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Influence of chemical pore-clearing method on infiltration rates of pervious asphalt concrete pavement

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ABSTRACT

Pervious asphalt concrete (PAC) pavement is an environmentally friendly type of pavement due to its highly porous structure. However, with the increase in the service life of PAC, small substances such as damaged rubber particles, industrial dust, sand, and grease collected in rainwater infiltrate the voids of PAC so that it loses its original pervious structure and functions. In order to explore the effects of chemical pore-clearing methods on the infiltration rate of blocked PAC pores in the present study, chemical agents such as sodium hydroxide solution (H_2O_2) and hydrogen peroxide (NaOH) solution were used to rinse the voids in PAC specimens obtained from field sampling and laboratory preparation. The effectiveness of different chemical pore-clearing methods in restoring the permeability and stability of PAC was evaluated by water infiltration rate measurements, Cantabro abrasion tests, and CT scanning. The results showed that the capability of H_2O_2 solution to restore PAC porosity was greater than that of tap water and NaOH solution, especially when the H_2O_2 content in the solution was 6%. In addition, the decomposition products of H_2O_2 are oxygen and water, which are environmentally friendly products, this method proved highly effective in preventing groundwater contamination from pavement-cleansing chemical solutions.

Keywords: Pervious asphalt concrete; Chemical pore-clearing methods; Infiltration rate; Environmental product.

1. INTRODUCTION

A sound drainage system is an essential condition for high-quality road engineering and for improving the quality of daily life [1]. Pervious asphalt concrete offers the structural characteristics of high porosity (15–30%) [2, 3]. Its interconnected pores enable rainwater to penetrate quickly from the top to the bottom of the pavement [4], reduce the volume of rainwater lingering on the pavement surface, eliminate the watery film of asphalt concrete pavement, and maintain its good skid resistance in heavy rainfall conditions [5]. In addition, the complex pore structure of PAC, which is a high-quality pavement material offering environmental protection and sustainable development capabilities, has been shown to effectively reduce temperature and noise [6, 7]. However, the detrimental effects of industrial dust and damaged rubber particles, together with ever-greater vehicle loads [8–10], on PAC porosity involve gradually reducing permeability as pores become increasingly plugged with particles [11]. Therefore, after a period of service PAC loses some of its drainage and noise reduction properties, so it is necessary to regularly restore the porosity of PAC [12].

The interaction between the bending degree of pore structure and plugging particles has been shown to cause a plugging phenomenon [13]. Some scholars established a porosity model for PAC and found that unless restored in time, the permeability of PAC was significantly reduced due to the accumulation of plugging particles [14]. Other researchers considered that sediment particle size distribution had an important impact on the development of siltation by analyzing this phenomenon [15]. In one study, ZHANG *et al*. [16] established that while coarse sand was more likely to cause surface blockage of PAC, fine sand penetrated it more deeply, resulting in pore obstructions deeper down, whereas in another experiment, ZHANG *et al*. [17] found that compared to sand, the plugging phenomenon of clay and asphalt proved more serious due to the Van der Waals

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force interaction. At present, the main pavement cleaning methods include the following: pressure washing, power brushing, milling, high-pressure showering, and the negative pressure adsorption method [18]. The results of some studies showed that most maintenance measures were effective in improving infiltration capacity but that the degree of restoration was limited. The reason was partly ascribed to the tendency of the plugging particles to adhere to the asphalt, which hindered the achievement of a high degree of pavement cleaning by mechanical methods alone. Therefore, research into alternative chemical methods to optimize PAC pore cleaning is urgently required.

In this study, PAC specimens with significant blockages were prepared from core drilling sampling from in-situ road tests and laboratory blockage simulation specimens. The pore size distribution parameters and the blockage distribution law of the two specimen types were investigated, and the blockage characteristics of the laboratory simulation blockage and the field blockage samples were compared. Based on the physical pore-clearing methods previously studied by the present authors [19], different solution concentrations of sodium hydroxide or hydrogen peroxide were used as chemical flushing fluids to wash the PAC prepared in the laboratory, and the permeability restoration rate and stability of the specimens after being washed by the different solutions were measured. The residual blockages after washing were observed by X-CT scanning, and the pore-clearing mechanisms of the different solutions were explored in accordance with chemical reaction principles. Lastly, the cleaning effects on PACs affected by significant pore blockages were analyzed to provide guidance for the application of chemical cleaning schemes in the maintenance of real-life PACs.

