls back slightly. After that it rises again slowly and finally becomes stable. The sand clogged the pores inside the specimen also blocks the pathway of NaCl solution, and this results in not only the reduction of permeability but also the increase of resistivity.

4.2. Relationship between NP and electrical conductivity

As analysed above, the permeability-time history is contrary to resistivity-time history, as Normalized Electrical Conductivity (NEC) can be obtained by taking the reciprocal of normalized resistivity, so the relationship of NP and NEC is analysed. Figure 5 shows that the variation of NEC agrees well with the NP in clogging process. Compared with the measurement of permeability, electrical conductivity measurement is much more convenient, therefore, permeability can be determined more easily by measuring electrical conductivity.

The permeability of clogged specimen can be obtained as the average value of permeability from 16 to 20 min after adding sand. Similarly, the electrical conductivity after clogging could be acquired. The NP agrees well with NEC of clogged specimens as shown in Figure 6.

4.3. Influence of pervious concrete porosity on clogging

Porosity of pervious concrete specimen is changed in the test to study its influence on clogging process (Case 1, 2 and 3 in Table 3). Figure 7 shows NP time history curves of different porosities. For the porosity of 15 and 25%, 20 min after adding sand, the

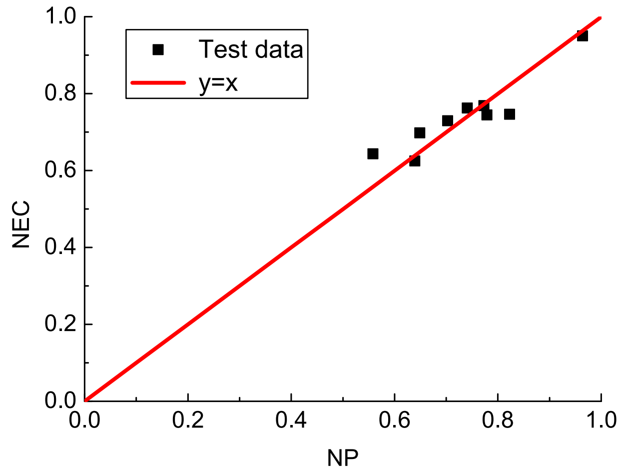

Figure 6. Average values of NP and NEC between 16 and 20 min after adding sand.

permeabilities become 0.74 and 0.64 times of their initial values, respectively. Therefore, specimens with larger porosity are more easily 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. Furthermore, larger porosity makes the transport time of fine sand through the specimen shorter. This is because specimens with larger porosity have smaller pathway tortuosity and larger effective diameter of pathways reduces the resistance of transport. From Figure 7, it can be also seen that permeability of the specimen with greater porosity (e.g. 25%) fluctuates largely after clogging. The probable reason is that the clogged particles move again and travel away through the pathways with seepage flow.

After the test, the sand outside the specimen is collected, dried and sieved. With the porosity increasing (15, 20 and 25%), the total mass of the sand left on the surface and passing through the specimen decreases (44.6, 42.2 and 24.1 g, respectively). In addition, as the specimen porosity increases, the coarser constituent of sand (0.3–0.6 mm) on the surface of the specimen reduces, and the mass of finer sand (0.15–0.3 mm) passing through the specimen increases. According to the research of Deo *et al.* (2010), there is a certain pore size to particle size ratio range in which the clogging occurs most severely.

4.4. Influence of storm water depth on pervious concrete clogging

In order to study the influence of storm water depth on clogging process, water head is changed in the test (Case 2, 4 and 5 in Table 3). Figure 8 shows NP time history curves of different water heads. For water heads of 100, 150 and 200 mm, 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 possibly because seepage velocity is larger under larger water head, more particles will get into the pore structure with seepage flow, thus increasing the possibility of particles clogged at the pathway. This phenomenon indicates pervious concrete pavement under deeper storm water is more easily to get clogged.

