Flow field analysis of micro particles passing through pervious concrete

Xuan Nan 1,2, Mingfei Zhang 1,2, Yanhui Liu 1,2,*, Jing Wang 1,2, Lina Wang 1,2, Ling Jing 1,2

1 School of architecture engineering, Yunnan Agricultural University, Kunming, 650021, China
2 Yunnan Provincial Key Laboratory of water safety and water saving and emission reduction, Kunming 650021, China

*Corresponding author e-mail: 171879506@qq.com

Abstract. In order to study the pore seepage and clogging problems in the permeable concrete, the permeable concrete blockage test device was used to simulate the flow law and distribution of the surface micro-particles through the concrete at the beginning of rainfall. The internal pore structure was reconstructed by CT scanning technique combined with avizo software. The DPM model in CFD was used to simulate the multiphase flow of Kunming surface microparticles through the permeable concrete. The results show: The results obtained by CFD numerical simulation are in good agreement with the experiment. The surface micro-particles with particle size range of 200-500um have a certain degree of blockage to concrete, and still have good water permeability (higher permeability coefficient), and after adding below 200um The particle clogging is more significant, and the permeability coefficient is basically close to 0, but more importantly, it is found by DPM simulation that the small particles of 0-100 um pass through the concrete and the seepage velocity is slow and the partial adhesion to the wall of the tunnel causes the diameter to decrease and affect the seepage.

Key words: CT scan; 3D reconstruction; permeable concrete; microparticles; flow rate.

1. Introduction

Due to frequent disasters in the city in recent years, it has indirectly driven the rapid development of China's sponge city construction. The permeable concrete has been applied to various roads in the city due to its good water permeability. The permeability of permeable concrete is generally between 15% and 25%, the permeability is generally 2~6 mm/s, and the highest is above 10mm/s. The main advantage of permeable concrete is that it can transport a large amount of water through the pore structure of the material, thereby reducing or eliminate the problems caused by stormwater runoff. However, at the same time, the application of permeable concrete in the practice of urban construction inevitably has the problem of service life. Due to the influence of external environmental factors and its internal structure, the permeable function of the permeable concrete is weakened, which affects the overall construction of urban flood control. Repeated replacement of permeable concrete will inevitably result in waste of
manpower and material resources. Therefore, it is of theoretical and practical value to explore the clogging mechanism of permeable concrete and to improve the functional life of permeable concrete.

Relevant experts and scholars at home and abroad have carried out research on this issue and achieved results. Montes [1] et al. and luck [2] conducted in-depth research on the drainage performance of permeable concrete in 2006. Ni Lanyuan et al. In the study of permeability of pervious concrete under rainfall conditions [3], Zhang Na et al. proposed an experimental study on the study of plugging mechanism in 2014 [4]. Previous studies have introduced the clogging and penetration of permeable concrete, but the flow law of granules inside permeable concrete is rarely studied. Therefore, based on previous studies, CFD is utilized by means of CT scanning and avizo reconstruction. The related technology of numerical simulation analyzes the flow law of particles inside permeable concrete [5].

Firstly, the surface micro-particles of Kunming were subjected to particle size classification by surface micro-particle sieving method, and different particle size levels were tested by a permeability test instrument and an osmotic device to measure the initial penetration to the final complete clogging process. And through the industrial ct scanning the permeable concrete to achieve 3D reconstruction in avizo, mesh optimization of the mesh through meshing, to ensure that the high-quality mesh will not affect the simulation results. Due to the formation of solid-liquid multiphase flow between the rainwater and the micro-particles on the pavement at the beginning of rainfall, there are also differences in the flow of different particles in the pores entering the permeable concrete [6-7]. Therefore, the multi-phase flow is observed by the DPM model of CFD. The flow situation, understand the distribution law of internal particle blockage, in order to bring more reasonable plans and countermeasures for the cleaning and maintenance of the spongy city permeable concrete pavement, so as to promote the generalization of the sponge city rational regulation [8].

