Journal of Architectural Research and Development, 2025, Volume 9, Issue 2
https://ojs.bbwpublisher.com/index.php/JARD
Online ISSN: 2208-3537
Print ISSN: 2208-3529

Effect of Pore Structure on Purification of Pervious Concrete

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Abstract: By adding zeolite aggregate with good adsorption properties, different mix ratios of added zeolite pervious concrete (ZPC) were designed to compare the water purification effect of ordinary pervious concrete and water purification tests that were conducted. The pore characteristics of the pervious concrete were identified using three-dimensional reconstruction software and the relationship between pore structure and water purification performance was quantified by gray entropy correlation analysis. The results showed that the purification efficiency of zeolite-doped pervious concrete was 17.6%–22.3% higher than that of ordinary pervious concrete. The characteristic parameters of the pore structure of permeable concrete, i.e. planar porosity and tortuosity, were determined using three-dimensional reconstruction software. The correlation between the degree of tortuosity and the removal rate reached more than 0.90, indicating that the internal pore structure of pervious concrete has a good correlation with the water purification performance .

Keywords: Pervious concretes; Water purification; Pore structure characteristics; CT scanning

Online publication: April 4, 2025

1. Introduction

Numerous studies have demonstrated that pervious concrete exhibits excellent water purification properties and plays a significant role in treating pavement runoff [1–3]. Given the severity of rural non-point source pollution, pervious concrete can effectively alleviate pollution loads. The pore structure characteristics play a crucial role in the removal of water pollutants, making it essential to explore the factors influencing its purification performance to provide guidance for improving its water purification capabilities.

Based on extensive research, pollutants purified by pervious concrete can be categorized into two types: organic nutrient pollutants, such as nitrogen and phosphorus, and heavy metal ions. Xie *et al.* investigated the water purification performance of sewage treatment using modified pervious concrete with varying biochar doping levels to evaluate its TN and TP removal capacities [4]. Shang *et al.* introduced organoclay into pervious concrete to remove polycyclic aromatic hydrocarbons (PAHs) and other organic pollutants through isothermal adsorption experiments [5]. Ali Yousefi *et al.* concluded that adding pumice aggregate to pervious concrete mixtures effectively removes heavy metals from aqueous solutions or urban runoff, with natural zeolites, silica fume, and iron oxides also serving as heavy metal adsorbents and supplementary admixtures [6]. The aforementioned studies incorporated admixtures with adsorbent properties into pervious concrete to enhance its water purification performance.

The porous structure plays a crucial role in the functional performance of pervious concrete. The advantage of nondestructive scanning is that the distribution of aggregate and pore structure inside the ecological concrete specimen can be more accurately obtained without changing the morphology of the pervious concrete specimen and without affecting its internal aggregate and pore structure. CT scanning combined with digital image processing (DIP) techniques can quickly obtain microstructural images of previous concrete. Zhang *et al.* used CT imaging technology to construct a visual virtual pervious concrete model, extracted and analyzed the pore structure characteristics of pervious concrete, and obtained a grid of connected pore models [7]. Zhou *et al.* used CT scanning and image processing technology to determine pore diameters and used code algorithms to compute pore geometric properties [8]. Wang *et al.* used X-CT scanning and image three-dimensional reconstruction technology to obtain a three-dimensional model of the internal pores of ceramic permeable pavement tiles, extracted the pore structure characteristic parameters, and carried out a correlation analysis of the pore structure characteristic parameters [9]. Thomas *et al.* evaluation by computerized axial tomography to understand the effect of continuous regeneration on concrete properties [10].

The complex pore structure inside pervious concrete plays a crucial role in its structure and properties. Characterizing the pore structure of pervious concrete and investigating its influence on its properties has become a current research trend. To further analyze the influence of pore structure characteristics of pervious concrete on water purification performance, this study constructs different pore structures by changing aggregate particle size gradation and scans the pervious concrete after curing and molding using CT technology for image identification and analysis. The static adsorption experiment was used to detect the water purification performance of permeable concrete for total nitrogen and the pore structure characteristic parameters were identified through three-dimensional reconstruction to obtain the key indexes for purifying pollutants. Gray correlation entropy analysis was used to analyze the degree of correlation between pore characteristic parameters and water purification performance.

2. Materials and methods

2.1. Materials

The cement used was P-O 42.5 ordinary silicate cement (OPC), the chemical composition of OPC is shown in **Table 1**. The crushed stone aggregate and zeolite aggregate were sieved through a square hole aggregate standard sieve. The crushed stone aggregate with a particle size of 10–15 mm and the zeolite aggregate with a particle size of 8–9 mm and 16–18 mm were selected.

