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Experiment Investigation and Influence Evaluation of Permeability Ability Attenuation for Porous Asphalt Concrete under Repeated Clogging Conditions

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Abstract: One of the problems that limit the development of porous asphalt concrete (PAC) is that the pores become clogged, which leads to severe deterioration in its permeability performance. This paper focuses on PAC’s permeability characteristics under repeated cycles of clogging. First, sand (S), clay (C), and sand and clay mixtures (S + C) were used as clogging materials for repeated clogging tests. Then, the permeability coefficients in the initial state and after clogging were measured with an improved permeability device. Based upon porosity, maximum nominal particle size, and clogging materials, the paper analyzed the permeability regulation of PAC under repeated clogging conditions. In addition, we compared the restoration effects of vacuum cleaning, high-pressure cleaning, and surface cleaning with cleaning tests and proposed a response surface methodology prediction model. Finally, the particle size distribution of sensitive particles that cause different porosities in PAC clogging was explored. The results showed that the initial permeability coefficient and the permeability coefficient with PAC’s repeated clogging increased with the increase in the nominal maximum particle size and porosity. PAC clogged by sand has the greatest rate of reduction in the coefficient of permeability. In addition, we suggested that in PAC pavement maintenance work, water is first sprinkled to wet the road, then high-pressure cleaning used, and finally vacuum cleaning. The prediction model is reliable and the cleaning method has the most significant effect on the permeability coefficient. Further, the particle size distribution that caused PAC-13 and PAC-10 clogging ranged from 0.15 to 2.36 mm and 0.075 to 2.36 mm, respectively.

Keywords: porous asphalt pavement; repeated clogging; permeability coefficient; clogging materials; cleaning methods

1. Introduction

With the global economy’s rapid development and the continuous promotion of road construction, asphalt pavement is used widely for urban roads and highways because of its good levelness, comfortable driving surface, and easy maintenance [1]. However, the pavement anti-slip coefficient is low in rain and snow, which can easily cause traffic accidents [2,3]. For example, the traffic accident rate in Japan in rainy weather is nine times higher than that in sunny weather [4]. In recent years, with the accelerated urbanization in China, the construction of a “sponge city” has been proposed with the goal to avoid urban flooding, make full use of water resources, protect the water environment, and alleviate the urban heat island effect [5]. Further, the high intensity, large coverage area, and long duration of road noise can have deleterious effects on people’s physical and mental health [6].
PAC is an environmentally friendly pavement [7] that contains a large number of connected pores between the aggregate skeleton, and the porosity content is usually between 15% and 25%. PAC’s internal unobstructed porosity structure provides good drainage and reliable noise reduction performance and has attracted much attention from the road construction industry in recent years. Countries such as the Netherlands, France, Belgium, and Denmark pave a large number of roads with PAC every year [8]. China applied PAC successfully in 2003, and since then, it has achieved better engineering application results in highways and other projects in several provinces [9]. It was found that the permeability coefficient is generally between 2~6 mm/s, and sometimes even as high as 10 mm/s. The larger the permeability coefficient, the better its drainage capacity [10].

Several authors to date have investigated PAC’s porosity and permeability performance. Kandhal et al. [11,12] indicated that such parameters as porosity, gradation, aggregate shape, pavement thickness, and forming method influence asphalt mixtures’ permeability characteristics. Krol et al. [13,14] established a model of the relationship between the distribution characteristics of porosity in PAC and the permeability coefficient and analyzed its permeability mechanism from a mesoscopic level. Yang et al. [15,16] demonstrated that there is a strong correlation between porosity measured by different test methods and established the regression curve between the permeability coefficient and the porosity fraction. However, because rainfall carries sediment, organic debris, and other pollutants, PAC’s pores become clogged in the process of use, which seriously attenuates its permeability [17,18]. Accordingly, this has become a major problem that limits PAC’s development and use.

To solve this problem, Chu [19] established a clogging model of PAC based upon the initial permeability coefficient, porosity, etc. Jiang et al. [20] discovered that the clogging resistance of PAC was positively correlated with the maximum nominal particle size and porosity of the specimens, while Hamzah [21] found that double-layer PAC had better clogging resistance than single-layer PAC. In addition, the grade of clogging material had an influence on the permeability performance of PAC. A larger particle size of clogging material is more likely to cause PAC to become clogged [22]. The key particle sizes considered to cause PAC to clog are 0.15~0.3 mm and 1.18~2.36 mm [23,24]. Further, clogged PAC requires maintenance cleaning, and various cleaning and maintenance methods are commonly used when PAC is clogged, including surface cleaning, air cleaning, and water cleaning [25,26].

The studies above analyzed only the influence of the macroscopic characteristics of the mixture on PAC’s permeability characteristics before and after clogging. However, this alone cannot reflect PAC’s permeability characteristics systematically in its initial state and after clogging. PAC experiences repeated clogging several times during its service life, but the systematic evaluation of its permeability performance in the initial state and after repeated clogging and cleaning is incomplete. Further, the influence of PAC’s structural and material parameters on clogging resistance is unclear, as is the distribution of sensitive clogging particles in PAC mixtures with different porosities.

