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Essay

Influence of Mineral Admixtures on the Performance of Pervious Concrete and Microscopic Research

Wenhua Yuan [1,2,*], Lianjie Ji [1,*], Long Meng [1], Min Fang [1] and Xiangchi Zhang [1]

[1] School of Civil Engineering and Architecture, Anhui University of Science and Technology, Huainan 232001, China; 2022200589@aust.edu.cn (M.F.); 2022200459@aust.edu.cn (X.Z.)
[2] Ministry of Education Research Center of Mine Underground Engineering, Anhui University of Science and Technology, Huainan 232001, China
* Correspondence: whyuan@aust.edu.cn (W.Y.); 2021200377@aust.edu.cn (L.J.)

Abstract: Pervious concrete is an innovative eco-friendly construction material. Through the application of mineral admixtures and microscopic analysis to optimize its performance and analyze its mechanisms, its traits as a sustainable building option may be further improved. This study primarily examines the impact of the optimal blend quantities of fly ash, silica fume, and reinforcing agent on the attributes, micro-morphology, and phase composition of porous concrete. The optimal admixture was chosen after analyzing the effects of various factors on the mix ratio and properties of permeable concrete. To understand the degree of impact, performance tests were conducted on the 28-day compressive strength, water permeability coefficient, and porosity. Furthermore, the micro-mechanisms of the admixtures and reinforcing agents on the properties of permeable concrete were analyzed from a microscopic point of view using scanning electron microscopy (SEM) and X-ray diffraction (XRD) analysis. This research found that the advantageous properties of permeable concrete were enhanced by the simultaneous integration of appropriate quantities of fly ash, silica fume, and reinforcing agent. This resulted in a 28-day compressive strength of 18.33 MPa and a permeability coefficient of 8.27 mm/s. Compared with the unadulterated mineral admixture, the optimal admixture of fly ash, silica fume, and reinforcing agent at the same time increased the 28-day compressive strength by about double; the permeability coefficient was reduced by 36%, but it was still at a high level; and the measured porosity did not differ much from the designed porosity. Through thorough microanalysis, the hydration reaction was significantly improved, which could enhance the microstructure and pore structure of the concrete. This was supported by a substantial increase in the macroscopic compressive strength and a decrease in the water permeability coefficient, which were consistent with the aforementioned enhancement found in the microanalysis.

Keywords: pervious concrete; optimum mix ratio; mineral admixture; micro-mechanism; performance study

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1. Introduction

In recent times, the progression of urbanization has resulted in a significant reduction in the natural permeability of the urban surface due to numerous buildings and road covers. Consequently, urban areas are prone to frequent flooding during certain seasons [1–3]. Permeable concrete pavements address the limitations of conventional pavements in enhancing urban drainage systems to prevent floods, minimizing their impact when they occur, and improving road conditions, the urban heat island effect, and overall community well-being. Pervious concrete pavement has an important role in the process of urbanization, since it can improve the flood prevention and drainage capacity of cities and thus improve the urban environment and traffic conditions. Therefore, in urban planning and construction, the use of permeable concrete pavement materials should be considered.

Pervious concrete is an innovative and environmentally friendly building material that exhibits remarkable functional utility. This material offers effective solutions to urban drainage issues, which are vital to mitigating water shortages and enhancing the urban ecological environment. Studies have demonstrated its potential to achieve these outcomes [4,5]. However, the performance of pervious concrete is influenced by multiple factors, including aggregate selection, particle size combination, and the type and quantity of cementing material. With these in mind, extensive attention and research have been devoted to the rapid development and broad application of pervious concrete both domestically and internationally.

Jinlin Huang et al. [6] discovered that the compressive strength of permeable concrete is increased with higher replacement levels of silica fume and decreased with higher replacement levels of fly ash. The highest permeability values for silica fume and fly ash individually were achieved at replacement levels of 6% and 10%, respectively. Meanwhile, Avinash et al.'s [7] test results showed that the compressive strength of pervious concrete mixed with mineral admixtures was superior to that of ordinary pervious concrete. Of the three different replacement percentages used, 20% was found to be the best value in both cases. The pervious concrete mixed with silica fume showed better strength in the two admixtures. Elsewhere, Ping Gong et al.'s [8] test results showed that the compound admixture of fly ash and silica fume had the best effect, and the 28 d compressive strength of concrete was higher than that of single or no mineral admixtures. In their study, Nazeer et al. [9] investigated the strength, durability, and microstructural properties of pervious concrete. The concrete was prepared by substituting cement with fly ash and silica fume. Their findings indicated that incorporating a 10% mass ratio of fly ash and silica fume resulted in a substantial improvement in the durability and strength of pervious concrete. It is worth mentioning that the improved pervious concrete possessed a remarkable microstructure. The microstructural analysis of pervious concrete prepared with fly ash and silica fume revealed the formation of uniformly layered C-S-H and C-A-S-H gels, resulting in denser micrographs. Consequently, the pervious concrete exhibited improved mechanical and durability characteristics. In another study, Zaetang et al. [10] investigated the addition of mineral additives (diatomaceous earth, fly ash, limestone powder, and fine sand) to slurries with a low water/cement ratio (w/c) to improve the strength and other properties of pervious concrete. It was shown that the additives increased the volume of the paste and improved the mechanical properties of the pervious concrete. Improvements brought about by the addition of diatomaceous earth or fly ash were due to a combination of chemical and filling effects, whereas improvements brought about by the addition of inert limestone powder or fine sand were due to filling effects alone. The strength and abrasion resistance of the pervious concrete with the addition of mineral additives were improved, but the density and thermal conductivity were slightly increased. In a further findinding, Goran et al. [11] showed that silica fume at around 5% performed best in improving workability, strength, and durability. Meanwhile, Kexiong, W.U. et al. [12] investigated the effects of the aggregate size, water–cement ratio, water reducer, reinforcing agent, and sand rate on the properties of porous concrete, and they found that the strength of pervious concrete could be increased by two grades by adding 5% homemade pervious concrete reinforcing agent. In their study, Bowen Tang et al. [13] investigated the microstructure and mineral composition by means of scanning electron microscopy (SEM), X-ray diffraction (XRD), and thermogravimetric analysis (TGA), and they also analyzed the strengthening mechanism and environmental benefits of carbonated recycled aggregate pervious concrete (CRAPC). The results of the study showed that both aggregate carbonation and concrete carbonation could improve the compressive strength of permeable concrete while maintaining acceptable permeability. Concrete carbonation was more effective, and under the same carbonation conditions, concrete carbonation sequestered more carbon dioxide than aggregate carbonation, which is more beneficial to the environment.