After the test, the sand outside the specimen is analysed. With the increasing of water depth (100, 150 and 200 mm), the total mass of the sand left on the surface and passing through the specimen decreases (42.2, 39.2 and 35.5 g, respectively); and the content of 0.3~0.6 mm sand increases (74.9, 75.7 and 77.2%),

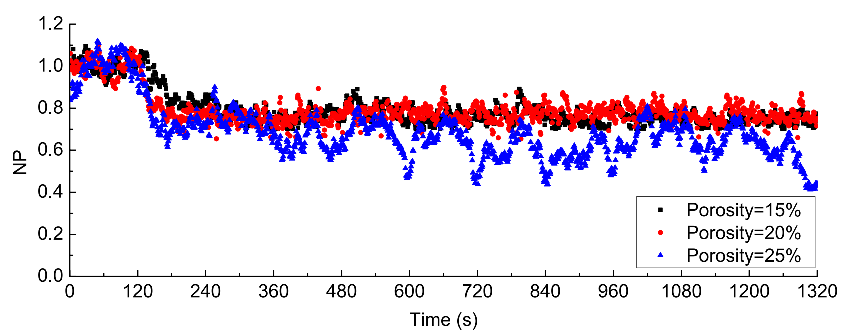

Figure 7. NP time histories of pervious concrete specimens with different porosities.

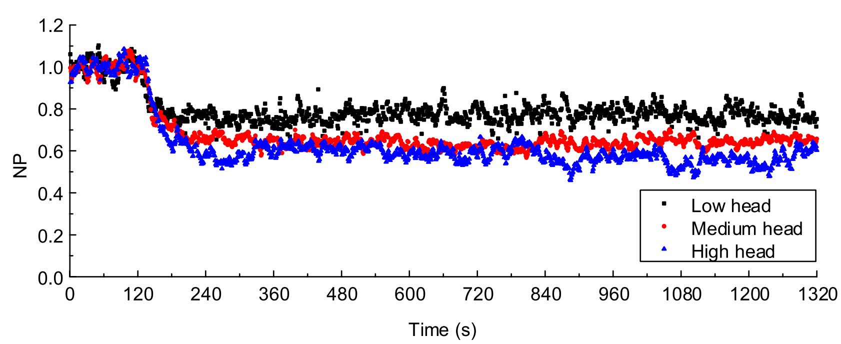

Figure 8. NP time histories of pervious concrete specimens under different water heads.

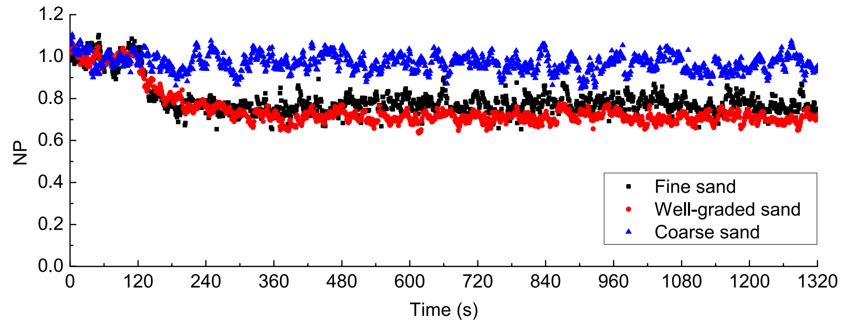

Figure 9. NP time histories with sand of different gradings added.

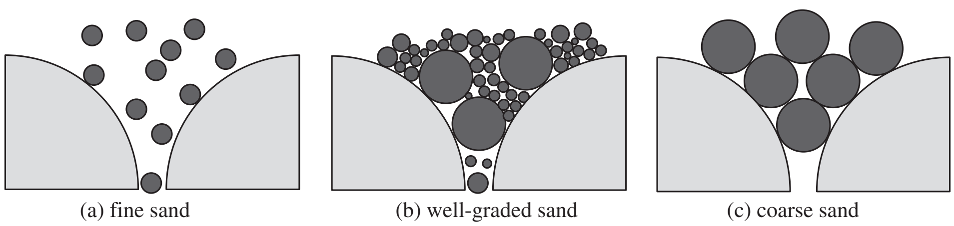

Figure 10. Schematic of pervious concrete surface clogging with different sand gradings (a, fine sand; b, well-graded sand; c, coarse sand).