Table 1. Chemical composition of OPC

Material	SiO_2	CaO	Al_2O_3	Fe_2O_3	MgO	Na_2O	K_2O	SO_3
Material content (by weight, %)	21.1	58.4	7.30	3.13	5.94	0.691	0.83	1.65

2.2. Mixing ratio

In this study, the aggregate grading of crushed stone of 10–15 mm and zeolite adsorbent aggregate of 8–9mm and 16–18mm were used first. The design ratio is shown in **Table 2**. According to the research of many scholars, it is known that the physical adsorbent property of zeolite-added permeable concrete (ZPC) will be improved by the increase of zeolite admixture [11–14].

Table 2. Mix proportion of pervious concrete

Number	Designed porosity(%)	Aggregate(g)	Zeolite(g)	Cement(g)	Water(g)
EC	25	1440	0	500	130
ZPC-1		1296	144		
ZPC-2		1152	288		
ZPC-3		1008	432		

2.3. Preparation and maintenance

This test employs the cement paste-wrapped stone method and considers two mixing techniques for pervious concrete: manual insertion pounding and mechanical vibration. Although mechanical vibration is relatively simple to operate, its vibration time and amplitude are difficult to control. Additionally, given the small overall volume of the test, this study uses the manual insertion pounding method.

The standard mold used was a three-link mold with dimensions of 100 mm × 100 mm × 100 mm. After 24 hours, the specimens were demolded and placed in a constant temperature and humidity curing box, maintained at 20 ± 2°Cand 95 ± 2% relative humidity.

2.4. Water purification performance test

This experiment used static adsorption experiments to investigate the purification effect of different zeolite particle size content on the simulated water pollutants and the factors affecting them in the static water state. Water quality tests are conducted every 6 hours, relying on the removal rate to analyze the performance of water purification. The rate was calculated using the equation below and the permeable concrete test block ratios are recorded.

$$\eta = \frac{C_0 - C_i}{C_0}$$

In this equation, η is the removal rate of pollutants(%), C_0 is the raw water pollutant concentration(mg /L), and C_i is the pollutant concentration(mg /L).

3. Results and discussion

3.1. Water purification performance

The surface fitting method was used to establish the functional relationship between time, zeolite gradation percentage, and removal rate, and the R^2 reached 0.980. As shown in **Figure 1**, the fitting curves of time, 8–9mm zeolite particle size, and removal rate were obtained.

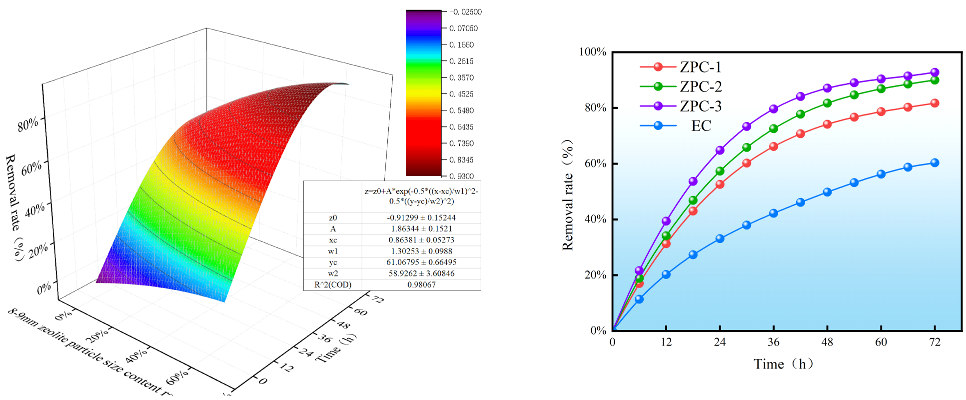

Figure 1. Three-dimensional/two-dimensional effect of total phosphorus purification with three mixing ratios

The corresponding fitting equations are as follows:

$$Rr = -0.864 + 11.023 \times \exp(-0.5 \times ((ZP_{8-9mm} - 13.972)/6.992)^2 - 0.5 \times ((T + 76.607)/74.427)^2$$

In this equation, Rr denotes the removal rate of total phosphorus, $ZP_{8\text{–}9\text{mm}}$ denotes 8–9 mm zeolite particle size content, and T denotes test time. The curve fitting results show that the increasing trend of the removal rate with the increase of 8–9 mm zeolite particle size content is more significant with the increase of test time. It is because with the increase of 8–9 mm zeolite particle size content, the internal surface area of concrete increases and the total phosphorus contacts more attachment points, thus improving the purification effect.