As these findings indicate, much progress has recently been made in the research and application of pervious concrete; however, few scholars have studied its microstructure and analyzed the hydration reaction process by means of SEM and XRD. The mechanism of interaction between the two is discussed here, as determined based on macroscopic performance and microstructural analysis. In this experiment, the optimal dosage of each factor was determined by the orthogonal test method, and the optimal mix combination of the orthogonal test was selected to explore whether there was any influence on the double-doped mineral admixture. In order to deeply inspect the performance and microstructure of pervious concrete, we systematically carried out a performance test and 28 d microstructure analysis, which allowed us to better understand the mechanism of action of the admixture in affecting the performance of pervious concrete. This study can provide theoretical support for optimizing the mix ratio of pervious concrete and improving the quality of pervious concrete in engineering practice, and, generally, it contributes to the research and application of pervious concrete.

2. Test Program

2.1. Raw Materials

(1) Cement

In pervious concrete raw materials, cement, as an important cementing material, plays a vital role. It cannot only bond various crushed stones and additives to form concrete with porous and lightweight characteristics but also enhances its compressive strength and wear resistance. P.O42.5 cement was selected for this experiment. The main performance parameters are shown in Table 1.

Table 1. Main performance parameters of cement.

Density (kg/m^3)	Specific Surface Area (m^2/kg)	Stability	Setting Time (min)		3 d Compressive Strength (MPa)		28 d Compressive Strength (MPa)	
			Initial Set	Final Set	Compressive	Flexural	Compressive	Flexural
3100	378	Eligible	245	294	21.8	5.1	50.8	8.3

(2) Coarse aggregate

In order to ensure the balance of water permeability and mechanical properties, single primary distribution or graded discontinuous aggregates must be used in pervious concrete. The particle size needs to be as uniform as possible and generally between 5 and 20 mm. Aggregates that are too large will affect the water permeability, and those too small will affect the mechanical properties. Permeable concrete aggregates should comprise crushed stone with angles, not rounded or flaky stone, because the irregular surface morphology of the crushed stone can improve the bonding between an aggregate and the concrete. The aggregates should be hard and strong enough to withstand the compressive and bending forces of the cementitious material. They should also have a finish that ensures the compactness and permeability of the cementitious material.

For this test, a single primary mix of aggregates was selected; we used unpolished basalt crushed stone with grain sizes of 3–6 mm, 6–9 mm, 9–12 mm, and 12–15 mm (as shown in Figure 1), all of which were cleaned and sun-dried before the test. The main performance indexes of the crushed stone are shown in Table 2.

Table 2. Main performance indexes of basalt crushed stone.

Aggregate Size	Density (kg/m^3)	Bulk Density (kg/m^3)	Voidage (%)	Mud Content (%)	Crushing Value (%)	Needle and Flake Content (%)
3~6 mm	2725	1624	40.40	<0.5	<15.0	<20.0
6~9 mm	2716	1599	41.13			
9~12 mm	2750	1601	41.78			
12~15 mm	2724	1539	43.50			

Figure 1. Different aggregate particle sizes.

(3) Mineral admixture

Fly ash and silica fume are commonly used as active mineral admixtures to improve the performance of concrete. In pervious concrete, fly ash and silica fume have different functions. The fly ash and silica fume samples selected for this test are shown in Figure 2, and their main performance indexes are shown in Table 3.

Figure 2. Fly ash and silica fume sample diagram.

Table 3. Main performance indexes of fly ash and silica fume.

Name	Test Item	Numerical Value
Fly ash	Density/kg·m^3	2550
	Packing density/kg·m^3	1120
	Fineness/% (5 μm square mesh screen $\leq$ 18%)	16
	Water content/%	0.85
	Silicon trioxide/%	24.2
	Silicon dioxide/%	45.1
Silica fume	Density/kg·m^{-3}	2800
	Silicon dioxide/%	98.1
	Burn reduction/%	1.48
	Specific surface area/%	21
	Water demand ratio/%	112
	Activity index (28 d)/%	105

(4) Reinforcing agent

In this test, we used the JIAJING ECO SR-2-type reinforcing agent. Its admixture amount is 3–6% of the weight of the cement, and after fully mixing the pervious concrete, the measurement of its caving degree should be zero. The main performance indexes of the reinforcing agent are shown in Table 4.

Table 4. Main performance indexes of the reinforcing agent.

Density	Fineness (0.315 mm Sieve Residue)	PH Value	Moisture Content	Total Alkali Content	Sodium Sulfate Content
2440 kg/m^3	1.52%	11.94	1.18%	5.10%	1.02%

(5) Water reducer and water

Water-reducing agents are indispensable for the preparation of pervious concrete; their functions are to reduce the water consumption of mixing, lower the water/cement ratio, and improve the strength of pervious concrete. Additionally, through the use of a water-reducing agent, the solubility of the permeable concrete slurry may be improved, and the slurry can uniformly wrap around the surface of the aggregates to form a good encapsulating slurry layer, which greatly improves the working performance of the permeable concrete. A polycarboxylic acid high-efficiency water-reducing agent was selected for this test, and the main performance indexes are shown in Table 5. The clean tap water in the laboratory was used as the added water.

Table 5. Main performance indexes of water-reducing agent.

Density	Water-Reducing Rate	Gas Content	Bleeding Rate Ratio	PH Value
1060 kg/m^3	28%	3.0%	20%	5.2

2.2. Preparation and Maintenance of Test Blocks

The mixing and molding process of pervious concrete has a great influence on its performance. The cement-coated stone method [14], a common mixing method, was used in this test to mix the cement and aggregates fully and ensure the uniformity of the concrete. The process is shown in Figure 3. Firstly, we poured the aggregates and 20% of the water into the mixer and stirred them together for 30 s. Secondly, after all the crushed stone was wetted for 90 s, we added the cement, fly ash, silica fume, and reinforcing agent so that the surface of the crushed stone formed a homogeneous cement shell layer. Finally, we added the water-reducing agent and the remaining 80% of the water and stirred it for 90 s. The mold specifications were 100 mm × 100 mm × 100 mm. We selected the plug pounding molding method, and the stirred mixture was divided into a three-layer mold, with the leading thickness of each layer approximately equal. Each layer was pounded about 25 times from the surrounding area to the center of the plug [15]. After filling the molds, we took the concrete out of them and placed it in a standard maintenance room. We set the temperature to 20 (± 2) °C and the relative humidity to 95% or more [16].

