

Research Article

Runoff Purification Effects of Permeable Concrete Modified by Diatomite and Zeolite Powder

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Diatomite and zeolite powder exhibit cellular structures that are beneficial to absorb pollutants in road surface runoff. In this work, the runoff purification effects of permeable concrete modified by diatomite and zeolite powder were studied. First, magnesium dihydroxide was used to modify diatomite; then the modified diatomite and the zeolite powder were innovatively adopted as binders to prepare permeable concrete. In addition, compressive strength, effective porosity, purification effect, and environmental scanning electron microscopy (ESEM) tests, as well as gray correlation analysis, were carried out. Finally, the optimal dosages of modified diatomite and zeolite powder in permeable concrete were suggested. The results show that diatomite (modified diatomite) and zeolite powder can improve the compressive strength, effective porosity, and runoff purification effects of permeable concrete. In addition, the 10% modified diatomite and the 3% zeolite powder exhibit the highest correlation with the properties of modified permeable concrete.

1. Introduction

Permeable concrete is an eco-friendly and cost-effective material that exhibits the effects of water storage, filtration, and purification; it plays an important role in the purification effect of road surface runoff [1–3]. Permeable concrete has many applications, such as a base for terraces and greenhouses on pavements, as well as reducing flow during floods and improving flow in road drainage. In addition, it is helpful for the recharge of groundwater resources [4–11].

Despite the ability of permeable concrete to improve the purification effect of road surface runoff, in many cases, the purification effect is far from the requirements of urban sewage discharge [12, 13]. Furthermore, the mechanical performance and durability of permeable concrete are poor [14, 15]. Many researchers have shown that zeolite, diatomite, pumice, vermiculite, kaolin, dolomite, and other minerals can remove various harmful substances from road surface runoff [3, 4, 16–18]. Among them, diatomite is most widely used as sorbents, filtration materials, fillers, and

insulation materials because of its unique cellular structure [19–23]. At the same time, the mechanical performance of cement can be improved by the higher fineness and higher reactive silica content in diatomite powder [3]. High specific surface area and the Al-O tetrahedron result in the adsorption ability and desorption ability of water by zeolite up to 30% by weight [4]. Furthermore, the high reactive silica and high specific surface area of zeolite can improve the mechanical performance of cement concrete [17, 21]. In addition, modified diatomite can increase the removal rate of various pollutants by 20%–50% [19, 20]. Therefore, it is necessary to improve the performance of permeable concrete and conduct the related study on modification of mineral powder.

In this work, modified permeable concrete (permeable concrete with zeolite powder and modified diatomite) was prepared. The runoff purification effects of modified permeable concrete with different dosages of modified diatomite and zeolite powder were analyzed by assessing compressive strength, effective porosity, purification effect,

and environmental scanning electron microscopy (ESEM) tests, as well as by gray correlation analysis. Finally, the optimal dosage of modified diatomite and zeolite powder was suggested. The objective of this work was to examine the runoff purification effect of permeable concrete pavement with modified diatomite and zeolite powder. In a word, this work is of great research value for improving the adsorption effect and compressive strength of permeable concrete, solving urban heat island effect and water resource shortage, and purifying rainwater runoff on road surface.

2. Experimental

2.1. Materials. Ordinary Portland cement (PO 42.5), diatomite, zeolite powder, aggregate, and water-reducing admixture were used in this work. The aggregate was 5 mm–10 mm discontinuous graded crushed stone; gradation of aggregate is shown in Table 1; and properties of aggregate met the requirements in Technical Specifications for Highway Cement Concrete Construction (JTGF30-2015). Polycarboxylic acid superplasticizer (water reduction percentage was 20%) was used as the water-reducing admixture. The polycarboxylate superplasticizer dosage did not exceed 1.0% of the mass of cementitious material. Tables 2–5 show the properties of ordinary Portland cement, diatomite, zeolite powder, and aggregate, respectively.

2.2. Preparation of Modified Diatomite. Figure 1 shows the chart of diatomite modification. First, 10 g thermally activated diatomite was added to 100 mL distilled water, followed by the slow addition of the water solution containing 3.81 g $MgCl_2$ (the total weight of the $MgCl_2$ solution was 103.81 g). The mixture was stirred by using a glass rod for 10 min, followed by the slow addition of the water solution containing 2.4 g NaOH (the total weight of the NaOH solution was 102.4 g). The mixture was stirred by using a glass rod for 5 min, and then left. Second, the mixture was filtered 5 times. Finally, the mixture was dried at 90°C for 10 h, affording modified diatomite. The effects of treating thermally activated diatomite using $MgCl_2$ and NaOH ($Mg(OH)_2$ was made from $MgCl_2$ and NaOH) were reduction of the blocking rate and the increase of the adsorption, the specific surface area, and the pore volume.

2.3. Mix Proportion Design. In this work, the water-to-binder ratio and target void fraction were 0.36 and 20%, respectively. The dosage of diatomite (modified diatomite) was 0%, 10%, and 20%. The dosage of zeolite powder was 0%, 3%, and 5%. The dosage of water-reducing admixture was determined by determining the workability of permeable concrete. Table 6 shows the mix proportion of permeable concrete.

2.4. Preparation of Specimens. First, the cement, diatomite, and zeolite powder were weighed correctly and poured into the iron plate. The mixture was mixed repeatedly until uniform, followed by the slow addition of crushed stone. The

TABLE 1: Gradation of aggregate.

Particle size (mm)	Passing percentage in sieve (mm)			
5–10	16	9.5	4.75	2.36
	100	92.5	10	0

mixture was mixed until uniform. Second, the water-reducing agent was mixed with the water, and then the solution was slowly added to the mixture until the mixture was well mixed. Then, the mixture was poured into molds (100 mm × 100 mm × 100 mm) and cured at 20°C. Finally, after 48 h, the specimen was demolded and placed into a standard curing room (temperature of 20°C and relative humidity of 95%) for 28 days.

