Research Article

Comprehensive Test and Evaluation Analysis of Permeable Concrete (PC) Clogging by Using Steel Slag

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Received 15 September 2021; Revised 10 December 2021; Accepted 7 January 2022; Published 8 March 2022

Academic Editor: Süleyman İpek

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In recent decade, researchers have more attention to water resource protection and forward the concept of sponge city construction. PC is becoming more and more popular as a rainwater management tool because of fast climate changes worldwide. In this experiment, PC specimens were prepared with steel slag as aggregate, and the targeted porosity of specimens was 15%, 20%, and 25% respectively, and the ratio of water to cement was 0.38, 0.4, and 0.42. The PC specimens under the 200 mm high head are the most severely blocked; 0.283 m/s high-speed horizontal runoff appears after the rapid plugging stage later in the other two types of speed tests. With time, the plugging effect of the test specimen is almost the same; the clogging degree of the PC sample with the porosity of 25% is more obvious than that of other porosity test specimens. The PC with large porosity is more serious to clogging because the higher seepage velocity will enter the internal tunnel with higher penetration force, which increases the possibility of clogging. Tests have shown that, at different rainwater runoff head heights, the PC specimens under the 200 mm high head are the most severely blocked; 0.283 m/s high-speed horizontal runoff appears after the rapid plugging stage later in the other two types of speed tests but over time. With time, the plugging effect of the test specimen was almost the same; the clogging degree of the permeable concrete sample with the porosity of 25% is more obvious than that of other porosity test specimens. While it is noticed that the compressive strength of the PC after clogging has decreased in the freeze-thaw environment, the destruction process is faster than the unblocked test specimen.

1. Introduction

Recently, due to the rapid urbanization and increasing consumption of natural resources, researchers are investigating various strategies to protect and restore natural ecosystems around the world to avail an economical and environmentally friendly way [1–3]. PC is the most widely used building material in sponge city construction because of its environmentally friendly characteristics. In recent years, the researcher has made considerable progress and development in PC, but there are still many problems in PC. It is necessary to develop its strengths and overcome its weaknesses. Permeable concrete pavement (PCP) is the type

of concrete that features an open network of pores to allow penetrating the rainwater through the concrete pavement to the base/subbase [4–8]. The pore-clogging of PC is the most prominent problem in the use of PC [9]. Due to the lack of rainfall, strong wind, and sand, the PC pore-clogging will not only reduce the permeability effect but also seriously affect its service life after a long winter [10].

Urban areas are associated with impenetrable infrastructure, which increases the potential of surface water runoff and flooding during periods of heavy rainfall. Permeable concrete is generally an important, sustainable, and cost-effective urban sanitation system that can reduce rainwater runoff and alleviate local flood problems [11].

High permeability ensures good drainage. Therefore, PC has been widely used in the quality and quantity management of urban runoff [12]. For the southern part of China, although there is more rainwater, the surface runoff generated by rainwater also carries the sediment of pavement, seeds of flowers and grass, and humus produced by road waste into the pore of PC, which also reduces the performance of PC [13]. Pratt found that when the road surface is dry, the accumulated particles will form a hard shell to seal the pore of PC. When the permeability coefficient of PC is less than the rainfall intensity, the pore-clogging will lead to the decrease of permeability rate, eventually leading to surface overflow and water accumulation [14]. Plant debris build-up is mainly responsible for physical clogging on the surface as well as in the pore structure; this is probably the most common mechanism. Similarly, biological clogging brought by bacteria and algae and penetration of plant roots can also happen [15]. Dry materials contain sand, silt, and clay sediments and cause clogging from surrounding areas [16], including waste from roads or other areas carried through a vehicle, small particles produced on the pavement due to surface wear or other degradation, and organic matter from plants [11, 17]. Schaefer studied that sand resulted in a significant decrease in permeability, while fine silty clay had a little effect. The combination of silty clay and sandy soil will lead to a decrease in permeability, and PC will be completely blocked after a small amount of cycling. This is due to the wider particle size distribution, which increases the probability of retention of various particle size plugs [18].

Guthrie evaluated the freeze-thaw resistance of PC under different soil clogging and water saturation. The sand was collected near the actual PCP to simulate the site environment. It was found that the samples with blocked or fully saturated pavement or both were more susceptible to disease than those without blocked or unsaturated pavement [19]. A less amount of sand can improve the working capacity, strength, and durability of freezing/thaw and strength of PCP without losing their permeability [20]. Freezing/thaw tolerance of durable PC arranged with the crushed layer can be acceptable for tolerated of low traffic loads pavement [21]. In PC, ignore the use of fine aggregates to create a network of pores. Porous structure makes the pavement perform good permeability and the rain infiltrates quickly into the ground because it can reduce the estimated flood [22–24]. According to ACI when the particle size of sediment is close to the pore size of PC, the probability of clogging may be the highest [25, 26]. Welker screened the materials from the pore of permeable asphalt and PC in the parking lot and found that there were few fine sediments. Because of the serious wear condition of PCP, most of the blocking materials came from the degradation of pavement [27].