In the whole experiment, the results of zeolite-doped pervious concretes and ordinary concrete are shown in **Figure 1**. Ordinary pervious concrete has some ability to purify total phosphorus, but its effectiveness is lower compared to zeolite-doped pervious concrete. The removal rate of zeolite-doped pervious concrete is 21.4% to 32.45% higher than that of ordinary pervious concrete, demonstrating its superior ability to purify total phosphorus. This is because zeolite is a porous aluminum silicate crystal with a skeleton structure. In the initial stage of adsorption, the removal rate of total phosphorus increases significantly with time, and then gradually tends to slow down until the adsorption equilibrium, which shows the characteristics of "fast adsorption, slow equilibrium". The effect of zeolite particle size and content on the adsorption equilibrium time is also relatively significant; the smaller the particle size of the zeolite content, the faster the adsorption, and the shorter the time required to reach the adsorption equilibrium. This is because the size of the particle on the specific surface area of phosphorus and adsorbate diffusion rate has an impact; the smaller the particle size, the larger the specific surface area, and the adsorbate diffusion rate is also larger, which is more favorable to the adsorption.

3.2. Analysis of planar porosity variation

To better reflect the influence of the internal pore structure of the pervious concrete on the water purification performance, the porosity of each layer cross-section was extracted equally spaced along the height direction of the specimen to obtain the planar porosity. **Figure 2** shows the two-dimensional porosity distribution of the specimens along the Z-axis, and its variance is shown in **Table 3**.

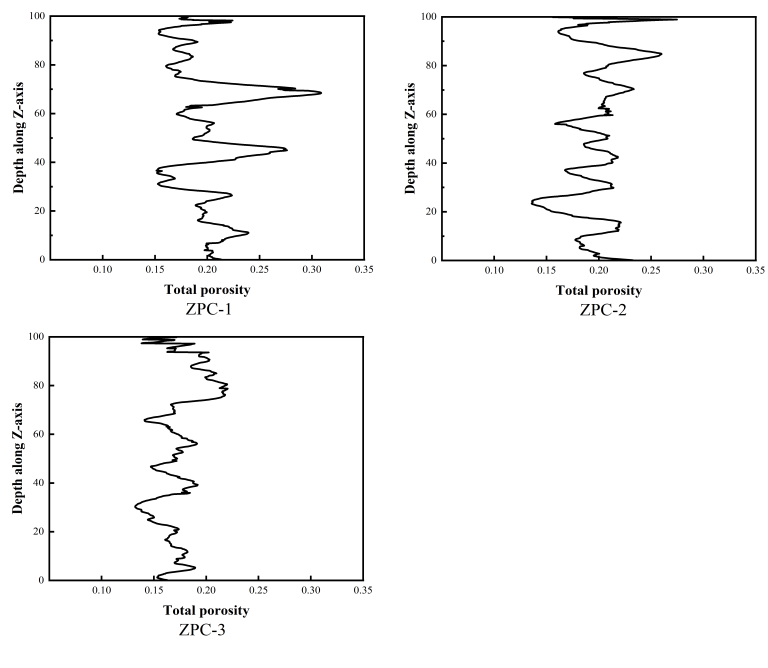

Figure 2. The porosity changes in different planes

Table 3. Results of 2D pore structure of ZPC.

Number	ZPC-1	ZPC-2	ZPC-3
Variance	0.0011	0.0006	0.0004

The larger value of the variance of the two-dimensional porosity change indicates that the homogeneity of the planar porosity decreases. In ZPC-1, ZPC-2, and ZPC-3, the internal pore structure exhibits different trends. As the content of 8–9 mm zeolite particles increases, the variation in two-dimensional porosity with depth remains minimal. The variance of ZPC-1 is the highest at 0.0011, whereas ZPC-3 shows a significantly lower variance of 0.0004. This indicates that permeable concrete specimens prepared with smaller-sized aggregates have a more uniform pore distribution. Additionally, aggregate particle size plays a crucial role in influencing the uniformity of pore distribution. Additionally, the porosity remained relatively stable without significant fluctuations near the top and bottom surfaces of the specimens, indicating that the top-bottom tamping was effective during the casting process.