2.5. Test Methods

2.5.1. Compressive Strength Test. The compressive strength of permeable concrete was tested according to the Test Methods of Cement and Concrete for Highway Engineering (JTG E30-2005). The specimen size of permeable concrete was 100 mm × 100 mm × 100 mm. Meanwhile, three specimens were prepared in each group. In addition, it was necessary to measure the size and shape of specimens after demolding. The temperature and loading speed for the compressive strength test were 20°C and 500 N/s, respectively.

The cubic compressive strength of permeable concrete is shown in the following equation:

$$f_{cu} = \frac{F}{A} \quad (1)$$

where f_{cu} is the cubic compressive strength of permeable concrete, MPa; F is the ultimate load, N; and A is the compression area, mm^2 . The error of data should not exceed 15.0% of the average value, and the average value was considered as the test result.

2.5.2. Effective Porosity Test. The effective porosity of permeable concrete was tested by the net basket method. Meanwhile, three specimens were prepared in each group. First, the specimens were immersed in water for 24 h, and then they were weighed in water. Second, the specimens were dried for 24 h in an oven at 60°C. Then, the dried specimens were weighed. Finally, the volume of the specimen was calculated by using the volumetric method.

The effective porosity is calculated by using the following equation:

$$n_e = \left(1 - \frac{m_2 - m_1}{v \times \rho_w} \right) \times 100, \quad (2)$$

where n_e is the effective porosity of permeable concrete, %; m_1 is the dry weight of the specimen after drying for 24 h at 60°C, g; m_2 is the weight of the specimen immersed in water for 24 h, g; v is the volume of the specimen, cm^3 ; and ρ_w is the density of the water, g/cm^3 .

TABLE 2: Properties of ordinary Portland cement.

Main chemical components (%)						Setting time (min)		Density (g/cm ³)	Fineness (80 μm, %)
CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	SO ₃	MgO	Initial	Final		
66.06	19.00	5.50	4.80	2.70	1.94	123	235	3.05	3.50

TABLE 3: Properties of diatomite.

Main chemical components (%)					Moisture content (%)	Loose density (g/cm ³)	Specific surface area (m ² /kg)
SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	CaO	MgO			
97.50	1.20	0.70	0.38	0.22	0.09	1.05	385

TABLE 4: Properties of zeolite powder.

Main chemical components (%)					Density (g/cm ³)	Porosity (%)	Moisture content (%)
SiO ₂	Al ₂ O ₃	CaO	Fe ₂ O ₃	SO ₃			
72.02	18.41	5.76	2.23	1.58	2.65	48	7.90

TABLE 5: Physical properties of coarse aggregate.

Crushing value (%)	Mud content (%)	Apparent density (kg/m ³)	Bulk density (kg/m ³)
7.8	0.3	2654	1435

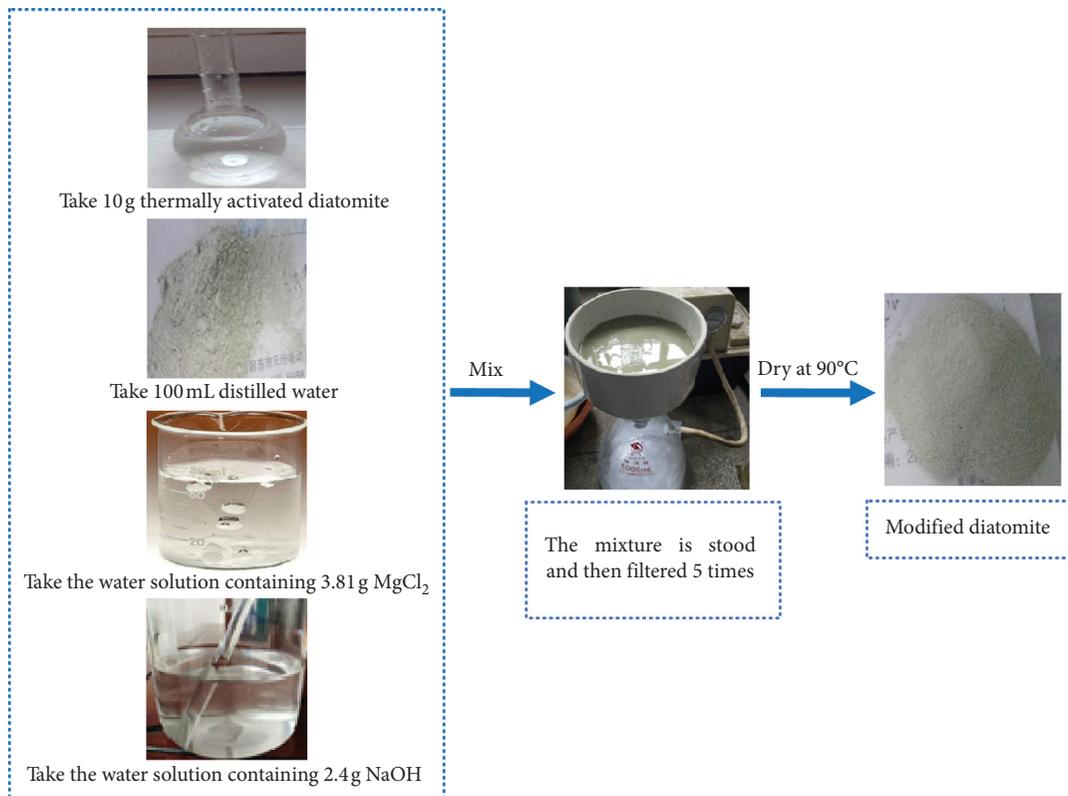


FIGURE 1: Chart of diatomite modification.

TABLE 6: Mix proportion of permeable concrete.

Specimen nos.	Raw material dosage (kg/m ³)							
	Cementitious materials			Coarse aggregate size			Water	Water reducer
	Cement	Diatomite (modified diatomite)	Zeolite powder	9.5	4.75	2.36		
0	375.9	0	0	105.5	1176.7	140.6	108.2	7.5
1	338.3	37.6	0	105.5	1176.7	140.6	108.2	7.5
2	327.0	37.6	11.3	105.5	1176.7	140.6	108.2	7.5
3	319.5	37.6	18.8	105.5	1176.7	140.6	108.2	7.5
4	300.7	75.2	0	105.5	1176.7	140.6	108.2	7.5
5	289.4	75.2	11.3	105.5	1176.7	140.6	108.2	7.5
6	281.9	75.2	18.8	105.5	1176.7	140.6	108.2	7.5

The dosage of diatomite (modified diatomite) and zeolite powder are calculated according to the percentage of cement mass.