2. MATERIALS AND METHODS

2.1. Raw materials and mix proportions

Two types of experimental PA specimens (Type PAC-13) were prepared for testing in this study: Specimens A were obtained by core drilling into the road selected for testing; and Specimens B were prepared in the laboratory of Dalian Jiaotong University.

Specimens A of 100 mm in diameter and 45 mm in depth were taken from the selected pervious asphalt pavement laid in 2018, the measured infiltration rate of which had been found to have reduced by 77.6%, that is, about 3,300 mL/min, after four years' use in its natural environment. Specimens A proved to be very severely affected by the plugging phenomenon so that the PAC failed to meet permeability performance requirements. As previously indicated, Specimens B were prepared in a laboratory. In order to facilitate comparisons with Specimens A, the dimensions of Specimens B were 300 × 300 × 45 mm. For the Cantabro abrasion and the X-CT tests, the specimens were cut into cylinders of 100 mm in diameter and 45 mm in height. A description of the implementation of the Cantabro abrasion test and infiltration rate calculations can be found in Standard JTG E20–2011.

The raw materials and aggregate gradation for Specimens B were the same as those for Specimens A, namely basalt as the coarse aggregate and limestone as the fine aggregate. The aggregate gradation is shown in Table 1 below. The asphalt Type was AH-90 petroleum asphalt, a high-viscosity agent was independently developed by the Highway Research Institute of Ministry of Transportation of China, and the ratio of high-viscosity agent to asphalt was 12:88. The asphalt's mass was 4.6% of the aggregate's mass, the tap water was supplied by the laboratory, and the various sodium hydroxide (NaOH) and hydrogen peroxide (H_2O_2) contents in the solutions were 2%, 4%, 6%, 8%, and 10%.

2.2. Sample preparation

Abundant study results have shown that blockages in PAC lead to a decreased infiltration rate due to the structural compaction caused by the penetration of fine particles such as dust, soil, and organic matter into the pores. The plugging simulation of Specimens B in the laboratory was carried out as follows:

(1) The fine sands (0–3 mm) and humus soils were mixed at a ratio of 1:1 and then placed in the specimen molds. The plugging particles were evenly spread and then tapped with a small hammer for full compaction.
(2) The specimens were then placed on a concrete vibration table and subjected to vibrations for 1 minute to ensure that fine sands and humus soils penetrated into the voids as much as possible.
(3) The surface of the specimens was sprinkled with water to moisten them.
(4) The samples were then placed for drying, so that any blockages on their surface and/or in their voids could be observed.
(5) Steps (1)–(4) above were repeated until no obvious gap could be detected on the surface of the samples, which was deemed to indicate that the specimen blockage simulation had been completed.

Table 1: Aggregate gradation of PAC-13.

GRAIN SIZE (mm)	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
PASS PERCENTAGE (%)	100	96.3	59.3	15.7	11.6	9.2	8.0	7.0	6.4	5.9

2.3. Testing and analysis techniques

The washing equipment used is shown in Figure 1a below. A fan-shaped jet was selected as the water outlet, and after experimental analysis, it was determined that the nozzle water pressure offering optimal hole cleaning efficacy was 15 MPa, with a water outlet angle of 45°, and number of flushes of 2. The negative pressure suction module was simulated by using the equipment shown in Figure 1b. The suction force of the device could be modified by adjusting the power. The experimental results showed that the best results were achieved when the suction power was set at 4,800 W.

