Research on strength distribution of natural pumice concrete based on precast porosity

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Abstract: In this study, the rubber natural pumice concrete was taken as the research object, and the orthogonal test method was employed to design the experiment, the rubber particles were added to the concrete as precast pores to test the actual porosity, compressive strength and splitting tensile strength of the natural pumice concrete under different precast porosities. According to the change rule, the actual porosity, compressive strength and split tensile strength distribution were respectively fitted. The results show that there is a good correlation between the actual porosity of natural pumice concrete and the precast porosity, and then the empirical formula of rubber particle content and concrete strength is established, which provides a certain theoretical reference for the research on the porosity of natural pumice concrete.

1. Introduction

Due to the influence of curing conditions, mixing methods, temperature and humidity changes, there are pores of different sizes and disorderly distribution after concrete molding [1]. Porosity is an important factor affecting the strength of concrete. To measure porosity, the proportion of pore volume can be measured by scanning electron microscope, then the relationship between compressive strength and porosity can be obtained [2]. Mercury intrusion method is also a common method for measuring porosity. The harmful porosity in concrete measured by mercury intrusion method is 2%~5%, therefore, the relationship between pore size distribution and strength can be established [3-5]. For concrete with larger porosity, the interconnected porosity of the concrete can be measured by the immersion method, and the porosity change during the concrete failure process can be studied [6]. In addition to directly determining the porosity of concrete, we can also indirectly establish the relationship between porosity and concrete strength by adding admixtures to concrete [7-9]. A common method of introducing pores is to introduce air into the concrete through foaming to obtain the relationship between concrete strength and pore characteristics [10-12].
The sources of rubber particles are wide and diverse, and the production cost is low [13]. In addition, waste tire rubber particles have the properties of light weight, high fluidity, and water repellency, which can be approximated as pores in concrete, and the porosity and concrete strength are studied [14]. Moreover, the density of rubber is stable, it is easy to accurately control the volume of the added rubber particles in the test, and it is convenient to control the porosity of the prefabricated concrete more accurately compared with traditional methods such as foaming, it is more accurate and easier to quantitative control. In this test, rubber particles are used to approximate the pores in the concrete, and the strength distribution of the concrete is measured under the condition of different porosity in the precast. On this basis, the influence of precast porosity changes on concrete strength is studied, and the relationship between the amount of rubber particles based on porosity and concrete strength is established, and the relationship between the exact number of pores and concrete strength is obtained.

2. Test

2.1 Test materials
Cement: Changchun Yatai P•O42.5 ordinary Portland cement is used; Coarse aggregate: Changbai Mountain natural pumice, bulk density 690 kg/m³, apparent density 1593 kg/m³, initial one-hour water absorption rate 16.48% (mass fraction); Sand: selected from Yitong River, medium sand, fineness modulus μf=2.5, bulk density 790 kg/m³, apparent density 2675 kg/m³, moisture content 2% (mass fraction), good particle gradation, fineness modulus 2.5, Zone II, medium sand; Waste tire rubber particles: particle size of 20 meshes, 60 meshes, 120 meshes; Water reducing agent: FDN-C naphthalene water reducing agent, the main component is β-naphthalenesulfonate formaldehyde condensate, and its dosage is 0.7% of the cementitious material. The water reduction rate is 20%, and there is no corrosion to the steel bars; Water: tap water from the municipal pipe network of Changchun City.

2.2 Test design
Orthogonal experiment was used to design the mix ratio, and three factors of rubber particle size, rubber particle content, and water-to-rubber ratio were selected, and three levels were selected for each factor. The factor levels are shown in Table 1. Design the mix ratio of rubber natural pumice concrete in accordance with "General Concrete Mix Proportion Design Regulations" (JGJ55-2011) and "Lightweight Aggregate Concrete Technical Specifications" (JGJ51-2002), and design three sets of benchmark groups according to three water-binder ratio In the orthogonal group test, the mix ratio design was carried out according to the orthogonal design table L9 (33), and the mix ratio of the reference group is shown in Table 2.

The rubber particles are added as a percentage of the cement mass, and the volume can be calculated from the density of the rubber particles, which approximates the pores in the concrete. According to literature [1-2], before adding prefabricated pores, namely rubber particles, concrete has a connected porosity of no more than 5%, but it is difficult to measure accurately, while the pores of natural pumice are generally 30% to 40%. Therefore, the test is based on the natural pumice concrete itself with a certain porosity, and then prefabricated a certain porosity, as shown in Table 3.