Coughlin suggested that the coarse sand particles of PCP did not significantly reduce its permeability because the large particles were prevented from entering the surface pore [28]. A durable and strong PCP can be recognized by using less quantity of fine aggregates, consuming a somewhat higher w/c ratio, addition of polypropylene, making known to entraining air and increase the paste volume, and replacing fly ash [29] and silica fume [30] with Portland cement or use

a latex admixture [31]. The compressive strength can be significantly increased by the addition of nanomaterials in PCP [32]. Wang et al. investigated the addition of steel slag as a partial aggregate, and the results showed an improvement in the mechanical properties of PC [33].

Concrete compressive strength behavior is depending on the size, distribution, and spacing of pores [34, 35]. PCP has a wide range of features, e.g., 15–30% of effectual air voids, 20–500 m/day permeability, and 5.5–20.5 MPa compressive strength [36]. The permeability coefficients of PCP are usually from the range of 2–6 mm/s, and some of them increase even up to 10 mm/s, and the porosity varies between 15 and 25%. The suspended particles can block the pores of PCP, like debris and sediment in the surface runoff causing to reduce the permeability and also reducing the age of PC [17, 37], and the compressive strength is generally between 3.5 MPa and 30 MPa. PC has been widely used in drainage facilities of municipal roads, park sidewalks, parking lots, and other places [38]. PCP can considerably advantage the environment in urban sites, which can reduce the rainwater runoff quantity and also can improve the quality of water regarding total [39, 40].

The objective of this research article is to conduct a comprehensive test on the clogging of PC and evaluate and analyze it. The main objective is to critically review available studies on clogging, summarize, and understand the problem and mitigating strategies. The influence of porosity, w/c ratio, and freeze-thaw times on the compressive strength of PC after freeze-thaw is studied by the response surface method. Response surface methodology (RSM) is used to analyze the influence of three factors, namely, the height of rainwater runoff, the horizontal runoff velocity, and the porosity, on the clogging of PC.

2. Materials and Methods

According to the construction requirements of Honghe Avenue, the low-alkali P.O 42.5 cement produced by Lafaji Dongjun Cement Co., Ltd., Kunming city, is selected for the test. The standards of cement that meet the requirements of ordinary Portland cement are the American ASTM C159. Its physical and mechanical properties of cement are given in Table 1. While, the coarse aggregate used in this test is steel slag, produced in Kunming Iron and Steel Holding Co., Ltd. Steel slag is a by-product of the steelmaking process, which mainly consists of tricalcium silicate, dicalcium silicate, calcium magnesium olivine, calcium magnesium rosopyroxene, dicalcium ferrite, and other minerals. Chemical composition of cement and steel slag is given in Table 2. The size of steel slag selected in this test is 4.75–9.5 mm, which conformed to ASTM D5106-15, and the physical properties of steel slag are given in Table 3. Similarly, the mineral admixture used in this experiment is fly ash; the physical properties are given in Table 4; the fine ash is collected from the flue gas after coal combustion. The main oxide composition is SiO_2 , Al_2O_3 , FeO , Fe_2O_3 , CaO , and TiO_2 . Its related indicators comply with the “Technical specifications for the application of fly ash concrete” (ASTM C618-19), and its physical parameters are given in Table 4. The w/c ratio in

TABLE 1: Mechanical properties of cement.

Density g/cm ³	Specific surface area m ² /kg	Stability	Flexural strength (MPa)		Compressive strength (MPa)	
			3 d	28 d	3 d	28 d
3.094	358	Eligible	5.1	8.2	25.3	48.7

TABLE 2: Chemical composition of cement and steel slag [41].

Material (%)	Chemical compositions						
	CaO	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	MnO	MgO	Na ₂ O
Cement	68.4	16.4	3.53	4.24	0.15	2.39	-
Steel slag	16.9	26.4	43.4	4.84	2.66	1.86	0.15

TABLE 3: Physical properties of steel slag aggregates.

Steel slag size Mm	Apparent density kg/m ³	Natural bulk density kg/m ³	Close packing density kg/m ³	Natural porosity %	Tightly packed porosity %
4.75–9.5	3518	1854	1940	47.3	44.9

TABLE 4: Fly ash physical properties.

Moisture content %	Density kg/m ³	Fineness %	Specific surface area %	Water requirement ratio %	Loss on ignition %
0.6	2100	0.4	309	95.6	0.8

this experiment is 0.38, 0.40, and 0.42, respectively, and the water used in the test mixing concrete is the local tap water, which meets the requirements of concrete mixing.

2.1. Mix Proportion. Various mix proportioning methods have been recommended, and the most key necessity is to provide satisfactory cement paste to bind aggregates and achieve the high void content and required strength. The absolute volume method is used to calculate the mix design [25, 34]. Less than 15% porosity of concrete tends to provide a very slow water filtration due to lacking interlocked voids [42]. Porosity is more than 35%, very highly permeable, but the strength of concrete decreases; therefore, the target porosity of this research experiment is divided into three groups as 15%, 20%, and 25%, respectively. The mix proportions are given in Table 5.

The air-entraining agent used in this test comes from Hongxiang Building Admixture Factory, Laiyang city, Shandong Province. The general content of the air-entraining agent is not more than 0.3% of the cement quality. This study selects 0.1% gel strength agent, fly ash, polymer emulsion, and cement must be mixed in a certain proportion to improve the strength of PC. The specimens were demolded after 48 hours of casting, and then, the specimen was placed in the standard curing room until the required age. The standard curing adopted in this experiment was to put the specimen blocks together in the standard curing room with a temperature of $20 \pm 2^\circ\text{C}$ and relative humidity of 95% for 48 hours.