An HDSS-3 type asphalt mixture seepage meter was used to measure the various pavement infiltration rates. The vector cylinder was filled with water, and the stopwatch was started upon the opening of the switch. A formula was devised where: t_1 indicated the time when the water surface dropped to 100 mL scale line; t_2 indicated the time when the water surface dropped to 500 mL scale line; and A (mL/min) was the infiltration rate of the samples, as represented in Equation 1:

$$A = \frac{500 - 100}{t_2 - t_2} \times 60 \tag{1}$$

The restoration rate of infiltration rate α (%) was obtained by Equation 2:

$$\alpha = \frac{(A_2 - A_1)}{(A_0 - A_1)} \times 100\% \tag{2}$$

Where A_0 (mL/min) is the infiltration rate of specimens before plugging; A_1 (mL/min) is the infiltration rate of the specimens after plugging; and A_2 (mL/min) is the infiltration rate of specimens after pore-clearing.

The influence of different solutions on the stability of pervious asphalt concrete specimens was investigated by the Cantabro abrasion test. The specimens were immersed in a water-filled tank at a constant temperature of 20±0.5°C for 20 hours, then removed, and any water was wiped off their surfaces before the specimens m_0(g) were weighed. The specimens were then placed in a Los Angeles testing machine fitted with steel balls. After closing the lid, the device was started and made to complete some 300 revolutions at a rate of 30 ± 3 r/min. After opening the lid, the specimens were removed and their residual quality m_1(g) was weighed. The mass loss ΔS (%) of the samples was then calculated by Equation 3:

In order to facilitate comparisons, the Specimens B were made using the core drilling sampling method, to the same size as Specimens A.

$$\Delta S = \frac{m_0 - m_1}{m_0} \times 100\% \tag{3}$$

Figure 1: Cleaning simulation equipment: (a) High pressure water jet module; (b) Negative pressure suction module.

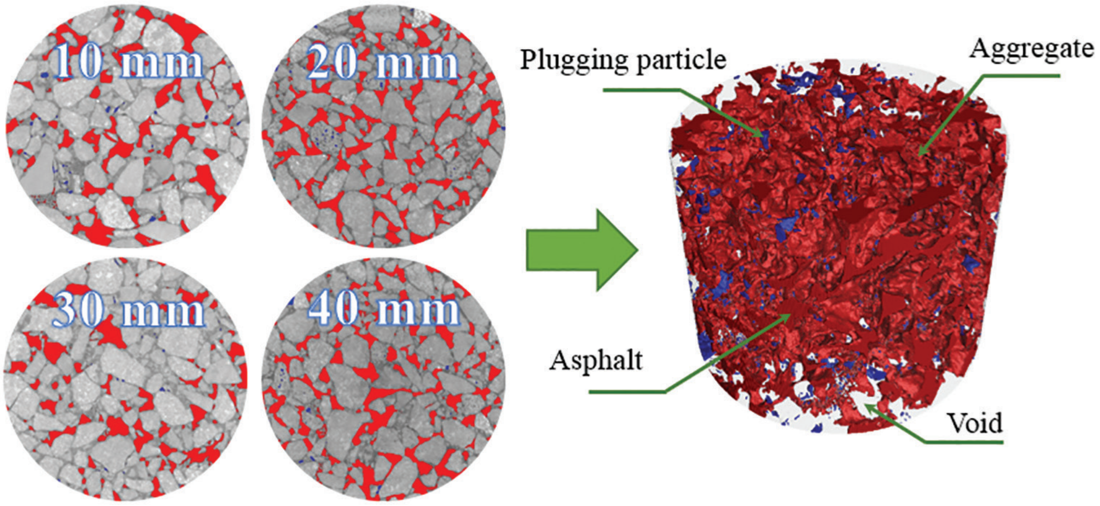

Figure 2: 3D reconstruction diagram.

X-ray computed tomography (X-CT) tests were performed using a German Diondo two-dimensional (2D) type micro-nano focus CT scanner. The data were reconstructed three-dimensionally (3D) by VG Studio MAX software to visualize the scanning results, as illustrated in Figure 2 below. The samples were rotated 360° within the detection range and irradiated, and a two-dimensional projection image was collected at each angle. The collected 2D projection images were reconstructed by computer data to obtain 3D CT volume data [20].

3. RESULTS AND DISCUSSION

3.1. Distribution of specimen voids

The void distribution characteristics at different specimen depths measured by X-CT scanning test are shown in Figure 3.