Therefore, the purpose of this paper is to investigate the clogging resistance of PAC mixtures with repeated clogging and cleaning. Repeated clogging tests were conducted using sand, clay, and an S + C mixture as clogging materials, and the permeability coefficients in the initial state and after clogging were measured with a permeability device. The influence laws of porosity, maximum nominal particle size, and clogging materials on PAC’s permeability performance under repeated clogging conditions were analyzed. Further, we used different cleaning methods, prediction models, and sensitive particle size distribution to explore the mechanism of PAC’s permeability characteristics and revealed the mechanism of different structural and material parameters’ influence on PAC’s permeability performance during actual use. This can provide potential guidelines for PAC maintenance and cleaning.
2. Materials and Methods

2.1. Raw Materials

2.1.1. Asphalt

The base asphalt was SK-70# asphalt in this study, and its technical index test results are shown in Table 1.

Table 1. Test results of the technical properties of SK-70# asphalt.

<table>
<thead>
<tr>
<th>Technical Specifications</th>
<th>Test Results</th>
<th>Technical Requirements</th>
<th>Test Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Penetration (25 °C, 100 g, 5 s)/0.1 mm</td>
<td>68.7</td>
<td>60~80</td>
<td>T0604</td>
</tr>
<tr>
<td>Softening point/°C</td>
<td>46.8</td>
<td>≥46</td>
<td>T0606</td>
</tr>
<tr>
<td>Ductility (5 cm/min, 10 °C)/cm</td>
<td>41.7</td>
<td>≥20</td>
<td>T0605</td>
</tr>
<tr>
<td>Ductility (5 cm/min, 15 °C)/cm</td>
<td>≥150</td>
<td>≥100</td>
<td>T0605</td>
</tr>
<tr>
<td>Density (25 °C)/g/cm³</td>
<td>1.032</td>
<td>Actual test records</td>
<td>T0603</td>
</tr>
<tr>
<td>Viscosity (60 °C)/Pa·s</td>
<td>191</td>
<td>≥180</td>
<td>T0620</td>
</tr>
<tr>
<td>RTFOT (163 °C, 75 min)</td>
<td>Penetration ratio/%</td>
<td>≥65</td>
<td>T0604</td>
</tr>
<tr>
<td></td>
<td>Ductility (10 °C)/cm</td>
<td>≥6</td>
<td>T0605</td>
</tr>
</tbody>
</table>

2.1.2. TPS High Viscosity Modifier

TAFPACK-Super (TPS) high viscosity modified additive was used and was mixed with 12% of the substrate asphalt when the mixture was prepared. The main component of TPS is thermoplastic rubber, while other components include adhesive resins and plasticizers. To prevent PAC from raveling, the asphalt should have sufficient adhesion. Its technical index test results are displayed in Table 2.

Table 2. Physical specifications of TPS.

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Shape</th>
<th>Color</th>
<th>Specific Gravity</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Results</td>
<td>Granular (3~5 mm)</td>
<td>Pale yellow</td>
<td>0.98</td>
<td>0.6 t/m³</td>
</tr>
</tbody>
</table>

2.1.3. Aggregate and Mineral Powder

The test aggregate composition of the high-quality basalt used was produced in Gansu Province Yongdeng Jianxin stone plant. The composition of the mineral powder in the test is limestone. Their technical index test results all met the requirements of specification JTG E42-2005 [27].

2.1.4. PAC Composition Design

In this paper, porous asphalt mixes with nominal maximum particle sizes of 13.2 mm (PAC-13) and 9.5 mm (PAC-10) were selected, while 18%, 20%, and 25% were used as the target porosity (VV) in the ratio design of the drainage asphalt mixture. The sieve passage rate was adjusted, and Marshall specimens were made based on reselecting the mineral gradation. Further, the gradation was readjusted according to the porosity of the specimens measured and was operated repeatedly. The grading curves of PAC-10 and PAC-13 were finally obtained in accordance with the design target, as shown in Figure 1.

2.2. Clogging Materials

Clogging samples were collected within 3 m × 3 m of the established sample point area of several highways in Gansu Province, China, and the main roads within the urban area of Lanzhou City. The sieving results of the clogging samples are shown in Figure 2.
As Figure 2a shows, the clogging material's particle size in Lanzhou city is mainly distributed in 0.075~1.18 mm and is primarily pulverized clay. In Figure 2b, the investigated highway clogging materials had a wide range of particle size distribution, and the types included sand, clay, and mixture. Meanwhile, Akihiro observed that particles smaller than 4.75 mm tend to clog PAC’s porosity [28].

Therefore, a certain gradation of sand (S), clay (C), and a 1:1 (mass ratio) mixture of sand and clay (S + C) were selected as clogging materials. Figure 3 shows the grading of clogging materials in paper.