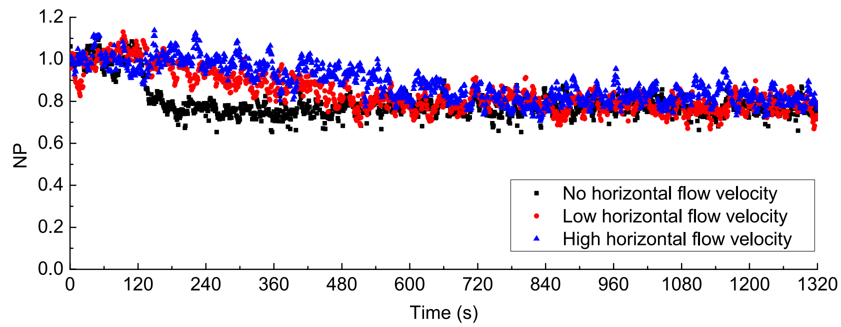

Figure 11. Time histories of NP for different horizontal flow velocities.

while 0.15–0.3 mm decreases (25.1, 24.3 and 22.8%). This is because a lower water head makes the coarser particles prone to be clogged at the gate of passageway and block the finer particles from getting inside of the specimen. While a higher water head makes the coarser particles which temporarily clogged easy to shift their positions under a larger pressure, allow finer sediments to enter the specimen, and increase the possibility of clogging.

4.5. Influence of clogging materials grading on pervious concrete clogging

The grading of clogging materials is changed in the test to study on its influence on clogging process (Cases 2, 6 and 7 in Table 3). Fine, coarse and well-graded sand are the clogging materials (Table 2). Figure 9 shows NP time history of different clogging materials. 20 min after adding sand, the permeabilities 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 coarser particles are prone to clog in the pores near the upper surface and hard to access into the specimen, which has little influence on the inner permeability. When the clogging processes reach equilibrium, 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, as shown in Figure 10. As seen in Figure 11, the reduction of permeability of fine sand closes to that of well-graded sand. This is because fine sand can easily get into the pore structure of the specimen, and clog at 'pore throats'.

The sand clogged inside the specimen is analysed when test finished. The specimen added well-graded sand is clogged most (mass of clogged is 12.3 g), while the specimen with coarse sand is clogged least (mass of clogged is 2.5 g), because the proportion of the pore sizes and particles diameter is smaller than the minimum proportion for serious clogging.

4.6. Influence of horizontal runoff on pervious concrete clogging

Rotation speed of horizontal runoff maker (impeller) is changed in the test to study on the influence of horizontal runoff on clogging process (Case 2, 8 and 9 in Table 3). Three rotation speeds are used in the test including low speed (5 rpm), medium speed

Table 4. Values of coefficient α for various clogging tests.

Cases	Coefficient α	P	H	Re	R_s	C_u
	2.51					
1	2.37	0.15	1.11	800	14.73	1.73
	2.53					
	2.89					
2	2.94	0.2	1.11	800	14.43	1.73
	2.68					
	2.97					
3	3.16	0.25	1.11	800	14.13	1.73
	2.83					
	4.03					
4	3.89	0.2	1.67	800	14.43	1.73
	4.26					
	4.04					
5	3.69	0.2	2.22	800	14.43	1.73
	3.37					
	1.6					
6	1.47	0.2	1.11	800	3.87	1.52
	1.58					
	2.93					
7	3.12	0.2	1.11	800	3.88	2.80
	2.87					
	3.02					
8	2.89	0.2	1.11	4700	14.43	1.73
	3.16					
	2.53					
9	2.58	0.2	1.11	14,100	14.43	1.73
	2.76					

Table 5. Equivalent characteristic sizes of solid grain in pervious concrete.