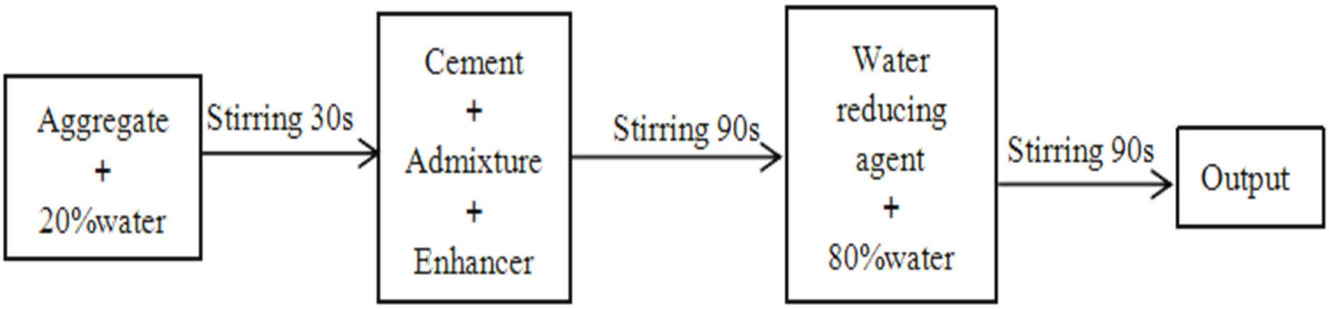


Figure 3. Cement-coated stone process flow diagram.

2.3. Test Methods

(1) Compressive strength

The compressive strength of the permeable concrete was tested according to the GB/T50081-2019 "Standard for test methods of concrete physical and mechanical properties" [17]. The WAW-1000 electro-hydraulic servo universal testing machine was used for pressurization (as shown in Figure 4), and the loading speed was 0.8 MPa/s. The final compressive strength value was determined by multiplying the average value of three specimens by a conversion factor of 0.95. The pressure strength was calculated according to the following formula:

$$f_{cu} = \frac{F_{max}}{A} \tag{1}$$

where f_{cu}—concrete cube compressive strength (MPa);

F_{max}—maximum load (N);
A—specimen compressive area (mm^2).

Figure 4. WAW-1000 electro-hydraulic servo universal testing machine.

(2) Permeability coefficient

In order to facilitate the operation and measurement, the water permeability method used by Wang Wuxiang [18] and Yang Jing et al. [19] was selected, on the basis of which a homemade variable head was used to measure the permeability coefficient (as shown in Figure 5). The permeability device was a rectangular transparent model with an opening of 100 × 100 mm for the top and bottom dimensions. The front side had a scale for measuring the height of the water level. The test block was placed underneath the model, the interfaces were tightly sealed, and a stopwatch was used to record the time it took for the water level to fall from 200 mm to 0 mm. This was calculated according to the following formula:

$$K = \frac{\Delta H}{\Delta T} \tag{2}$$

where K—water permeability coefficient (mm·s^{-1});

ΔH—water level difference, i.e., 200 mm;
ΔT—time taken for the water level to drop from 200 mm to 0 mm.

Each group had 3 specimens, and each specimen was tested 3 times. Then, the average values were taken as the individual specimen test results, and finally, the average value of the 3 specimens was obtained.

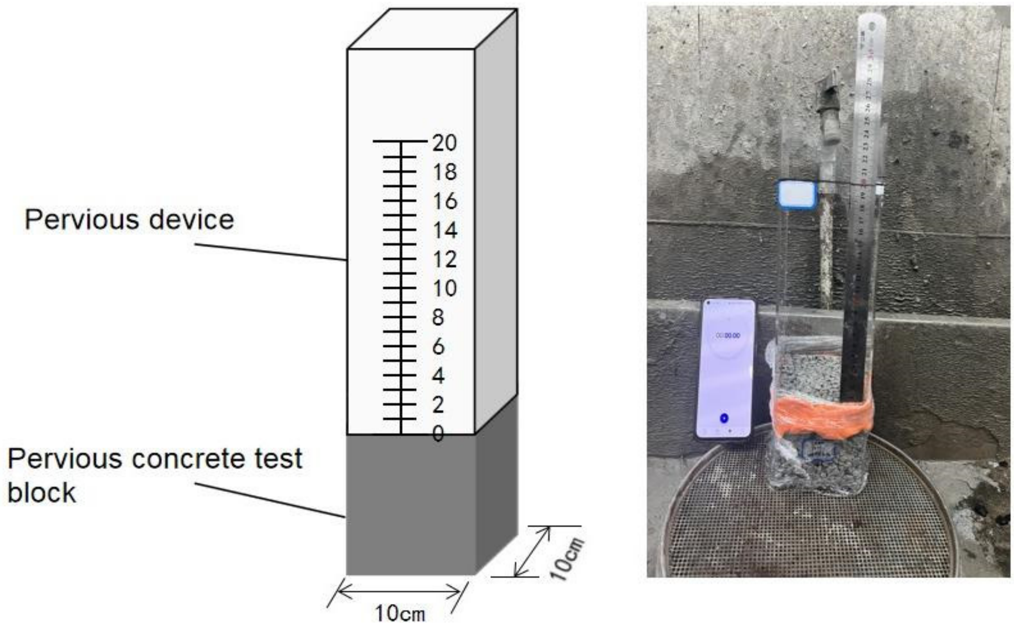


Figure 5. Self-made variable head osmotic flowmeter schematic and physical drawings.

(3) Porosity

There are three kinds of pores in permeable concrete. The first are closed pores. Then, the second are open but discontinuous pores, which we call "bag-type" pores. The excessive existence of these first two kinds of pores is unfavorable for the water permeability of concrete. The third kind are continuous effective pores through the concrete, which guarantee the water permeability of permeable concrete [20].

