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A field performance evaluation of the periodic maintenance for pervious concrete pavement

Nian Hu, Jiong Zhang *, Shuang Xia, Ruonan Han, Zhaoxia Dai, Rui She, Xinzhuang Cui, Bowen Meng

School of Civil Engineering, Shandong University, Jingshi Road, Jinan, 250061, PR China

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ABSTRACT

The pores of pervious concrete pavement will be clogged by sediment carried by rainwater runoff and atmospheric deposition on the pavement in the course of using, thus reducing the permeability of pavement. It is necessary to adopt effective maintenance measures to keep the permeability of the pavement. In this study, an improved single ring infiltrometer is used to measure the permeability of a newly constructed pervious pavement. In order to study the deterioration process of the pavement permeability under periodic clogging maintenance conditions, four different gradations of clogging materials and eight different maintenance methods were used for 32 test cases. Different maintenance methods are designed to find the best combination, including different pressure wash, sweep + vacuum and pressure wash + vacuum. The study shows when the pressure wash is between 5 and 20Mpa, the maintenance effect has little difference, and the combination of pressure wash and vacuum suction has the best maintenance effect.

1. Introduction

The pervious concrete pavements (PCPs), defined as a type of concrete pavement which features an open network of pores to allow infiltration of stormwater through the pavement into the base/sub-base layers. The pervious concrete pavements like porous asphalt pavements (Wang et al., 2017a; Zhang and Leng, 2017) have many advantages over traditional pavement, such as reducing the risk of flooding, cleaning the runoff and groundwater, decreasing erosion, reducing heat island effect and noise pollution (Fassman and Blackbourn, 2010; Msce et al., 2013; Pratt et al., 1989, 1995). Bean et al. (2007a) reported that rainfall at the Swansboro the pervious interlocking concrete pavement (PICP) monitoring sites did not produce runoff during the monitoring period, the Kinston concrete grid pavers (CGP) test point reduced more than 25 mm of rainfall runoff and in Wilmington porous concrete (PC) site only 4 mm runoff was generated by a rainfall 30 mm. Pervious pavements also have many environmental benefits, including settling of sediment and sediment-bound pollutants and filtration nutrients and heavy metals and automotive oils that is produced in urban environments (Brattebo and Booth, 2003; He et al., 2001; Pagotto et al., 2000; Roseen et al., 2012; Rushton, 2001; Sansalone and Buchberger, 1995). Rushton (2001) and Brattebo and Booth (2003) reported that the concentration of zinc (Zn) and copper (Cu) in seepage from pervious pavement is lower than that of asphalt pavement. Pagotto et al. (2000) comparing the effects of impervious asphalt and porous asphalt on runoff pollutants on bridges reported that heavy metals loads discharged decreased from 20% (Cu) to 74% (Pb), solid pollutants detained at a rate of 87% and hydrocarbons intercepted at a higher rate (90%). Hu et al. (2019) studied the application of activated carbon in porous asphalt mixtures, which can improve the pollution removal rate for porous asphalt concrete and reduce the pH value of runoff, a thickness of 6 cm and a porosity of 18% for the permeable asphalt pavement is recommended to obtain the optimum filtration effectiveness of pavement runoff. Wang et al. (2017b) proved that the scrap tires can be reused for building porous elastic pavement. Lu et al. (2019) used bio-based polyurethane binder and recycled ceramic aggregate to maximize environmental benefits.

* Corresponding author. School of Civil Engineering, Shandong University, Jingshi Road, Jinan, 250061, China.
E-mail addresses: 1471075200@qq.com (N. Hu), jiongzhang@sdu.edu.cn (J. Zhang), 2544685798@qq.com (S. Xia), 1348128762@qq.com (R. Han), 1657780470@qq.com (Z. Dai), 295663142@qq.com (R. She), cuixz@sdu.edu.cn (X. Cui), 514016548@qq.com (B. Meng).

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Unfortunately, the porosity of the pervious concrete pavement also exhibits loss of the in-situ permeability over time due to collect solids such as soil sediment and organic matter in stormwater runoff (Deo et al., 2010). Zhang et al. (2018a,b) studied the clogging mechanism of pervious pavement by numerical simulation and experiment. It was found that the clogging of coarse sand, full-graded sand and fine sand was within the range of 10 mm, 30 mm, 60 mm–100 mm below the pavement surface, respectively. At present, vacuum suction, high-pressure wash and their combination are used as repairing maintenance measures (Balades et al., 1995; Bean et al., 2007b; Dougherty et al., 2011; Pe et al., 2013; Vancura et al., 2012). Vancura et al. (2012) studied the restoration of permeability of pervious pavement by vacuum hose, vacuum sweeper and regenerative air sweeper, respectively. It shows that all these methods can clean clogging material in the void within the range of 3.18 mm on the surface of pervious concrete and the permeability of the pervious concrete was restored. Chopra et al. (2010) and Dougherty et al. (2011) suggested that pressure washing results in higher rejuvenation than vacuum sweeping and considered the most effective way to combine the two methods. Some studies even show that pressure cleaning and vacuum cleaning can restore the permeability of the pavement to more than 90% of its original permeability (Pe et al., 2013). However, research by Henderson and Tighe, 2011 found that wash with a large diameter hose is the best cleaning method for restoring pavement permeability, while power spray cleaning can reduce permeability. Winston et al. (2016) tested and compared mechanical street sweeping, regenerative-air street sweeping, vacuum street sweeping, hand-held vacuuming, high pressure washing, and milling of porous asphalt and suggested that the effectiveness of permeability recovery increases in turn according to milling, pressure cleaning and hand-held vacuum cleaning Chen et al. (2018) found that porous polyurethane mixtures have a better resistance to clogging caused by sediment. Although there have been some studies on the cleaning methods of pervious pavement such as those mentioned above, the existing studies generally hard to ensure the consistency of external factors when comparing, especially the degree of clogging at different test points is inconsistent, which makes it difficult to compare the advantages and disadvantages of each method; in addition, almost all the studies did not consider the effect of periodic clogging process on cleaning effect.

This study explores the recovery effect of permeability of pervious concrete pavement during periodic clogging and maintenance. During each clogging-maintenance cycle, pervious pavement is affected by different gradations of clogged sediment. Different cleaning methods, such as pressure wash, sweep + vacuum and pressure wash + vacuum, are used to clean up the pervious concrete pavement for seeking the best measures to restore the permeability.

2. Methods

A test field was built within this research project in Qianfoshan Campus of Shandong University, Jinan, China. The pervious cement concrete pavement structure with full permeable structure is adopted as showed in Fig. 1. The thickness of the surface layer is 100 mm. The Single graded gravel with 5–10 mm and P.O42.5 ordinary Portland cement is used. The target porosity is 20%, and the concrete is C30 grade.