2.5.3. Purification Test. In the purification test, the immersion method was used to simulate the adsorption of permeable concrete on rainwater runoff. Firstly, the specimens were completely immersed into water samples for 3 days. Then, the pollutant (chemical oxygen demand (COD), suspended solids concentration (SS), total nitrogen (TN), total phosphorus (TP), and ammonia nitrogen (NH₃-N)) content of each water sample was tested according to the water and wastewater monitoring and analysis method. Among them, the contents of COD, TN, TP, and NH₃-N were tested by spectrophotometry, as shown in Beer-Lambert law (fd3equation (3)). The SS content was tested by using the filter method, as shown in equation (4). Then, the pollutant content of each sample was compared with the control group. Finally, the runoff purification effects of permeable concrete modified by diatomite and zeolite powder were analyzed:

$$A = KLC, \quad (3)$$

where A is the absorbance; K is the absorption coefficient; L is the thickness of absorption layer, cm; and C is the concentration of the solution to be tested, mol/L.

$$D = \frac{[(M_1 - M_2) \times 1000 \times 1000]}{V}, \quad (4)$$

where D is the concentration of SS, mg/L; M_1 is the total weight of suspended matter, filter membrane, and weighing bottle, g; M_2 is the total weight of filter membrane and weighing bottle, g; and V is the sample volume, L.

2.6. Microstructure Test. The effects of diatomite (modified diatomite) and zeolite powder on the microstructure of permeable concrete with a curing age of 28 days were observed by the S-4800 cold-field environmental scanning electron microscopy (ESEM). First, the specimen was cut into small particles, followed by their examination at an applied accelerating voltage of 5.0 kV and a temperature of 25°C.

3. Results and Discussion

3.1. Properties of Modified Permeable Concrete

3.1.1. Compressive Strength. Figure 2 demonstrates the change in the compressive strength of permeable concrete at

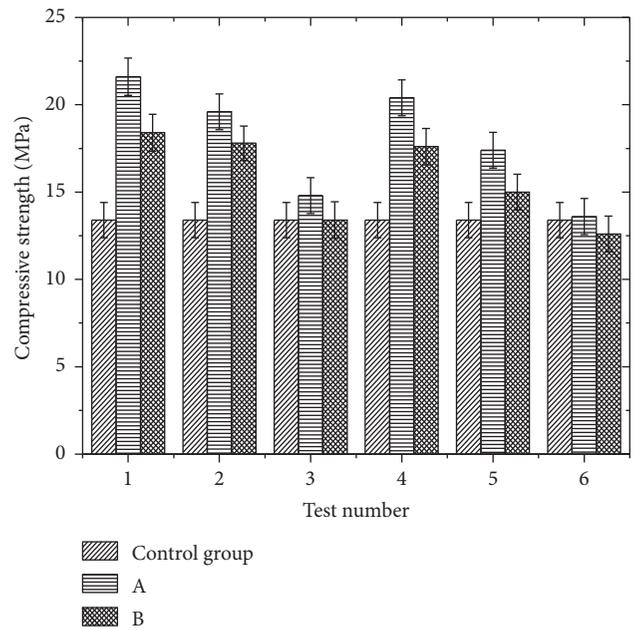


FIGURE 2: Compressive strength of permeable concrete. Note: A-1~A-6: permeable concrete specimens with unmodified diatomite and zeolite powder in different dosages. B-1~B-6: permeable concrete specimen with modified diatomite and zeolite powder in different dosages.

different mix proportions at a curing age of 28 days. Based on the observation in Figure 2, the compressive strength of permeable concrete with diatomite (modified diatomite) and zeolite powder is improved. However, the dosage of diatomite (modified diatomite) and zeolite powder should not be excessive; otherwise, it can lead to the decrease of the compressive strength. Therefore, there is an optimum dosage (10% diatomite (10% modified diatomite) and 3% zeolite powder). In addition, in contrast to A-1~A-6 and B-1~B-6, the compressive strength of permeable concrete with modified diatomite and zeolite powder is about 5% lower than that of permeable concrete with diatomite and zeolite powder.

Diatomite and zeolite powder exhibit pozzolanic effects that are beneficial to enhancing the compressive strength. In this work, the modified diatomite makes the internal structure of permeable concrete more compact. In addition, the number of large pores in permeable concrete is reduced

due to the microaggregate effect of diatomite and zeolite powder, while the number of small pores is increased [21], which improves the compressive strength of permeable concrete.

However, the content of cement and cement hydrates decreases, when the dosage of diatomite (modified diatomite) and zeolite powder is too high. At the same time, the cementation ability of diatomite (modified diatomite) and zeolite powder is weakened, leading to a lower strength of cementation layer among aggregates. Thus, the compressive strength decreases. In addition, each 12 g of modified diatomite contains 2 g $Mg(OH)_2$. Thus, the content of active silica in modified diatomite is less than that in diatomite at the same mix proportion. The hydration degree of cement in B-1-B-6 is less than that in A-1-A-6. Therefore, the compactness of B-1-B-6 decreases, leading to a lower compressive strength of B-1-B-6 lower than that of A-1-A-6. Accordingly, based on the observation in Figure 3, the compactness of cement paste with 10% diatomite and 3% zeolite powder (Figure 3(a)) is higher than that of cement paste with 10% modified diatomite and 3% zeolite powder (Figure 3(b)).

3.1.2. Effective Porosity. Figure 4 demonstrates the changes of effective porosity of permeable concrete with different mix proportions. Based on the observation in Figure 4, the effective porosity of permeable concrete with diatomite (or modified diatomite) and zeolite powder is slightly higher than that of the control group. There is an optimum dosage (10% diatomite (or modified diatomite) and 3% zeolite powder), which is consistent with the compressive strength result. In addition, in contrast to A-1-A-6 and B-1-B-6, the effective porosity of permeable concrete with modified diatomite and zeolite powder is slightly higher than that of permeable concrete with diatomite and zeolite powder.