The porosity test was selected as the method for determining the effective porosity of eco-permeable concrete, as described in *Ecological Concrete Slope Protection Technology and Application* [21]. The test block was placed in a drying oven at 105 ± 50 °C to dry to a constant weight, and then it was removed and cooled to room temperature. The mass m_1 after drying was measured first, and then the dried test block was placed in a water tank and completely immersed in water for 1–2 d. The mass m_2 in the water was measured with a portable electronic scale. We calculated the porosity P using the following formula:

$$P = \left(1 - \frac{m_1 - m_2}{V \cdot \rho_w}\right) \times 100\% \quad (3)$$

where $\boldsymbol{V}$ is the volume of the test block;

$\boldsymbol{\rho_w}$ is the density of the water.

(4) Microscopic tests

Scanning electron microscopy (SEM) and X-ray diffraction (XRD) analysis were used to detect the reaction products of the reinforcing agents and fly ash and silica fume after 28 days in pervious concrete from a microscopic point of view, to analyze the microscopic mechanisms of the effects of admixtures and reinforcing agents on the properties of pervious concrete [22,23].

Optimal samples of the pervious concrete were selected, crushed, and sieved, and flaky cement particles with a diameter of about 2 mm were selected, sealed, and preserved with alcohol to terminate the hydration. SEM was used to observe the microscopic morphology of the hardened cementing material between the coarse aggregates. The magnification of the SEM pictures was 5000 times, and the scale was 2.0 µm. We analyzed the morphology of the hydration products and the mechanism of the reinforcing agent to improve the physical properties of the concrete. XRD was used to measure the diffraction spectra of the permeable concrete. This was carried out by milling the permeable concrete into a powder to determine the composition of its physical phases [24].

3. Experimental Design

3.1. Orthogonal Design of Experiment

An orthogonal experimental design [25,26] is a very effective experimental design method that can obtain the equivalent results of a large number of comprehensive tests with the lowest number of tests by selecting representative points for testing. It can greatly reduce the test workload and improve test efficiency, and it is widely used in scientific research, industrial production, and other fields.

The orthogonal design table of this experiment included 16 groups of experiments, i.e., $L_{16}(4^5)$. The five factors considered were the bone particle size (A), water/binder ratio (B), target porosity (C), fly ash content (D), and silica fume content (E). Furthermore, the influences of the compressive strength, porosity, and permeability coefficient at different levels were analyzed. The levels of the factors in the orthogonal test are shown in Table 6. Then, the five-factor four-level orthogonal table of the design of this experiment is shown in Table 7.

Table 6. Orthogonal test levels of factors.

Level \ Factor	Gravel Size /mm (A)	Water–Binder Ratio (B) /% (B)	Designed Porosity/% (C)	Fly Ash Content/% (D)	Silica Fume Content/% (E)
Level 1	3~6	0.25	15	10	2
Level 2	6~9	0.28	20	15	4
Level 3	9~12	0.31	25	20	6
Level 4	12~15	0.34	30	25	8

Note: Fly ash content and silica fume content are shown as percentages of cement content.

Table 7. Orthogonal table of five factors and four levels in this experiment.

Test \ Factor	A	B	C	D	E
T-1	1	1	1	1	1
T-2	1	2	2	2	2
T-3	1	3	3	3	3
T-4	1	4	4	4	4
T-5	2	1	2	3	4
T-6	2	2	1	4	3
T-7	2	3	4	1	2
T-8	2	4	3	2	1
T-9	3	1	3	4	2
T-10	3	2	1	3	1
T-11	3	3	4	2	4
T-12	3	4	2	1	3
T-13	4	1	4	2	3
T-14	4	2	3	1	4
T-15	4	3	2	4	1
T-16	4	4	1	3	2

3.2. Optimal Mix Ratio

In orthogonal experimental research, range analysis [27] is often used to deeply explore the influence of various factors on the test results. Using this method, we can intuitively determine the primary and secondary orders of each factor and find the best combination of each factor to achieve the optimal results. This plays an important role in the design or optimization of experiments. The results of the orthogonal design experiment are shown in Table 8, and the polar analysis of the test results is shown in Table 9.

Table 8. Results of orthogonal design test of pervious concrete.

Test	Average 28-Day Compressive Strength/MPa	Average Permeability Coefficient/cm·s^{-1}	Average Value of Measured Porosity/%
T-1	17.9	1.03	18.6
T-2	23.8	1.29	20.4
T-3	12.6	1.98	28.4
T-4	6.2	2.41	32.9
T-5	21.8	0.89	22.5
T-6	27.7	0.45	14.8
T-7	6.1	3.10	30.3
T-8	12.2	1.25	25.4
T-9	13.4	2.72	24.1
T-10	25.3	1.26	17.4
T-11	8.5	2.73	27.7
T-12	13	0.58	19.6
T-13	7.2	2.10	26.7
T-14	16.3	0.92	22.7
T-15	10.7	0.66	18.1
T-16	7.9	0	6.3

Table 9. Range analysis of each test result.

	28-Day Compressive Strength /MPa					Permeability Coefficient /c m·s^{-1}					Measured Porosity /%				
	A	**B**	**C**	**D**	**E**	**A**	**B**	**C**	**D**	**E**	**A**	**B**	**C**	**D**	**E**
K_1	60.5	60.3	62	53.3	66.1	6.7	6.7	4.2	5.6	4.2	100.3	91.9	67.4	86.6	79.5
K_2	67.8	93.1	69.3	51.7	51.2	5.7	3.9	3.4	7.4	7.1	93	75.3	80.6	100.2	81.1
K_3	60.2	37.9	54.5	67.6	60.5	7.3	8.5	6.9	4.1	5.1	88.8	104.5	100.6	74.6	89.5
K_4	42.1	39.3	44.8	58	52.8	3.7	4.2	8.9	6.2	6.9	73.8	84.2	107.3	89.9	105.7
k_1	15.1	15.1	15.5	13.3	16.5	1.7	1.7	1.1	1.4	1.1	25.1	23	16.9	22.8	19.9
k_2	16.9	23.3	17.3	12.9	12.8	1.4	1.0	0.8	1.8	1.8	23.3	18.8	20.2	25.1	20.3
k_3	15.1	9.5	13.6	16.9	15.1	1.8	2.1	1.7	1.0	1.3	22.2	26.1	25.2	18.7	22.4
k_4	10.5	9.8	11.2	14.5	13.2	0.9	1.1	2.2	1.6	1.7	18.5	21.1	26.8	22.5	26.4
R	6.4	13.8	6.1	4.0	3.7	0.9	1.1	1.4	0.8	0.7	6.6	7.3	10.1	6.4	6.5

Note: K_i and k_i, respectively, represent the sum and average of test results for each factor at level i; R stands for range.

