Review of Characterization and Testing Methods for the Mechanical, Microstructure, Pore, Permeability, and Freeze-Thaw Properties of Porous Concrete

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ABSTRACT

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| Porous concrete, with its unique pore structure and excellent permeability, is widely used in modern engineering, particularly in urban drainage, environmental protection, and transportation. This paper systematically introduces the testing methods for the mechanical properties, microstructure, pore characteristics, permeability, and freeze-thaw durability of porous concrete, and explores the intrinsic relationships between these properties. Through experiments on compressive strength, flexural strength, porosity, permeability coefficient, and freeze-thaw cycles, the study reveals the influence mechanisms of pore characteristics on the mechanical and permeability properties of porous concrete. The results indicate that the porosity, pore size, and pore coordination number of porous concrete significantly affect its permeability and durability, while its mechanical properties are closely related to the uniformity of the microstructure and pore distribution. Specifically, the porosity of the tested specimens ranged from 15% to 30%, with pore sizes varying between 0.1 mm and 2.0 mm. The permeability coefficient was found to increase with higher porosity and larger pore sizes, while the compressive strength decreased. This paper provides theoretical support for the engineering applications of porous concrete and points out directions for future research. |

*Keywords: Porous concrete, Mechanical properties, Microstructure, Pores, Permeability, Freeze-thaw resistance*

1. INTRODUCTION

As a novel construction material, porous concrete has gained extensive applications in modern engineering, particularly in urban drainage, environmental protection, and transportation, thanks to its unique pore structure and exceptional permeability[1,2]. Its distinct pore characteristics not only endow it with excellent water permeability but also effectively mitigate urban flooding and enhance the ecological environment. Nevertheless, the relationship among the microstructure, pore characteristics, and permeability of porous concrete is intricate, directly impacting its mechanical properties, durability, and functionality[3-5]. Thus, delving into how the microstructure and pore characteristics of porous concrete influence its permeability is of paramount importance for enhancing its engineering applications[6-8].

In recent times, with the continuous advancement of microscopic techniques, researchers have progressively explored the structural characteristics of porous concrete at a microscopic level. Conventional examination methods encompass scanning electron microscopy (SEM), X-ray diffraction (XRD), acoustic emission (AE), and computed tomography (CT)[9-11]. These technologies can provide images of the microstructure and three-dimensional models of porous concrete, offering crucial insights into the relationship between pore characteristics and permeability[12]. Moreover, precise measurements of parameters such as porosity, pore size, and pore coordination number have become a research focus.

Nonetheless, current research faces several challenges. For instance, the complex pore structure of porous concrete makes accurately characterising its three-dimensional structure problematic[13]. Additionally, the specific mechanisms by which pore characteristics affect permeability have not been fully elucidated, especially regarding performance variations under different environmental conditions, such as clogging and freeze-thaw cycles. Consequently, this study aims to systematically characterise the microstructure, pore characteristics, permeability, and freeze-thaw properties of porous concrete through experimental methods, exploring the intrinsic links among these factors and providing theoretical support for the engineering application of porous concrete.

Therefore, the aim of this study is to systematically characterize the mechanical properties of porous concrete (compressive strength, bending strength, split tensile strength, etc.), microstructure testing (SEM, CT scan, etc.), porosity test (connected porosity, closed porosity, etc.), permeability test (constant head method, overhead method), and durability properties of freeze-thaw cycle (rapid freeze-thaw test, Cantabro experiment). Through these experiments, we reveal the influence mechanism of pore properties of porous concrete, provide theoretical support for engineering application of porous concrete and provide reference for future research directions.