2.2. Determination of Porosity of PC. In combination with the test conditions, the gravimetric method is used to determine the porosity of PC. The cured test specimens were placed in a drying box for 24 hours, the mass m_1 after drying is weighed, and the size of the test specimens was measured with a ruler to calculate the volume V of the test specimen. Then, the test specimen is placed in water for 6 hours, and then, the mass m_2 of the test specimen in the water is weighed by an electronic scale with a hook. The difference in mass before and after weighing is the actual buoyancy of the specimen due to the filling of the pores by water. If the porosity of the specimen is zero, then the buoyancy of the specimen is theoretically subtracted from the buoyancy received by the specimen. The porosity P is obtained by the following formula:

$$P = \left[1 - \frac{m_2 - m_1}{\rho_w V} \right] \times 100\%, \quad (1)$$

where P is the porosity of PC (%), m_1 is the mass of the test specimen in water (g), m_2 is the quality of the test specimen after drying in the drying box for 24 h (g), ρ_w is the density of water (g/cm^3), and V is the volume of the test specimen (cm^3).

The porosity measured by the gravimetric method and the measurement data is shown in Figure 1.

2.3. Determination of Compressive Strength of PC. The compressive strength is measured according to the standards (ASTM C39/39M–18). The concrete mix design ratio for C20

TABLE 5: Mix proportions of steel slag modified pervious concrete (in kg/m³).

S. no.	Aggregate kg/m ³	Cement kg/m ³	Fly ash kg/m ³	Polymer emulsion kg/m ³	Gel kg/m ³	Air-entraining agent kg/m ³	Water kg/m ³
1	1901.2	397.78	43.09	3.88	19.39	0.39	163.73
2	1901.2	325.15	36.13	3.25	16.26	0.33	144.51
3	1901.2	262.52	29.17	2.63	13.13	0.26	122.51
4	1901.2	377.28	41.92	3.77	18.86	0.38	159.30
5	1901.2	316.34	35.15	3.16	15.82	0.32	140.60
6	1901.2	255.41	28.38	2.55	12.77	0.26	119.19
7	1901.2	367.33	40.81	3.67	18.37	0.37	155.09
8	1901.2	308.00	34.22	3.08	15.40	0.31	136.89
9	1901.2	248.68	27.63	2.49	12.43	0.25	116.05

FIGURE 1: Determined porosity data of PC specimen test results.

and C30 was calculated for all specimens [43, 44], with a 0.38 water-cement ratio. Clean and free of deleterious matter tap water was used in the concrete mix, as given in Table 6, which requires the standard specimen to have compressive strengths of 20 MPa and 30 MPa, respectively, after reaching the curing period. The mixtures were prepared and cast into 150 mm × 150 mm × 150 mm cubical and cylindrical specimen Φ100 mm × 100 mm molds into layers per the ASTM C 1435 standard. The test loading speed is controlled at 0.3–0.8 MPa/s. The compressive strength of PC is given in Table 6, which was determined by using the following formula:

$$f = \frac{F}{A}, \quad (2)$$

where f is the permeability of the PC cube (MPa), F is PC cube test specimen damage load (N), and A is the bearing area of the PC specimen (mm²).

2.4. Determination of Water Permeability of PC. The fixed water head method was used to determine the permeability coefficient. To record the change of the permeability coefficient of PC in real-time, the device is equipped with two electronic water pressure sensors and one ultrasonic flow sensor, all measured data. When the permeability coefficient test is carried out, the two water pressure sensors can record the pressure changes on the upper and lower surfaces of the

test specimen in real-time, which can reflect the head loss. The hydraulic gradient is obtained by using the following formula:

$$i = \frac{hw}{L} = \frac{h_1 - h_2}{L}, \quad (3)$$

where h_1 and h_2 are the pressure values of the upper and lower surfaces of the PC specimen (KPa), h_w is the head loss after water flowing through the PC specimen (KPa); L is the height of the test specimen (mm), and i is the hydraulic gradient.

The outlet pipe of the device is equipped with an ultrasonic flow sensor; it can dynamically collect and transmit the flow velocity v_2 of the water pipe, and then, the flow velocity v_1 in the PC specimen block can be derived by the formula, according to Darcy's law and formula (4). It is concluded that the permeability coefficient k is determined by the hydrostatic concrete method. The derivation formula is [45]

$$k = \frac{v_1}{i} = \frac{A_{ou}L}{A_s h_w} v_2, \quad (4)$$

where k is the permeability coefficient of PC specimen (mm/s), v_1 is the water flow velocity in the PC specimen (mm/s), v_2 is the water flow velocity in the outlet pipe (mm/s), i is the hydraulic gradient, L is the height of the test specimen (mm), h_w is the head loss after water flowing through the PC

TABLE 6: Permeable concrete specimen compressive strength test results.