(1) The influence of different factors on the 28-day compressive strength (as shown in Figure 6)—aggregate particle size, water–binder ratio, designed porosity, and fly ash—showed a trend of first increasing and then decreasing, while silica fume showed a trend of decreasing. It was determined that the optimal mix horizontal combination for the compressive strength of pervious concrete was A2B2C2D3E1, that is, an aggregate particle size of 6–9 mm, the water–binder ratio if 0.28, designed porosity of 20%, fly ash content of 20%, and silica fume content of 2%.

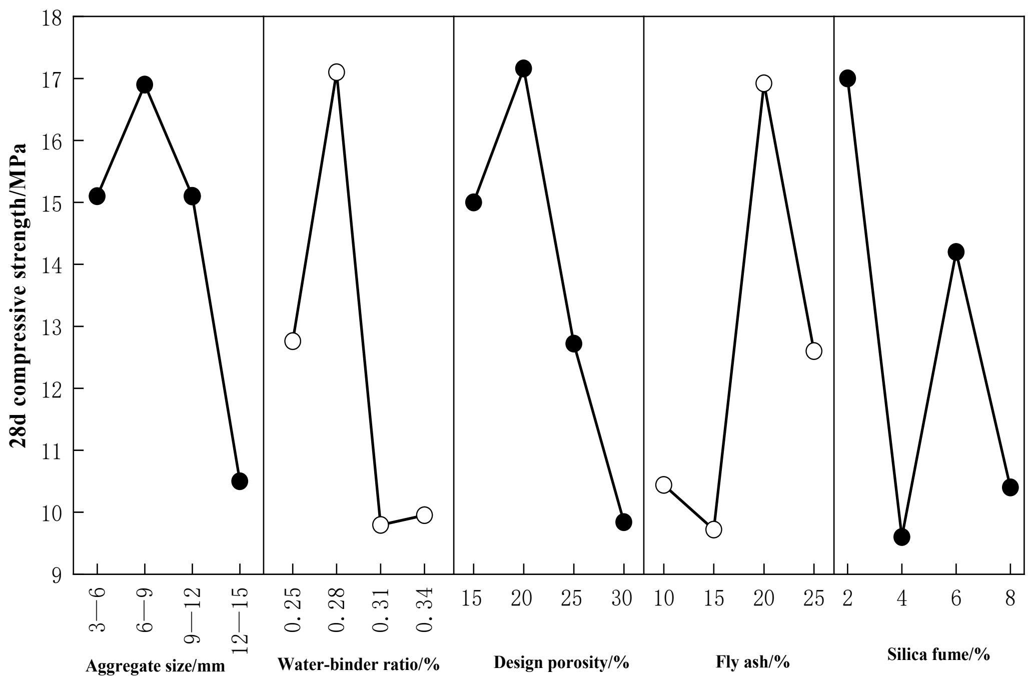


Figure 6. Influence of various factors on 28 d compressive strength of pervious concrete.

(2) The influence of different factors on the permeability coefficient (as shown in Figure 7) —aggregate particle size, water–binder ratio, and design porosity—showed a trend of first decreasing, then increasing, and then decreasing, while fly ash and silica fume showed a trend of first increasing, then decreasing, and then increasing. The optimal mix horizontal combination of pervious concrete for the permeability coefficient was determined as A3B3C4D2E2, that is, an aggregate particle size of 9~12 mm, water–binder ratio of 0.31, design porosity of 30%, fly ash content of 15%, and silica fume content of 4%.

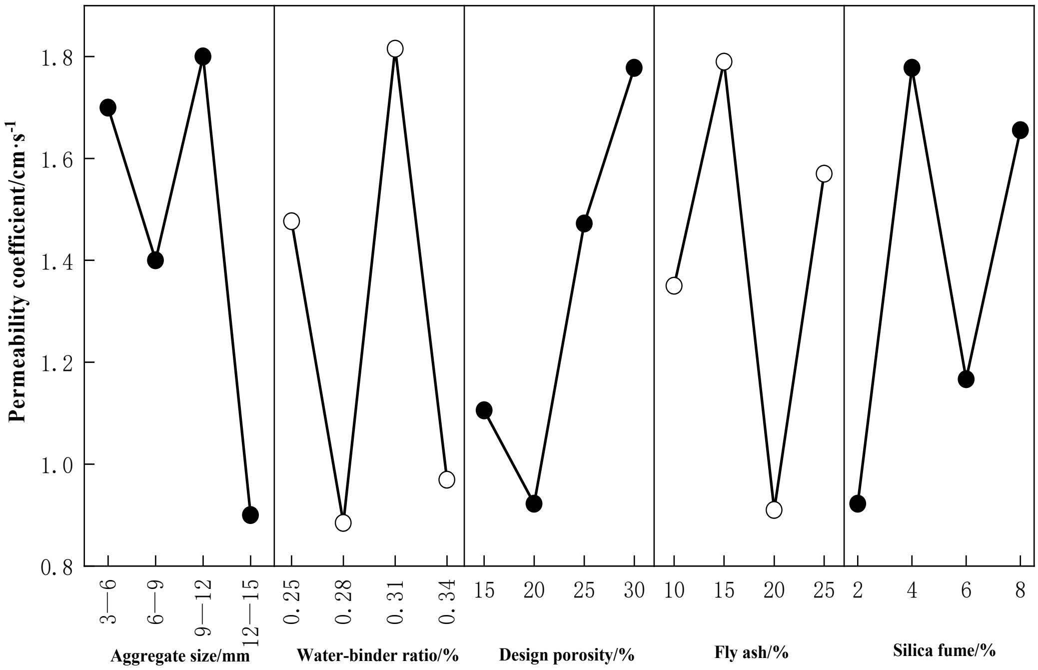


Figure 7. Influence of various factors on permeability coefficient of pervious concrete.

(3) The influences of different factors on porosity (as shown in Figure 8) were as follows: the aggregate particle size showed a downward trend, the water–binder ratio decreased first, then increased, and then decreased, the designed porosity and silica fume showed an upward trend, and the fly ash rose first, then decreased, and then increased. The optimal mix horizontal combination of pervious concrete for porosity was determined as A1B3C4D2E4, that is, an aggregate particle size of 3~6 mm, water–binder ratio of 0.31, designed porosity of 30%, fly ash content of 15%, and silica fume content of 8%.