Overall, ZPC-3 exhibits the lowest planar porosity and the uniformity of pore distribution improves as the content of 8–9 mm zeolite particles increases. This is closely linked to water purification performance, as the smaller-sized aggregates fill the interior of the ZPC, reducing overall porosity while enhancing planar porosity uniformity. This improved uniformity allows for better contact with pollutants during adsorption, leading to more effective purification. Therefore, water purification performance is positively correlated with planar porosity uniformity.

3.3. Analysis of changes in tortuosity

A higher tortuosity indicates a more complex internal pore structure within the porous concrete, creating a more intricate and rugged path for artificial simulated pollutants to travel from the top to the bottom. Additionally, the reticulated structure of zeolite in ZPC, along with the surface characteristics of the pore holes, prolongs the retention time of the pollutant solution. The curved pore channels further enhance contact, allowing for more effective pollutant adsorption and filtration. As shown in **Figure 3**, the average tortuosity of ZPC-1, ZPC-2, and ZPC-3 exhibits an increasing trend. This suggests that as the content of 8–9 mm zeolite particles increases and the proportion of 16–18 mm zeolite particles decreases, the internal pore structure of ZPC becomes more complex. The maximum tortuosity of ZPC-3 reaches 4.65, which is higher than that of ZPC-1 and ZPC-2. Combined with the experimental results, it can be concluded that a higher average tortuosity correlates with improved purification performance of ZPC for total phosphorus.

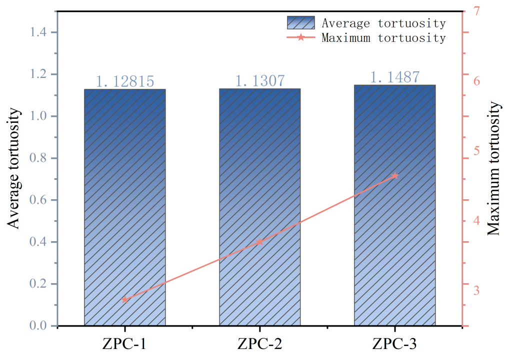

Figure 3. Tortuosity parameter analysis diagram of specimen

3.4. Multivariate regression analysis

The one-dimensional linear analysis of planar porosity and average tortuosity versus removal rate can be concluded that there is a good correlation between the pore structure parameters and water purification performance, as shown in **Figure 4** and **Figure 5**. All of them can reach R^2 above 0.9.

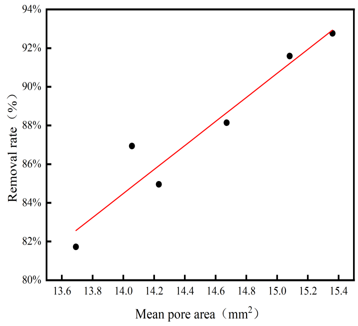

Figure 4. Fitting effect of plane porosity and removal rate

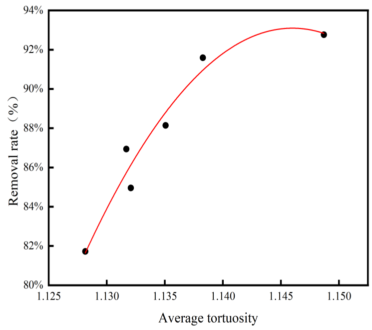

Figure 5. Fitting effect of average tortuosity and removal rate

The univariate linear regression equation obtained from the linear fit of mean pore area to removal rate is shown below:

$$R_1 = 0.0621x_1 - 0.02454$$

$$R_1 = -359.55711x_2 + 824.10217x_2 - 471.27802$$

In this equation, R_1 is the removal rate(%), x_1 is average pore area(mm^2), x_2 is average tortuosity.As seen in **Table 5** and **Table 6**, the planar porosity was linearly distributed with water purification performance, and the R^2 adjusted was 0.9042, which had a good fitting status. The results of polynomial fitting of mean tortuosity to water purification performance when R^2 is adjusted to 0.8691 are greater than the linear fitting results, indicating that for linear fitting, polynomial fitting is more suitable to characterize the tortuosity in relation to the permeability coefficient. The derived regression equation is as follows.