S. no.	Failure load KN	Compressive strength MPa	Average compressive strength MPa
1	631.6	28.07	25.84
2	577.1	25.65	
3	535.4	23.80	
4	469.9	20.88	20.85
5	446.2	19.83	
6	491.3	21.84	
7	382.1	16.98	18.44
8	383.6	17.05	
9	479.3	21.30	
10	571.8	25.41	28.16
11	684.5	30.42	
12	644.2	28.63	
13	480.6	21.36	21.36
14	485.8	21.59	
15	475.6	21.14	
16	391.4	17.40	18.01
17	381.5	16.96	
18	442.7	19.68	
19	547.6	24.34	27.21
20	544.1	24.18	
21	745.1	33.12	
22	412.9	18.35	19.20
23	394.4	17.53	
24	488.4	21.71	
25	341.7	15.19	16.86
26	382.1	16.98	
27	414.5	18.42	

specimen (KPa), A_{ou} is the cross-sectional area (the outlet pipe is mm^2), and A_s is the effective area of the cross-section after applying Vaseline on the PC specimen (mm^2).

2.5. Determination of Freeze-Thaw Resistance of PC. In this experiment, the quick-freezing method is used for the freeze-thaw test. The KDR-V9 rapid freeze-thaw test machine is used, and the concrete has a cubical shape with the size of $150 \text{ mm} \times 150 \text{ mm} \times 150 \text{ mm}$. Dry the surface with a dry cloth to record the transverse fundamental frequency, modulus of elasticity, and mass of the specimens used to characterize the freeze-thaw durability of PC. The minimum temperature was -18°C , the maximum temperature was 7°C , the temperature difference between the inside and outside of the test specimen should not be greater than 28°C , the freeze-thaw is controlled within 10 min, and the time for each freeze-thaw cycle test is controlled to about 4 hours. The quick freeze-thaw of the PC weight loss after the test (called the Cantabro loss) is calculated in percentage by using the following formula:

$$W = \frac{G_0 - G_n}{G_0} \times 100\%, \quad (5)$$

where W is the mass loss rate of the PC specimen after n freeze-thaw cycles (%), G_0 is the initial mass of PC specimen before freeze-thaw cycle test (Kg), G_n is the quality of the PC specimen after n freeze-thaw cycle test (Kg).

2.6. Comprehensive Test of PC Clogging. The PC clogging experiment uses the aforementioned permeability coefficient test equipment, and the test is carried out according to the following steps: before performing the test, put the test specimen into clean water and soak it for 24 hours, so that the test specimen reaches the saturated water state. After the soaking time is reached, take out the test specimen, wipe the moisture on the surface of the test specimen with a dry cloth, then apply petroleum jelly to the test specimen, pack the test specimen, and then put the test specimen into the plexiglass sleeve inside the tube. To prevent water leakage between the flanges and affect the test data, a rubber gasket can be added between the sleeve and the base, and finally, tighten the screws between the flanges to fix the upper and lower parts of the device. Turn off the ball valve switch on the base of the equipment, turn on the water pump, and spray the water evenly into the sleeve with a spray device. When the water head reaches the predetermined water head height, open the ball valve on the base again, which will let the sleeve a relatively stable head height is generated inside, and there are no bubbles in the water flow. At this time, the pressure sensor and the flow sensor are connected to the power supply, and the two sensors are connected to the seepage test pressure and the flow test system with a data cable, so that the measured flow value and the water pressure on the upper and lower surfaces of the test specimen can be transmitted to the data collection in real-time in the system.

After the permeability coefficient becomes stable, add 50 g of the plugging material uniformly into the sleeve. At this time, record the start time and end time of adding the plugging material and then test until the permeability coefficient approaches stability. To simulate the effect of rainwater runoff depth on the pore-clogging of PC, this set of test equipment is equipped with three different head heights, which are 100 mm, 150 mm, and 200 mm, respectively. Considering that horizontal runoff at different speeds will also affect pore-clogging, the spiral action of the blades is used to produce a horizontal rotation disturbance on the upper surface of the specimen. The diameter of the propeller blade is 60 mm, and its distance from the upper surface of the specimen is 10 mm. In this test, a total of 3 different speeds are set, which are divided into low-speed, medium-speed, and high-speed rotation. The maximum runoff velocity and average runoff velocity produced by each rotation speed are given in Table 7. Adding blocking substances and a certain rotation speed can simulate the clogging of PC in a real rainfall environment.

2.7. Permeability Test and Test Plan of PC Blocked. The main factors affecting the permeability coefficient after clogging of PC are the height of the head, the porosity of the test specimen, and the horizontal runoff generated by the different water flow velocities on the surface of the test specimen. The test scheme is given in Table 8, and the actual operation of the test is shown in Figure 2. Before and after, the test specimen is blocked, as shown in Figure 3.

2.8. Analysis of the Influence of Rainwater Runoff Head Height on the Clogging of Permeable Concrete. This test analyzes the influence of the head height generated by surface rainwater runoff on the clogging of PC by changing the height of the water head. Take the test schemes 1, 2, and 3 in Table 8 as examples. The height of the test water head was set to 100 mm, 150 mm, and 200 mm, without stir, to simulate the process of plugging with low speed just as normal rainfall condition, and the permeability of PC used in this set of tests was 20%. Figure 4 shows the normalized permeability coefficient of PC under different head heights. It can be seen from Figure 3 that PC under the high head is more prone to clogging, mainly because the higher the head height, the higher the seepage velocity. The larger the clogging material, the easier it is to block as the water under high permeation forces enters the pores. Due to the surface runoff with different flow rates generated by heavy rains, the blocking material will aggravate the clogging of the permeable concrete under the synergistic effect of surface runoff. In this experiment, the speed of the blade is used to simulate different runoff velocities, taking schemes 2, 4, and 5 in Table 8 as examples.