2.3. Methods

2.3.1. PAC Porosity Test Method

The PAC specimens were prepared in accordance with the JTG E20-2011 [29] asphalt mixture specimen preparation methods. The asphalt mixture’s porosity is controlled generally by its gross bulk density, apparent density, and maximum theoretical density. According to Martin [30] and ASTM D7063 [31], PAC’s gross bulk density is determined using the volumetric method.

\[
V = \frac{\pi \times d^2}{4} \times h
\]
where $V$ is the bulk volume of the specimen (cm$^3$), $d$ is the diameter of the Marshall specimen (cm), and $h$ is the height of the specimen (cm).

The bulk density of the specimen is calculated according to Equation (2):

$$\rho_s = \frac{m_a}{V}$$  \hspace{1cm} (2)

where $\rho_s$ is the bulk density (g/cm$^3$), and $m_a$ is the mass of the dry specimen (g).

The relative density of the bulk volume of the specimen is calculated with Equation (3):

$$\gamma_f = \frac{\rho_s}{0.9971}$$  \hspace{1cm} (3)

where $\gamma_f$ is the relative density of bulk volume.

The porosity of the specimen is calculated with Equation (4):

$$VV = \left(1 - \frac{\gamma_f}{\gamma_l}\right) \times 100$$  \hspace{1cm} (4)

where $\gamma_l$ is the mixture’s theoretical maximum relative density obtained by calculation.

Three types of pores can be obtained by calculation as shown in Figure 4, but only the connected pores played a drainage role.

![Figure 3. Grading curve of clogging material.](image3)

![Figure 4. Schematic diagram of PAC’s pore distribution.](image4)
The connected porosity is measured by the weight-in-water method and is calculated as shown in Equations (5) and (6).

\[ VV' = \frac{V - V'}{V} \times 100\% \]  
\[ V' = \frac{(A - C)}{\rho_w} \]  

where \( VV' \) is the connected (effective) porosity (%); \( V' \) is the volume of the mixture and closed pores (mm\(^3\)); \( V \) is the test piece’s volume (mm\(^3\)); \( A \) is the test piece’s mass at room temperature, dry state; \( C \) is the test piece’s mass in water, and \( \rho_w \) represents the density of water at room temperature (1.0 g/cm\(^3\)).

2.3.2. PAC Permeability Coefficient Test Method

PAC permeability coefficient tests were conducted indoors, and Martin et al.’s variable head permeability device and method to test the permeability coefficient were adapted and improved in part. Figure 5 shows the test device. The permeability coefficient was calculated using Darcy’s law, as shown in Equation (7).

\[ K = \frac{aL}{At} \ln \frac{h_1}{h_2} \]  

where \( K \) is the permeability coefficient, mm/s; \( a \) is the riser’s cross-sectional area, mm\(^2\); \( L \) is the specimen’s height, mm; and \( A \) is the specimen’s cross-sectional area, mm\(^2\).

![Figure 5. Falling-head permeability setup.](image)

2.3.3. Cyclic Clogging Test Method

To avoid the phenomenon of agglomeration clog, 5 g of clogging substance was spread evenly on the specimen’s surface during each clogging cycle. Before each test, we prepared the same mass of blocking material and placed it on the white paper; we placed the PAC specimen on the turntable rotating at a uniform speed, slowly shaking the white paper to make the blocking material fall freely from the same height until there was no blocking material on the paper. The specific steps in the test are as follows.

1. Test the specimen’s initial permeability coefficient, \( k_0 \), using the variable head percolator, as shown in Figure 5.
2. Remove the standpipe, a, spread 5 g of clogging grit, and sprinkle 800 mL of water evenly on the test piece’s surface.

3. Replace the standpipe, a, and determine the permeability coefficient, \( k_N \), after clogging according to the permeability coefficient test method in (2).

4. Remove the standpipe, a, and rubber band, a; remove the standpipe, b; again, repeat 2 and 3, and determine the water permeability coefficient, \( k_{N+1} \), after clogging.

5. Repeat steps 2 to 4 until the water permeability time is greater than 5 min.

6. When the clogged specimen is completely dry, use vacuum cleaning, high-pressure washing, or surface cleaning to clean it (specific cleaning test method as shown in (4)).

7. Replace the standpipe, b, according to the permeability coefficient test method to determine the permeability coefficient after cleaning.

2.3.4. Cleaning Test Method

One of three methods can be used to clean the test piece after it becomes clogged: high-pressure washing, vacuum cleaning, and surface cleaning. These three methods have good continuity and do not disrupt the permeameter conditions. The high-pressure washing method uses a high-pressure cleaning machine with a 5 MPa water pressure and 330 L/h flow rate and the test piece’s surface is flushed for 3 min. Vacuum cleaning suction uses a \( \geq 14 \) kPa vacuum HC-T2103Y-type cleaner and surface suction is applied to the test piece for 3 min. Surface cleaning is used to sweep the particles from the sample surface with a brush.

2.3.5. Clogging Sensitivity Particle Test Method

Seven grades of fine material with particle size <4.75 mm were selected, and 3 g of each grade was chosen as the clogging material. Their composition is shown in Table 3.