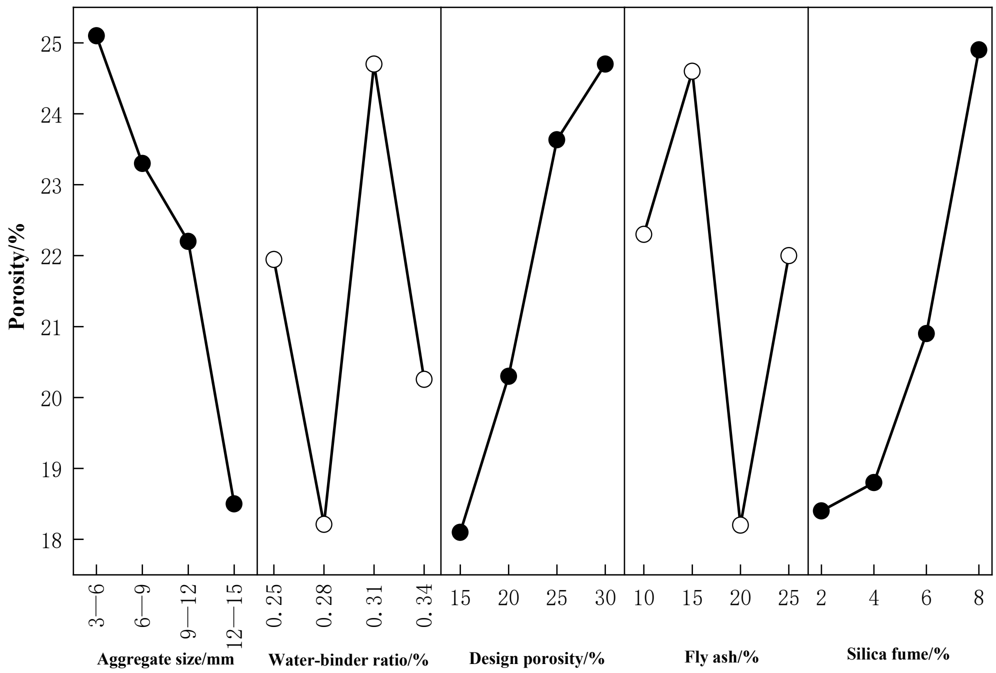


Figure 8. Influence of various factors on porosity of pervious concrete.

The R value of our range analysis was used to analyze the influence of each factor on the experimental results, so that the optimal mix could be obtained. According to Table 9, the optimal mix combination was as follows: A2B2C2D3E3, that is, an aggregate particle size of 6–9 mm, water–binder ratio of 0.28, designed porosity of 20%, fly ash content of 20%, and silica fume content of 6%.

3.3. Design Methodology for the Effect of Mineral Admixtures on the Optimum Mix Ratio

In this experiment, in order to analyze the degree of influence of mineral admixture and reinforcing agent on permeable concrete, three different ratio groups were designed for the test: TS-1 (without admixture or reinforcing agent), TS-2 (without admixture but with reinforcing agent), and the optimal ratio group TS-3 (with admixture and reinforcing agent). The volume method was used to calculate the amount of material for each test mix group, as shown in Table 10.

Table 10. Material consumption of each test mix proportion.

Number	Water–Cement Ratio/%	Porosity/%	Fly Ash/%	Silica Fume/%	Material Usage						
					Aggregate /kg·m^{-3}	Cement/kg·m^{-3}	Fly Ash/kg·m^{-3}	Silica Fume/kg·m^{-3}	Water /kg·m^{-3}	Reinforcing Agent/kg·m^{-3}	Water-Reducing Agent/kg·m^{-3}
TS-1	0.28	20	0	0	1592	353.35	0	0	98.93	0	0.71
TS-2	0.28	20	0	0	1592	342.91	0	0	98.93	10.44	0.71
TS-3	0.28	20	20	6	1592	261	65.25	16.66	98.93	10.44	0.71

4. Results and Analysis

4.1. Results of 28 d Compressive Strength, Permeability Coefficient, and Measured Porosity

Table 11 shows the 28 d compressive strength, permeability coefficient, and measured porosity for the test results of TS-1 (without admixture or reinforcing agent), TS-2 (without admixture but with reinforcing agent), and TS-3 (with admixture and reinforcing agent). This can be analyzed according to the list of the test results in Table 3 and the histogram of the test results in Figure 9:

(1) Analysis of 28 d compressive strength: The compressive strength of TS-3 was significantly enhanced compared to TS-1 and TS-2. Compared to TS-1, TS-2 had some improvement in compressive strength, but the enhancement was limited. The 28 d compressive strength of TS-3 was nearly doubled. Fly ash and silica fume were used as mineral admixtures to improve the compactness and strength of concrete. Silica fume reacted with the hydration products of cement and could fill the pores of concrete, further improving its strength and impermeability. At the same time, reinforcing agents could also increase the cohesion and compressive strength of concrete, thus improving its overall performance. When the added amounts were all optimal, the combined admixture of fly ash, silica fume, and reinforcing agent could effectively increase the 28-day compressive strength of permeable concrete.

(2) Analysis of permeability coefficient: Relative to TS-1, TS-3 and TS-2 showed different degrees of decline. The permeability coefficient of TS-2 decreased by about 6%, and that of TS-3 decreased by about 36% but was still higher. TS-2 contained a small amount of reinforcing agent admixture, which had a slight effect on the size of the pore space of the permeable concrete. TS-3 contained fly ash, silica fume, and reinforcing agent, which filled part of the pore space of the permeable concrete through the hydration reaction, resulting in a larger decrease in the water permeability coefficient. It was determined that the permeability coefficient and 28-day compressive strength have a relationship of mutual constraint.

(3) Analysis of measured porosity: The designed porosity of this test was 20%. The measured porosity was close to the designed porosity, and the degree of influence was not significant.

Table 11. Performance test results of water-permeable concrete.