In order to evaluate the permeability of the pavement, the improved single ring infiltrometer test method was used to measure the initial permeability of 32 test points (Fig. 2), which served as a reference for subsequent tests.

Sediment (Table 1 for gradation) is evenly laid on the test points which has a diameter of 300 mm in each maintenance cycle in order to evaluate the recovery effect of various cleaning methods. The quantity of sediment is 600 g which is tested enough to achieve the worst clogging of the pavement pores. Water is sprinkled on the laid sediment until there is no obvious sediment entering pores (Fig. 3). The process of clogging maintenance is repeated, and the permeability after each clogging-maintenance cycle is measured until the permeability of the cleaned pavement is less than 0.5 mm/s (The Chinese Technical Specification for pervious Cement Concrete Pavement (CJJ/T 135–2009) requires that the permeability of pervious concrete pavement should be greater than 0.5 mm/s) or the permeability remains within a certain range.

Accurate measurement of the permeability is important for evaluating the permeability of pavement and the effectiveness of recovery measures. Bean et al. (2007c) used a single-ring test and sealed with a putty at the single-ring and road interface to prevent side leakage of water. Some people also use ASTMD3385-03 standard double-ring permeability test to test the permeability of pervious concrete pavement. Chopra et al. (2010) considered using

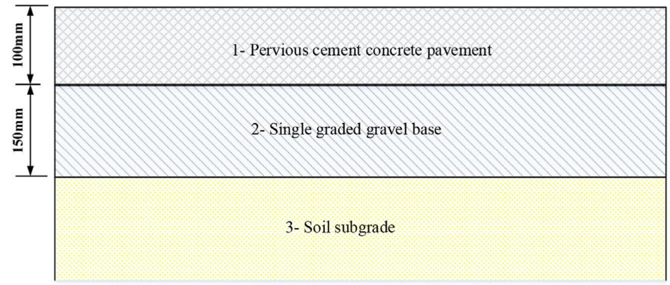


Fig. 1. Pervious cement concrete pavement structure.

Fig. 2. The field test points.

Table 1
The size gradations of the sediment.

Size (mm)	Material I (%)	Material II(%)	Material III(%)	Material IV(%)
1.18–2.36	15.0	12.5	0.0	48.1
0.6–1.18	20.0	13.5	0.0	51.9
0.3–0.6	20.0	35.0	47.3	0.0
0.15–0.3	20.0	22.4	30.3	0.0
0.075–0.15	15.0	11.5	15.5	0.0
<0.075	10	5.1	6.9	0.0

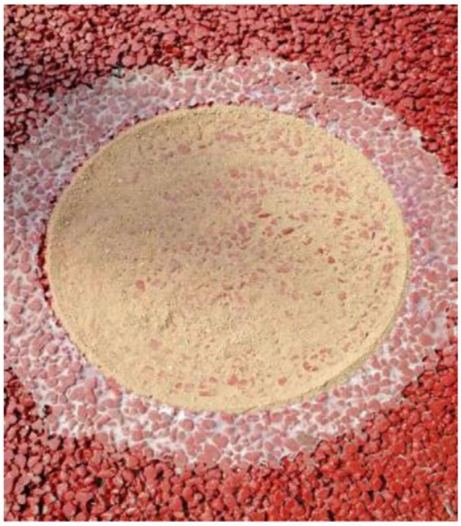


Fig. 3. The site clogging.

the embedded single-ring infiltrometer is better than the standard double-ring infiltrometer (ASTMD3385-03), because it allows the tube to be embedded below the pavement to prevent lateral flow of water, while the standard double-ring infiltrometer is only tested on the road surface. However, for a constructed pervious pavement, it is not merely very difficult to embed a single ring infiltrometer below the pavement but also damage the pavement structure. Kayhanian et al. (2012) used a non-embedded single-ring method and used Ecoflex5 silicone rubber instead of putty, and they achieved satisfactory results. Li et al. (2013) found that the standard single-ring method in ASTM C1701 using a larger tube diameter (300 mm) can obtain more reliable results than the method described by Kayhanian et al. (2012). In this study, in order to find a method that is accurate and minimize the damage on the pavement, a large number of tests on site were conducted and found that the use of putty can seal the permeate and pavement interface well, but the water will flow to the interconnected pores and then flow out of the surface. This phenomenon will greatly increase the measured permeability and makes the results unreliable. Therefore, this study used the ASTMC1701 single-ring test method (Fig. 4) and two types of waterproof adhesives as sealing materials. Firstly, the waterproof silicone sealant is used to seal more than 50 mm periphery of the permeameter to prevent lateral flow, and secondly the hot melt adhesive is used to bond the interface between the permeameter and the pavement as it can solidify rapidly during the periodic studies. If leakage is founded, it should be sealed immediately. The permeability is obtained by falling head method and it is finally calculated by dividing the height of the water head of infiltrated water by the time required.

The high-pressure cleaner is driven by a Honda GX390 engine with a maximum flow of 15 L/min and a maximum output power of 9.5 kW. The water pressure can be regulated by a pressure valve and can be adjusted between 0 and 28 MPa in the pressure range. High-pressure wash equipment uses 45° nozzle as cleaning method. The distance between the nozzle and the ground is about 10 mm, and the angle between the nozzle and the horizontal ground is 45° (Fig. 5a).

The vacuum cleaner used in this research is driven by a GX160 engine, with a maximum output power of 4 kW and a 240 L filter bag (Fig. 5b). The air intake is 800 mm long and 110 mm wide. The distance between the air intake and the ground is 20 mm.

3. Clogging and recovery measures

Four different gradations of sediment are used as the clogging materials, as showed in Table 1. The materials I and II are referred to as full-gradation sediment, and the materials III and IV are fine and coarse sediment, respectively. Material I is an artificially designed clogging material, the composition of which has a large content of fine sediment, which has been tested to be able to cause a quick and completely clogging to the pervious pavement. In order to reflect the real case, Material II is a mixture of sediment collected within the 2-km range of pavement near the test site, the mass is about 3.5 kg, and the collected sediment is sieved to obtain the sediment size gradation. Material III and Material IV are the relative proportions of the fine sediment (<0.6 mm) and the coarse sediment (>0.6 mm) in the material II, respectively.