It can be seen from Figure 3 that the void fraction at the depth of 0–5 mm of Specimens A was abnormally high because the blockages were loosened or flew off under the abrasive effect of the machine on the specimens at high speed. The void fraction of Specimens A then decreased continuously at the 5 mm to 7.5 mm depth and was 13% at 7.5 mm. As the depth increased from 7.5 mm to 30 mm, however, the void fraction of Specimen A gradually rose, after which it gradually decreased at the 30–45 mm depth range, measuring 10% at 45 mm. The surface void fraction of Specimen B was about 6% but rose significantly as the depth increased from 0 to 10 mm. The average void fraction of Specimen B was 12% between 7.5 and 25 mm, and about 15% between 25 mm and 45 mm.

The test results showed that whereas the depth range where serious blockages occurred in the laboratory-prepared Specimens B was 0–20 mm, in the case of Specimens A sampled in-situ, it was 30–45 mm. Because the blockages of Specimens B were mainly caused by fine sand and soil particles, they primarily occurred at the surface of the samples. In contrast, as Specimens A had been exposed to a natural environment for 4 years, any blockages in their superficial layer had been irregularly washed away by rainwater so that any blockage-causing particles had been flushed underground along the pathways of the voids. However, various hydrophobic substances, such as stripped asphalt particles and natural organic matter, had agglomerated at the bottom of the specimens, which could not be washed away.

3.2. Infiltration rate of laboratory-produced Specimens B

The infiltration restoration rates of Specimens B after being washed with different chemical solutions are shown in Figure 4 below. When the specimens were washed with tap water, the infiltration restoration rate was 62.01%. When the NaOH content was below 4%, the infiltration restoration rate increased with the increase in NaOH content in the solutions and reached 69.02% when the NaOH content was 4%.

It was observed that as the solution concentration increased, the cleaning effect decreased. When the NaOH content was 10%, the infiltration restoration rate was only 54.58%. When the H_2O_2 content was below 6%, the cleaning effect increased as the H_2O_2 content rose. When the H_2O_2 content was 6%, the infiltration restoration rate reached 72.16%, however, no significant difference in the cleaning effect Was detected when the H_2O_2 content increased to 6–10%.

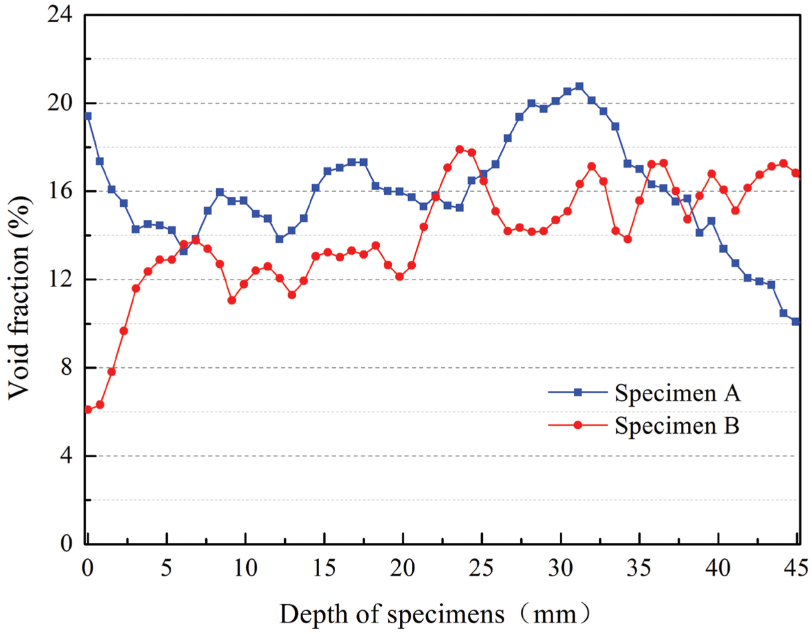

Figure 3: Void distribution along depth in specimens.