2. Experiment of permeability change

2.1. Production of permeable concrete specimens

In this experiment, two models of recycled aggregate concrete with different admixture ratios were prepared. One is a 150*150*150 square test piece for ct scanning, and the other is the diameter required for permeability test and plugging device. 100 height cylindrical test piece. At the same time, according to different references, there are two kinds of clogging schemes. Firstly, according to the micro-particles of Kunming road surface, the particle size grading experiment is carried out, one is blocked by large particles between 200-500 um, and the other is blocked by small particles of 1-200. Experiments, and 1-500 particle experiments.

| Particle size range /um | 200-500um | 1-200um | 1-500um |
|-------------------------|-----------|---------|---------|
| 1-100                   | 0         | 70      | 35      |
| 100-200                 | 0         | 30      | 25      |
| 200-300                 | 20        | 0       | 20      |
| 300-400                 | 30        | 0       | 10      |
| 400-500                 | 50        | 0       | 10      |

Cement: Red Lion brand P. O grade 42.5 cement, performance indicators see Table 2.

| Initial setting time /min | 3D flexural strength /mpa | 3D compressi strength /mpa | fineness /% | specific surface area /m2/kg |
|---------------------------|---------------------------|---------------------------|------------|-----------------------------|
| Initial coagulation       | 25                        | 5                         | 370        |
| End coagulation           | 171                       | 247                       |            |                             |

Table 2. Properties of cement
Water, ash F GB / T1596 - 2005, water reducer, coarse aggregate are in line with the experimental requirements, through the laboratory concrete production and maintenance device to make [9]. Previous experiments found that when the water cement ratio is 0.35-0.4, the design porosity is 15%-20%, and the aggregate diameter is 4.5-16.5 mm, the comprehensive performance of pervious concrete is the best, so this group of experiments.

2.2. Blocking experiment and determination of permeability coefficient.
The permeability coefficient is measured and the working principle of the clogging device is installed: two electronic water pressure sensors and one ultrasonic flow rate device are installed on the experimental device, and all the sensors are connected to the computer through an analog-to-digital converter. The head loss of the upper and lower surfaces of the test piece can be measured by the water pressure sensor, and the flow rate of the water in the water pipe can be measured by the flow rate sensor, and the formula (1) can be introduced. During the experiment, attention should be paid to avoid leakage of the side wall of the permeable concrete specimen in the penetration test; the change process of the permeability coefficient must be continuously recorded on-line; the clogging process of rainwater and particle seepage of the permeable concrete pavement is simulated [10].

![Image](image1.jpg)

**Figure 1. Permeability test device and permeable concrete**

Permeability coefficient:

\[
K = \frac{v_1 A_{in} L}{\Delta v_2 A_{eff} \Delta h}
\]

In the formula: K is the permeability coefficient; \(v_1\) is the average flow velocity inside the concrete; \(\Delta i\) is the head difference; \(v_2\) is the average flow velocity of the outlet in the outlet pipe; \(A_{eff}\) is the effective sectional area of the concrete test piece; \(A_{ou}\) is the effective sectional area of the outlet pipe; \(L\) is the length of the test piece.
Firstly, the unblocked recycled aggregate permeable concrete was tested, and then the permeability change under the condition of blocking the particles in the 200-500 um level was tested, and the permeability change under the condition of blocking the 1-200 um clogging particles was further performed [11]. (1-500um experimental results with 1-200um results and not shown in the annex).

3. Microstructure reconstruction of permeable concrete under CT scanning

3.1. Refactoring steps
Try to explain how microparticles flow in the pores by CT scanning techniques and software for building three-dimensional pores, which will help to understand the mechanism of blockage inside the concrete. First, the previous square 150*150*150 specimens were scanned under industrial CT to obtain 100 consecutive scanned images, which were visualized by avizo software, from binarization processing, threshold processing to final 3D construction. In the process, due to the scattered distribution of some aggregates at the edge, the subsequent three-dimensional solids are difficult to form. Therefore, in the post-processing process, the scanned images are trimmed to ensure the reconstruction effect without affecting the reconstruction [12]; then in avizo Patch repair, STL file output after repair is completed, imported into ANSYS SCDM for entity transformation to form a model that CFD can recognize.

Figure 2. Changes before and after permeability blockage

Figure 3. comparison before and after binarization
3.2. Scan results analysis and grid processing
By scanning the 150*150*150 specimens, the data of the internal porosity distribution was obtained by avizo treatment:

Table 3. Situation of internal porosity

| parameter  | Pore volume fraction | Total pore volume | Total volume of concrete |
|------------|----------------------|-------------------|--------------------------|
| pore       | 0.2098               | 7.4085e6          | 3.456e7                  |

It shows that the test specimen meets the requirements.