### Table 3. Clogging material gradation for clogging sensitivity particle test.

<table>
<thead>
<tr>
<th>Particle Size Range/mm</th>
<th>2.36–4.75</th>
<th>1.18–2.36</th>
<th>0.6–1.18</th>
<th>0.3–0.6</th>
<th>0.15–0.3</th>
<th>0.075–0.15</th>
<th>&lt;0.075</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dosage/g</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

The clogging materials in Table 3 were spread evenly on the PAC specimen’s surface. The water that filtered out of the specimen was collected and dried to a constant weight for sieving, and the mass of each grade of material was weighed. After the water permeability test was completed, the particles that failed to enter the specimen were collected by brushing the specimen’s surface, and then they were dried to a constant weight for sieving and the mass of each grade of material was weighed. The mass of each grade that did not enter the specimen, but filtered out, was subtracted from the total mass of each grade, 3 g, and the mass of each grade that remained inside the specimen was obtained. The particle size distribution of the sensitive particles that caused clogging in the PAC specimen can be obtained by calculating their percentage.

3. Results and Discussion

3.1. Initial Permeability Capacity

3.1.1. Nominal Maximum Particle Size

Design parameters may affect the performance of the initial permeability of the PAC, and thus, the effect of PAC mix grading parameters on its initial permeability performance needs to be investigated. Figure 6 shows the effect of PAC’s nominal maximum particle size and porosity on its initial permeability capacity. The maximum nominal particle size in the legend refers to the smallest standard size of screen mesh through which the aggregate can pass in its entirety or with only a small amount of non-passage.
3.1.1. Nominal Maximum Particle Size

Design parameters may affect the performance of the initial permeability of the PAC mixture with small particle size. Thus, it can be concluded that the larger maximum nominal particle size has a higher permeability coefficient.

3.1.2. Porosity

As Figure 6 shows, there are significant differences in the initial permeability coefficients of PAC with different nominal maximum particle sizes. It was clear that at 25% porosity, the initial permeability coefficient was 0.54 for the nominal maximum particle size of 13.2 mm and 0.43 for 9.5 mm. When the porosity was 20% and 18%, the PAC’s initial permeability coefficient with the nominal maximum particle size of 13.2 mm was 33.3%, 38.5% higher than that of 9.5 mm, respectively.

The larger the nominal maximum particle size, the greater the initial permeability capacity. The reason for this is that the effective porosity percentage is greater than that of PAC-10. PAC-13 contains more 10–15 mm aggregates, and the embedded structure formed between the aggregates is more obvious than that of the mixture with small particle size. Thus, it can be concluded that the larger maximum nominal particle size has a higher permeability coefficient.

3.1.2. Porosity

As Figure 6 shows, the higher the porosity, the higher the PAC specimen’s permeability coefficient. The initial permeability coefficients of PAC-13 with 20% and 25% porosity were 0.54 and 0.36, 50% and 125% higher, respectively, than those of the mix with 18% porosity. For PAC-10, the initial permeability coefficients at 20% and 25% porosity were 44.4% and 139% higher, respectively, than those of the mix with 18% porosity.

This suggested that PAC’s permeability coefficient increases as the porosity increases. There was a positive correlation between the permeability coefficient and porosity or effective porosity. Consequently, the study used a power function model (as in Equation (8)) to regress the relation between the permeability coefficient and PAC’s porosity and effective porosity. The regression results are shown in Figure 7.

\[ k = aV^b \]  (8)

where \(a\) and \(b\) are regression coefficients, and \(V\) is the PAC specimen’s (effective) porosity in %.

In Figure 7, PAC-10 and PAC-13’s permeability coefficients increased as the porosity increased, and their deterministic coefficients \(R^2\) were 0.919 and 0.937, respectively. This demonstrated that there was a more obvious power function relation between the two mixes’ porosity and permeability coefficient. In addition, their effective porosity showed a strong correlation with the permeability coefficient (\(R^2\) between effective porosity and the permeability coefficient = 0.931 and 0.973, respectively). They were larger than the \(R^2\) between the porosity and the permeability coefficient because only the effective pores can store and drain water in PAC.
3.2. Permeability Capacity under Cyclic Clogging

3.2.1. Nominal Maximum Particle Size

Design parameters affect not only the performance of the initial permeability of the PAC, but also its clogging resistance. Figure 8 shows the results of PAC-10 and PAC-13’s performance with different porosities and different clogging materials. The number of loading times in the legend were chosen based upon the fact that the permeability coefficient of PAC specimens under repeated clogging largely tends to be stable and constant.