P	R_v	R_d	D_{10} (mm)	D_{15} (mm)	D_{60} (mm)	D_{85} (mm)
15%	1.40	1.12	7.93	8.25	10.38	11.58
20%	1.31	1.10	7.77	8.08	10.17	11.35
25%	1.23	1.07	7.60	7.91	9.96	11.11

Table 6. Characteristic sizes of clogging materials.

Clogging materials	d_{10} (mm)	d_{15} (mm)	d_{60} (mm)	d_{85} (mm)	C_u
Fine sand	0.29	0.32	0.50	0.56	1.73
Coarse sand	1.18	1.25	1.79	2.09	1.52
Full grading sand	0.61	0.73	1.70	2.08	2.80

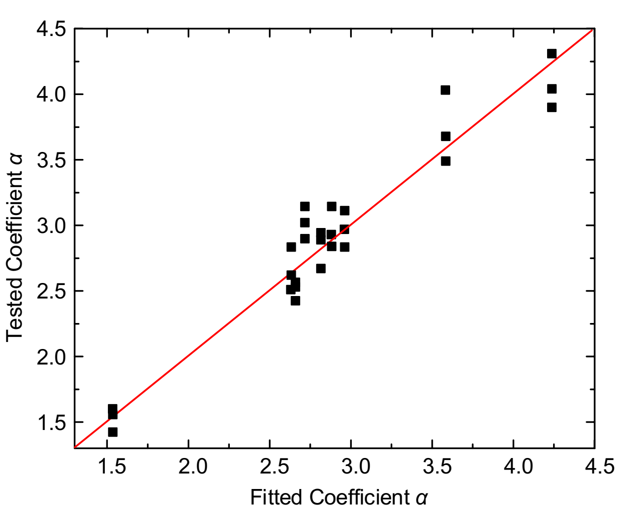

Figure 12. Relationship between tested coefficient α and fitted coefficient α.

(30 rpm) and high speed (90 rpm). As Figure 11 shows, the transport time of particles is prolonged as the horizontal flow velocity increased, the t_{1-2} are 120, 480 and 720 s, respectively. This phenomenon is related to the theory of multiphase flow that the particles carried by horizontal runoffs tend to jump on the surface of specimen or suspend in water with higher flow velocity.

Both permeabilities and electrical conductivities of specimens 20 min after tests with different horizontal flow velocity are similar after the tests. The permeabilities of specimens are 0.77, 0.78 and 0.82 times of their initial values, respectively, 20 min after sand has been added. Thus, increasing horizontal flow velocity only postponed the clogging process, but not influences the final extent of clogging. The permeabilities for different horizontal flow velocities are roughly equal after clogging stabilised. This is because the kinetic energies of particles decrease when they fall back to the zone with a lower horizontal flow velocity near the upper surface of specimen and they may enter into the specimen with seepage flow.

The sand is collected and analysed after the test. With the horizontal flow velocities increasing, the total mass of the sand left on the surface and passing through the specimen is 42.2, 41.4 and 41.9 g, respectively, which has little change. Also, compared with the coarser sand, the content of finer sand outside the specimen increases (10.6, 10.7 and 10.9 g) as the flow velocities increase. It might be because the finer particles 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 holes.

4.7. Rapid clogging model of pervious concrete

The Kozeny–Carmen equation (Montes and Haselbach 2006) forms the basis for the derivation of the empirical model to predict the deterioration in permeability of pervious concrete due to clogging. Several researchers used the same equation to study other similar phenomena. Wu and Huang (2000) used this equation as a basis to derive their theoretical model for studying the effects of sediment intruding into gravel beds. Tan *et al.* (2003) derived an empirical theoretical formulation from the same equation to predict the reduction in permeability of permeable bases.

The Kozeny–Carmen equation can be used to describe a decreased permeability as a result of clogging:

$$k = k_0 \frac{(1-P)^2}{P^3} \frac{(P-\alpha\sigma)^3}{[1-(P-\alpha\sigma)]^2} \tag{2}$$

where k is permeability of clogged pervious concrete specimen; k_0 is initial permeability of specimen; P is porosity of specimen; σ is specific deposit, which is the volume of sediment deposit divided by the bulk volume of pervious concrete specimen; and α is empirical coefficient.

