Simulation Analysis of Pervious Concrete Performance Based on Discrete Element Method

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Abstract. In order to study the uniaxial loading failure process of pervious concrete and the influence of water-cement ratio and loading rate on the compressive strength, we carry out indoor uniaxial compression test and establish parallel bond model by discrete element program PFC²D to analysis from the angle of micro. By comparing the indoor test data with discrete element simulation results, we found that the compressive strength of pervious concrete increased with the increase of water cement ratio, and there is a difference between the state of failure and the distribution of cracks. With the increase of loading rate, the compressive strength of pervious concrete is improving, the corresponding peak point strain is reducing, the number of microscopic cracks is decreasing, and the degree of breakage is reducing.

1. Introduction

Pervious concrete is a three-phase composite material consisting of cement, water and aggregates, and its engineering properties are complex. Under load, the granular materials in the structure exhibit a relatively discrete motion state [1-3]. Pervious concrete is a product of “sponge cities”, which has a large porosity. In rainy days, precipitation seeps through permeable pavement, reduces road surface water and supplements groundwater. At the same time, it guarantees traffic safety and eases the “heat island effect” of a city. At present, pervious concrete is the hot research direction of domestic and foreign experts, and the problem of the improvement of its compressive strength is a research difficult.

PFC was first proposed by Cundall in 1979 to solve soil mechanics problems. It was later developed by Itasca as commercial software PFC²D and PFC³D, and its application scope was extended to many fields such as mining mechanics, geotechnical mechanics, and road engineering. The essence of the discrete element method is to separate the medium into finite elements, follow the Newton's second law, and connect discrete units that contact each other through the law of force and displacement [4]. It has significant advantages in dealing with stress discontinuities and large deformation problems. Regarding the importance of discontinuity and mechanical properties of pervious concrete materials to practical engineering, based on the results of indoor uniaxial loading test data, the author analyzes the uniaxial loading failure process of pervious concrete from a microscopic point of view by using discrete element numerical simulation method, and investigates the impact of single factor such as water-cement ratio and loading rate on its compressive strength.
2. Indoor Uniaxial Compression Test

Pervious concrete test blocks for indoor uniaxial compression test, the cement used is Shanshui PM42.5 Ordinary Portland Cement produced by a factory in Qingdao, Shandong Province, water is tap water, and aggregates are basalts produced in Linyi, with a particle size of 2.36-4.75mm, 4.75-9.5mm, 9.5-13.2mm and the mass ratio is 2:7:1. The water-cement ratio was selected as a variable factor when designing mixture ratio and divided into three groups of 0.27, 0.30 and 0.33. To pour the mixed mixture into a steel mold whose size is 100×100×100 mm. After compaction, spray water and cover plastic film for 24 hours and then remove the model and put it into a standard curing box for 28 days. After the curing was completed, the test blocks with good molding effect and no visible defects on surface are used for subsequent laboratory tests. See Figure 1(From left to right, the water-cement ratios is 0.27, 0.30, and 0.33 respectively. Observing the surface of test blocks and the compactness of it is increasing).

![Figure 1. Pervious concrete test blocks.](image)

2.1. Effect of Water-Cement Ratio on Mechanical Properties of Specimens

The indoor uniaxial compression test was carried out by TAW-2000 electro-hydraulic servo triaxial apparatus. Test blocks were divided into 3 groups with different water-cement ratios, and which group has 5 blocks. According to JTG E30-2005 "Highway Engineering Cement and Cement Concrete Test Procedure", we are loading until test blocks were destroyed and recording data. During loading process, the load and displacement were read by the instrument. To ensure the validity of test data, the maximum and minimum values of each group are removed. The test date of three groups is collated, as shown in Table 1.

| Water-cement ratio | Cement(kg) | Water(kg) | Peak strength(MPa) |
|--------------------|------------|-----------|-------------------|
| 0.27               | 350        | 91        | 14.220            |
|                    |            |           | 14.696            |
|                    |            |           | 15.021            |
|                    |            |           | 20.140            |
| 0.30               | 350        | 105       | 19.586            |
|                    |            |           | 19.424            |
|                    |            |           | 25.322            |
| 0.33               | 350        | 115.5     | 24.687            |
|                    |            |           | 26.324            |
In order to compare the impact of water-cement ratio on the compressive strength of pervious concrete, the stress-strain curve was plotted by taking the median data of each group in Table 1, as shown in Figure 2. It can be found that the peak strength of test blocks increases with the increase of water-cement ratio.