The formation of solid permeable concrete in ANSYS, meshing into mesh, through medium partition model and high-quality partition model. It is determined that the quality of the grid at 7226302 has no effect on the calculation result, and continuing to increase the grid quality will affect the calculation speed and cause the server to stagnate. When the grid number of 7226302 is Grid, the basic unit of the grid is 0.189 quality. Grid size: 10-8 to 10-10 m³, so this grid is fully compliant with the calculations that follow. At the same time, the model of equivalent pore and pore distribution established in avizo conforms to the concrete proportioning requirement and is close to the porosity of 20% of the specimen. Therefore, the modeling after the ct scan is successful and satisfies the calculation requirements [13-14].

4. Simulation of microscopic flow field
At the beginning of rainfall, the multiphase flow of surface microparticles and rainwater enters the permeable concrete at different initial flow rates, and how it changes during this process. A large number of experimental studies have shown that the permeable concrete can be summarized according to the characteristics of seepage and seepage in porous media: nonlinear law with starting pressure gradient. At the same time, the flow state of the multiphase flow in the permeable concrete, as well as the time and speed of the microparticles staying, and the distribution of the microparticles, it is necessary to study the movement of the clogging microparticles in the pores from these aspects [15-16].

4.1. Seepage law and mathematical equation
The mechanism of particle seepage is expressed by Darcy's law, forchheimer's law, NS equation, continuity equation and so on.

Darcy's law:

Figure 4. skeleton structure and pore model
\[ q = kA(h_1 - h_2)/L \]  

In the formula: \( q \) is the volume of water flow per unit time; \( A \) is the cross-sectional area; \( h_1 - h_2 \) is the head difference; \( L \) is the length.

Forchheimer's law:
\[ J = \frac{\mu}{K} v + \beta \rho v^2 \]  

In the formula: \( J \) Pressure gradient (pa/m); Hydrodynamic viscosity coefficient \((1.005 \times 10^{-3} \text{ Pa} \cdot \text{s})\); \( v \) Seepage velocity (m/s); \( \beta \) non-Darcy coefficient \((\text{m}^4)\); \( k \) Permeability \((10^{-10} \text{ m}^2)\); \( k \) Hydraulic conductivity (permeability coefficient) (m/s).

Navier-stokes:
\[ p \frac{dv}{dt} = -\nabla p + pF = \mu \Delta v \]  

Continuity equation:
\[ V_1 \times A_1 = V_2 \times A_2 \]  

Is the area flowing through section 1; is the flow rate through section 1; is the area flowing through section 2; is the flow rate through section 2.

Reynolds number:
\[ \text{Re} = \frac{\rho u D_{\rho}}{\mu} \]  

\( D_{\rho} \) is the equivalent pore diameter (mm) of the permeable concrete; is the average flow velocity of the pore water flow. Since the equivalent aperture is determined, it can be equivalent according to avizo, so the Reynolds number is only related to the flow rate to determine the flow state within the aperture. When Re is less than 10 for Darcy flow and greater than 10 is non-Darcy linear flow, it is determined that the seepage changes from Darcy flow to non-Darcy flow by varying the flow velocity at different starting pressures. A large number of studies have shown that when Re<1 The dimensionless permeability of the porous medium remains almost the same, but as the Reynolds number Re increases, the permeability gradually decreases. Since the residual curve is difficult to converge, the turbulence is not discussed too much [17-18].

Seepage velocity: average velocity of pore water flow multiplied by porosity

When in the laminar flow state, the seepage velocity of the permeable concrete can be obtained by the rainwater velocity cloud map of the permeable concrete section, and the velocity at the center of the concrete is large because of the large internal pores.

4.2. Simulation results and analysis
Effect of pressure changes on internal flow rate See the average seepage velocity at different pressures as follows:

| Table 4. Inlet pressure and maximum flow rate |
|---------------------------------------------|
| Inlet pressure(pa) | 100  | 200  | 300  | 400  | 500  |
| Internal velocity(mm/s) | 0.264 | 0.58 | 0.81 | 1.15 | 0.135 |
The maximum internal flow velocity is also increased by the increase of the inlet pressure. It is known by Darcy's law that the influence of the inlet pressure on the seepage coefficient in the laminar flow range increases as the pressure increases.