In order to repair the permeability of clogged pavement, eight maintenance measures (Table 2) are adopted, including pressure wash, sweep + vacuum and pressure wash + vacuum. The pressure wash is divided into five grades, which are 2.5, 5, 10, 15 and 20 MPa, respectively. The vacuum is always kept at 50 kPa to achieve the best suction effect. A cleaning process includes two times back and forth on each tested case.

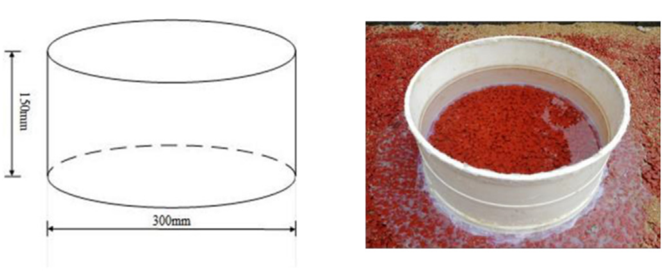
There are 32 cases, which are divided into four groups by using four clogging materials mentioned above. Eight different maintenance measures are adopted for each group (Table 2).

4. Result and discussion

4.1. Initial permeability of pervious pavement

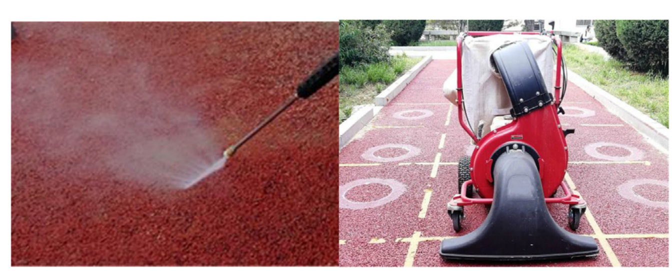
The initial permeability of 32 test points is tested after the completion of pavement construction, the results are shown in Fig. 6.

Fig. 6 shows that the maximum permeability is 16.67 mm/s, the minimum permeability is 3.85 mm/s, and the average permeability is 9.71 mm/s. All test points have higher permeability than required



(a) (b)

Fig. 4. Single-ring infiltration test: (a) Dimension requirement specified, (b) Photo of the permeameter.



(a) (b)

Fig. 5. Cleaning vehicle apparatus (a) Pressure washer, (b) Vacuum equipment.

Table 2
Maintenance scheme of pervious pavement clogging.

Groups	Cases	Clogging material	Maintenance measures	Pressure (MPa)
Group1	1	Material I	Pressure Wash	2.5
	2			5
	3			10
	4			15
	5			20
	6		Pressure Wash + Vacuum	10 + 0.05
	7			20 + 0.05
	8		Sweep + Vacuum	0.05
Group2	9	Material II	Pressure Wash	2.5
	10			5
	11			10
	12			15
	13			20
	14		Pressure Wash + Vacuum	10 + 0.05
	15			20 + 0.05
	16		Sweep + Vacuum	0.05
Group3	17	Material III	Pressure Wash	2.5
	18			5
	19			10
	20			15
	21			20
	22		Pressure Wash + Vacuum	10 + 0.05
	23			20 + 0.05
	24		Sweep + Vacuum	0.05
Group4	25	Material IV	Pressure Wash	2.5
	26			5
	27			10
	28			15
	29			20
	30		Pressure Wash + Vacuum	10 + 0.05
	31			20 + 0.05
	32		Sweep + Vacuum	0.05

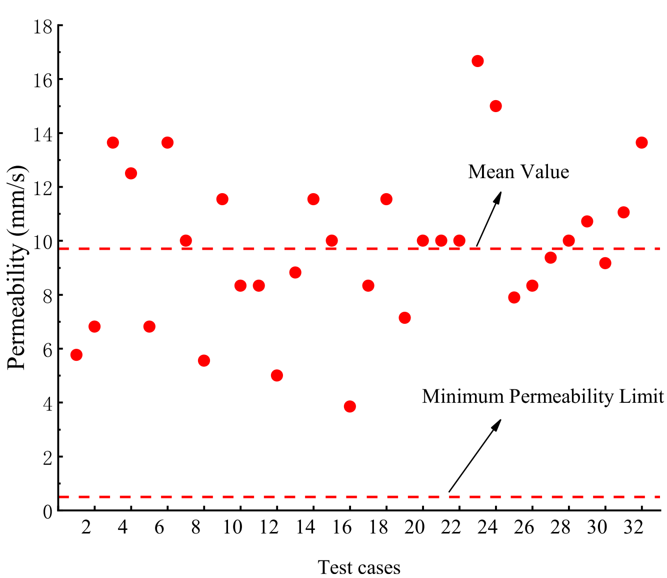


Fig. 6. Initial permeability of pavement.

value (≥0.5 mm/s) in the Chinese Technical Specification for pervious Cement Concrete Pavement (CJJ/T 135—2009). The connected porosity is the most important factor to influence the permeability. During the construction of permeable concrete pavement, it is difficult to ensure that the connected porosity at each point is the same or similar. Therefore, it will cause large differences at different test cases on the same road section.

4.2. Deterioration process of permeability of pervious pavement

After measuring the initial permeability, 600 g of four types clogging materials are used to clog the pavement repeatedly, and eight maintenance measures are used to maintain the pavement after each clogging. Then the permeability after each clogging and maintenance are measured respectively. The test results are shown in Fig. 7.

The cumulative number of clogging and maintenance at each test site is up to 18 time, including 9 clogging and 9 maintenance. From Fig. 7, it can be seen that the permeability of the pavement presents a periodic change of decreasing after clogging and rising after maintenance, and the overall permeability shows a gradual decline. The Group 1 and Group 2 of pavements lose permeability in each clogging stage. Only part of the test sites lost their permeability for Group 3 during the first three stages. After the fourth clogging, the permeability of all the test sites was below 0.5 mm/s. For Group 4, although the first three clogging stages cause the permeability of the pavement decline, the pavement still maintains a permeability larger than 0.5 mm/s. However, in subsequent clogging stages, the permeability was less than 0.5 mm/s. Although these four materials can reduce or eliminate the permeability of the pavement, the permeability of the pavement will recover after different maintenance methods are adopted at each test point, but the recovery rate of the permeability varies with the maintenance measures. It was also found that the cumulative test time of Case 1 was 8 time, which was due to the use of 2.5 MPa pressure wash. In the sixth clogging stage, the permeability cannot be restored to more than 0.5 mm/s, and the two subsequent attempts still cannot restore the permeability. Therefore, this point loses the permeable function and the testing is stopped. Using the same maintenance measure, Case 9 can continue until the 10th test, while Case 17 and Case 25 can continue until the 18th test. It can be