![Figure 2. Stress-strain curves of indoor test.](image1)

2.2. Effect of Loading Rate on Mechanical Properties of Specimens
The indoor uniaxial compression test was performed by TAW-2000 electro-hydraulic servo triaxial apparatus, and the loading rate was regulated. In the indoor test, pervious concrete blocks with a single water-cement ratio were divided into 3 groups, and which group has 5 blocks. The design loading rates were 0.5 mm/min, 1 mm/min, and 1.5 mm/min, respectively. The data was recorded automatically by the instrument and the stress-strain curve was obtained. After finishing, it is plotted in Figure 3, and at the same time, it is found that the results of changing loading rate of test blocks with different water-cement ratios are similar, so only the date of water-cement 0.27 is recorded here.

![Figure 3. Stress-strain curves of indoor test.](image2)

Figure 3 shows that as the loading rate increases, the peak strength of the pervious concrete block increases, and the corresponding peak point strain decreases. When the loading rate is large, the specimen rapidly breaks after reaching the peak value of the load, showing a brittle failure mode.

3. Discrete Element Modeling
Discrete element method discretizes component materials and regards them as a randomly distributed combination of particles, which can mimic the interaction of particles inside a component from a micro point of view and truly reflect the stress state and failure process of materials [5].

In the PFC2D modeling process, Liu Guohua [6] et al. proposed that the discrete element particles are simplified to spherical or ellipsoidal particles, then occlusion and interlocking between aggregates will be ignored. Xing Xinkui [7] thought that the irregular shape of aggregates in concrete affects its performance, and the larger the aggregate size, the more significant the impact. Lu [8] et al. studied the coarse aggregate and proposed the typical shape of coarse aggregates. Based on the above research results at home and abroad, in order to reduce errors caused by the aggregate shape, the author first select various aggregate shapes used in the indoor test to compare in front of building a PFC2D model, then determine to use three typical aggregate shapes to replace three grading particles in the model. As shown in Figure 4(The particle size from left to right is 2.36-4.75mm, 4.75-9.5mm, 9.5-13.2mm).
Before building a model of PFC\textsuperscript{2D}, it is necessary to consider converting the three-dimensional porosity measured in laboratory tests to two-dimensional porosity. Based on theoretical analysis and experimental verification the literature [9] proposes the following conversion formulas:

\[ \varepsilon_{3d} = 1 - \xi (1 - \varepsilon_{2d})^{3/2} \]

\[ \xi = \frac{\sqrt{2}}{\sqrt{\pi \sqrt{3}}} + D_r \left( \frac{2}{\sqrt{\pi \sqrt{3}}} - \frac{\sqrt{2}}{\sqrt{\pi \sqrt{3}}} \right) \]

In this formula, \( \varepsilon_{2d} \) is two-dimensional porosity, \( \varepsilon_{3d} \) is three-dimensional porosity, \( \xi \) is correction coefficient, and \( D_r \) is relative density.

This formula has its limitations. It assumed that the particle sizes in a model are all equal, and the influence of different particle sizes on porosity is ignored. In view of the imperfection of this formula, He Yongrui [10] proposed a linear modification formula of \( y = 1.4618x + 0.08794 \) by simulating the particle vibration test and considering the effect of particle size on porosity. Based on this linear modification formula, the author converted porosity from 3d to 2d. The data is shown in Table 2.

| Water-cement ratio | Three-dimensional porosity | Two-dimensional porosity |
|--------------------|-----------------------------|--------------------------|
| 0.27               | 26.2                        | 11.9                     |
|                    | 24.9                        | 11.0                     |
|                    | 25.2                        | 11.2                     |
|                    | 20.2                        | 8.2                      |
| 0.30               | 19.7                        | 7.8                      |
|                    | 21.2                        | 8.5                      |
|                    | 18.2                        | 6.4                      |
| 0.33               | 18.4                        | 6.6                      |
|                    | 18.8                        | 6.8                      |

The density of cement used in the indoor test was 3100kg/m\textsuperscript{3} and the water was 1000kg/m\textsuperscript{3}. When mixing mixture, the amount of cement added per cubic meter was 350kg. Calculating the gradation of each cubic meter of mixture according to water-cement ratio and mass ratio of the aggregate, and finally determine the area percentage of cement slurry and aggregates in a discrete element model. The specific data was shown in Table 3.
Table 3. The gradation of discrete element model.