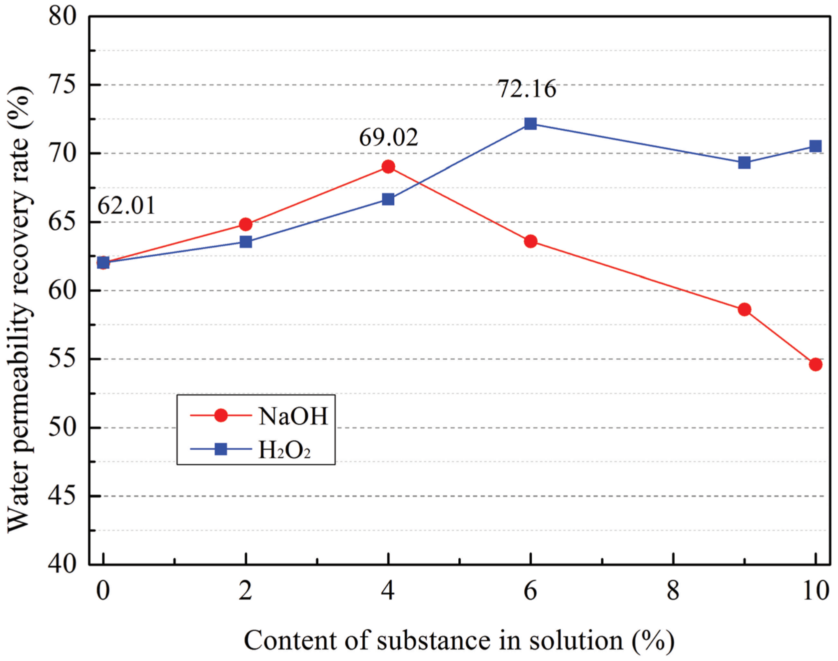

Figure 4: Restoration rate of specimen B after cleaning.

3.3. The Cantabro abrasion test of Specimens B

In order to verify whether being washed by different concentrations of NaOH and H_2O_2 solutions affected specimen stability, a Cantabro abrasion test was carried out on the washed specimens, and the results are shown in Figure 5 below.

As can be observed, when the concentrations of NaOH and H_2O_2 were below 6%, the mass loss of all specimens measured by the Cantabro abrasion test was basically the same, indicating that washing with a low concentration solution essentially affected the stability of the specimens in the same way as using tap water washing. When the concentration of NaOH and H_2O_2 exceeded 6% however, the mass loss of the specimens increased gradually. When the NaOH and H_2O_2 concentrations were 10%, the mass loss of the samples washed

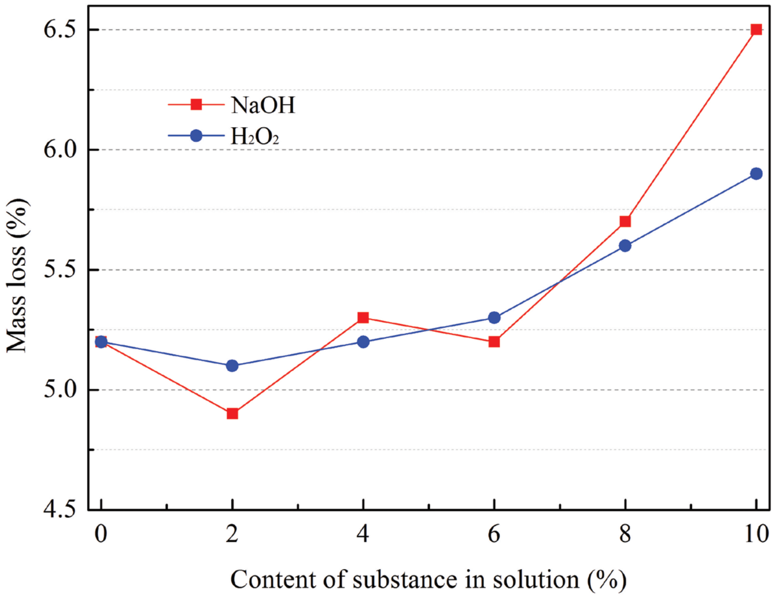

Figure 5: Mass loss of Specimens B following the Cantabro abrasion test.

with the NaOH solution was 6.5%, while that of the specimens washed with H_2O_2 was 5.9%. It was therefore concluded that from the perspective of specimen stability, the concentration of both of the NaOH and H_2O_2 solutions should not exceed 6%. From combining these findings with the experimental results shown in Figure 4, concentrations of 4% NaOH and 6% H_2O_2 were selected for subsequent experiments.