2.Mechanical Property Testing

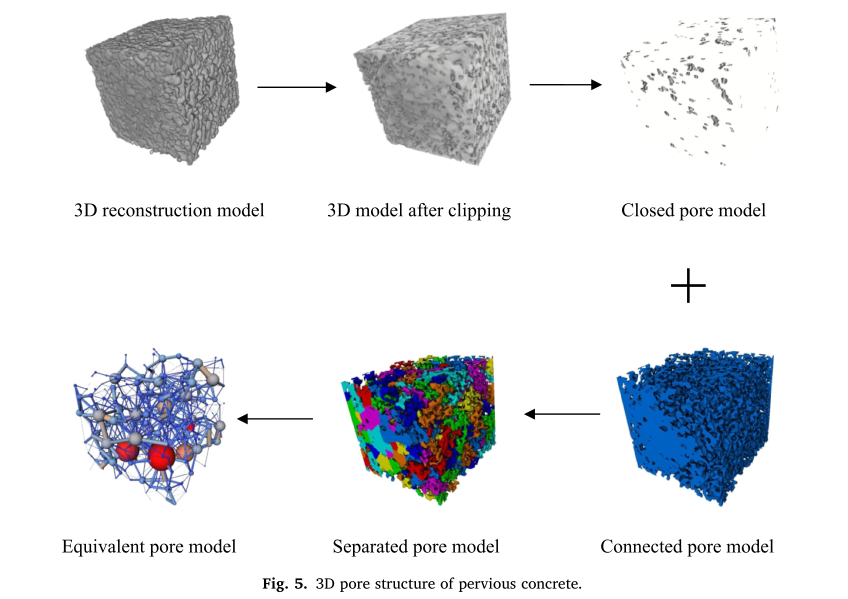
Mechanical property testing experiments include compressive strength testing, flexural strength testing, splitting tensile strength testing, static loading tests, cyclic loading tests, and impact loading tests. The mechanical strength of porous concrete is influenced by several factors, including the water-cement ratio, aggregate size, and pore structure. Take flexural strength as an example,a lower water-cement ratio typically results in higher flexural strength due to reduced porosity and improved interfacial bonding. Additionally, larger aggregate sizes can enhance the flexural strength by providing better load distribution. However, excessive aggregate sizes may lead to uneven stress distribution and reduced strength.These factors were considered in the experimental design, and their effects were analyzed in conjunction with the flexural strength results. The relevant experimental information for mechanical property testing is shown in Table 1. The first five tests are similar and are conducted on testing instruments. The last impact loading test is a simple drop weight impact test, where a 6.5 kg disc is dropped from a height of 1.5 m. The impact resistance of the specimen is determined by counting the number of impacts and measuring the crack dimensions of the specimen.

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| Property Type | Formula | | Notes | Reference |
| Mechanical Properties | Compressive Strength | = | is compressive strength (MPa)，F is the failure load of the porous concrete specimen(N)，A is the cross-sectional area of the specimen (mm2) | [14] |
| Flexural Strength |  | Flexural tensile strength test is conducted on prismatic specimens, with two concentrated loads applied at one-third and two-thirds of the span. is flexural tensile strength(MPa),F is the fracture load (N)，L is the distance between supports（mm）; W is the average width of the specimen (mm); h is the average height of the specimen (mm) |
| Splitting Tensile Strength |  | For cubic specimens, is splitting tensile strength(MPa)，F is the ultimate load (N)，A is the cross-sectional area of the splitting surface () |
|  | For cylindrical specimens,is splitting tensile strength (MPa),Fis the ultimate load (N),is the diameter of the cylindrical specimen (mm)，is the average length of the cylindrical specimen (mm) |
| Impact Loading | e=m×g×h  EAu=Nu×e  Ru=EAu/(Lc×T×Wc) | e is the energy of a single drop (N·mm),m is the mass of the falling object, g is gravitational acceleration (9.81 m/s²), h is the drop height;EAu is the final absorbed energy (N·mm), Nu is the number of drops to final fracture, Ru is the ultimate impact strength (MPa), Lc is the total crack length,T is the plate thickness,wc is the maximum crack width | [15] |
| Table 1 Mechanical Property Testing | | | | |

3.Microstructure Testing

　　Conventional methods for detecting the microstructure of porous concrete include scanning electron microscopy (SEM), X-ray diffraction (XRD), acoustic emission (AE), computed tomography (CT), etc. Among these, CT scanning, combined with digital image processing using DIP technology, can conveniently obtain microstructure images of porous concrete. Three-dimensional pore models of porous concrete are established using computed tomography (CT) technology and AVIZO software[16]. The former involves scanning samples with X-rays and converting the acquired data into images using a computer. During this process, X-rays scatter and are absorbed between materials of different densities in the sample, enabling the measurement of information such as material density and position[17]. By conducting multiple scans and reconstructions, a three-dimensional structural model can be generated. The latter is a software commonly used for the processing and visualisation of three-dimensional images, capable of handling and analysing data obtained from CT scans, including functions such as data segmentation, reconstruction, and visualisation[18]. Through AVIZO software, analysis and model building of pores in porous concrete can be realised.