Diatomite and zeolite powder are porous materials that can increase the effective porosity of permeable concrete. The effective porosity of permeable concrete increases greatly when the dosage of diatomite (modified diatomite) and zeolite powder is too high. This affects the compressive strength of permeable concrete. In addition, the effective porosity of diatomite is increased by $Mg(OH)_2$ modification to improve the effective porosity of permeable concrete. However, the content of $Mg(OH)_2$ in the modified diatomite is less, which cannot significantly improve the effective porosity of permeable concrete.

3.2. Rainwater Runoff Purification Effect of Modified Permeable Concrete

3.2.1. COD Purification Effect. Figure 5 shows the change of permeable concrete on COD purification effect with different mix proportions. The COD purification rate of the control group is only 28.13%. The COD purification rate of A-1-A-6 and B-1-B-6 is higher than that of the control group, which shows that permeable concrete with diatomite (modified diatomite) and zeolite powder can improve COD purification effect. From A-1 to A-6, permeable concrete

with 10% diatomite and 5% zeolite powder exhibits the highest COD purification effect, and the purification rate is 59.86%. The purification effect of B-1-B-6 is higher than that of A-1-A-6, which shows that modified diatomite exhibits better purification effect than diatomite.

In addition, permeable concrete with 10% modified diatomite and 3% zeolite powder exhibits the most excellent COD purification effect, and the purification rate is 74.58%. The reason for better COD purification effect of samples is the porous structure, higher specific surface, and more superficial pores of zeolite powder and modified diatomite as compared to cement. During the drainage of road surface runoff, pollutants are trapped inside the cavities and pores of the zeolite powder and modified diatomite; thus, the content of COD in road surface runoff is decreased.

3.2.2. SS Purification Effect. Figure 6 shows the change of permeable concrete on SS purification effect with different mix proportions. The SS purification rate of the control group is only 15.16%. The SS purification rate of A-1-A-6 and B-1-B-6 is higher than that of the control group, which shows that permeable concrete with diatomite (modified diatomite) and zeolite powder can improve the SS purification effect. The main reason is that SS purification effect is directly related to the porosity and the pore size of permeable concrete. The adsorption of SS by macropores in permeable concrete is less. Diatomite and zeolite powder can refine the pore size to improve the SS purification effect [17, 21].

From A-1 to A-6, permeable concrete with 20% diatomite and 5% zeolite powder exhibits the highest SS purification effect, and the purification rate is 52.97%. From B-1 to B-6, permeable concrete with 10% modified diatomite and 5% zeolite powder exhibits the highest SS purification effect, and the purification rate is 54.25%. The SS purification effect of B-1-B-6 is higher than that of A-1-A-6 with the appropriate dosage.

3.2.3. TN Purification Effect. Figure 7 shows the change of permeable concrete on TN purification effect with different mix proportions. The TN purification rate of the control group is only 30.61%. The TN purification rate of A-1-A-6 and B-1-B-6 is higher than that of the control group, which shows that permeable concrete with diatomite (modified diatomite) and zeolite powder can improve the TN purification effect. From A-1 to A-6, permeable concrete with 20% diatomite and 5% zeolite powder exhibits the highest TN purification effect, and the purification rate is 66.33%.

From B-1 to B-6, permeable concrete with 10% modified diatomite and 5% zeolite powder exhibits the highest TN purification effect, and the purification rate is 71.43%. In addition, the TN purification rate of B-1-B-6 is about 5% higher than that of A-1-A-6, which shows that modified diatomite can improve the TN purification effect of permeable concrete.

3.2.4. TP Purification Effect. Figure 8 shows the change of permeable concrete on TP purification effect with different mix proportions. The TP purification rate of the control

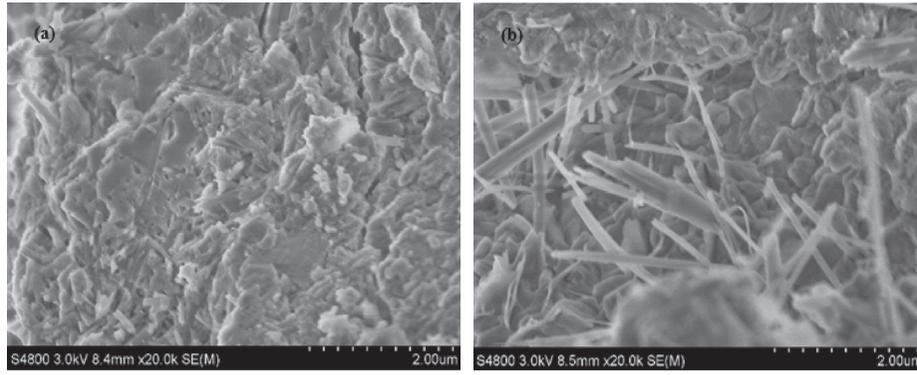


FIGURE 3: ESEM pictures of cement paste at a curing age of 28 days: (a) paste with 10% diatomite and 3% zeolite powder; (b) paste with 10% modified diatomite and 3% zeolite powder.

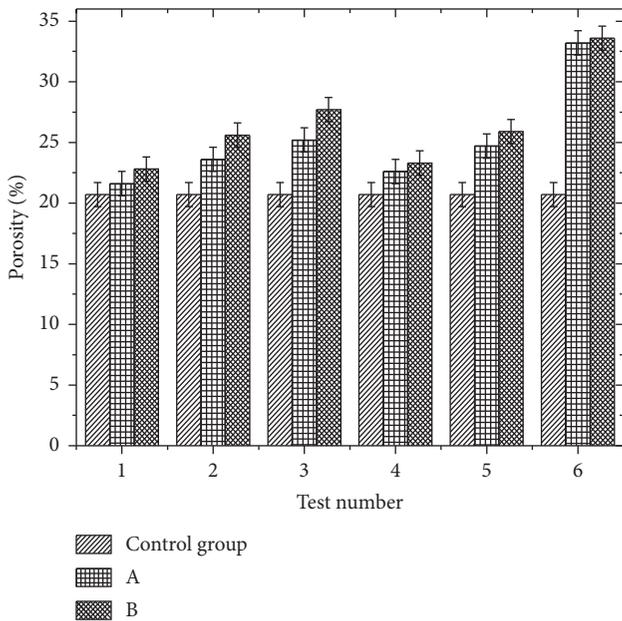


FIGURE 4: Effective porosity of permeable concrete. Note: A-1~A-6: permeable concrete specimens with unmodified diatomite and zeolite powder in different dosages; B-1~B-6: permeable concrete specimen with modified diatomite and zeolite powder in different dosages.