In Figure 8, when the PAC specimens were clogged repeatedly with sand (Figure 8a,d), the PAC-10 specimens were loaded one, three, and five times at 18%, 20%, and 25% porosity, respectively, while the PAC-13 specimens were loaded two, four, and six times, respectively. For clay materials (Figure 8b,e), the PAC-10 specimens were loaded two, three, and five times for 18%, 20%, and 25% porosity, respectively, and the PAC-13 specimens were loaded three, four, and eight times, respectively. In the case of clogging with sand and clay mixtures (Figure 8c,f), the PAC-10 specimens were loaded two, three, and five times for 18%, 20%, and 25% porosity, respectively, and the PAC-13 specimens were loaded two, three, and seven times, respectively.
sand and clay mixtures (Figure 8c,f), the PAC-10 specimens were loaded two, three, and five times for 18%, 20%, and 25% porosity, respectively, and the PAC-13 specimens were loaded two, three, and seven times, respectively.

It was clear that the loading times of PAC specimens with different nominal maximum particle sizes differed when the same clogging material was used for repeated clogging. This difference was more obvious at 25% porosity when the loading times of PAC specimens with a nominal maximum particle size of 13.2 mm were one, three, and two times more than those of 9.5 mm, respectively. This phenomenon was apparent when the PAC specimens

**Figure 8.** Clogging resistance results under different porosities and clogging materials.
were clogged repeatedly with sand (S), clay (C), and the sand and clay mixture (S + C). These results demonstrated that PAC specimens’ nominal maximum particle size is related to greater clogging resistance during the cycle. This can be attributed to the larger size of the aggregate in the mix, which can form an embedded structure within the mix more easily, and accordingly, does not clog readily.

3.2.2. Porosity

The clogging loading times of PAC specimens with the same nominal particle size and different porosities loaded with the same clogging material were compared to determine the clogging resistance performance of PAC with different porosities.

The PAC-13 specimens with 25% porosity were loaded six times until they were clogged completely with sand (Figure 8d). The specimens with 20% and 18% porosity were clogged and loaded four and two times, respectively. When clay was the clogging material (Figure 8e), the specimens with 25% porosity were loaded eight times until they were clogged completely, while the specimens with 20% and 18% porosity were loaded four and three times, respectively. The specimens with 25% porosity were loaded with the S + C mixture six times until they were clogged completely, which was four and five times more than the clogging load of the specimens with 20% and 18% porosity (Figure 8f).

Because the large size of the aggregate particles embedded in contact with the pores is larger than the small size of the aggregate’s pores, the clogging process entails more clogging materials with the flow of water out of the specimen. It can be seen that the clogging resistance performance of PAC with different porosities is different. The porosity was positively correlated with clogging resistance of PAC, regardless of the variation in the clogging materials’ properties.

3.2.3. Clogging Material Type

In addition to PAC’s grading parameters, the clogging materials’ properties also affected the clogging resistance performance of PAC. Figure 9 shows the loading times and permeability coefficients of PAC-10 and PAC-13 specimens with 25% porosity under different clogging material loadings.

As Figure 9a shows, the permeability coefficient with sand clogging was 0.42 cm/s, 0.41 cm/s for the S + C mixture, 0.37 cm/s for clay when unloaded, and 0.027 cm/s for all three clogging materials by the time the specimens were clogged completely. This indicated that the PAC-10 specimens’ permeability coefficients gradually reduced with the increase in the number of clogging loads. However, the decay rates of the specimens’ permeability coefficients with different clogging materials differed, with the sand the largest, the S + C mixture the second, and the clay the smallest.

This indicates that the particle size distribution of sand is wider because sand contains more coarse particles than the clay and S + C mixture. The coarse particles may enter PAC’s interior and rapidly form a skeleton in its internal pores. On the other hand, as the number of clogging cycles increases, the gradual accumulation of clogging particles on the surface connects the pores. Only the small clogging particles can enter the pores, after which they flow out of the test piece with water.

Figure 9a,c shows that it required five loading cycles for PAC-10 to become clogged completely, and it was more sensitive to all three clogging materials and tolerated only a narrow range of clogging particle sizes because PAC-10’s internal pores are small. Further, the three clogging materials clogged the specimens’ internal pores very easily after they entered the specimens.

Figure 9b,c show that the permeability coefficient with sand clogging was 0.53 cm/s, the S + C mixture was 0.5 cm/s, and the clay was 0.52 cm/s when unloaded. By the time the specimens were clogged completely, all three clogging materials’ permeability coefficients were 0.03 cm/s. It can be observed that PAC-13’s permeability coefficient had the same change law as that of PAC-10, but the number of loading cycles when PAC-13 became clogged completely was different from that of PAC-10. When clogged completely, the clay,
S + C mixture, and sand were loaded eight, seven, and six times, respectively, because the small particle size of clay will be deposited in the connected pore channel, between the semi-connected pores, or flow out with the water. Specimens clogged with clay were loaded more times under the same conditions. Hence, it can be concluded that clay has the best clogging resistance performance and sand the worst.

Figure 9. Clogging resistance results of clogging material type.

(a) Permeability coefficient of PAC-10 at 25% porosity
(b) Permeability coefficient of PAC-13 at 25% porosity
(c) Loading times of PAC specimens with different clogging materials.