| Water-cement ratio | cement slurry ratio | 2.36-4.75mm ratio | 4.75-9.5mm ratio | 9.5-13.2mm ratio |
|--------------------|---------------------|-------------------|-----------------|-----------------|
| 0.27               | 0.250               | 0.150             | 0.525           | 0.075           |
|                    | 0.254               | 0.149             | 0.522           | 0.075           |
|                    | 0.259               | 0.148             | 0.519           | 0.074           |
| 0.30               | 0.276               | 0.145             | 0.507           | 0.072           |
|                    | 0.274               | 0.145             | 0.508           | 0.073           |
|                    | 0.274               | 0.145             | 0.508           | 0.073           |
| 0.33               | 0.280               | 0.144             | 0.504           | 0.072           |
|                    | 0.281               | 0.144             | 0.503           | 0.072           |

In order to simulate the mechanical properties of cement slurry and aggregates in pervious concrete, two contact models, a contact stiffness model and a parallel bond model were used in PFC2D modeling. The difference is that the contact stiffness model can only transmit force and cannot transmit moment, while the parallel bond model can transmit both force and moment. In pervious concrete, aggregates and aggregates are interlocked to form skeletons and provide strength. Therefore, a contact stiffness model is used for modeling. The cement slurry acts as glue inside the structure, so when modeling, cement slurry and aggregates, the cement slurry itself uses a parallel bond model.

Because of the limitation of computer conditions, the excessive number of particles added during PFC2D modeling will lead to a slower calculation speed. At the same time, the accuracy of simulation results should be taken into consideration. After repeated debugging, the author decided to use R=1mm round particles to characterize cement slurry. The microscopic contact parameters between particles were repeatedly debugged with the trial and error method, and with reference to relevant literatures, the final determination of microscopic parameters of the PFC2D model is shown in Table 4. The comparison between the generated model and the indoor forming test block is shown in Figure 5.

Table 4. Model parameters.

| Microscopic parameters | Parallel Bonding Model |
|------------------------|------------------------|
| Particle radius(mm)    | 1mm, 2.36-4.75mm, 4.75-9.5mm, 9.5-13.2mm |
| Density(kg×m-3)         | 2600                   |
| Friction coefficient    | 0.7                    |
| Normal stiffness(N×m-1) | 1.5e11                 |
| Shear stiffness(N×m-1)  | 1.5e11                 |

Figure 5. Indoor forming block and discrete element model.
4. Analysis of Discrete Element Simulation Results

4.1. Analysis of Loading Failure Process of Pervious Concrete

PFC2D was used to simulate the uniaxial compression test of pervious concrete, the failure process of specimens was explored according to the development trend of microscopic cracks. Figure 6 shows the development curve of microscopic cracks in the loading process. According to the variation of the curve, the failure process of specimens is divided into four phases, as follows:

Phase 1 is compaction stage (ab). At this stage, the test block is compressed, the porosity is reduced, and no microscopic cracks are generated. This indicates that there is no damage inside the test block at this stage and the stress-strain curve fluctuates slightly. Phase 2 is elastic deformation stage (bc). At this stage, pervious concrete exhibits elastic characteristics, axial cracks begin to develop, but tangential cracks are not developed, the test block is only compressed, and the stress-strain curve is linear.

Phase 3 is elasto-plastic deformation stage (cd). At this stage, the pervious concrete exhibits elastoplastic characteristics, axial cracks and tangential cracks develop rapidly. The total number of microscopic cracks in the test block also increases rapidly. Axial compression failure and longitudinal shear failure occur at the same time, and the stress-strain curve has large fluctuations and nonlinearity. Phase 4 is peak destruction stage (de). Microscopic cracks in pervious concrete develop macro fractures, the test block splits and loses strength. Afterwards, as the loading progresses, the number of microscopic cracks does not substantially increase, and the stress-strain curve reaches peak strength.

4.2. Simulation Analysis of the Effect of Water-Cement Ratio on Pervious Concrete Strength

In a mixing process of pervious concrete mixture, part of added water is used for the cement hydration reaction, which accounts for about 25% of the total amount of added water, and the other part is used to improve the workability. Under the premise of same amount of cement, excessively large or small water-cement ratio is not conducive to the improvement of its strength.

Discrete element simulation takes the same amount of cement and controls the change of water-cement ratio. When water-cement ratio is large, more water is added, and the mass ratio of cement slurry in the test block is larger. The simulation result of PFC2D is shown in Figure 8.
Figure 8. Stress-strain curves of different water cement ratios.