Equation (2) is used by Tan *et al.* (2003) to predict the reduction in permeability of permeable bases. A higher value of α implies a more rapid decrease in permeability. Hence α value can be used as a means of evaluating the rate of deterioration and for comparing the clogging effects. In the case where the clogging particles are able to completely fill up the entire void space within the specimen, α will be taken as 1.

Values of the coefficient α can be calculated using Equation (2). Table 4 shows the coefficient α for the various cases at the end of each test. It can be seen from Table 4 that when the specimens are clogged with sand, α values are approximately between 1.6 and 4.1. In this study, in order to investigate the value of α under the testing conditions, five dimensionless variables are used to represent the governing factors (Table 4), including the porosity of pervious concrete P, the dimensionless storm water depth H (the height of pervious concrete specimen divides by the storm water depth), the Reynolds number of horizontal runoff Re, the aggregate-sediment size ratio $R_s = D_{15}/d_{85}$, and the coefficient uniformity of clogging material C_u.

In this study, as the aggregates in pervious concrete specimens are coated with hydration products of cement and water, the sizes of solid grains are 'expanded' and part of voids among aggregates are filled and the seepage flow and clogging process can be influenced. The volume of solid grain of pervious concrete specimens contains the volume of aggregate and hydration products coating layer. The volume of hydration products coating layer varies with the porosity of specimen. The hydration-product-induced volume expansion ratio of aggregates can be defined as the volume of solid of pervious concrete divided by volume of aggregates.

$$R_v = \frac{(1-P)}{V_a} = \frac{(1-P)\rho_a}{m_a} \tag{3}$$

where R_v is the volume expansion ratio, in the case where there is no hydration products coating layer on the aggregate, R_v will be taken as 1; V_a is volume of aggregates in per cubic meter concrete; m_a is mass of aggregates in per cubic meter concrete; ρ_a is density of aggregates; P is pervious concrete porosity.

Thus, the expansion ratio of aggregate equivalent diameter R_d is,

$$R_d = \sqrt[3]{R_v} \tag{4}$$

Equivalent characteristic sizes of solid grain (aggregate with hydration product coating layer) in pervious concrete are shown in Table 5.

The characteristic sizes of clogging materials are shown in Table 6. Obtaining equivalent D_{15} of aggregate and d_{15} of sediment, the aggregate-sediment size ratio R_s can then be calculated, as shown in Table 4.

The Reynolds number of horizontal runoff Re is calculated as follows.

$$Re = \frac{v_h D}{\nu} \tag{5}$$

where v_h is the flow velocity of horizontal runoff, D is the diameter of the specimen, ν is the kinematic viscosity of water.

By the regression analysis method, the relationship of the coefficient α with the five dimensionless variables is obtained as shown in Equation (6), with $r^2 = 0.99$ (r is correlation coefficient), residual sum of squares = 1.18, mean squared error = 0.05 and standard error = 0.014. Figure 12 shows that the regression equation established has a good fitting effect.

$$\alpha = P^{0.26} H^{0.59} Re^{-0.02} R_s^{0.36} C_u^{1.03} \tag{6}$$

Equation (6) indicates that the influences of porosity of pervious concrete, water depth, and aggregate-sediment size ratio on the coefficient α have slight differences (the powers of P, H and R_s are 0.26, 0.59 and 0.36, respectively), the coefficient uniformity of clogging material has a relatively major influence on coefficient α (the power of C_u is 1.03), while the influence of Reynolds number of horizontal runoff on α is relatively minor (the power of Re is −0.02).