3. Results

The analytical test design includes contour lines and response surface diagrams for quadratic terms of data such as analysis of variance, quadratic regression equation fitting, and residuals. Three factors are optimized: water-cement

ratio, porosity, and the number of freeze-thaw cycles, and finally, the maximum response value, the value of the corresponding three factors, and the predicted result are obtained. The target porosity (A), w/c ratio (B), and the number of freeze-thaw cycles (C) were used as the three influencing factors to freeze and thaw PC. The design test factor and its level for determining the compressive strength are given in Table 9.

The response surface test plan and results are given in Table 10.

By using the Design-Expert software to regress the fitting analysis of the compressive strength data of PC in Table 10, after freeze-thaw, the quadratic multiple regression formula of the compressive strength coding value after freeze-thaw can be obtained: compressive strength of PC after freeze-thaw = $18.7 - 4.81A - 1.13B - 0.51C + 0.67AB + 0.15AC + 0.63BC + 2.13A^2 - 1.08B^2 - 0.15C^2$ ($R^2 = 0.9773$).

Perform analysis of variance and test the significance of the regression equation, and the results are given in Table 11. Observe the analysis of variance table, where $P < 0.0001$; the model can be considered to be extremely significant; the lack of fit in the table reflects the degree of difference between the model and test; the lack of fit in this test $P = 0.0593 > 0.05$; it can be concluded that the model is related to the test data and is significant. Adj $R^2 = 0.9481$ represents the model's correction determination coefficient, which shows that the model can explain 94.81% of the response value change; the multiple correlation coefficient $R^2 = 0.9773$, which proves that the model fits well; the coefficient of variation (CV) represents the confidence of the model. The smaller the value, the higher the confidence of the test. In this test, $CV = 4.51\%$, which shows that the model can reflect the test situation. Based on the above analysis, it can be concluded that the reliability of this model is high, and the regression equation can analyze the test results very well.

Correlation coefficient: $R^2 = 0.9773$; Adj $R^2 = 0.9481$; $CV = 4.51\%$; Adeq precision = 17.966.

It can be seen from Figure 5 that when the A(B) factor is a certain value, the compressive strength of PC after freeze-thaw increases with the increase of the value of the factor B(A), indicating that the slope of the surface is steep at this time. The contour line is more concentrated, which can explain that factors A and B have a significant effect on the compressive strength of PC after freeze-thaw [46], but from the trend of the three-dimensional surface map, it can be seen that the A factor is resistant to freeze-thaw of PC. The compressive strength is significantly higher than factor B [47, 48]. As can be seen from Figure 6, the density of the medium-high line of the abscissa is higher than that of the contour of the ordinate, indicating that the influence of factor A on the compressive strength of PC after freeze-thaw is higher than that of the C factor. It can be seen from Figure 7 that the distortion of the three-dimensional surface is small, indicating that the interaction between the two factors B and C is not obvious, and the contour of the abscissa is higher than the contour of the middle coordinate, indicating the influence of factor B on the compressive strength of PC after freezing and thawing is greater than factor C.

TABLE 7: Maximum runoff velocity and average runoff velocity produced by each rotation speed.

Runoff velocity	Low velocity (m/s)	Medium velocity (m/s)	High velocity (m/s)
Maximum runoff velocity	0.094	0.188	0.283
Average runoff velocity	0.047	0.094	0.141

TABLE 8: Test plan.

Plan	PC target porosity (%)	Head height (mm)	Blade speed
1	20	100	Medium speed
2	20	150	Medium speed
3	20	200	Medium speed
4	20	150	Low speed
5	20	150	High speed
6	15	150	Medium speed
7	25	150	Medium speed

FIGURE 2: Test actual operation diagram.

FIGURE 3: Comparison of PC specimens before and after plugging.

It can be seen from the data in Table 10 that the compressive strength of PC after freeze-thaw is less than the compressive strength before freeze-thaw, which is mainly because the freeze-thaw cycle test destroys the skeleton structure inside PC. The order of influence of three factors on the compressive strength of PC after freeze-thaw is as follows: A porosity > B w/c ratio > freeze-thaw cycle C, which appears as a steep curve in the three-dimensional

response surface. Flat, the absolute value of the coefficient in the model regression equation can be verified by sorting $A > B > C$ as given in Table 11.

The above contours cannot compare the significance of the interaction of various factors, but the absolute value comparison of the interaction factor coefficients in the model regression equation can be known: $AB > BC > AC$, indicating that the interaction between the two factors of AB

FIGURE 4: Normalized permeability coefficients after clogging caused by different head heights.

TABLE 9: Design test factors and their level.

Factor	Level		
	-1	0	1
Target porosity (%) (A)	15	20	25
W/c ratio (B)	0.38	0.4	0.42
Number of freeze-thaw (C)	25	50	75

TABLE 10: Compressive test plan and results.