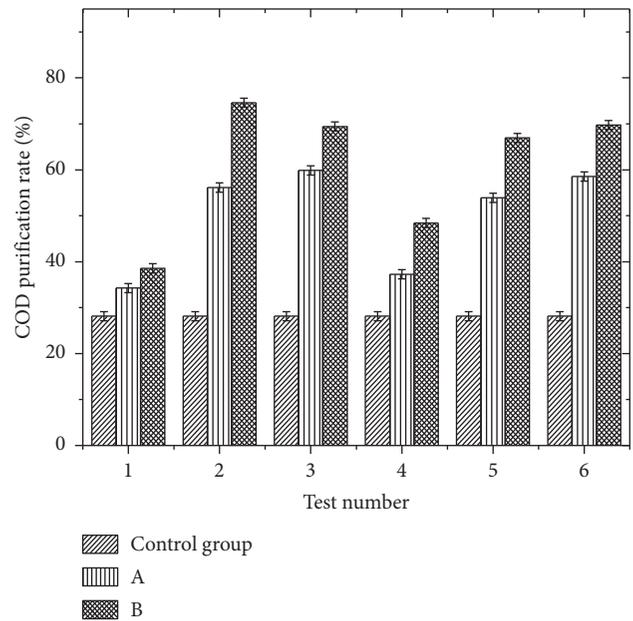


FIGURE 5: COD purification effect of permeable concrete. Note: A-1~A-6: permeable concrete specimens with unmodified diatomite and zeolite powder in different dosages; B-1~B-6: permeable concrete specimen with modified diatomite and zeolite powder in different dosages.

group is only 27.08%. The TP purification rate of A-1~A-6 and B-1~B-6 is higher than that of the control group, which shows that permeable concrete with diatomite (modified diatomite) and zeolite powder can improve the TP purification effect. From A-1 to A-6, permeable concrete with 10% diatomite and 5% zeolite powder exhibits the highest TP purification effect, and the purification rate is 70.83%.

From B-1 to B-6, permeable concrete with 20% modified diatomite and 3% zeolite powder exhibits the highest TP purification effect, and the purification rate is 91.67%. The TP purification effect of permeable concrete with 10% diatomite and 3% zeolite powder is also excellent, and the purification rate is 89.58%. In addition, the TP purification rate of B-1~B-6 is about 20% higher than that of A-1~A-6, which indicates that modified diatomite can improve the TP

purification effect. However, excessive zeolite powder dosage can lead to the reduction of TP purification effect.

3.2.5. NH₃-N Purification Effect. Figure 9 shows the changes of permeable concrete on ammonia nitrogen (NH₃-N) purification effect with different mix proportions. The NH₃-N purification rate of the control group is only 33.07%. The NH₃-N purification rate of A-1~A-6 and B-1~B-6 is higher than that of the control group, which shows that permeable concrete with diatomite (modified diatomite) and zeolite powder can improve NH₃-N purification effect. The Al-O tetrahedron of zeolite powder results in its high cation exchange ability and high adsorption ability [24–26]. Thus, the content of NH₃-N in permeable concrete is less.

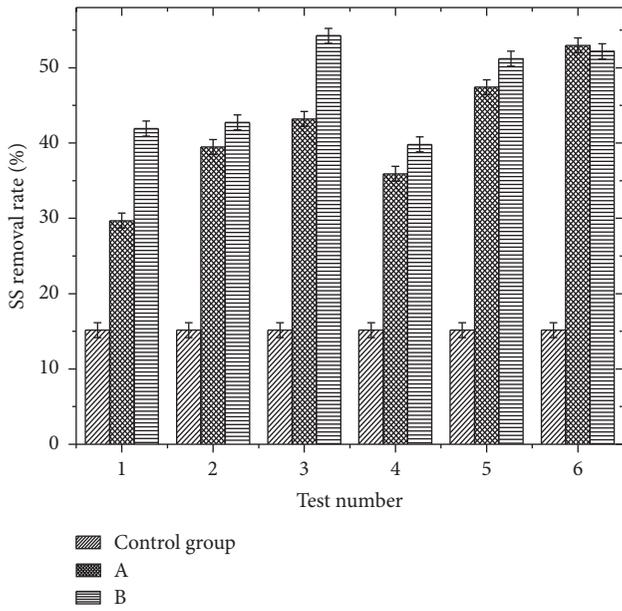


FIGURE 6: SS purification effect of permeable concrete. Note: A-1~A-6: permeable concrete specimens with unmodified diatomite and zeolite powder in different dosages; B-1~B-6: permeable concrete specimen with modified diatomite and zeolite powder in different dosages.

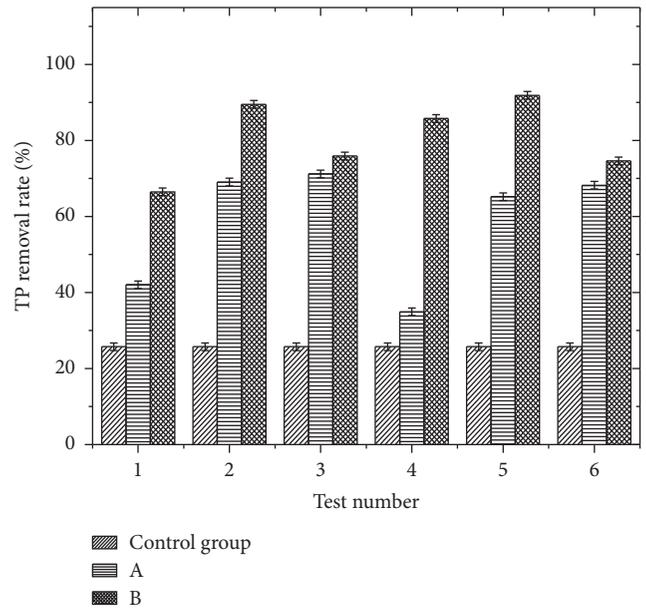


FIGURE 8: TP purification effect of permeable concrete. Note: A-1~A-6: permeable concrete specimens with unmodified diatomite and zeolite powder in different dosages; B-1~B-6: permeable concrete specimen with modified diatomite and zeolite powder in different dosages.