3.4. The X-CT scanning test of Specimens B

The 3D X-CT scanning graphs of specimens cleaned by different solutions are shown in Figure 6.

Figure 6a shows an unwashed specimen. It can be seen that its voids were filled with a large number of particles and that the greatest blockage was occurring at a depth of 30–40 mm. In Figure 6b, most of the plugging particles can be observed to have been washed away by tap water, but some of the larger particles still remained and were slightly agglomerated. Figure 6c shows a specimen cleaned with 4% NaOH solution. Compared to the sample washed with tap water, the voids of this specimen were cleaner and showed fewer residual blockages, but these revealed obvious agglomerations. It can be observed that the specimen in Figure 6d cleaned with 6% H_2O_2 solution comprised minimal blockages in its voids, with no obvious agglomeration. It was thus concluded that compared to the 4% NaOH solution and tap water, the 6% H_2O_2 solution proved the most suitable chemical agent to wash PAC pavements.

3.5. Cleaning mechanisms of different solutions

Although tap water proved capable of washing away sand, soil, mud, stone, and other inorganic matter particles and of effectively reducing the number of blockages in voids of asphalt concrete, some plugging particles remained adhered to the asphalt and could not be washed away by tap water alone. This option was consequently deemed of very limited efficacy in restoring asphalt concrete permeability.

Carboxyl and ester organic matter groups are known to react with NaOH [21], as shown in Equation 4 and Equation 5 below. NaOH has the capacity to strip plugging particles from asphalt, thus restoring the voids in asphalt concrete to a higher degree. However, high concentrations (>6%) of NaOH solution are known to erode certain organic substances, and the ensuing products agglomerate and cannot be washed away by water. It is furthermore important to note that unreacted NaOH is flushed into the ground, where it alters the pH value of soil and contaminates groundwater.

$$NaOH + RCOOH \rightarrow RCOONa + H_2O \tag{4}$$

$$NaOH + R_1COOR_2 \rightarrow R_1COONa + R_2OH \tag{5}$$

In its decomposition process, H_2O_2 produces new oxygen atoms ($H_2O_2 \rightarrow H_2O + [O]$), which can effectively oxidize and decompose organic matter [22]. At the same time, the hydroxyl group of H_2O_2 can