Observing Figure 8, we can see that the increase in water-cement ratio, the increase in peak stress of pervious concrete test blocks is significant, indicating that water-cement ratio has a marked impact on its compressive strength. With a large water-cement ratio, the proportion of cement slurry in structure will increase. During compaction process, aggregates are interlocked to form skeletons to provide strength. The cement slurry adheres to surface of aggregates to provide a glue effect, while surplus cement slurry will fill up the gap between skeletons. When water-cement ratio is large, the porosity inside the test block is low. Under the dual effect of cement slurry adhesion enhancement and porosity reduction, the strength of pervious concrete increases with the increase of water-cement ratio. However, if water-cement ratio exceeds a certain limit, the concentration of cement slurry will decline, the adhesive ability with aggregates will decrease, resulting in a decrease in the strength of pervious concrete (The water-cement ratio from left to right is 0.27, 0.30 and 0.33).

Figure 9. PFC\textsuperscript{2D} simulation of crack images. Figure 10. Destruction images of indoor test.

Figure 9 shows the crack image after the simulated test block is loaded and destroyed. Figure 10 is an image when test blocks are broken in the indoor test. By comparison, it is found that the damage state of test blocks is different, and the distribution of cracks is also different. When water-cement ratio is relatively low, the test block shows V-shaped shear cracking. When water-cement ratio is relatively large, it shows a vertical split.

The water-cement ratio in test blocks is small, and the thickness of cement slurry on the surface of aggregates is thin. As loading progresses, microscopic cracks are mainly carried out along the interface between aggregates, so macro fractures also occur mainly in contact surfaces of aggregates. When water-cement ratio is large, the content of cement slurry in test blocks is high, and the thickness of it on the surface of aggregates is thick. Microscopic cracks will not only occur between the contact surfaces of aggregates, but will also occur inside cement slurry as the loading site proceeds. The number of cracks formed before destructed increases, and their locations are less regular.

4.3. \textit{Simulation Analysis of the Effect of Loading Rate on Pervious Concrete Strength}

PFC\textsuperscript{2D} modeling to simulate the impact of loading rate on the strength of previous concrete is achieved by giving different moving speeds to the upper and lower walls (0.25 mm/min, 0.5 mm/min, 0.75 mm/min). The simulation result of PFC\textsuperscript{2D} is shown in Figure 11.
Figure 11. Stress-strain curves of different loading rates.

Figure 12. Relationship between loading rate and microscopic crack.

Observing the stress-strain curve in Figure 11, we can see that with the increase of loading rate, the test block shows an increase in peak strength and a decrease in peak strain. Pervious concrete is a kind of lightweight concrete without sand and fine aggregates. When loading rate is low, the microscopic cracks in test blocks are continuously generated and developed along with the loading process. The internal damage of test blocks before destructed is greater. After increasing loading rate, the test block stored energy for a short period of time at the initial damage stage and entered a stable stage of damage development without complete deformation. The internal microscopic cracks were poorly developed, and the test block has good structural integrity when loaded to failure. The compressive strength increases.

Figure 12 shows the number of microscopic cracks produced when test blocks were broken at different loading rates in PFC2D modeling. The loading rate was regarded as a single variable, simulation results show that with the increase of loading rate, the number of microscopic cracks generated when the model reaches the peak failure will decrease, and the overall fragmentation degree will decrease. Under the condition of high loading rate, the test block will focus on a certain macro fracture surface when it breaks, and the peak strain will be lower on the stress-strain curve.

5. Conclusions
The results of discrete element simulation are similar to the indoor test. It can replace an indoor test to analyze the stress characteristics and loading failure process of pervious concrete from a mesoscopic point of view. The results are more accurate and repeatable. Comparing the results of indoor tests and PFC2D simulations, this paper proposes following conclusions:

(1) Using PFC2D to simulate the microscopic crack development curve and stress-strain curve in uniaxial loading process, the failure process is divided into four stages: compaction stage, elastic deformation stage, elastic-plastic deformation stage and peak destruction stage.

(2) Within a reasonable range, with the increase of water-cement ratio, the compressive strength of the compacted pervious concrete test blocks increases, the damage morphology changes from V-shaped shear cracking to vertical splitting. The number of cracks increases and their distribution locations are less regular.

(3) With increasing loading rate, the compressive strength of pervious concrete increases significantly, the strain corresponding to peak strength decreases. The simulation results of PFC2D show that the number of microscopic cracks is reduced, and the overall fragmentation degree of test blocks is low.

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