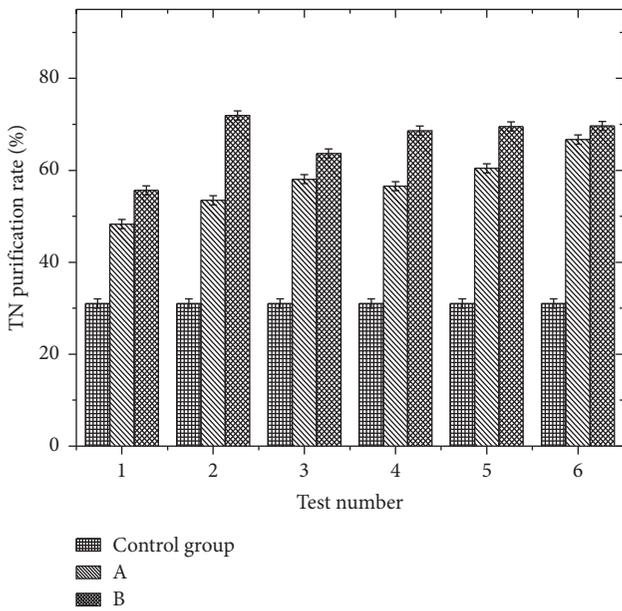


FIGURE 7: TN purification effect of permeable concrete. Note: A-1~A-6: permeable concrete specimens with unmodified diatomite and zeolite powder in different dosages; B-1~B-6: permeable concrete specimen with modified diatomite and zeolite powder in different dosages.

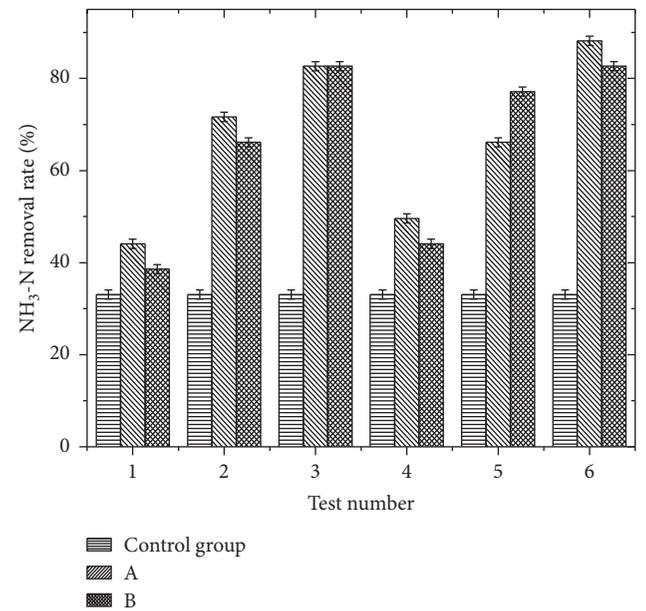


FIGURE 9: NH₃-N purification effect of permeable concrete. Note: A-1~A-6: permeable concrete specimens with unmodified diatomite and zeolite powder in different dosages; B-1~B-6: permeable concrete specimen with modified diatomite and zeolite powder in different dosages.

From A-1 to A-6, permeable concrete with 20% diatomite and 5% zeolite powder exhibits the highest NH₃-N purification effect, and the purification rate is 88.15%. The highest purification rate of B-1~B-6 is 82.67%. The NH₃-N purification effect of B-1~B-6 is less than that of A-1~A-6.

The main reason is that diatomite modified by magnesium dihydroxide can enhance the adsorption of negatively charged pollutants and reduce the adsorption of positively charged pollutants. Thus, the NH₃-N purification effect of B-1~B-6 is not obvious as compared to A-1~A-6.

3.2.6. Purification Effect of Permeable Concrete. The rainwater runoff pollutants are mainly COD, SS, TN, TP, and $\text{NH}_3\text{-N}$. The general purification effect can be determined by the proportion of the purification effect of these five pollutants. The results are shown in the Figure 10. The general purification rate of the control group on rainwater runoff is only 26.63%. The maximum general purification rate of permeable concrete with diatomite is 42.85%. The general purification rate of permeable concrete is 2.5 times higher than that of the control group, and the highest purification rate is 71.35% (B-5). At the same time, the general purification rate of B-1-B-6 is higher than that of A-1-A-6, which shows that the modified diatomite has better adsorption.

The porous structure of diatomite and zeolite powder affects the purification effect of permeable concrete. Among them, there are a lot of nanopores on the surface and inside of diatomite. These nanopores make diatomite have similar adsorption with activated carbon. And the shape of diatomite's frustules (empty, perforated sheaths) with their high capillary suction pressure can draw pollutants into their interiors [27].

In addition, diatomite contains a lot of silanol that can ionize a lot of hydrogen ions in water, resulting in the negative charge of diatomite. Therefore, diatomite exhibits a strong adsorption on positively charged pollutants. Zeolite powder exhibits a tetrahedron structure. There are many voids in the structure due to the different connection ways. Meanwhile, the dispersion force on the surface of zeolite powder is strong, which can form a strong electric field around. Under the combined action of strong dispersion force and electrostatic force, zeolite powder exhibits high adsorption ability. The adsorption is a kind of selective adsorption, which has a strong adsorption ability for substances with strong molecular polarity and small molecular size. Notably, high specific surface area and the Al-O tetrahedron result in high cation exchange and high adsorption ability in zeolite powder, as shown in Figure 11. Therefore, zeolite powder exhibits strong adsorption ability of ammonia nitrogen.