S. no.	Target porosity in percentage (A)	W/c ratio (B)	Freeze-thaw cycles (C)	Permeability coefficient (mm/s)	Initial compressive strength (MPa)	Compressive strength after freeze-thaw (MPa)
1	15	0.38	50	10.86	28.07	25.75
2	25	0.38	50	12.98	21.30	18.26
3	15	0.42	50	9.10	24.34	21.94
4	25	0.42	50	15.89	18.42	14.72
5	15	0.4	25	10.83	28.63	26.93
6	25	0.4	25	15.28	17.40	15.59
7	15	0.4	75	10.71	30.42	25.48
8	25	0.4	75	15.07	19.68	14.72
9	20	0.38	25	12.04	20.88	19.58
10	20	0.42	25	10.59	18.35	16.25
11	20	0.38	75	11.37	21.84	17.43
12	20	0.42	75	10.87	21.71	16.62
13	20	0.4	50	12.09	21.36	19.14
14	20	0.4	50	12.38	21.59	19.10
15	20	0.4	50	12.75	21.14	17.97
16	20	0.4	50	12.51	22.21	18.47
17	20	0.4	50	13.04	20.83	18.83

is the greatest. After the Box-Behnken center combination design and response surface optimization, it can be predicted that the PC pores are at 18.31%, the w/c ratio is at 0.41, and

the strength is the largest after 75 freeze-thaw cycles, and the value reached 18.73 MPa, which indicates that PC is more suitable for engineering use.

TABLE 11: Regression equations for the analysis of variance and significance test.

Source	Sum of squares	Df	Mean square	F value	P value prob > F	Significant value
Model	223.79	9	24.87	33.45	<0.0001	Highly significant
A, porosity	184.80	1	184.80	248.60	<0.0001	Highly significant
B, w/c ratio	10.28	1	10.28	13.83	0.0075	Significant
C, freeze-thaw times	2.10	1	2.10	2.83	0.1366	Not significant
AB	1.81	1	1.81	2.43	0.1627	Not significant
AC	0.08	1	0.08	0.11	0.7465	Not significant
BC	1.59	1	1.59	2.14	0.1873	Not significant
A2	19.15	1	19.15	25.76	0.0014	Significant
B2	4.89	1	4.89	6.57	0.0373	Significant
C2	0.10	1	0.10	0.14	0.7235	Not significant
Residual error	5.20	7	0.74			
(Missing items) lack of fit	4.25	3	1.42	5.92	0.0593	Not significant
Pure error	0.96	4	0.24			
Total	228.99	16

FIGURE 5: Influence of porosity A and w/c ratio B on compressive strength after freeze-thaw.

FIGURE 6: Influence of porosity A and freeze-thaw C on compressive strength after freeze-thaw.

FIGURE 7: Effect of w/c ratio B and freezing-thawing times C on compressive strength after freeze-thaw.

3.1. Performance Analysis after Clogging of PC

3.1.1. Analysis of the Clogging Process of PC. The process of the permeability coefficient of PC after clogging can be divided into three stages: in the first stage, the permeability coefficient drops sharply after the clogging material is added; in the second stage, the permeability coefficient shows a certain rise, phenomenon; in the third stage, the permeability coefficient begins to slowly decrease and finally approaches stability [49]. As can be seen from Figure 8, the first phase can be considered as a fast-clogging phase, which lasts for approximately 160 seconds. The second stage can be considered as a partial clogging phase, which lasts for approximately 90 s. The oscillating rebound of the permeability coefficient at this stage is because the smaller particle size clogging material will flow out of the pore channel with the pore water flow. As the clogging material accumulates in the pore channel inside PC [50], its permeability coefficient approaches stability, and this stage can be regarded as a progressive clogging stage.

This test simulates different runoff flow rates by the rotational speed of the blades, taking schemes 2, 4, and 5 in Table 8 as examples. The height of the test head was set to 100 mm, 150 mm, and 200 mm [51], and the permeability of PC used in this set of tests was 20%. The normalized permeability coefficient is shown in Figures 9 and 10. It can be seen from the experimental results that after the horizontal runoff of different speeds, the high-level flow rate appears to be faster than the other two types of runoff speeds. This is mainly because high-level runoff will cause the clogging material to suspend. In the water body, when the clogging material approaches the low flow velocity region on the surface of the test specimen, it enters the pore of the test specimen with the action of the penetrating force. In addition, their permeability coefficients are approximately equal during the progressive stabilization phase, indicating that the high horizontal flow rate delays the clogging of PC.

3.1.2. Porosity Analysis of Clogging of PC. The clogging test is carried out with PC specimens of different porosities [52, 53]. Taking schemes 2, 6, and 7 in Table 8 as examples,

the test results are shown in Figure 10. It can be seen that the larger the porosity of the specimen block, the more easy the specimen is clogged. This is because the larger the porosity of the test specimen, the greater the seepage velocity inside the pore [54, 55]. More clogging materials will enter the internal pore with high penetration force, which increases the possibility of clogging of the test specimen. It can also be seen from the image that the permeability coefficient of the 25% porosity of the test specimen after clogging has a certain fluctuation.

It can be known from the above analysis that the factors affecting the permeability coefficient after clogging of PC are the porosity of the test specimen, the height of the head, and the horizontal runoff velocity of the surface. To analyze the weight of the three factors in this experiment, the above three factors are analyzed based on Design-Expert 8.0.6 software, and the experiment was conducted by using Box-Behnken in the Design-Expert 8.0.6 software [56].