| Factors | Levels |
|---------|--------|
| A rubber particle size/mesh | B rubber particles content/% | C ratio of water to rubber |
| 1       | 20     | 3      | 0.40 |
| 2       | 60     | 6      | 0.42 |
| 3       | 120    | 9      | 0.45 |
Table 2 Reference group test mix ratio

| Group | cement /kg·m³ | sand /kg·m³ | pumice /kg·m³ | water /kg·m³ | Rubber powder /mesh | Rubber powder content /kg·m³ | Water reducing agent /kg·m³ |
|-------|---------------|-------------|---------------|--------------|---------------------|----------------------------|---------------------------|
| J-1   | 450           | 750         | 570           | 180          | 0                   | 0                          | 3.15                      |
| J-2   | 430           | 770         | 580           | 180          | 0                   | 0                          | 3                         |
| J-3   | 400           | 780         | 590           | 180          | 0                   | 0                          | 2.8                       |

Table 3 Prefabricated porosity

| Rubber pellet density/kg·m³ | Prefabricated porosity /% |
|----------------------------|---------------------------|
| 13.5                       | 1.18                      |
| 25.8                       | 2.26                      |
| 36                         | 3.15                      |
| 12.9                       | 1.13                      |
| 24                         | 2.11                      |
| 40.5                       | 3.55                      |
| 12                         | 1.05                      |
| 27                         | 2.37                      |
| 38.7                       | 3.39                      |

2.3 Test method

To avoid agglomeration of rubber particles in the concrete molding process, the cement, rubber particles and water reducing agent are mixed uniformly, and then poured into a mixer for mixing. Tests show that this approach can effectively reduce the agglomeration of rubber particles. According to the method in "Determination of Density of Vulcanized Rubber or Thermoplastic Rubber" (GB/T 533-2008), the rubber density is determined to be 1140 Mg/m³, and the precast porosity is calculated as follows:

\[ P = \frac{m_o}{\rho_o} \]  

(1)

In the formula, \( P \) is the prefabricated porosity, \( m_o \) is the mass of rubber particles, \( \rho_o \) is the rubber density, and \( V \) is the volume of the specimen.

We use RapidAir concrete porosity structure analyzer to measure concrete porosity. The test block size is 100 mm × 100 mm × 100 mm non-standard test block. We use a forced concrete mixer to mix according to the test mix, place it on a shaking table for compaction, and disassemble mold after 24 hours., standard curing (temperature 20°C±2°C, humidity 95%) in a curing box for 28 days. According to the "Standard for Test Methods of Mechanical Properties of Ordinary Concrete" (GB/T 50081-2002), the compressive strength and split tensile strength of concrete with different precast porosities were tested.

3. Test results and analysis

According to the above method for measuring porosity and strength, 9 sets of test pieces were measured. The results are shown in Table 4.

Table 4 Porosity and strength test results

| Group | Prefabricated porosity /% | Measured porosity /% | Compressive strength / MPa | Split tensile strength / MPa |
|-------|---------------------------|----------------------|----------------------------|------------------------------|
| 1     | 1.18                      | 10.85                | 33.41                      | 3.38                         |
| 2     | 2.26                      | 7.21                 | 38.59                      | 3.25                         |
| 3     | 3.15                      | 6.49                 | 38.22                      | 3.48                         |
| 4     | 1.13                      | 7.95                 | 35.89                      | 3.21                         |
| 5     | 2.11                      | 11.3                 | 31.34                      | 3.16                         |
| 6     | 3.55                      | 5.92                 | 41.79                      | 3.62                         |
| 7     | 1.05                      | 9.95                 | 32.92                      | 3.19                         |
| 8     | 2.37                      | 6.53                 | 41.73                      | 3.64                         |
3.1 Distribution of prefabricated porosity
Before concrete is subjected to external load, there is a certain amount of pores in its interior, but its pores are difficult to measure. To quantitatively study the strength distribution of concrete with different porosity, rubber particles were added as the prefabricated porosity. Rubber particles are difficult to react with the substances in concrete, and the physical and chemical properties of rubber are stable, and they have the conditions for quantitative research. Therefore, rubber particles are used as prefabricated pores.

\[
y = 0.232x^2 - 4.3328x + 21.148
\]

(2)

3.2 Distribution law of compressive strength
Figure 2 shows the relationship between test porosity and compressive strength. The porosity is 6.49%, the corresponding compressive strength is 38.22 MPa, the porosity is 6.53%, the corresponding compressive strength is 41.73 MPa, the porosity increases, the compressive strength increases; the porosity is larger than 6.53%, except for fluctuations at 11.3%, the compressive strength decreases with the increase of porosity.