　　During the experiment, first, the prepared porous concrete samples are placed in a CT scanner to obtain three-dimensional structural information of the samples, including pores and particle distribution. Then, the data obtained from the CT scan are processed using AVIZO software. Operations such as segmentation and thresholding are used to convert images into three-dimensional models. The models are also cleaned and smoothed to enhance their accuracy and visualisation effects. Through AVIZO software, pores in the samples can be analysed, including the number, size, and shape of the pores. Finally, the three-dimensional pore models generated by AVIZO are compared and verified with the actual samples to ensure the accuracy of the models. As shown in Fig.1, Jingsong Shan[16] conducted a study on the three-dimensional pore structure of porous concrete using CT scanning and AVIZO software.



**Fig.1 Three-Dimensional Pore Structure Study of Porous Concrete [16]**

4.Pore Characteristic Testing

The pores in porous concrete include interconnected pores and closed pores. Experimental tests include measurements of interconnected porosity, closed porosity, and total porosity. In this experiment, the weight of the sample dried in air for 24 hours, the weight after complete drying in an oven, and the weight when fully immersed in water are collected. The porosity is then calculated using the weight differences and the volume of the sample, as detailed in Table 2.

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| Performance Type | Calculation Formula | Notes | Reference |
| Porosity | )×100% | Here, is the interconnected porosity, is the closed porosity, is the total porosity, W1 is the weight of the specimen fully immersed in water, W2 is the weight of the specimen dried in air for 24 hours,W3 is the weight of the specimen fully dried in an oven, V1 is the volume of the specimen,is the density of water | [19] |
| )×100% - |
| + |
| **Table 2 Porosity Testing** | | | |

5. Permeability Testing

The permeability testing experiments for porous concrete include the constant head method and the falling head method, as shown in Table 3. The experimental steps for both methods are similar. Before the experiment, the porous concrete is soaked in water for 24 hours. The sample is then removed, and its sides are sealed (by applying petroleum jelly and covering with a rubber membrane) to prevent water leakage. The sample is fixed at the bottom of the permeability test tube, and the gap between the specimen and the sleeve is sealed with lightweight rubber clay. This ensures that the sample does not shift during the experiment due to water pressure and impact forces and that water does not leak from the gap between the specimen and the sleeve throughout the entire test process. The water injection speed inside the test tube is strictly controlled to maintain a stable water level. The stability of the water flow at the overflow ports of the permeability test tube and overflow trough is accurately determined. The water collection duration is set, and the volume of water in the collection cylinder before and after water collection is recorded.

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|  | Constant Head Method | Falling Head Method | Simplified Falling Head Method |
| Test Setup Diagram | image4 | C:\Users\Administrator\Desktop\渗透实验1.51.png渗透实验1.51 | image7 |
| Calculation Formula |  | K |  |
| Notes | Here,is the hydraulic conductivity at temperature T (cm/s); Q is the collected water volume in time t (s); L(cm) is the thickness of the porous concrete sample (10 cm in this study); A is the cross-sectional area of the sample (cm²); H is the water head above the sample (cm) (15 cm in this study); t is the water collection time after the overflow port flow stabilises (s) | The falling head method permeability test is based on ACI 522R-10, where K is the permeability coefficient (cm/s), a is the cross-sectional area of the standpipe (cm²), L is the length of the sample (cm), A is the cross-sectional area of the sample (cm²), t is the recorded time from h1 to h2 (s), h1 is the initial water level, and h2 is the final water level | During the test, the time it takes for the water flow in the pipe to pass from the upper mark to the lower mark is recorded. Here, K is the permeability coefficient of porous concrete (cm/s), hu is the upper mark height (cm), which is taken as 22 cm in this study, h1 is the lower mark height (cm), which is taken as 2 cm in this study, and t is the time it takes for the water level to go from the upper mark to the lower mark (s) |
| Reference | [20] | [21] | [14] |
| **Table 3 Permeability Testing** | | | |