The target porosity, head height, and surface horizontal runoff velocity were used as the three influencing factors to penetrate the PC after clogging. The coefficient is the response surface, and the test factors and design are given in Table 12. Regression fitting analysis of the permeability coefficient data of the PC in the table by Design-Expert software can be used to obtain the quadratic multiple regression equation of the coded value of the permeability coefficient after clogging: permeation rate after clogging = $5.64 - 0.4A - 2.34B - 0.22C - 0.042AB - 0.11AC + 0.061BC - 0.54A^2 - 0.41B^2 - 0.25C^2$ ($R^2 = 0.9911$).

The response surface test protocol and results are given in Table 13.

The regression equation and the significance test were performed on the regression equation. The results are given in Table 14.

In the analysis of variance table, $P < 0.0001$, $P = 0.0533 > 0.05$; it can be concluded that the model is related to the test data and significant. $\text{Adj } R^2 = 0.9798$, complex correlation coefficient $R^2 = 0.9911$, coefficient of variation, $\text{CV} = 4.51\%$; it can be further explained that the test reliability is high and the model fitting degree is good. The response surface and contour plots

FIGURE 8: PC specimen clogging process. Analysis of clogging of PC by different horizontal runoff velocities.

FIGURE 9: Different flow rates result in normalized permeability coefficients after clogging.

for the above three factors are shown in Figures 11, 12, and 13. It can be seen from Figure 11 that when the A factor is constant, the permeability coefficient of PC is reduced as the value of the factor B increases, indicating that the slope of the curved surface is steep and the contour line is more concentrated. The factor B permeability coefficient after clogging of PC is more significant, so for PCP that are not cleaned for a long time.

Correlation coefficient: $R^2 = 0.9911$, Adj $R^2 = 0.9798$, CV = 4.86%, Adeq precision = 30.033. In the case of strong rain, there will still be water accumulation on the road. From the trend of the three-dimensional surface map, it can be seen that the B factor has a significantly higher permeability coefficient after clogging of PC [57]. The shape of the contour line in Figure 12 is approximately elliptical, indicating that the

FIGURE 10: Normalized permeability coefficients after clogging for specimens of different porosities. Comprehensive analysis of PC clogging.

TABLE 12: Design test factor level and number.

Factor	Level		
	-1	0	1
Target porosity (%) (A)	15	20	25
Head height (mm) (B)	100	150	200
Horizontal runoff speed (m/s) (C)	0.047	0.094	0.141

TABLE 13: Response surface test plan and results.

Porosity (%)	Head height (mm)	Horizontal runoff speed (m/s)	Permeability coefficient (mm/s)
15	100	0.094	7.142
25	100	0.094	6.524
15	200	0.094	2.947
25	200	0.094	2.162
15	150	0.047	5.471
25	150	0.047	4.795
15	150	0.141	5.127
25	150	0.141	4.017
20	100	0.047	7.743
20	200	0.047	2.558
20	100	0.141	7.291
20	200	0.141	2.351
20	150	0.094	5.835
20	150	0.094	5.462
20	150	0.094	5.675
20	150	0.094	5.583
20	150	0.094	5.634

interaction between factor A and factor C is obvious. This can reflect the interaction between target porosity and surface horizontal runoff. The degree of influence on the permeability coefficient after clogging is large, but from the viewpoint of the

contour mass, it is impossible to discriminate the degree of influence of the A factor and C factor.

Figure 13 shows that when the C factor is fixed, the slope of the B factor is steep and the contour is dense, indicating

TABLE 14: Regression equations for the analysis of variance and significance test.

Source	Sum of squares	Df	Mean square	F value	P value prob > F	Significant
Model	47.759	9	5.307	87.063	<0.0001	Highly significant
A, porosity	1.271	1	1.271	20.856	0.0026	Significant
B, w/c ratio	43.627	1	43.627	715.777	<0.0001	Highly significant
C, freeze-thaw times	0.396	1	0.396	6.505	0.0381	Significant
AB	0.007	1	0.007	0.114	0.7451	Not significant
AC	0.047	1	0.047	0.773	0.4086	Not significant
BC	0.015	1	0.015	0.246	0.635	Not significant
A2	1.222	1	1.222	20.043	0.0029	Significant
B2	0.692	1	0.692	11.353	0.0119	Significant
C2	0.256	1	0.256	4.203	0.0795	Not significant
Residual error	0.427	7	0.061			
(Missing items) lack of fit	0.352	3	0.117	6.334	0.0533	Not significant
Error	0.074	4	0.019			
Total	48.185	16

FIGURE 11: Influence of target porosity A and head height B on the permeability coefficient after clogging.

FIGURE 12: Target porosity A and horizontal runoff velocity C affect the permeability coefficient after clogging.

FIGURE 13: Effect of head height B and horizontal runoff velocity C on the permeability coefficient after clogging.

TABLE 15: Crushing strength data of freeze-thaw PC before and after clogging.