Test	Average 28d Compressive Strength/MPa	Average Permeability Coefficient Value/mm·s^{-1}	Average Measured Porosity Value/%
TS-1	9.2	12.90	22.80
TS-2	12.23	12.07	21.16
TS-3	18.33	8.27	19.53

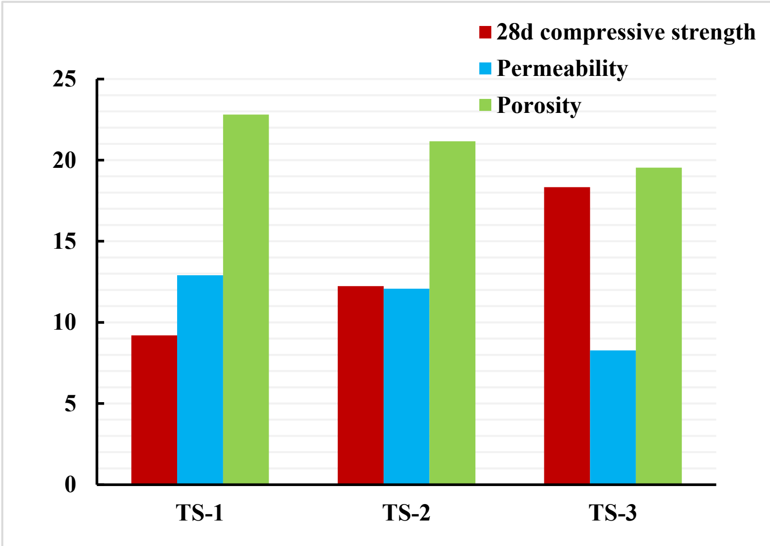


Figure 9. Histogram of performance test results of permeable concrete.

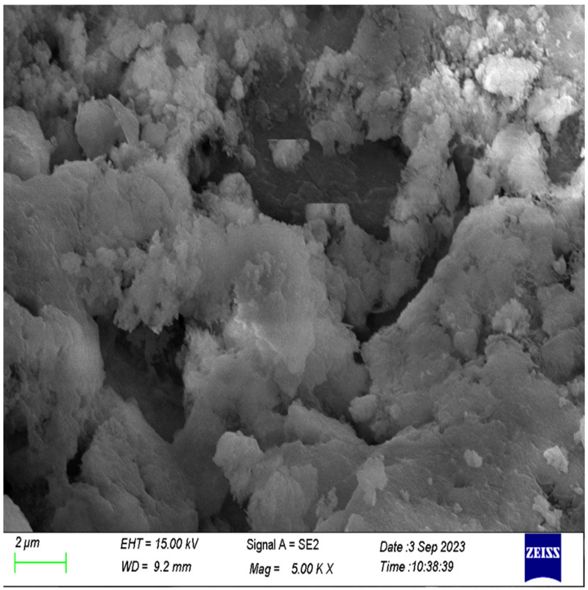
4.2. Microanalysis

(1) SEM

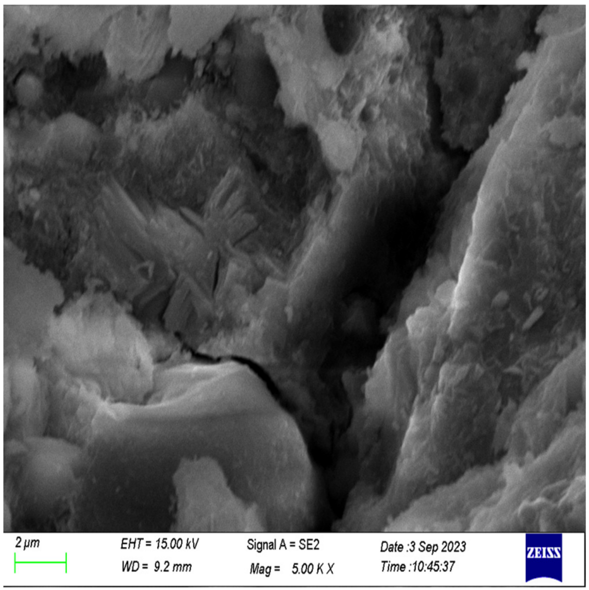
Cement, fly ash, and silica fume produce a series of hydration reactions after being mixed with water, which produces various hydration products, such as calcium silicate (C-S-H), calcium aluminate gel (C-A-H), a small amount of columnar calcium alumina (AFt), and irregular petal-shaped hydrated calcium sulphoaluminate (AFm) [28]. Figure 10 shows the scanning electron micrographs of the TS-1, TS-2, and TS-3 specimen samples of permeable concrete after 28 d.

It can be seen in Figure 10a that since no admixtures or reinforcers were added, TS-1 had a lot of surface voids, the structure was relatively soft and flocculent, and the cement stone was more likely to be attached around the aggregate. There could be gels, such as calcium silicate hydrate, and although calcium hydroxide crystals could not be seen under an electron microscope, this does not mean that calcium hydroxide did not exist. In fact, in fully hydrated cement, the amount of calcium hydroxide accounts for 20–25%. This may be because calcium hydroxide crystals are too small for electron microscopy. It may also be because the hydration reaction is incomplete, and because the content of calcium hydroxide is low, and therefore, difficult to observe under an electron microscope.

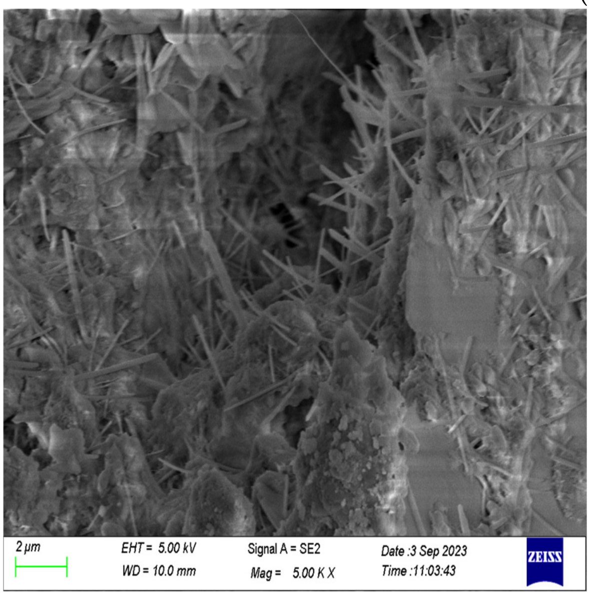
In Figure 10b, it can be seen that the reinforcement agent participated in the hydration reaction of cement to form a polymer cement hydration body, which can improve the compressive and bond strength of that body. The reinforcement agent can allow the cement paste to fully cover the stones, ensuring the strength and porosity of pervious concrete. Only a small amount of $Ca(OH)_2$ crystal existed on the surface of TS-2, and the structure was relatively dense, but there were many cracks.