6.Freeze-Thaw Cycle Durability Testing

The freeze-thaw cycle durability of porous concrete can be evaluated through rapid freeze-thaw experiments. In the experiment, porous concrete specimens are immersed in a freeze-thaw cycle testing instrument containing tap water or magnesium chloride solution. After every 30 cycles, the specimen is removed from the F-T testing platform after thawing and placed on the steel bracket of the measuring instrument to measure the lateral frequency until the specimen undergoes 300 cycles or its relative dynamic elastic modulus (RDME) drops below 60% of the initial modulus. The freeze-thaw cycle testing instrument is shown in Fi.2(a, b).

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|  |  |  |  |
| (a) | (b) | (c) | (d) |
| Fig.2 (a) Freeze-Thaw Cycle Tester (b) Lateral Frequency Tester[22];(c) Los Angeles Abrasion Machine (d) Cantabro Test Specimen[15]。 | | | |

The Cantabro test can also be used to evaluate the durability of porous concrete. In the experiment, 28-day-cured specimens of 70 mm × 70 mm × 70 mm are placed in an abrasion machine and operated at 30-33 revolutions per minute for 300 revolutions. The remaining mass of the specimen passing through a 25 mm sieve is weighed, and the mass loss percentage is calculated to reflect the specimen's resistance to rapid freeze-thaw cycles. The experimental instruments are shown in Fig.2 (c, d), and the calculations are presented in Table 4.

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| Property Type | Formula | | Notes | Reference |
| Durability | Rapid Freeze-Thaw Test | ×100% | Conducted according to ASTM C666-03, is the relative dynamic elastic modulus RDME, after c F-T cycles, n is the transverse frequency at 0 F-T cycles, and is the transverse frequency after c F-T cycles | [22] |
| Cantabro Test | Massloss(%)=×100% | The experimental procedure complies with ASTM C666 / C666M-2015, formula, M1 initial mass; M2 final mass of measured test sample; Massloss (%) mass loss percentage | [15] |
| Table 4 Performance Characterisation Tests | | | | |

6.Conclusions

Porous concrete, as a building material with special properties, has an extremely close intrinsic relationship between its mechanical properties, microstructure, pore characteristics, permeability, and durability. Through a series of experiments, such as compressive strength, flexural strength, porosity, permeability coefficient, and freeze-thaw cycles, the study revealed the significant impact of the characteristics of porous concrete, such as its porosity, pore size, and pore coordination number, on its permeability and durability.

　　Experiments have shown that higher porosity and larger pore sizes can significantly improve the permeability of porous concrete. This is because the higher the porosity and the larger the pore size, the more unobstructed the flow of water or gas within the concrete, thereby enhancing the permeability. However, this structural advantage may reduce its mechanical properties and durability. The compressive strength and flexural strength of porous concrete typically decrease with increasing porosity, as the presence of pores weakens the continuity and integrity of the concrete, making it more prone to cracks and failure when subjected to loads. Moreover, larger pore sizes may make the microstructure of the concrete more fragile, thereby reducing its durability.

　　The uniformity of the microstructure and the distribution of pores have a significant impact on the mechanical properties of porous concrete. A uniform microstructure and a reasonable pore distribution can allow loads to be transmitted more evenly within the concrete, thereby enhancing its mechanical properties. For example, a "honeycomb-like" pore structure can effectively transmit and disperse external loads. Moreover, the microstructure of the interfacial transition zone also has a significant impact on the mechanical properties and durability of concrete. The introduction of porous aggregates affects the microhardness of the cement stone in the interfacial transition zone, which in turn affects the overall performance of the concrete.

　　Although this study provides important theoretical support for the engineering application of porous concrete, how to further optimize its microstructure to balance permeability and mechanical properties remains a key direction for future research. Future studies should focus on the long-term performance changes of porous concrete under complex environmental conditions and explore new characterization techniques and optimization methods to promote its wide application in practical engineering.

COMPETING INTERESTS DISCLAIMER:

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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