Movement law of multiphase flow in the tunnel under DPM model in CFD

![Graph](image1.png)

**Figure 5.** Internal maximum flow rate under different pressure inlets

![Image](image2.png)

**Figure 6.** Residence time of particles in different parts of concrete
Figure 7. Particle motion state at initial time to the ending time of particle motion

From the simulation, it can be seen that the micro-particles are distributed inside the permeable concrete. The flow rate of 200-500 um particles in the inlet is deposited faster below, and the particles below 200 um slowly pass through the permeable concrete along with the water flow and some of the particles will adhere to the wall of the tunnel. At the same time, due to the slow flow of 0-200 particles in the permeable concrete, the particle movement of 200-500 is hindered, and the next flow of the particles causes the overall flow to slowly affect the small penetration, due to the proper gap between the 200-500 particles, small The particles will enter into the gap between the particles to form a blockage; then, with the next entry of the particles, a layer of 200-500 um particles and a layer of 0-200 particles are alternately covered on the upper layer of the permeable concrete. Inside the pores, the concrete is completely blocked with time, so that the permeability drops to almost zero, which is consistent with the previous permeability test, but it should be well understood that the movement of small particles inside the pores is extremely slow and partially adhered to On the wall of the tunnel, this is not observed in the experiment; overall, the particles The flow resistance and fluid buoyancy have an increasing trend under the action of gravity. However, the initial percolation phase of the 0-200um particle is extremely slow, which affects the infiltrated microparticles behind, resulting in the formation of various particles within a few centimeters of the surface layer. The mix is blocked [19].

The number of imported and exported particles was counted using the DPM model after the large particles were exported:
The references

The diameter of a particle is an important parameter affecting permeability. Microparticles with diameters of 100um will directly result in a decrease in the flow rate, and will cause some particles to adhere to the wall of the tunnel resulting in a decrease in permeability. Under high pressure, the flow rate of microparticles with diameters of 100um or less will be slower.

5. Conclusion

The microscopic pore structure and solid model of the permeable concrete were reconstructed by CT scanning and Avizo 3D visualization software to verify the distribution and clogging of the microparticles in the surface runoff through the permeable concrete. At the same time, the flow rate under different pressures was also satisfied. Determination of permeability of permeable concrete. Correct understanding of the internal structure of the permeable concrete, and found that 1-100um particles flow slowly inside the concrete and will cause some particles to adhere to the wall of the tunnel to reduce the permeability directly, resulting in a decrease in the penetration effect (with previous research results: 0-100um) The most important reason for granule blockage is completely consistent [23]). It provides some references for further research on concrete blockage control in the future. This is also the deep understanding of seepage through permeable concrete through microstructural and particle flow laws. The situation is mainly as follows:

1. Particles with a diameter of 100 μm or less in surface microparticles are the main reason for reducing the permeability of permeable concrete.
2. Although the large particles with a diameter of 200-500 μm in the surface micro-particles enter the permeable concrete, the initial flow rate is faster, but as time goes by, the small particles of 0-200 um continuously stick to the pores in the permeable concrete, causing the flow rate of the large particles to slow down, so that It continuously adheres to the subsequent entry of small particles and completely blocks the pores of the permeable concrete.
3. After the surface micro-particles with a diameter of 1-500um enter the permeable concrete at the same time, the flow rate of the micro-particles below 100μm is obviously slower than that of the micro-particles with a diameter of more than 100μm.

Due to time constraints, this paper fails to make a more detailed study on the particles below 1μm in diameter and the surface micro-particles in the range of 1-200μm. In the subsequent work, the diameter range of different surface micro-particles will be refined. For the flow field analysis.

![Figure 8. size distribution of import and export](image-url)
Acknowledgments
This work was financially supported by Yunnan Science and Technology Plan Project (2011FZ088), Yunnan Provincial Water Resources Department Science and Technology Project (k2400128) fund.