Some micropores on the surface of diatomite are blocked by impurities, which reduces the adsorption effect [20]. The modified diatomite is modified by magnesium dihydroxide to reduce the blocking rate. In addition, the hydroxide on magnesium dihydroxide can be dissociated to promote the formation of $\text{Mg}_2(\text{OH})_3^+$ and $\text{Mg}(\text{OH})^+$, which enhances the adsorption of modified diatomite for negatively charged pollutants. At the same time, magnesium dihydroxide can fill the pores of diatomite to improve the specific surface area and pore volume of diatomite, as shown in Figure 12. Therefore, the adsorption of modified diatomite is excellent.

3.3. Gray Correlation Analysis. The gray correlation analysis is an effective method that inspects the micro- or macro-geometric proximity among the factors through analyzing and determining the influence degree of each factor or the contribution degree of several subfactors (subsequence) to the main factor (parent sequence).

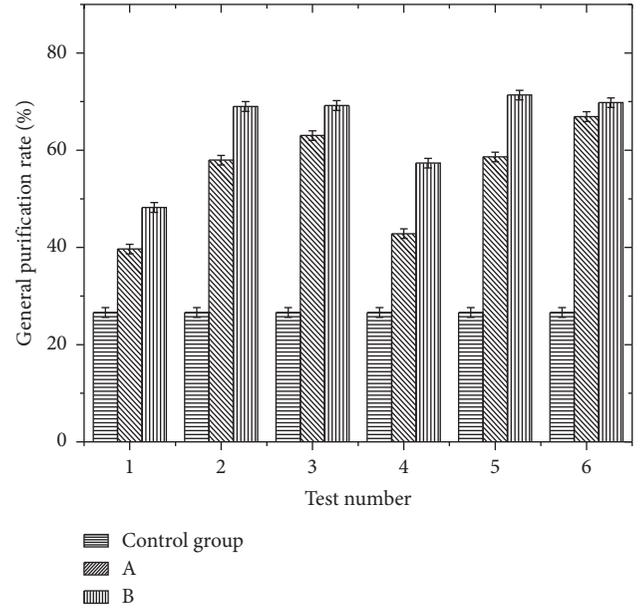


FIGURE 10: General purification effect of permeable concrete. Note: A-1~A-6: permeable concrete specimens with unmodified diatomite and zeolite powder in different dosages; B-1~B-6: permeable concrete specimen with modified diatomite and zeolite powder in different dosages.

- (1) The evaluation indexes include effective porosity, compressive strength, and general purification effect. The optimal value of each evaluation index is selected as the reference sequence (Y_0), as shown in equation (5). The results are shown in Table 7:

$$Y_i = \{y_i(k) \mid k = 1, 2, 3\}. \quad (5)$$

- (2) The sequence of each index needs to be normalized and dimensionless, as shown in equation (6). The result is shown in Table 8:

$$X_i = \left\{ \frac{y_i(k)}{y_i(1)} \mid k = 1, 2, 3 \right\} = \{x_i(k) \mid k = 1, 2, 3\}. \quad (6)$$

- (3) The gray correlation coefficient is calculated by using equation (7). Then, the correlation degree of each dosage is calculated by using the correlation coefficient, as shown in equation (8). The result is shown in Table 9:

$$\xi_i(k) = \frac{\min_i \min_k |x_0(k) - x_i(k)| + \rho \max_i \max_k |x_0(k) - x_i(k)|}{|x_0(k) - x_i(k)| + \rho \max_i \max_k |x_0(k) - x_i(k)|}, t \quad (7)$$

where $|x_0(k) - x_i(k)| = \Delta_i(k)$ is the absolute deviation between x_0 and x_i at point k ; $\min_i \min_k |x_0(k) - x_i(k)|$ is the two-grade minimum difference; $\max_i \max_k |x_0(k) - x_i(k)|$ is the two-grade maximum difference; and ρ is the distinguishing coefficient, generally $\rho = 0.5$:

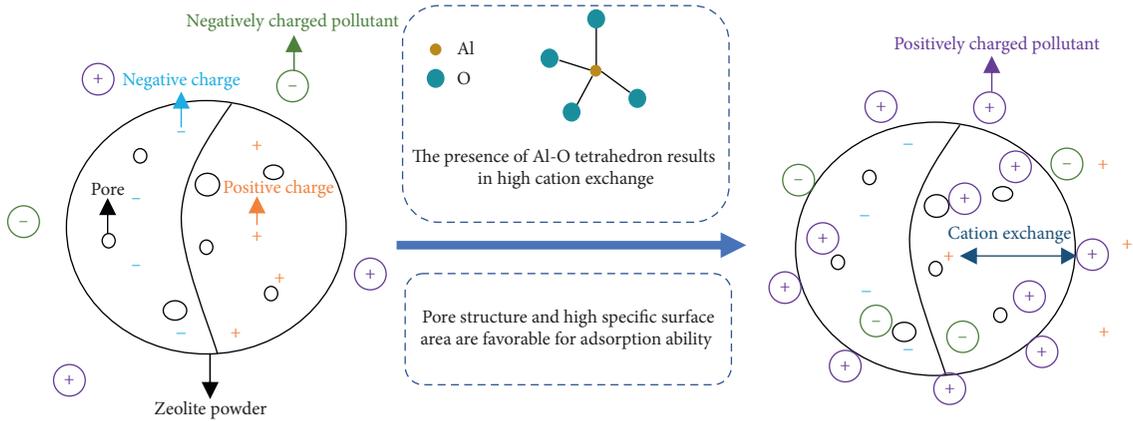


FIGURE 11: Characteristics of zeolite powder.