Fig. 1 Relationship between prefabricated porosity and actual porosity
Figure 1 shows the relationship between prefabricated porosity and actual porosity. When the prefabricated porosity is 1.18%, the corresponding test porosity is 10.85%. As the prefabricated porosity and the amount of rubber particles increase, the corresponding test porosity becomes larger. The reason is that, when the amount of rubber particles is small, because natural pumice is selected as the concrete aggregate, the pumice itself has large pores, and the rubber particles are basically used to fill the holes of the pumice during the mixing process. When the amount of rubber particles is large, it can fill the pumice pores and disperse into the cementitious material, causing the porosity to change. The correlation coefficient R\(^2\)=0.9422, indicating that the function can reflect the relationship between the two well, setting a target porosity can calculate the prefabricated porosity and the rubber particle content by formula (2).
The reason is that, under the action of external load, due to the increase of porosity of concrete, internal pores and micro-cracks are more likely to expand and penetrate, so its compressive performance is continuously reduced. The trend line in the figure shows that as the porosity increases, the compressive strength shows a downward trend. Under uniaxial load, due to the pores produced by air and rubber particles in the concrete, the air and rubber particles are like elastic bodies, which can deform under external force. The air-generated pores are gradually connected to large pores by external force, which develop into cracks and cause concrete damage. The rubber particles are deformed by the external force, but they will not be connected to produce large pores, which delays the destruction of concrete. Moreover, the rubber particles make the pores in the natural pumice divided into small pores, so that the internal structure of the concrete is dense and the compressive strength is improved. Therefore, when the porosity is small, the compressive strength of concrete fluctuates. As the pressure increases, the pore diameter becomes larger and exceeds the rubber particle size, forming through cracks and causing concrete damage.

Fitting the test porosity and compressive strength distribution, as shown in Figure 3. The two conform to the change law of the quadratic function, and the fitting function is:

$$y = 0.1385x^2 - 4.2366x + 61.687$$ (3)

The correlation coefficient $R^2=0.9372$, indicating that the function can reflect the relationship between the two very well.

3.3 Distribution law of split tensile strength

Figure 4 shows the relationship between porosity and split tensile strength. The porosity is between 6% and 8%. As the porosity increases, the split tensile strength decreases significantly. When the porosity is 8%~10%, the splitting strength tends to be stable, and then it shows a significant downward trend. When the porosity is 10.85%, the splitting strength is 3.38 MPa, and the strength has a significant increase.

Analyzing the reason, under the action of tensile load, there is a transition zone between concrete aggregate and cementitious material. The tensile strength of the interface transition zone is weak, and the concrete breaks down along the transition zone. The rubber particles reduce the integrity of the transition zone, and the rubber particles are hydrophobic and form tiny gaps around them. Therefore, as the porosity and rubber particles increase, the split tensile strength decreases significantly. As the amount of rubber particles increases, the rubber particles gradually fill the holes in the natural pumice stone, the dense pumice stone resists a certain degree of damage, and the rubber particles as an elastomer can absorb part of the damage stress. The rubber particles reduce the integrity of the interface transition zone. However, due to the irregular shape of the rubber particles, the gap between the rubber particles decreases with the increase of the content. The rubber particles form a "holding force" to resist tensile stress, so when the porosity is 10.85%, the split tensile strength increases. When the "binding force" between the rubber particles is insufficient to resist the breaking stress caused by the pores, the split tensile strength decreases.
tensile strength is significantly reduced. Fitting the test porosity and split tensile strength distribution, as shown in Figure 5. The two conform to the change law of the quadratic function, and the fitting function is:

\[ y = -0.0122x^3 + 0.3481x^2 - 3.292x + 13.509 \]  

(4)

The correlation coefficient shows that the function can well reflect the relationship between the two.

3.4 Derivation of empirical formula

Porosity is an important factor affecting the strength of concrete. Due to the large range of pore size changes and the large difference in shape, it is difficult to accurately quantify the distribution and amount of pores. Most of the pores are quantified in the form of porosity. The rubber particle content is used as the precast porosity, and the experimental porosity is used to construct the relationship between the precast porosity and the concrete strength by using the test porosity to establish the mathematical relationship between the rubber particle content and the concrete strength.

From (1)(2), we can know that:

\[ x = 9.34 \pm \sqrt{5.46m_0 - 4.76\rho_0V} \]  

(5)

Where \( x \) is the test porosity, \( m_0 \) is the mass of rubber particles, \( \rho_0 \) is the rubber density, and \( V \) is the volume of the test piece. Substituting formula (5) into formula (3) (4) can obtain the mathematical relationship between the mass of rubber particles and the strength of concrete.

4. Conclusion

(1) The compressive strength and split tensile strength of natural pumice concrete decrease with the increase of porosity. The addition of rubber particles can well characterize the pores in natural pumice concrete.

(2) The prefabricated porosity is generated by adding rubber particles. The prefabricated porosity has a strong correlation with the experimental porosity, which satisfies the changing law of the quadratic function, thereby establishing the relationship between the rubber particle content, which has a strong correlation.

(3) The addition of rubber particles delays the destruction of natural pumice concrete, however, when the precast porosity exceeds 1.5%, the test porosity is extremely poor and exceeds 4%. In practical applications, the amount of rubber particles should be strictly controlled.

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