3.3. Different Cleaning Methods on Restoring Permeability

3.3.1. Different Cleaning Methods

When PAC loses its permeability performance, drawing on Winston’s [32] research, we can restore its permeability performance with such cleaning methods as high-pressure washing, vacuum cleaning, and surface cleaning. After the PAC specimens were clogged completely, they were tested for permeability restoration to compare the different cleaning methods’ restoration effects. The test results are shown in Table 4.
Table 4. Permeability coefficient after cleaning with different cleaning methods.

<table>
<thead>
<tr>
<th></th>
<th>Sand</th>
<th>Clay</th>
<th>S + C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High-Pressure Wash</td>
<td>Vacuum Clean</td>
<td>Surface Clean</td>
</tr>
<tr>
<td>PAC-13 18%</td>
<td>0.11</td>
<td>0.12</td>
<td>0.09</td>
</tr>
<tr>
<td>PAC-13 20%</td>
<td>0.15</td>
<td>0.13</td>
<td>0.11</td>
</tr>
<tr>
<td>PAC-13 25%</td>
<td>0.28</td>
<td>0.23</td>
<td>0.12</td>
</tr>
<tr>
<td>PAC-10 18%</td>
<td>0.11</td>
<td>0.12</td>
<td>0.08</td>
</tr>
<tr>
<td>PAC-10 20%</td>
<td>0.13</td>
<td>0.12</td>
<td>0.09</td>
</tr>
<tr>
<td>PAC-10 25%</td>
<td>0.24</td>
<td>0.21</td>
<td>0.11</td>
</tr>
</tbody>
</table>

As Table 4 shows, vacuum cleaning had a better restoration effect when the porosity was small. When PAC specimens with 18% porosity were clogged with sand and the S + C mixture, the permeability coefficient after vacuum cleaning remained approximately 0.12 cm/s, which was greater than high-pressure washing and surface cleaning’s restoration effects. However, in general, the permeability restoration increased as the porosity and nominal maximum particle size increased. High-pressure washing had the best effect and surface cleaning was the worst. The permeability coefficient of PAC-13 at 25% porosity clogged with the S + C mixture was 0.27 cm/s after high-pressure washing and was greater than PAC-10’s permeability coefficient of 0.22 cm/s and 225% higher than that of surface cleaning.

Surface cleaning’s effect on restoring PAC specimens clogged with clay was poor, but those clogged with sand and the S + C mixture were restored to a certain extent. This is because some of the particles of sand and the S + C mixture with larger sizes were attached to the surface layer of PAC, and a sweeping brush can remove these particles. In contrast, the particles of clay are small in size and are deposited deeply in the PAC.

Using high-pressure washing and vacuum cleaning can restore the permeability coefficient to an average of 53.1% of its initial value, so it is recommended to adopt high-pressure washing and then vacuum cleaning to maximize the PAC permeability’s restoration. Because the high-pressure washing reaches the internal pores, it can reverse flush out the particles within the test piece, or flush out the skeleton of the clogged material not brought out of the test piece, while subsequent vacuum cleaning can suck out the particles in the test piece easily.

The test process showed that when the PAC specimen’s surface was sprinkled with water and then cleaned, the cleaning effect was better. The specimen may become clogged completely in the drying process so that some of the particles in the clogged material adhere to the pore wall, and wetting the specimens first weakens the bond between the pore wall and particles. In PAC pavement’s actual maintenance, it is recommended to wet the pavement before cleaning and then carry out high-pressure washing followed by vacuum cleaning to enhance the restoration of water permeability.

3.3.2. Model Prediction Based on Response Surface Methodology

Based on the above study, three factors were selected as independent variables and the permeability coefficient of PAC was used as the test response. A three-factor, three-level experimental design was conducted using Design-Expert 13 software. The values of each factor level are listed in Table 5. The response surface test design is shown in Table 6.

Table 5. Response surface methodology factor levels.

<table>
<thead>
<tr>
<th>Independent Variable</th>
<th>−1</th>
<th>0</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Clogging materials</td>
<td>S</td>
<td>C</td>
<td>S + C</td>
</tr>
<tr>
<td>B: Porosity</td>
<td>18</td>
<td>20</td>
<td>25</td>
</tr>
<tr>
<td>C: Cleaning methods</td>
<td>High-pressure wash</td>
<td>Vacuum clean</td>
<td>Surface clean</td>
</tr>
</tbody>
</table>
Table 6. Response surface methodology results.