(**a**) TS-1



(**b**) TS-2



(**c**) TS-3

Figure 10. Scanning electron microscope image of pervious concrete at 28 d.

According to Figure 10c, there was a large amount of fibrous hydrated calcium silicate, which has the property of rapidly dispersing and forming a gel in water, on the surface of TS-3. This will directly grow on the surface of fly ash particles, forming a structure termed “microfiber reinforcement” [29]. The network structure can enhance the mechanical properties and crack resistance of fly ash concrete. This structure also plays a key role in the hardening process by lessening the brittleness of concrete and its likelihood of cracking when subjected to external pressure or tension. Meanwhile, fly ash can fill the voids in pervious concrete, reduce the porosity, and improve the compactness. At the same time, silica fume, which has SiO_2 and Al_2O_3 as its main components, has high activity and a high specific surface area. It can react with the cement hydration product $Ca(OH)_2$ twice to generate a stable hydrated calcium silicate gel, which has an obvious enhancement effect. This is consistent with a large increase in macroscopic compressive strength and a decrease in permeability coefficient. Therefore, it seems that adding an appropriate amount of fly ash and silica fume to pervious concrete can improve its performance.

(2) XRD

Figure 11 shows the XRD patterns of test blocks TS-1, TS-2, and TS-3 ground into powder after standard maintenance for 28 d. The positions of the main characteristic peaks of the three samples are basically the same, i.e., they are the characteristic peaks of the main hydration products C-S-H and C-A-H. As TS-2 and TS-3 contained mineral admixture, their main characteristic peaks of AI_2O_3 are at $2\theta \approx 31.5°$. As TS-2 and TS-3 contained mineral dopants, their main characteristic peak of AI_2O_3 is at $2\theta \approx 31.5°$. Compared to the three samples, the changes in the main characteristic peaks at $2\theta \approx 39.5°$ and $2\theta \approx 47.5°$ are more obvious, which is due to the fact that TS-2 and TS-3 were rich in reactive SiO_2 and Al_2O_3, which can react with the alkaline hydration products of cement to form C-S-H and C-A-H. C-S-H and C-A-H can increase the strength of pervious concrete. Meanwhile, it can be seen that the peak intensity of the main characteristic peak of C-S-H for TS-3 at 28 d of standard curing is higher than that of TS-1 and TS-2, and it can be inferred that the addition of admixture and reinforcing agent can improve the performance of pervious concrete. Furthermore, the addition of certain amounts of fly ash, silica fume, and reinforcing agent significantly improved the performance of the standard curing of pervious concrete at 28 d.

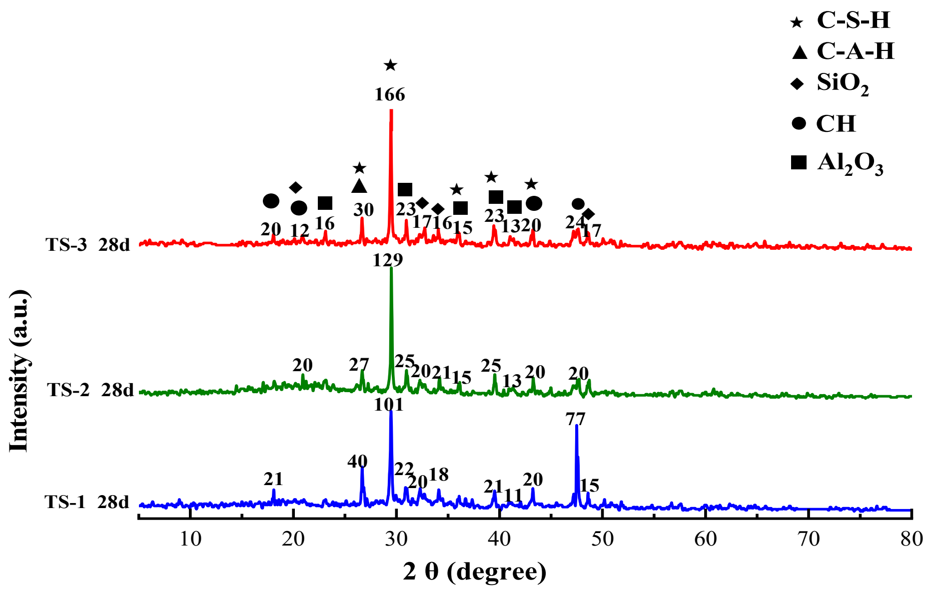


Figure 11. XRD pattern of hydration products of permeable concrete.

5. Conclusions

This experiment was based on an orthogonal design, which we adopted to determine the optimal level of each factor on permeable concrete, derive the optimal mix group, explore the effects of mineral admixture on it, carry out microstructure and hydration reactions, and combine macroscopic performance and microstructure analysis. The following conclusions can be drawn:

(a) A variety of factors influence the proportion and performance of permeable concrete. The preparation of a specimen with the optimal aggregate particle size of 6~9 mm, water/cement ratio of 0.28, designed porosity of 20%, fly ash admixture of 20%, and silica fume admixture of 6% resulted in a 28 d compressive strength of 18.33 MPa, permeability coefficient of 8.27 mm/s, and measured porosity of 19.53%. The compressive strength and permeability coefficient of the specimen met the scope of a "sponge city", which can provide a reference basis for its application in relevant research projects.

(b) The performance of pervious concrete can be effectively improved by adding fly ash, silica fume, and the optimum content of reinforcement (TS-3) at the same time. Compared with the unblended mineral admixture (TS-1), the 28-day compressive strength is about double. Furthermore, the permeability coefficient decreased by 36%, but still remained at a high level. Additionally, there was little difference between the measured porosity and the designed porosity. In practical applications, the amount of cement can be reduced and costs can thus be saved. As well as improving the quality of the project, this can also achieve the goal of resource reuse and environmental sustainability.

(c) According to scanning electron microscopy and XRD pattern analysis, the optimum admixture of fly ash, silica fume, and reinforcing agent had a positive effect on the main properties of pervious concrete. Its hydration reaction was more thorough, generating a large number of hydrated C-S-H gels, which could improve the microstructure and pore structure of the concrete, giving it a denser microstructure and fewer pores. This was consistent with the substantial increase in the macroscopic compressive strength and decrease in the permeability coefficient.

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