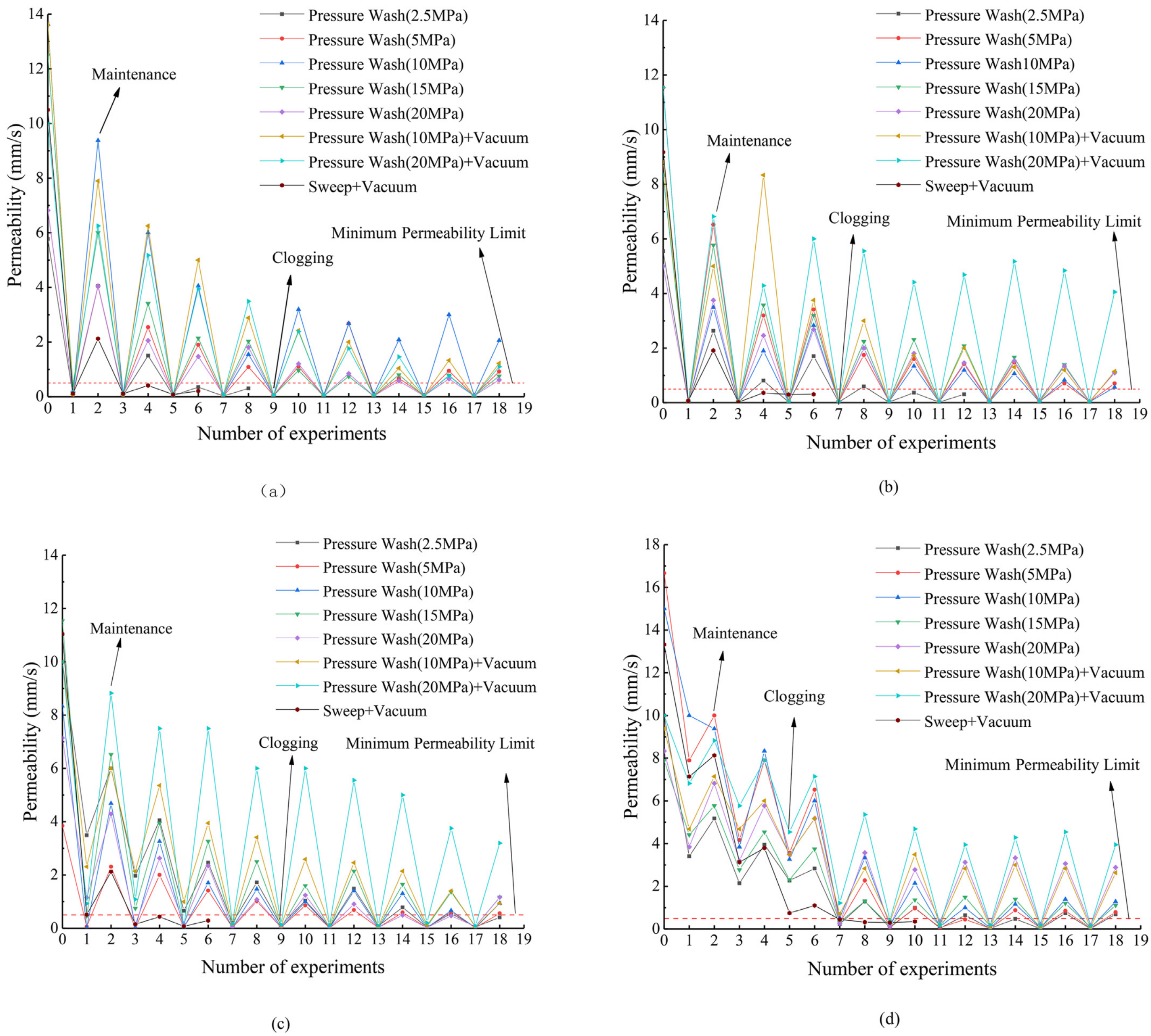


Fig. 7. Deterioration process of permeability: (a) Group 1, (b) Group 2, (c) Group 3, (d) Group 4.

seen from Fig. 7 that when sweep + vacuum is used for maintenance, the permeability of the pavement cannot be restored to more than 0.5 mm/s after the fourth test on the four groups of pavements, so the recovery effect of sweep + vacuum maintenance alone is much lower than the pressure wash or pressure wash + vacuum suction.

4.3. *Effect of gradation of clogging material on pervious pavement permeability*

In this part the change of permeability after each clogging stage in the clogging maintenance cycle is studied. According to Table 2, each group includes eight test points clogged with the same clogging material. The average permeability from eight test cases is got after each clogging, and the influence of clogging material on permeability of pervious pavement was obtained. The results are presented in Fig. 8.

Material I and II are full-graded materials. It can be seen from Fig. 8 that the permeability of these two groups are much lower than 0.5 mm/s after the first stage clogging, in which material II is more severe than material I. After the fourth clogging, the permeability of pavement clogged by Material I is slightly lower than that clogged by Material II. The possible reason is that the mass ratio of the material I (<0.15 mm) is 25%, and this part of the material II is 16.6%, and this part of the fine sediment gradually accumulates inside the pores of the road surface as the number of clogging increases. Material III and IV are fine sand and coarse sand respectively. At the beginning of clogging, the pavement clogged by both of them can maintain a certain permeability. With the increase of clogging stages, the permeability of pavement decreases sharply. Their permeability decreased to less than 0.5 mm/s after the second and fourth clogging stage, respectively.

Full-graded sand is more likely to cause fatal clogging than coarse sand or fine sand. This is because the coarse sand in the full-

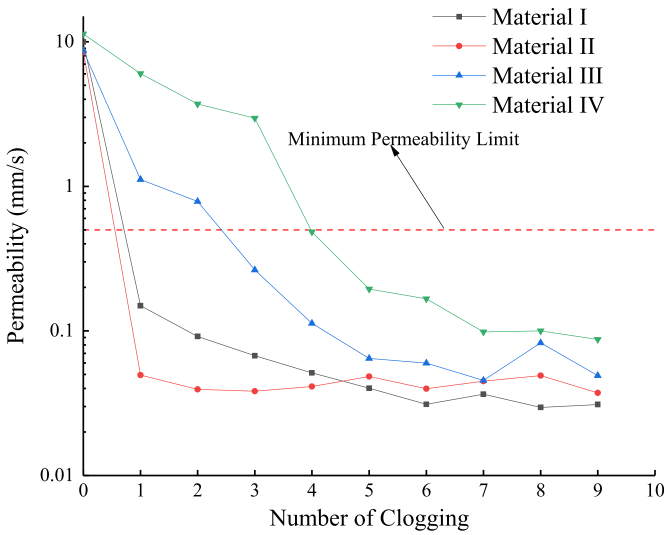


Fig. 8. The average permeability for different groups after each clogging.