S. no.	Porosity in percentage	W/c ratio	Freeze-thaw cycles no.'s	Initial compressive strength (MPa)	Compressive strength after freeze-thaw (MPa)	Compressive strength of freeze-thaw after blogging (MPa)
1	15	0.38	50	28.07	25.75	22.31
2	25	0.38	50	21.30	18.26	14.52
3	15	0.42	50	24.34	21.94	18.68
4	25	0.42	50	18.42	15.11	12.61
5	15	0.4	25	28.63	26.93	23.51
6	25	0.4	25	17.40	15.59	13.42
7	15	0.4	75	30.42	25.48	19.57
8	25	0.4	75	19.68	14.72	11.43
9	20	0.38	25	20.88	19.58	17.82
10	20	0.42	25	18.35	16.25	14.73
11	20	0.38	75	21.84	17.43	13.09
12	20	0.42	75	21.71	16.62	12.87
13	20	0.4	50	21.36	19.14	16.29
14	20	0.4	50	21.59	19.10	16.52
15	20	0.4	50	21.14	17.97	16.07
16	20	0.4	50	22.21	18.47	15.95
17	20	0.4	50	20.83	18.83	16.34

that the B factor is more influential than the C factor. The order of influence of three factors on the permeability coefficient after clogging of PC is as follows: B head height is higher than A target porosity and C surface horizontal runoff speed, but the degree of influence of A and C factors cannot be discerned [58].

3.1.3. Effect of the Freeze-Thaw Cycle Test on the Performance of PC after Clogging. The connection form between the PC aggregates is a point contact connection; the special skeleton structure relies on the connection of the cementing material. When PC is frozen and thawed after being blocked, the internal structure will change. Kevern et al. [20] believed that clogging will not only lead to a decrease in the permeability coefficient but also accelerate the process of PC under freeze-thaw conditions. Soil

particles and other clogging substances will saturate and expand by 2-3% under freezing conditions. In response to this, the freeze-thaw test of the PC after clogging becomes critical. The PC after the clogging of the 6 test plans is subjected to the freeze-thaw test. It can be known from the previous conclusion that the horizontal surface runoff velocity has a little effect on the clogging degree of the PC. Therefore, medium-speed surface runoff is used in this test. To make the PC block full and achieve the most unfavorable effect, each test specimen is blocked under the high head. Table 15 provides the compressive strength data of PC before and after clogging.

It can be seen from the above table that the PC specimen block undergoes freeze-thaw action after clogging, and its compressive strength decreases. It can be explained that clogging shortens the service life of PC, so the clogging of PC pores becomes clear.

4. Conclusions

This study carefully observes the PC specimens after clogging, and there is a small period of flattening of the permeability coefficient at the beginning of clogging. Then, the plugging particles continue to enter the pores of the test specimen under the action of permeability, and the permeability coefficient of the test specimen drops sharply, entering the rapid clogging stage [59]. Under the action of horizontal runoff, part of the clogging material remains on the surface of the test specimen returned to the water flow. At this time, the permeability coefficient of the test specimen had a short recovery stage. With the passage of time and the continuous accumulation of blocking substances in the pores inside the specimen, the PC specimen finally enters the gradual clogging stage [60].

In this study, related experiments are done in three aspects: different rainwater runoff head heights, different horizontal runoff velocities, and different porosities. The test shows that at different rainwater runoff head heights, the clogging of the PC specimens under high water heads is the most serious. This is mainly because a high water head will produce greater penetration force, and small particle blocking substances will enter the test under the action of penetration force. In the clogging test of PC by horizontal runoff at different speeds, due to the different carrying capacities of the clogging material by the horizontal runoff at different speeds, combined with the effect of inertia, the rapid clogging stage of the high-speed horizontal runoff is slightly later than the other two speed tests, but with time, the clogging effect of the specimen is roughly the same.

In the plugging test of PC with different porosities, it can be seen from the images obtained from the test that after the test specimens with different porosities are blocked, the clogging of the test specimens with large porosity is the most serious. This is mainly because the higher the seepage velocity inside the PC specimen with larger porosity, the more clogging material will enter the internal pores with high permeability, which increases the possibility of specimen clogging.

After the test, it is found that the quadratic regression equation of the compressive strength of the specimens has a better fit after freeze-thaw. It can be seen from the obtained response surface that the porosity of the PC specimen has a higher degree of influence on the compressive strength of the specimen after freeze-thaw than the other two factors and the interaction between the porosity of the PC and the w/c ratio. The effect also has a higher degree of influence on the compressive strength of the specimen after freeze-thaw. Through the analysis of the test data, it is predicted that when the porosity of the PC is 18.31% and the w/c ratio is 0.41, the resistance strength value of the specimen is the largest after 75 freeze-thaw cycles, and its value can reach 18.73 MPa. This study uses the same test indicators to perform related tests on the blocked permeable concrete. From the test data, the compressive strength of the blocked permeable concrete has decreased. In a freeze-thaw environment, the destruction process is faster than that of unblocked specimens.

Utilizing steel slag and recycled concrete as fine aggregate could save the consumption of natural resources and reduce environmental pollution; the successful use of slag steel as a permeable pavement provides a new and more cost-effective method for increased resources and reduces the threat from solid waste to the environment.

However, more studies should be carried out on the mechanical characteristics of PCP with different additives, recycled materials, and wastes.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Ismail Shah and Cao Yang contributed equally to this work.

Acknowledgments

The authors would like to thank supervisor, Prof. Dr. Li Jing, for the patient guidance, encouragement, and advice he has provided throughout this research work. This project was supported by "Yunnan Science and Technology Major Project" under the project "R&D and application demonstration for key technologies of digital agriculture of Yunnan plateau characteristics" (202002AE090010).

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