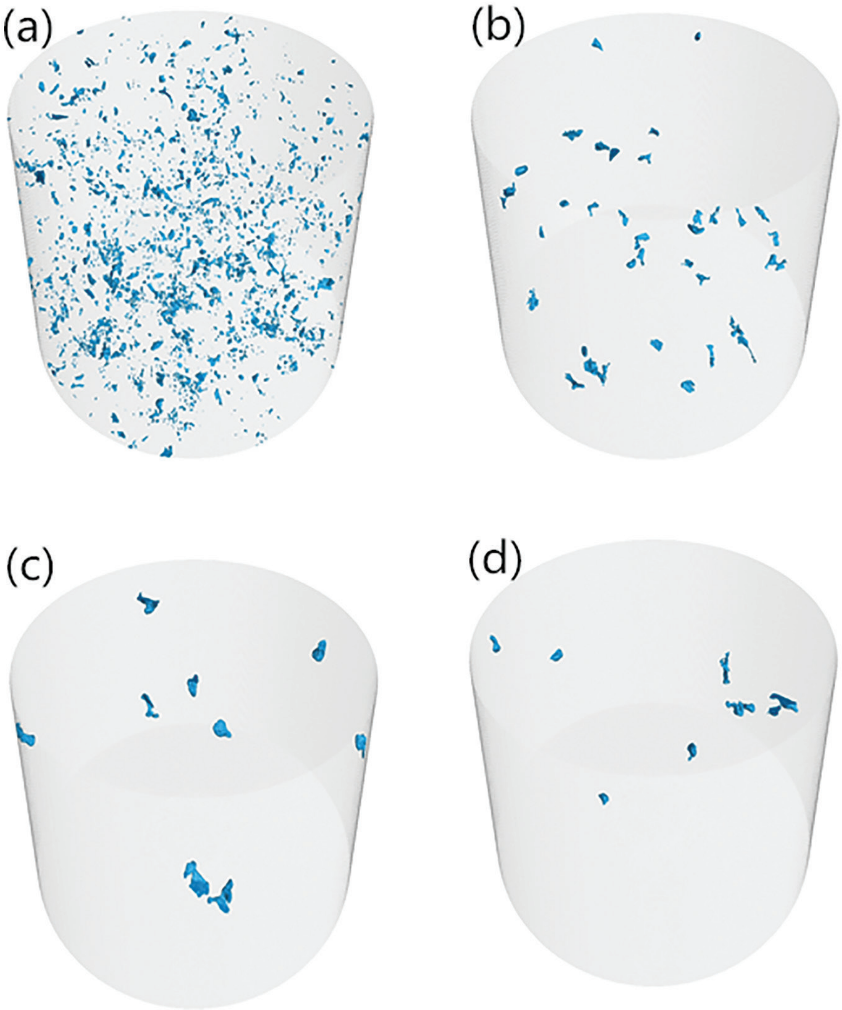

Figure 6: CT scanning graphs of specimens: (a) unwashed specimen; (b) specimen cleaned by tap water; (c) specimen cleaned by 4% NaOH solution; (d) specimen cleaned by 6% H_2O_2 solution.

mineralize some organic matter. Therefore, a 6% concentration of H_2O_2 solution can effectively improve the situation of void clogging. Even if some of the H_2O_2 fails to react and flows into the ground, it decomposes to produce clean products such as O_2 and H_2O, which do cause groundwater contamination as a result of the pavement washing process.

3.6. Infiltration rate of Specimen A from engineering sampling

Based on the above research results, non-destructive permeability tests of PAC sampled from the test site were carried out. According to the cleaning design in this study, tap water, 6% H_2O_2 solution, and 4% NaOH solution were used, respectively, to wash the samples, infiltration rate results of which are shown in Tables 2–4 below. It should be noted that the average infiltration rate before the pavement was put into use was 10,240.7 mL/min.

The results of the infiltration rate tests showed that prior to any cleaning, the samples displayed very significant void blockages, and the infiltration rate was lower than the standard specified for PAC of 5,000 mL/min. It was found to be significantly improved following the cleaning tests and was restored to about 6,000–6,700 mL/min, 6,900–7,300, 7,000–7,900 mL/min after washing with tap water, 4% NaOH solution, and 6% H_2O_2 solution, respectively. It should be noted that the infiltration restoration rate of Specimens A was significantly lower than that of Specimens B. This was hypothesized to be because, besides the influence of external blockages, particles affecting Specimens had been flushed slowly during the past four years, resulting in lower void ratios, which could not be achieved by pavement washing only. Not only did the cleaning effects of the 6% H_2O_2 solution prove significantly greater than those of the 4% NaOH solution and of tap water, but its infiltration regeneration rate reached 65%, and its detrimental environmental impact is small. It was therefore concluded that a 6% H_2O_2 solution was the recommended formula as a cleaning agent for void blockage recovery.

Table 2: Permeability test results of pavement cleaned with tap water.

PAVEMENT POINT POSITION	INFILTRATION RATE BEFORE CLEANING (mL/min)	INFILTRATION RATE AFTER CLEANING (mL/min)	RESTORATION RATE OF INFILTRATION RATE (%)	AVERAGE VALUE (%)
1	3,075.2	6,452.5	47.1	44.8
2	3,332.6	6,433.7	44.9	
3	3,272.7	6,398.2	44.9	
4	3,316.2	6,245.8	42.3	
5	3,101.1	6,027.2	41.0	
6	3,247.6	6,174.9	41.9	
7	3,135.8	6,645.2	49.4	
8	3,206.5	6,325.1	44.3	
9	3,126.2	6,467.3	47.0	

Table 3: Permeability test results of pavement cleaned with 4% NaOH solution.