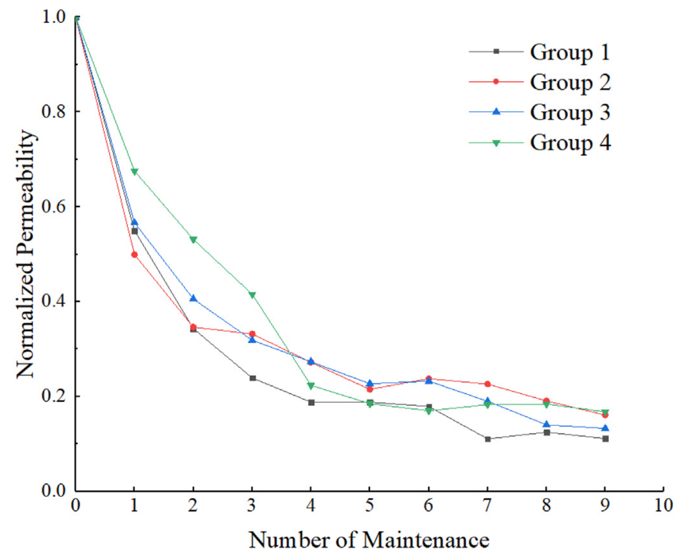


Fig. 9. The normalized average permeability for different groups after each maintenance.

graded sand will enter and get clogged in the larger pores, and form a new skeleton structure in the pore, while the fine sediment will fill the smaller voids in the skeleton (Cui et al., 2019). Therefore, the permeability of the pavement will be greatly reduced, and the clogging structure is also relatively stable.

The previous study (Zhang et al., 2018a, b) indicates that fine sediment will move down with the seepage flow and distribute evenly in the pores. Some fine sediment even enters the bottom of the subbase with the seepage flow. Therefore, for clogging material III with only fine sediment, in the initial clogging stages, after the maintenance measures taken, the pavement can still restore to a certain degree of permeability, but with the increase of clogging cycles, more and more residual sediment cannot be cleared out of the voids, resulting in the reduction of voids, which ultimately leads to the decrease of the permeability of the pavement.

It can be seen from Fig. 8 that material IV, which is composed of coarse sand, can experience more clogging-maintenance cycle and still maintain a high permeability. This is because the coarse sand can only clog larger pores of road surface, while the connected pores between sediment and sediment-aggregate are relatively large.

After each clogging stage, different maintenance methods are tested to restore the permeability of the pavement. Fig. 9 shows the normalized average permeability for different groups after each maintenance. It can be seen that the permeability can be restored for all groups of clogging materials. During the first 3 stages of clogging, the maintenance results for coarse sediment are better than full-graded sediment and fine sediment. But as clogging process continues, permanent clogging accumulates, the advantage of coarse sediment is disappearing.

In summary, different clogging materials will induce differences in the cleaning difficult. The gradation of clogging materials influences the service life of pervious pavement, and effects the maintenance cycle of pervious concrete pavements in different regions, for example, the contents of coarse sediment in the piedmont area are high, while the fine sediment is abundant in the coastal areas, the dirt in inland municipals are more comprehensive.

4.4. Effect of maintenance measures on pavement permeability

In order to study the variation histories of pavement permeability after adopting different maintenance measures, eight different maintenance measures are carried out after each clogging for 32 test cases. The average restored permeability is obtained for each maintenance measure, and the results are shown in Fig. 10.

From Fig. 10, it can be seen that all the maintenance measures can make the permeability of the pavement greater than 0.5 mm/s in the initial period. With the increase of the number of clogging maintenance cycles, the permeability of the pervious pavement still shows a downward trend. The permeability cannot be restored to 0.5 mm/s after the third sweep + vacuum maintenance, while the permeability could not be restored to 0.5 mm/s after the sixth clean stage by pressure wash with 2.5 MPa. The other six maintenance measures can keep the permeability of the pavement above 0.5 mm/s during the whole test process.

The pressure wash between 5 and 20 MPa can recover the pavement to a certain permeability, and the change of pressure value does not cause a significant difference in cleaning effect. Among all the maintenance measures, the most effective is

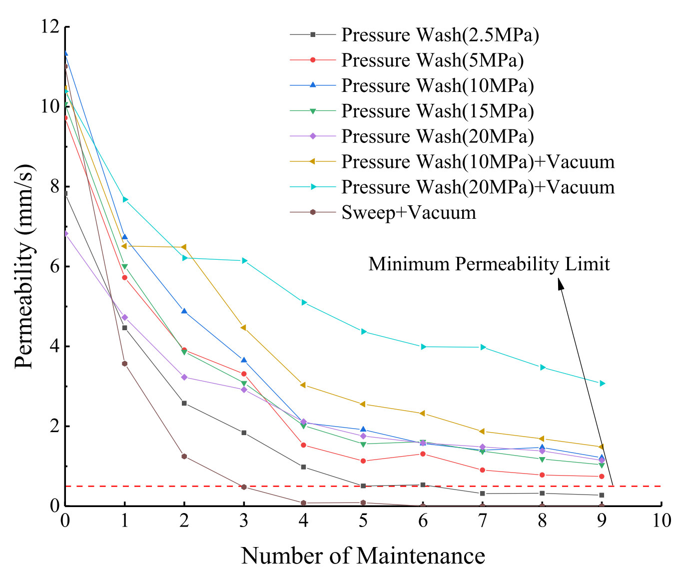


Fig. 10. Variation histories of pavement permeability with number of maintenances.