<table>
<thead>
<tr>
<th>Serial Number</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>Permeability Coefficient (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.12</td>
</tr>
<tr>
<td>2</td>
<td>-1</td>
<td>1</td>
<td>0</td>
<td>0.21</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>1</td>
<td>-1</td>
<td>0.21</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.12</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.12</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>-1</td>
<td>0</td>
<td>0.12</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>-1</td>
<td>-1</td>
<td>0.09</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.12</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.12</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0.07</td>
</tr>
<tr>
<td>11</td>
<td>1</td>
<td>0</td>
<td>-1</td>
<td>0.06</td>
</tr>
<tr>
<td>12</td>
<td>0</td>
<td>-1</td>
<td>1</td>
<td>0.05</td>
</tr>
<tr>
<td>13</td>
<td>-1</td>
<td>0</td>
<td>-1</td>
<td>0.13</td>
</tr>
<tr>
<td>14</td>
<td>-1</td>
<td>0</td>
<td>1</td>
<td>0.09</td>
</tr>
<tr>
<td>15</td>
<td>1</td>
<td>0</td>
<td>-1</td>
<td>0.14</td>
</tr>
<tr>
<td>16</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0.19</td>
</tr>
<tr>
<td>17</td>
<td>-1</td>
<td>-1</td>
<td>0</td>
<td>0.12</td>
</tr>
</tbody>
</table>

The ANOVA for the Response Surface methodology model is shown in Table 7. The model equations of the permeability coefficients on three factors of clogging materials, porosity, and cleaning methods are obtained in Equation (9).

\[ R_1 = 0.12 - 5E^{-3}A + 0.038B - 0.038C - 5E^{-3}AB - 1E^{-2}AC - 0.0258C + 0.02A^2 + 0.02B^2 - 0.035C^2 \]  

(9)

Table 7. ANOVA for the Response Surface methodology model.

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F-Value</th>
<th>p-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>0.034</td>
<td>9</td>
<td>3.756 \times 10^{-3}</td>
<td>52.29</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>A-A</td>
<td>2 \times 10^{-4}</td>
<td>1</td>
<td>2 \times 10^{-4}</td>
<td>2.8</td>
<td>0.1382</td>
</tr>
<tr>
<td>B-B</td>
<td>0.011</td>
<td>1</td>
<td>0.011</td>
<td>157.5</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>C-C</td>
<td>0.011</td>
<td>1</td>
<td>0.011</td>
<td>157.5</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>AB</td>
<td>1 \times 10^{-4}</td>
<td>1</td>
<td>1 \times 10^{-4}</td>
<td>1.4</td>
<td>0.2753</td>
</tr>
<tr>
<td>AC</td>
<td>4 \times 10^{-4}</td>
<td>1</td>
<td>4 \times 10^{-4}</td>
<td>5.6</td>
<td>0.0499</td>
</tr>
<tr>
<td>BC</td>
<td>2.5 \times 10^{-3}</td>
<td>1</td>
<td>2.5 \times 10^{-3}</td>
<td>35</td>
<td>0.0006</td>
</tr>
<tr>
<td>A^2</td>
<td>1.684 \times 10^{-3}</td>
<td>1</td>
<td>1.684 \times 10^{-3}</td>
<td>23.58</td>
<td>0.0018</td>
</tr>
<tr>
<td>B^2</td>
<td>1.684 \times 10^{-3}</td>
<td>1</td>
<td>1.684 \times 10^{-3}</td>
<td>23.58</td>
<td>0.0018</td>
</tr>
<tr>
<td>C^2</td>
<td>5.158 \times 10^{-3}</td>
<td>1</td>
<td>5.158 \times 10^{-3}</td>
<td>72.21</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Residual</td>
<td>5 \times 10^{-4}</td>
<td>7</td>
<td>7.143 \times 10^{-5}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lack of Fit</td>
<td>5 \times 10^{-4}</td>
<td>3</td>
<td>1.667 \times 10^{-4}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pure Error</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cor Total</td>
<td>0.034</td>
<td>16</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The results of the analysis in Table 7 show that the F-value of the mathematical model is 52.59, which indicates the high significance of the model \((p < 0.0001)\). The model’s R-Squared is 0.9854, Adj R-Squared is 0.9854, and Pred R-Squared is 0.7668. The difference between Adj R-Squared and Pred R-Squared is less than 0.2, indicating that they are reasonably consistent. “Adeq Precision” indicates the signal-to-noise ratio. The signal-to-noise ratio should be greater than 4. In this study, it is 23.912, which represents an adequate signal and a reliable model.

The predicted value of the permeability coefficient was 0.225 and the measured value was 0.22 with an error of 2.27% under the conditions of S + C clogging, 25% porosity, and high-pressure cleaning, and the model was verified to be reliable.

Using the above implementation data and the Response Surface mathematical model, the response surface plot of the permeability coefficient to each factor was established,
as shown in Figure 10. The greater the slope of the fitted surface and the denser the contours in the response surface plot, the more significant the influence of the factor on the permeability coefficient.

From Table 7 and Figure 10, it can be seen that in the experimentally selected level range, the order of significance of the effect of each factor on the permeability coefficient is: cleaning methods > porosity > clogging materials. The order of the effect of the interaction between the factors on the correlation is: BC > AC > AB.