Table 5. One-dimensional linear fit of mean pore area to removal rate

	DF	Square sum	Mean square	F	Probability > F
Mould	1	0.00783	0.00783	48.19975	0.00226
Inaccuracies	4	6.50151E-4	1.62538E-4		
Total	5	0.00848			
Adjusted R^2	0.90421				

Table 6. One-dimensional linear fit of average tortuosity to removal rate

	DF	Square sum	Mean square	F	Probability > F
Mould	2	0.00376	0.00188	14.28322	0.06543
Inaccuracies	2	2.62909E-4	1.31454E-4		
Total	4	0.00402			
Adjusted R^2			0.86914		

4. Conclusion

In this paper, different mixing ratios of zeolite-doped pervious concrete specimens are prepared. Based on CT scanning technology, to obtain the microscopic internal pore structure characteristic parameters of pervious concrete and the method of multiple regression analysis, the main conclusions are as follows:

(1) The porosity of zeolite-added pervious concrete with different mixing ratios at different heights is distributed in wave shape, the uniformity of planar porosity is positively correlated with the water purification performance, and the average tortuosity is positively correlated with the water purification performance.

(2) The planar porosity and tortuosity have good correlation with the removal rate and this result indicates that there is a close relationship between the internal pore structure of zeolite-added pervious concrete and its water purification performance.

Funding

Hunan Provincial Department of Water Resources: Research on Formula Optimization and Performance Evaluation System of Ecological Concrete for River Water Quality Purification Based on the Dual Carbon Goal (Project No.: XSKJ2024064-44)

Disclosure statement

The authors declare no conflict of interest.

References

[1] Azad A, Saeedian A, Mousavi SF, et al., 2020, Effect Of Zeolite And Pumice Powders On The Environmental And Physical Characteristics Of Green Concrete Filters. Construction And Building Materials, 240: 117931.

[2] Kurtay M, Gerengi H, Kocak Y, et al., 2020, The Potency Of Zeolite And Diatomite On The Corrosive Destruction Of Reinforcing Steel In 1 M HNO3 Environment. Construction And Building Materials, 236(3): 117572.

[3] Yang S, Guo M, Duan S, et al., 2019, Study On Strength Variation Of Permeable Concrete Based On Differential Calorimetry Method And Multi-Index Test. Advances In Materials Science And Engineering, 2019(9): 1–9.

[4] Jia J, Yu Y, Guo Y, et al., 2021, Study On Composition Design Of Water-Purifying Functional Pervious Concrete. Bulletin Of The Chinese Ceramic Society, 40(08): 2554–2563.

[5] Shang H, Sun Z, 2019, PAHs (Naphthalene) Removal From Stormwater Runoff By Organoclay Amended Pervious Concrete. Construction And Building Materials, 200: 170–180.

[6] Yousefi A, Matavos-Aramyan S, 2018, Mix Design Optimization Of Silica Fume-Based Pervious Concrete For

Removal Of Heavy Metals From Wastewaters. Silicon, 10(4): 1737–1744.

[7] Zhang J, Ma G, Ming R, et al., 2018, Numerical Study On Seepage Flow In Pervious Concrete Based On 3D CT Imaging. Construction And Building Materials, 161: 468–478.

[8] Zhou H, Li H, Abdelhady A, et al., 2019, Experimental Investigation On The Effect Of Pore Characteristics On Clogging Risk Of Pervious Concrete Based On CT Scanning. Construction And Building Materials, 212: 130–139.

[9] Wang Y, Tan J, Li W, et al., 2024, Quantitative Relationship Model Research Between Pore Characteristic And Permeability Coefficient Of Permeable Pavement Brick. Journal Of Building Materials, 27(02): 174–180.

[10] Liu S, Chen X, Li S, et al., 2021, Mesoscopic Structure Analysis Of Recycled Aggregate Ecological Porous Concrete Based On CT. Water Resources And Hydropower Engineering, 52(02): 174–183.

[11] Liu J, Li Y, 2020, Runoff Purification Effects Of Permeable Concrete Modified By Diatomite And Zeolite Powder. Advances In Materials Science And Engineering, 2020(2): 1–11.

[12] Sudagar AJ, Andrejkovicova S, Rocha F, et al., 2023, Compressive Strength And Heavy Metal Adsorption Of Cork Residue, Natural Zeolite, And Low-Grade Metakaolin-Based Geopolymers. Construction And Building Materials, 366: 130125.

[13] Teymouri E, Wong KS, Tan YY, et al., 2023, Mechanical Behaviour Of Adsorbent Pervious Concrete Using Iron Slag And Zeolite As Coarse Aggregates. Construction And Building Materials, 388: 131720.

[14] She X, Chen J, 2021, Research Progress On Preparation And Properties Of Zeolite Porous Concrete. New Building Materials, 48(10): 75–79 + 99.