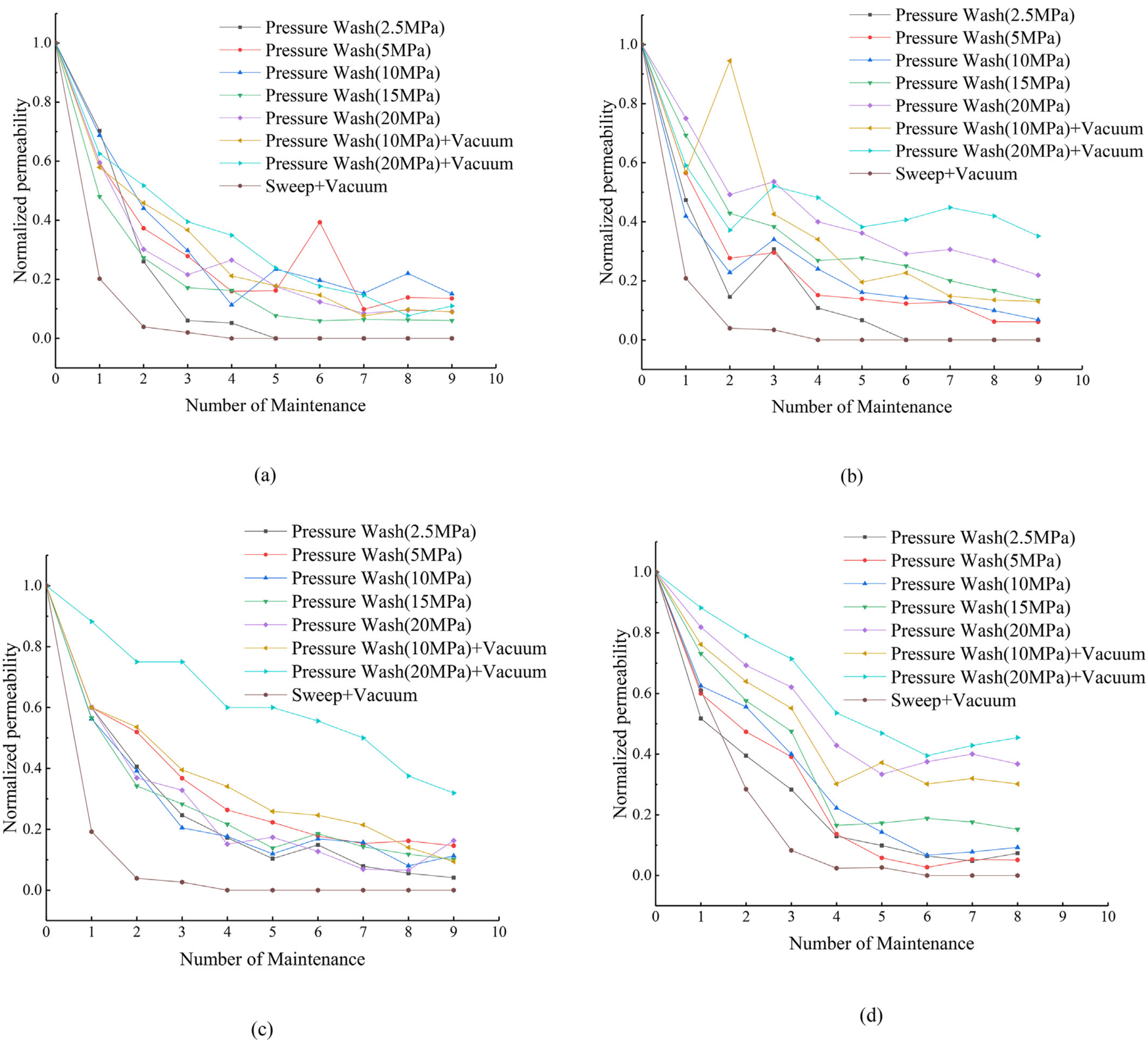


Fig. 11. The normalized permeability for each case after maintenance: (a) Group 1, (b) Group 2, (c) Group 3, (d) Group 4.

pressure wash (20 MPa) + vacuum, followed by pressure wash (10 MPa) + vacuum. The reason may be that the strong impact of high-speed water flow on the clogged sediment forces the sediment to move away from the original clogged position. If pressure wash is used alone, some clogged sediment in the pavement pore will fall back into the pores again after leaving the pavement, resulting in secondary clogging. However, when pressure wash and sweep + vacuum are carried out simultaneously, the sediment leaving the original position will be sucked away by the vacuum, which reduces the possibility of secondary clogging.

Clogging material contains a large number of micro particles, these particles have strong physical adsorption capacity due to the large surface area. The micro particles in the pavement pores will disperse in the rainwater, and form a double electric layer structure due to the effect of static electricity. During the rain evaporation, the thickness of water film on the surface of particles tends to decrease, which causes the thickness of diffusion layer to decrease, further causes the attraction between particles to increase, and gradually condenses into loose colloid, which further agglomerates and finally causes the particles compaction. Because of the strong impact force of pressure wash, it is easy to destroy the harden structure of particles. However, for the cleaning measure of sweep + vacuum, because the vacuum degree of vacuum suction in this study is not large enough, the intensity and depth of sweeping are limited, it is only effective for the shallow range of the surface, and it is difficult to destroy the clogged structure.

In order to analyze the effectiveness of different methods on different clogging materials, the normalized permeability for each case after maintenance are compared (as shown in Fig. 11). For clogging materials II, III, IV, the most effective maintenance method is 20 MPa pressure wash + vacuum, the restored permeabilities can be higher than 30% of the initial value. For clogging materials I the effectiveness of this method is disappearing after 5 stages of periodic maintenance, finally the restored permeabilities for all the

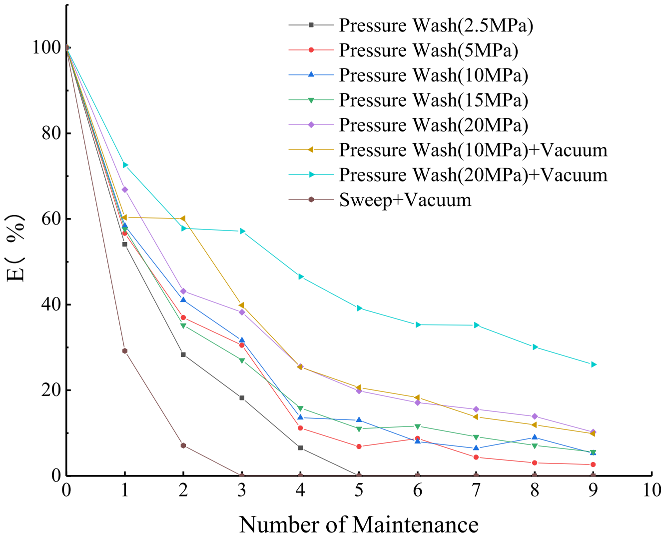


Fig. 12. Efficiency of maintenance method.