In view of Terzaghi's filter criterion (1929), for the cases that $D_{15}/d_{85} < 4$, the physical implication of a small R_s is that it reduces the risks of soil piping (seepage of soil) through the granular filter. This means that if the particle sizes of the clogging material on the top of the specimen are large relative to the finer aggregate sizes within the specimen, there is a higher tendency for the clogging materials to be retained on the top of specimen, e.g. clogging materials in Case 6 and 7 have R_s of 3.88 and 3.87, and the sediments in both cases are retained on the top of pervious concrete (as shown in Figure 10(b) and (c)). However, the permeability reduction of Case 6 and 7 is quite different. The reason is that they have different values of C_u (2.80 in Case 7 and 1.52 in Case 6). A large C_u value indicates that the clogging material contains particles with a large range of sizes, which can effectively form a 'bridge' over the void openings (as shown in Figure 10(b)). Therefore, the permeability of the specimen will be reduced drastically.

Meanwhile, for cases with fine clogging materials, it is found that clogging is intensified, e.g. the clogging of fine sediment in Case 2 is more serious than that of coarse sediment in Case 6, as shown in Figure 9. This is inconsistent with the results of Tan *et al.* (2003). They proposed that α is inversely proportional to R_s, while in this study it is found that α is directly proportional to R_s. One reason may be that the range of R_s in their tests is between 3.53 and 8.75, fine sediment was not taken into account in their study; however, the range of R_s in our tests is between 3.87 and 14.73. Another probable explanation is that the tests of this study focus on the clogging process of pervious concrete. Compared with gravel, the pore channel of pervious concrete has quite different shape, tortuosity and roughness, which can be the cause of clogging. A further study on the influence of R_s on coefficient α is needed.

As shown in Figure 11, the increase of horizontal flow velocity only postpones the clogging process, but has little influence on the final extent of clogging. In other words, though Re can influence the clogging process, Re has little influence on the value of α. As horizontal flow velocity increased, the shear stress of fluid is increased; the effect of hydrodynamic lift or drag forces inhibits the deposition. Some of the particles may jump on the pervious concrete surface; the energy of particles decreases when they fall back to the zone with lower horizontal flow velocity near the upper surface of the specimen and from where they may enter into the specimen with seepage flow.

The coefficient α of stable stage is a characteristic resulting from the rapid clogging process that depends on five variables. By using Equations (2) and (6), engineers can estimate the permeability reduction of pervious concrete pavement after a rapid clogging. However, the regression is based on the experimental data, the applicability of Equation (6) outside the range of tests is not warranted.

Table 7. Comparison of calculated *α* using clogging model and tested *α*.

Date	Samples	Tested *α*	Calculated *α* by clogging model
19 June 2014	No. 1	2.47	2.56
	No. 2	2.54	2.52
	No. 3	2.38	2.49
3 August 2015	No. 1	2.42	2.57
	No. 2	2.45	2.53
	No. 3	2.51	2.47

4.8. Validation of clogging model

Lvyou Road is a pervious concrete pavement in Jinan, China. Samples were cored from research site after construction to determine the permeability. Two storm events hit Jinan on 19 June 2014 and 3 August 2015, respectively. The permeabilities of cored samples from test site were measured after flood events. To minimise the influence of fragment and water on clogging during coring process, a plastic film was stuck on the sampling location. The values of α were calculated using Equation (6) and compared with the tested α (as shown in Table 7). This indicates that the clogging model is applicable.

5. Conclusions

In order to study the permeability reduction of pervious concrete pavement during a heavy storm process, an innovative real-time permeability measurement system combined with the electrical conductivity measurement is developed. Laboratory simulation tests are conducted with this system to demonstrate the effects of different parameters on the permeability reduction due to rapid clogging. A rapid clogging model has been developed and validated by field cases. The following conclusions are drawn:

(1) The continuous pore clogging process generally includes three phases, i.e. quick clogging, temporary mitigation of clogging and progressive clogging.
(2) Measurement of electrical conductivity can be used as an indicator of pervious concrete clogging, which is much more convenient.
(3) The porosity of pervious concrete and storm water runoff depth are approximately equally positive influential to the coefficient α, the coefficient uniformity of sediment has a relatively major positive influence on coefficient α, while the Reynolds number of horizontal runoff has a relatively minor negative influence on α of stable stage, though larger Re can postpone the clogging. In the range of this study, the aggregate-sediment size ratio has a positive influence on coefficient α.

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