PAVEMENT POINT POSITION	INFILTRATION RATE BEFORE CLEANING (mL/min)	INFILTRATION RATE AFTER CLEANING (mL/min)	RESTORATION RATE OF INFILTRATION RATE (%)	AVERAGE VALUE (%)
1	3,269.7	7,137.6	55.5	54.2
2	3,385.4	7,095.3	54.1	
3	3,478.9	7,156.4	54.4	
4	3,854.5	7,036.5	49.8	
5	3,129.6	6,923.7	53.4	
6	2,946.4	7,312.5	59.9	
7	3,456.8	6,893.4	50.7	
8	3,469.6	7,129.5	54.1	
9	3,397.1	7,211.2	55.7	

Table 4: Permeability test results of pavement cleaned with 6% H_2O_2 solution.

PAVEMENT POINT POSITION	INFILTRATION RATE BEFORE CLEANING (mL/min)	INFILTRATION RATE AFTER CLEANING (mL/min)	RESTORATION RATE OF INFILTRATION RATE (%)	AVERAGE VALUE (%)
1	3,326.2	7,764.2	64.2	65.1
2	3,410.3	7,813.5	64.5	
3	3,440.1	7,909.3	65.7	
4	3,071.5	7,729.2	65.0	
5	3,311.1	7,788.6	64.6	
6	3,080.2	7,960.4	68.2	
7	3,496.6	7,869.2	64.8	
8	3,276.2	7,810.9	65.1	
9	3,456.8	7,809.4	64.2	

4. DISCUSSION

The optimal maintenance measure should be determined by maintenance efficiency, maintenance cost, and environmental implication.

Among the three methods of high-pressure water washing, low pressure suction and high-pressure air flushing, the low pressure suction method has the best effect on pervious concrete pavement. After the maintenance times of pavements exceeded 3 times, the maintenance efficiency was no longer significantly improved, and the optimal maintenance times were 2–3 times [23]. And most importantly, it is difficult to clean the bottom part of pervious concrete pavement effectively only by mechanical cleaning method.

Adding sodium hydroxide and hydrogen peroxide to tap water will increase the cost of flushing, but sodium hydroxide and hydrogen peroxide could bring deep cleaning to pervious concrete pavement, which can effectively reduce the number of flushing times, the total flushing cost will be reduced on the contrary [24].

After chemical pore-clearing, hydrogen peroxide breaks down into water and oxygen, so it has very little impact on the environment. However, in order to improve the cleaning efficiency, mechanical pore-clearing will increase the mechanical power, consume more energy and discharge more tail gas.

5. CONCLUSION

In this study, PAC Type PAC-13 pavement was selected as the research object. Firstly, the void distribution of PAC was laboratory-analyzed after blocking testing and field sampling had been performed. Permeability and Cantabro abrasion tests were then used to verify the water permeability and stability of PAC after cleaning with NaOH solution, H_2O_2 solution, and tap water, respectively. X-CT scanning was utilized thereafter to view and compare blockages in the voids before and after cleaning with the different solutions. Lastly, the optimal pore-clearing agent was determined by comprehensively scrutinizing their respective effects from field testing and environmental impact perspectives. The conclusions of this study were as follows:

(1) The depth at which serious blockages occurred in specimens prepared in the laboratory was 0–25 mm, while that of specimens from engineering sampling was 30–45 mm. Because the blockage of specimens prepared in the laboratory mainly consisted of fine sand and soil particles, the blockages were mainly located at the surface of the samples. The blockage of specimens from engineering sampling consisted of larger organic matter and stripped asphalt particles, so that the blockages were mainly sited at the bottom of the specimens.

(2) The infiltration restoration rate was 62.01% and the mass loss was 5.2% when the specimens were washed with tap water. The infiltration restoration rate of specimens was 69.02% and their mass loss 5.3% when the concentration of NaOH was 4%. When the content of H_2O_2 in the solution was 6%, the infiltration restoration rate reached 72.16% while the mass loss remained 5.3%.

(3) The permeability restoration rate results for the engineering samples showed that the cleaning effect of 6% H_2O_2 solution was significantly greater than that of 4% NaOH solution and of tap water, while the H_2O_2 solution was found to have a minimal detrimental environmental impact. Compared to the NaOH solution and tap water, the H_2O_2 solution thus proved more suitable as a chemical agent for pavement washing.

6. ACKNOWLEDGMENTS

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