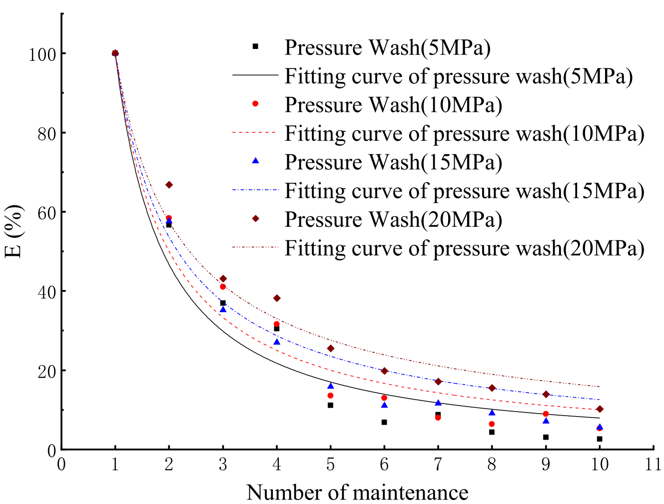


Fig. 13. Fitting results for the efficiency of pressure wash.

methods are under 20% of the initial value. This is because Material I is an artificially designed clogging material combining 25% of the sediment smaller than 0.15 mm, and this fine sediment gradually accumulates inside the pores as the number of clogging increases, even most effective method has lost its effectiveness.

4.5. Efficiency of the maintenance measures

In order to further compare the cleaning effect of various maintenance measures and eliminate the influence of initial permeability, the cleaning efficiency of various maintenance measures can be calculated as follows:

$$E = \frac{P - 0.5}{P_i - 0.5} \times 100\% \quad (1)$$

where E is the recovery efficiency of a maintenance measure, P_i is the initial permeability of the pavement, P is the average permeability measured after pavement clogging. If P-0.5 $\leq$ 0, it is considered that the efficiency of maintenance measures is 0, $E = 0$. The results are shown in Fig. 12.

It can be seen from Fig. 12 that the highest maintenance efficiency is pressure wash (20 MPa) + vacuum, which can restore permeability to 73% of the initial permeability rate after the first cleaning stage, and the permeability can still be maintained at about 26% after nine cycles. The second most effective measure is pressure wash (10 MPa) + vacuum, followed by pressure wash (20, 15, 10 and 5 MPa), the worst are pressure wash (2.5 MPa) and sweep + vacuum. Sweep + vacuum can only restore the permeability to 29% after the first stage, and the pervious pavement will fail after three cycles. It can also be seen that the maintenance efficiency tend to be stable with the increase of clogging maintenance cycles.

A non-linear fitness has been done for the efficiency curves of pressure wash (5, 10, 15 and 20 MPa) in Fig. 12, and the following relationship is obtained:

$$E = N^{(0.02p - 1.2)} \times 100\% \quad (2)$$

where E is the efficiency of pressure wash, p is the pressure used, and N is the number of maintenance cycle. The fitting results are shown in Fig. 13.

It can be seen from Fig. 13 that Eq. (2) can well reflect the relationship between the efficiency of pressure wash and the number of maintenance cycles.

In combination with Eq. (1) and Eq. (2), the relationship between the permeability after the N time maintenance and the initial permeability, pressure and the number of maintenance cycles can be obtained.

$$P = (P_i - 0.5)N^{(0.02p - 1.2)} + 0.5 \quad (3)$$

According to Eq. (2) and Eq. (3), the cleaning efficiency and permeability of permeable concrete pavement after N time of complete clogging maintenance cycle can be estimated rapidly. It should be noted that these two relations are applicable under

Table 3
Maintenance cost estimation of permeable pavement.

Maintenance measures	Equipment cost (RBM)	Time cost (h/100m^2)	Fuel cost (RBM/100m^2)	Labor cost (RBM/100m^2)	Fuel + Labor cost (RBM/100m^2)
Pressure wash (2.5 MPa)	14000	0.5	2	10	12
Pressure wash (5 MPa)		0.5	4	10	14
Pressure wash (10 MPa)		0.5	8	10	18
Pressure wash (15 MPa)		0.5	11	10	21
Pressure wash (20 MPa)		0.5	15	10	25
Pressure wash (10 MPa) + Vacuum	30000	0.5	13	10	23
Pressure wash (20 MPa) +Vacuum		0.5	21	10	31
Sweep + vacuum	17000	0.5	9	10	19

certain conditions, because the pressure range in this study is between 5 and 20 MPa.

The cost is also important for the choice of maintenance. It can be estimated based on the equipment, fuel, labor, and time used during the test in field, based on local price system. The calculation results are shown in Table 3. It can be seen that the maintenance cost for pressure wash (20 MPa) + vacuum is 0.31 RMB/m^2, and it is the highest among all the methods, while the cost for pressure wash (5 MPa) is the 0.14 RMB/m^2. The maintenance frequency needed is only 2–5 times per year, but the service life of pavement is largely prolonged. The cost is worth, because the reconstruction is much more expensive (120-200RMB/m^2) if the pervious pavement has lost its function.

5. Conclusion

A series field cases are designed to evaluate the maintenance measures of pervious concrete pavement. Sediment with four different gradations is firstly used to clog the pavement, and then the maintenance effectiveness of eight maintenance measures is compared. The test results are as follows:

(1) The permeability of pervious pavement will completely be lost after periodic clogging. Among the clogging materials used, well graded sediment is easier to make the pervious pavement clogged, followed by fine sediment, and finally coarse sediment.
(2) All the maintenance measures can restore the permeability of pervious pavement to a certain extent. The efficiency of pressure wash is much higher than that of sweep + vacuum suction. When the pressure of pressure wash is between 5 and 20 MPa, the change of pressure has little effect on the maintenance effect. The combination of pressure wash and vacuum suction has the best effect.
(3) Periodic maintenance can extend the service life of pervious pavement. In the whole test process, the recovery efficiency of pressure wash (20 MPa) + vacuum is the best, even in the case of the most serious clogging of the pavement pores, the permeability can still be restored to 26% after nine cycles. $P = (P_i - 0.5)N^{(0.02p-1.2)} + 0.5$ is used to quickly evaluate the permeability of permeable concrete pavement after a certain pressure wash and periodic maintenance.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Nian Hu: Investigation, Formal analysis, Writing - original draft. **Jiong Zhang:** Conceptualization, Methodology, Resources, Writing - review & editing, Supervision, Formal analysis. **Shuang Xia:** Formal analysis, Data curation, Writing - review & editing. **Ruonan Han:** Writing - review & editing, Data curation. **Zhaoxia Dai:** Writing - review & editing. **Rui She:** Writing - review & editing. **Xinzhuang Cui:** Writing - review & editing, Supervision. **Bowen Meng:** Visualization.