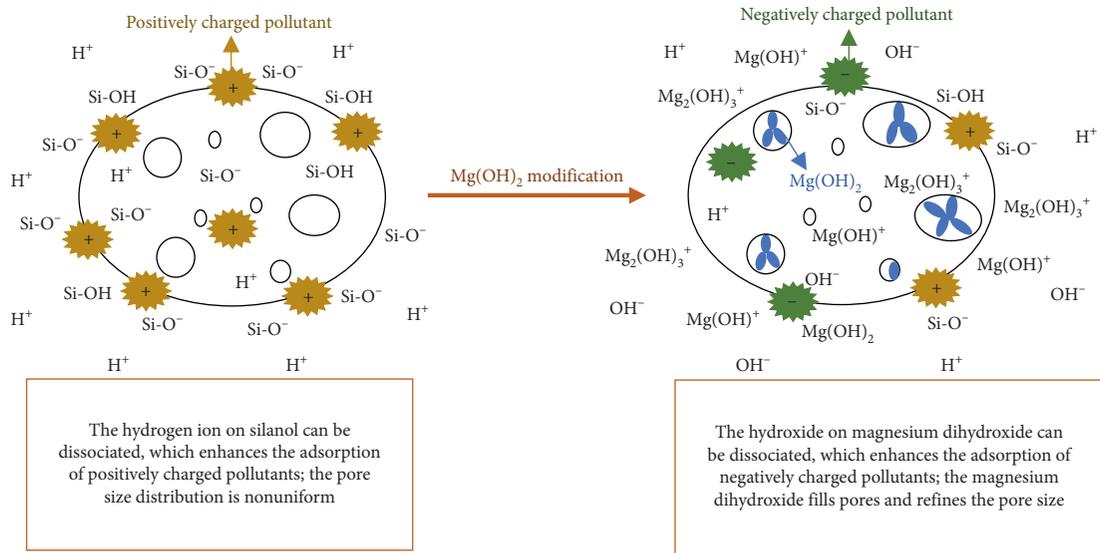


FIGURE 12: Diagram of the diatomite modification mechanism.

TABLE 7: Evaluation indexes for gray correlation analysis.

Number	Effective porosity (%)	Compressive strength (MPa)	General purification effect (%)
Y_0	25.60	21.60	69.78
Y_1 (control)	20.70	13.40	26.63
Y_2 (A-1)	21.60	21.60	39.68
Y_3 (A-2)	23.60	19.60	57.96
Y_4 (A-3)	25.20	14.80	63.01
Y_5 (A-4)	22.60	20.40	42.85
Y_6 (A-5)	24.70	17.40	58.62
Y_7 (A-6)	33.20	13.60	66.92
Y_8 (B-1)	22.80	18.40	48.23
Y_9 (B-2)	25.60	17.80	68.98
Y_{10} (B-3)	27.70	13.40	69.19
Y_{11} (B-4)	23.30	17.60	57.35
Y_{12} (B-5)	25.90	15.00	71.35
Y_{13} (B-6)	33.60	12.60	69.78

TABLE 8: Dimensionless results of gray correlation analysis.

Number	Effective porosity (%)	Compressive strength (MPa)	General purification effect (%)
X_0	1.00	0.84	2.73
X_1	1.00	0.65	1.29
X_2	1.00	1.00	1.84
X_3	1.00	0.83	2.46
X_4	1.00	0.59	2.50
X_5	1.00	0.90	1.90
X_6	1.00	0.70	2.37
X_7	1.00	0.41	2.02
X_8	1.00	0.81	2.12
X_9	1.00	0.70	2.70
X_{10}	1.00	0.48	2.50
X_{11}	1.00	0.76	2.46
X_{12}	1.00	0.58	2.75
X_{13}	1.00	0.38	2.08

TABLE 9: Correlation degree of gray correlation analysis.

Correlation coefficient	Correlation degree (r_i)
$\xi_1 = (1.000, 0.791, 0.333)$	0.708
$\xi_2 = (1.000, 0.818, 0.447)$	0.755
$\xi_3 = (1.000, 0.986, 0.727)$	0.905
$\xi_4 = (1.000, 0.742, 0.758)$	0.833
$\xi_5 = (1.000, 0.923, 0.465)$	0.796
$\xi_6 = (1.000, 0.837, 0.667)$	0.835
$\xi_7 = (1.000, 0.626, 0.503)$	0.710
$\xi_8 = (1.000, 0.960, 0.541)$	0.834
$\xi_9 = (1.000, 0.837, 0.960)$	0.932
$\xi_{10} = (1.000, 0.667, 0.758)$	0.808
$\xi_{11} = (1.000, 0.900, 0.727)$	0.876
$\xi_{12} = (1.000, 0.735, 0.973)$	0.903
$\xi_{13} = (1.000, 0.610, 0.526)$	0.712

$$r_i = \frac{1}{n} \sum_{k=1}^n \xi_i(k). \quad (8)$$

The results of gray correlation analyses show that $r_9 > r_3 > r_{12} > r_{11} > r_6 > r_4 > r_8 > r_{10} > r_5 > r_2 > r_{13} > r_7 > r_1$; that is, 10% modified diatomite and 3% zeolite powder have the highest correlation with the performance of permeable concrete. At the same time, the compressive strength, effective porosity, and general purification effect of modified permeable concrete with 10% modified diatomite and the 3% zeolite powder are improved, which is consistent with the experiment results.

4. Conclusions

In this work, the runoff purification effects of permeable concrete modified by diatomite and zeolite powder were studied by experimental tests and gray correlation analysis. The effects of modified diatomite and zeolite powder on modified permeable concrete were analyzed. In addition, the optimum dosage of modified diatomite and zeolite powder was suggested. The following conclusions can be drawn:

- (1) Modified diatomite and zeolite powder can improve the compressive strength of permeable concrete.

However, the compressive strength of permeable concrete can be inversely influenced by excessive diatomite and zeolite powder dosages.

- (2) Modified diatomite and zeolite powder can significantly improve the effective porosity of permeable concrete. And the effective porosity of permeable concrete with modified diatomite and zeolite powder is higher than that of permeable concrete with diatomite and zeolite powder.
- (3) Modified diatomite and zeolite powder can significantly improve the purification effect of permeable concrete. Among them, permeable concrete with modified diatomite and zeolite powder exhibits significant purification effects on COD, SS, TN, and TP. However, the purification effect of permeable concrete with modified diatomite and zeolite powder on $\text{NH}_3\text{-N}$ is not significant.
- (4) From the gray correlation analysis, 10% modified diatomite and 3% zeolite powder have the highest correlation with the performance of permeable concrete. Thus, the optimum dosage of modified diatomite and zeolite powder in permeable concrete is recommended as 10% and 3% in cement weight in this work, respectively.

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.

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