3.4. Clogging-Sensitive Particle Analysis
3.4.1. Clogging Particle Distribution in PAC-13 Specimens

The three clogging materials’ different particle size distributions cause different repetitive clogging characteristics. To understand the clogging materials’ influence more fully, the distribution characteristics of clogging particles with different particle sizes in the specimens were analyzed by the clogging-sensitive particle test. Figure 11 shows the clogging particle distribution results of PAC-13 with different porosities.
3.4. Clogging-Sensitive Particle Analysis

3.4.1. Clogging Particle Distribution Results of PAC-13 with Different Porosities

In Figure 11, the larger the clogged particle size, the greater the proportion that did not enter the test piece. Most of the clogged fine material with particle size less than 0.15 mm can flow out of the specimen under the action of water flowing along the connected pores. However, when the larger particles do enter the specimen, they can clog the smaller pores inside the specimen easily, which causes smaller particles to become trapped inside the specimen as well. This was also the reason why 35%, 25.3%, and 19.3% of the specimens with pore sizes of 18.2%, 19.7%, and 25.1%, respectively, still remained inside the specimen. This illustrated further that the larger the porosity, the better the PAC specimens’ resistance to clogging.

Particles in the size range of 0.15–2.36 mm were the key sizes that caused clogging in the PAC-13 specimens’ pores. The most significant clogging material particle size for PAC-13 specimens with 18% and 20% porosity was 0.15–0.6 mm, while the maximum particle size with 25% porosity was 0.6–1.18 mm, indicating that the larger the porosity, the larger the particle size that causes it to clog.

As the porosity increased, the percentage of clogged particles in the range of 0.15–1.18 mm that filtered out of the specimens increased from 19% to 76%. This is because the average number of pores in the PAC specimens’ cross-sections decreased gradually. However, the equivalent diameter of the pores increased gradually, which indicated that more particles of larger sizes pass through the specimens as the porosity increases.
3.4.2. Clogging Particle Distribution of PAC-10 Specimens

Figure 12 shows the distribution of clogging particles in PAC-10 specimens with different porosities. The clogged particle size was in the range of 0.15–4.75 mm at 18% and 20% porosity (Figure 12a,b). The percentage of clogged particles remaining in the specimens increased as the particle size decreased. However, when the clogged particle size was in the range of 0.075–0.15 mm, the percentage of clogged particles remaining in the specimens decreased as the clogged particle size decreased. The same trend was observed for PAC-10 with 25% porosity (Figure 12c) in the range of 0.3–4.75 mm and 0.075–0.3 mm, respectively.

As the porosity increased, the percentage of clogged particles in the range of 0.15–1.18 mm that filtered out of the specimens increased from 19% to 76%. This is because the average number of pores in the PAC specimens’ cross-sections decreased gradually. However, the equivalent diameter of the pores increased gradually, which indicated that more particles of larger sizes pass through the specimens as the porosity increases.

The results for PAC-13 were similar. Neither large nor small clogging particles clogged PAC-10, in which clogging particles of 2.36–4.75 mm and <0.075 mm basically do not clog PAC-10. The particle sizes that caused PAC-10 to become clogged were distributed primarily in the range of 0.075–2.36 mm. However, there are differences in the particle sizes that cause clogging in PAC-10 with different porosities. In addition, the percentage of clogged particles in the filtered specimens increased gradually as the clogged particle size decreased. Because the size of PAC-10’s internal pores is smaller than the larger size of the clogged particles, they entered the specimen and intensified the clogging process.

4. Conclusions

In the study, the influence rule of PAC grading parameters and different clogging materials on PAC’s initial permeability performance and clogging resistance were investi-
gated. Further, different cleaning methods’ ability to restore permeability performance was explored. The following conclusions can be drawn:

1. PAC’s initial permeability coefficient increases with the increase in the nominal maximum size and porosity. The initial permeability coefficient and porosity and effective porosity have a significant linear correlation. The use of void ratio and effective void ratio can indirectly reflect the water infiltration performance of the same or different PAC species.

2. PAC-13’s clogging resistance was better than that of PAC-10, as the permeability characteristics increased with the increase in porosity and number of clogging cycles. The decay rates of the permeability coefficient were highest with sand, while the S + C mixture was the second largest and clay the smallest.

3. Among the three cleaning methods, high-pressure cleaning’s effect is the greatest and surface cleaning the worst. It is suggested to wet the pavement before cleaning and then carry out high-pressure washing first followed by vacuum cleaning to achieve the best restoration effect in actual maintenance.

4. The response surface methodology model proposed in this paper is reliable. The interaction of porosity and cleaning method has the most significant effect on the permeability coefficient.

5. The particle sizes that caused PAC-13 and PAC-10 to become clogged were distributed largely in the range of 0.15–2.36 mm and 0.075–2.36 mm, respectively. The larger the void ratio, the larger the particle size of the particles that cause it to clog, and the percentage of clogged particles filtered out of the specimen gradually increases as the particle size of the clogged particles decreases.

Author Contributions: Conceptualization, B.W. and Y.Z.; methodology, X.Z.; software, J.W.; formal analysis, Y.Z.; resources, D.W.; data curation, J.W.; writing—original draft preparation, B.W.; writing—review and editing, Y.Z. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to the privacy of article data and are currently inconvenient to disclose.

Conflicts of Interest: The authors declare no conflict of interest.

References


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