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References

Msce, P.E.M.F., Dougherty, P.E.M., Mbc, T.H., 2013. Cleaning methods for pervious concrete pavements. Int. J. Construct. Educ. Res. 9, 102–116.
Balades, J., Legret, M., Madiec, H., 1995. Permeable pavements: pollution management tools. Water Sci. Technol. 32, 49–56.
Bean, E.Z., Hunt, W.F., Bidelspach, D., 2007a. Evaluation of four permeable pavement sites in Eastern North Carolina for runoff reduction and water quality impacts. J. Irrigat. Drain. Eng. ASCE 133, 583–592.
Bean, E.Z., Hunt, W.F., Bidelspach, D., 2007b. Evaluation of four permeable pavement sites in Eastern North Carolina for runoff reduction and water quality impacts. J. Irrigat. Drain. Eng. ASCE 133, 583–592.
Bean, E.Z., Hunt, W.F., Bidelspach, D., 2007c. Field survey of permeable pavement surface infiltration rates. J. Irrigat. Drain. Eng. ASCE 133, 249–255.
Brattebo, B.O., Booth, D.B., 2003. Long-term stormwater quantity and quality performance of permeable pavement systems. Water Res. 37, 4369–4376.
Chen, J., Yin, X., Wang, H., Ding, Y., 2018. Evaluation of durability and functional performance of porous polyurethane mixture in porous pavement. J. Clean. Prod. 188, 12–19.
Chopra, M., Kakuturu, S.P., Ballock, C., Spence, J., Wanielista, M., 2010. Effect of rejuvenation methods on the infiltration rates of pervious concrete pavements. J. Hydrol. Eng. 15, 426–433.
Cui, X., Zhang, J., Huang, D., Tang, W., Wang, L., Hou, F., 2019. Experimental simulation of rapid clogging process of pervious concrete pavement caused by storm water runoff. Int. J. Pavement Eng. 20, 24–32.
Deo, O., Sumanasooriya, M.S., Neithalath, N., 2010. Permeability reduction in pervious concretes due to clogging: experiments and modeling. J. Mater. Civ. Eng. 22, 741–751.
Dougherty, M., Hein, M., Martina, B.A., Ferguson, B.K., 2011. Quick surface infiltration test to assess maintenance needs on small pervious concrete sites. J. Irrigat. Drain. Eng. ASCE 137, 553–563.
Fassman, E., Blackbourn, S.D., 2010. Urban runoff mitigation by a permeable pavement system over impermeable soils. J. Hydrol. Eng. 15, 475–485.
He, W., Wallinder, I.O., Leygraf, C., 2001. A laboratory study of copper and zinc runoff during first flush and steady-state conditions. Corros. Sci. 43, 127–146.
Henderson, V., Tighe, S., 2011. Evaluation of pervious concrete pavement permeability renewal maintenance methods at field sites in Canada. Can. J. Civ. Eng. 38, 1404–1413.
Hu, X., Dai, K., Pan, P., 2019. Investigation of engineering properties and filtration characteristics of porous asphalt concrete containing activated carbon. J. Clean. Prod. 209, 1484–1493.
Kayhanian, M., Anderson, D., Harvey, J.T., Jones, D., Muhunthan, B., 2012. Permeability measurement and scan imaging to assess clogging of pervious concrete pavements in parking lots. J. Environ. Manag. 95, 114–123.
Li, H., Kayhanian, M., Harvey, J.T., 2013. Comparative field permeability measurement of permeable pavements using ASTM C1701 and NCAT permeameter methods. J. Environ. Manag. 118, 144–152.
Lu, G., Liu, P., Wang, Y., Fasbender, S., Wang, D., Oeser, M., 2019. Development of a sustainable pervious pavement material using recycled ceramic aggregate and bio-based polyurethane binder. J. Clean. Prod. 220, 1052–1060.
Pagotto, C., Legret, M., Cloirec, P.L., 2000. Comparison of the hydraulic behaviour and the quality of highway runoff water according to the type of pavement. Water Res. 34, 4446–4454.
Pe, M.F.H., Mark Dougherty, P., Mbc, T.H., 2013. Cleaning methods for pervious concrete pavements. Int. J. Construct. Educ. Res. 9, 102–116.
Pratt, C.J., Mantle, J.D.G., Schofield, P.A., 1989. Urban stormwater reduction and quality improvement through the use of permeable pavements. Water Sci. Technol. 21, 769–778.
Pratt, C.J., Mantle, J.D.G., Schofield, P.A., 1995. UK research into the performance of permeable pavement, reservoir structures in controlling stormwater discharge quantity and quality. Water Sci. Technol. 32, 63–69.
Roseen, R.M., Ballestero, T.P., Houle, J.J., Briggs, J.F., Houle, K.M., 2012. Water quality and hydrologic performance of a porous asphalt pavement as a storm-water treatment strategy in a cold climate. J. Environ. Eng. 138, 81–89.
Rushton, B.T., 2001. Low-impact parking lot design reduces runoff and pollutant loads. J. Water Resour. Plann. Manag. 127, 172–179.
Sansalone, J.J., Buchberger, S.G., 1995. An infiltration device as a best management practice for immobilizing heavy metals in urban highway runoff. Water Sci. Technol. 32, 119–125.
Vancura, M., Macdonald, K., Khazanovich, L., 2012. Location and depth of pervious concrete clogging material before and after void maintenance with common municipal utility vehicles. J. Transport. Eng. ASCE 138, 332–338.
Wang, D., Schacht, A., Leng, Z., Leng, C., Kollmann, J., Oeser, M., 2017. Effects of material composition on mechanical and acoustic performance of poroelastic road surface (PERS). Construct. Build Mater. 135, 352–360.
Wang, D., Liu, P., Leng, Z., Leng, C., Lu, G., Buch, M., Oeser, M., 2017. Suitability of PoroElastic Road Surface (PERS) for urban roads in cold regions: mechanical and functional performance assessment. J. Clean. Prod. 165, 1340–1350.
Winston, R.J., Alrubaei, A.M., Blecken, G.T., Viklander, M., Hunt, W.F., 2016.

Maintenance measures for preservation and recovery of permeable pavement surface infiltration rate–The effects of street sweeping, vacuum cleaning, high pressure washing, and milling. J. Environ. Manag. 169, 132–144.
Zhang, Y., Leng, Z., 2017. Quantification of bituminous mortar ageing and its application in ravelling evaluation of porous asphalt wearing courses. Mater. Des. 119, 1–11.
Zhang, J., Ma, G., Dai, Z., Ming, R., Cui, X., She, R., 2018. Numerical study on pore clogging mechanism in pervious pavements. J. Hydrol. 565, 589–598.
Zhang, J., She, R., Dai, Z., Ming, R., Ma, G., Cui, X., Li, L., 2018b. Experimental simulation study on pore clogging mechanism of porous pavement. Construct. Build Mater. 187, 803–818.