References
[1] Montes F, Haselbach L. Measuring Hydraulic Conductivity in Pervious Concrete[J]. Engineering Science, 2006, 23(6):960-969.
[2] Luck J D, Workman S R, Higgins S F, et al. Hydrologic Properties of Pervious Concrete[M] Transactions of the ASABE. 2006:1807-1813.
[3] Zhang Na. Experimental study on the plugging mechanism of pervious concrete [D]. Shandong University, 2014.
[4] Ni Tongyuan, Hu Kanghu, He Feng. Permeable Concrete Permeability under Rainfall Conditions [J]. Urban Roadways and Bridges and Flood Control, 2011 (11): 137-138+143+154-155.
[5] Lim E, Tan K H, Fwa T F. Effect of Mix Proportion on Strength and Permeability of Pervious Concrete for Use in Pavement[J]. Journal of the Eastern Asia Society for Transportation Studies, 2013, 10:1565-1575.
[6] Zhang Na, Cui Xinzhuang, Zhang Jin, Zhou Yaxu, Gao Zhijun, Sui Wei. Study on the Decompression and Settlement Effect of Pervious Concrete Piles under Embankment Loading [J].Journal of Shandong University (Engineering Edition), 2013, 43 (04): 80-86.
[7] Zuo Xiaojun, Li He, Fu Min, Bu Xianting, Hou Fangdong. Experimental study on rainfall settlement characteristics of highway pavement runoff [J].Water Supply and Drainage, China, 2011, 27 (15): 60-63.
[8] Wang Shumin, Guo Shugang, He Qiang, Yan Wentao, Song Li. Water quality characteristics and initial scouring phenomena of rainfall and runoff in urban watersheds[J]. Environmental Science Research, 2015, 28(04): 532-539.
[9] Yao Minglai, Wang Xin, Chen Zhou, Liu Qinnan, Xue Kuo, Rao Biyu. Experimental study on performances of sand-free pervious concrete with recycled aggregate [J]. Concrete, 2017 (12): 83-86.
[10] Cui Xinzhuang, Zhang Jiong, Huangdan, Jinqing, Hou Fei. Experimental simulation of rapid clogging of pervious concrete pavement under torrential rain[J].Chinese Journal of Highways, 2016, 29(10): 1-11+19.
[11] Prince Jia, Du Xinqiang, Ye Xueyan, Song Xiaoming, Zhang Jiashuang, Gao Cuiping. Surface clogging of suspended solids during urban rainwater recharge [J]. Journal of Jilin University (Geoscience), 2012, 42 (02): 492-49
[12] Yang Xiaolong, Li Bo, Li Yanbo. Non-destructive evaluation method for blockage rate of pervious concrete based on CT scanning technology[J].Chinese and foreign highways, 2014, 34(05): 257-262.
[13] CUI Xinzhuang, LIUNaike, Experimental Study on Pore Clogging of a PorousPavement under Surface Runoff[J].Geotechnical special publication, 2014, 246: 138-146 (EI) (36)
[14] Jiong Zhang, Xinzhuang Cui*, Weize Tang, Junjie Lou. Approximate Simulation of Storm Water Runoff over Pervious Pavement. International Journal of Pavement Engineering, 2015 (SCI & EI)
[15] Huang Yanzhang, Yang Zhengming, He Ying, Wang Xuewu, Luo Yutian. Nonlinear seepage theory in low permeability porous media [J]. Mechanics and practice, 2013, 35 (05).
[16] Zhang Wenjuan, Wang Yuan, Ni Xiaodong. Characteristic analysis of non-Darcy seepage parameters of Forchheimer type [J].Hydropower and Energy Science, 2014, 32 (01): 52-54+164.
[17] Zheng Multian. Permeability coefficient and testing method of porous concrete [J]. Journal of traffic and transportation engineering, 2006 (04): 41-46.
[18] Chen Chongxi, Wan Junwei. Is Forchheimer and other basic equations for non-Darcy flow in porous media universal? [J].Journal of Water Conservancy, 2011, 42 (10): 1257-1259.
[19] Ye Xi. Study on the percolation characteristics of polymer solution in porous media [D]. China University of Petroleum, 2008.

[20] Guo Liejin. Dynamics of two phase and multiphase flow [M]. Xi'an Jiao Tong University, Xi'an, Shaanxi.

[21] CFD–DEM study of mixing and dispersion behaviors of solid phase in a bubbling fluidized bed[J]. Kun Luo, Fan Wu, Shiliang Yang, Jianren Fan. Powder Technology. 2015

[22] Chen Xingxin. Migration and deposition characteristics of particles in saturated porous media [D]. Beijing Jiaotong University, 2013.

[23] Liu Yinyu, Jiang Cheng, Liu Jie, Liu Hui, Wu Yuxuan, Zhao Jinhui. Research Progress on Pervious Concrete Pavement Blockage and Its Restoration [J]. Environmental Science and Technology, 2016, 39 (S1): 159-163+198.