Effect of Different Mineral Admixtures on the Properties of Pervious Concrete

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Abstract. Taking pervious concrete with a target porosity of 15% as the research object, the influence of three factors, including the contents of silica fume (mass fraction 3%, 5%, 7%), metakaolin (mass fraction 8%, 10%, 12%) and Polypropylene fiber content (volume fraction 1%, 2%, 3%), on the mechanical properties, permeability and frost durability of pervious concrete were investigated by utilizing the orthogonal testing method. Through the range analysis of the test results, the significant influence degree of the three factors were obtained, and the freeze-thaw cycle test was carried out with the optimal mix ratio. The results indicated that the content of silica fume and metakaolin has the most significant influence on the mechanical properties of pervious concrete, the fiber has the most significant influence on the continuous porosity, but the influence on the compressive strength is small. The best mix proportion was obtained, and the silica fume content is 7%, metakaolin content is 10%, and fiber content is 2%. The results of freeze-thaw cycle test of pervious concrete with optimal mix ratio show that the relative dynamic modulus and compressive strength of pervious concrete decrease gradually with the increase of freezing-thawing cycles, and the change rate of mass loss, continuous porosity increases gradually with the increase of freeze-thaw cycles. The relative residual compressive strength and dynamic elastic modulus of pervious concrete show a parabolic decline trend subjected to freeze-thaw cycles. The results also can provide technical reference for the engineering application of pervious concrete in cold regions.

1. Introduction

Pervious concrete is a kind of porous material with high porosity and good permeability, which is commonly used in urban park roads, parking lots, residential areas, sidewalks and other light load pavement [1]. Generally, there is no sand or a small amount of sand in pervious concrete. The pervious concrete has been widely used in the construction of sponge city. However, due to the bonding layers between aggregate are thin and relatively contact area is less, which leads to its poor mechanical property, poor durability and easy blockage. These disadvantages make the pervious concrete difficult to be used in cold regions.

A series of research has been carried out to prove the mechanical performance and durability of the pervious concrete. Literature [2-3] systematically studied the effects of fly ash, EVA latex, air-entraining agents, fibers on the permeability, compressive strength and frost resistance of pervious concrete. The results show that the mechanical properties and anti-freezing performance of pervious concrete have been improved with different admixtures, but the influence degree and mechanism are different. The research results of literature [4-6] show that adding fly ash, silica fume, ultra-fine mineral powder, nano-SiO$_2$ and other mineral admixtures into the pervious concrete can increase the compactness of the
cementitious paste, improve the interface strength of the cementing material and the aggregate and microscopic pore structure of pervious concrete. Mechanism are analyzed from the macro and micro perspectives to improve the mechanical properties and frost resistance of pervious concrete.

Metakaolin (MK) is the main component of aluminum silicate (Al₂O₃·SiO₂), which can react with Ca(OH)₂ generated during cement hydration. The formation of new auxiliary cements such as C-S-H and C-A-S-H can improve the cement hydration products and the microstructure of the paste to a certain extent, thereby improving the strength of the cement paste and the mechanical properties of concrete. There have been a lot of research results on improving of the mechanical properties and durability of ordinary concrete with MK[7-8], but the research about the application of MK in pervious concrete is more rarely. In view of this, in order to study the influence of the content of silica fume and MK on the performance of pervious concrete, a three-factor three-level orthogonal test of silica fume, metakaolin and polypropylene fiber was designed. The influence of changes in various factors on the permeability and mechanical properties of pervious concrete is discussed in detail, and the optimal mix ratio scheme is obtained through the range analysis of the orthogonal test results. Then, based on this mix ratio, test pieces were prepared to carry out a freeze-thaw cycle test to investigate the freezing-thawing resistance performance of pervious concrete mixed with silica fume and MK. The research results can provide technical reference for the practical engineering application of pervious concrete in cold regions.

2. Experimental study

2.1. Material properties and Mix proportions
P.O 42.5 ordinary Portland cement was utilized for preparing concrete in this study. Silica fume(SF) with SiO₂ content of 94.33% was selected as mineral admixture, the basic physical properties of SF are listed in Table 1. The main chemical components of MK are shown in Table 2. The natural coarse aggregates are made of limestone with apparent density of 2600kg/m³ and particle size of 4.75-9.5mm. For fine aggregate, the ISO standard sand with fineness modulus of 2.78 was used, the amount of sand is 7% of coarse aggregate. FDN water reducer agent was selected as superplasticizer with water reduction rate of 21% and solid content of 91.51%. The parameters of polypropylene(PP) fiber are shown in Table 3.

| Table.1 Physical properties of silica fume |
|------------------------------------------|
| SiO₂/% | Loss on ignition/% | Specific surface area (m²/g) | Water demand ratio/% | Activity index/% |
| 94.33 | 2.2 | 20 | 113 | 117 |

| Table.2 Chemical composition of Metakaolin(MK) |
|-----------------------------------------------|
| SiO₂/% | Al₂O₃/% | Fe₂O₃/% | Na₂+K₂O/% | CaO+MgO/% | TiO₂/% |
| 54±2 | 43±2 | ≤0.8 | ≤0.3 | 0.8 | 1.2 |

| Table.3 Physical properties of Polypropylene fiber |
|---------------------------------------------|
| Length/mm | Density/t/m³ | Fracture strength/MPa | Elongation at break/% | Elasticity modulus/GPa |
| 12 | 0.91 | 458 | 30 | >3.5 |

2.2. Mix design for the orthogonal test
The volume method in the specification Technical specification for pervious concrete pavement CJJ/T135-2009 is used to calculate the mix ratio [9], and the specific mix ratio is shown in Table 4. The method of orthogonal experiment design is adopted to arrange the test group. The factors and levels considered are as follows: Silica fume content (factor A: mass fraction 3%, 5%, 7%), MK content (factor B: mass fraction 8%, 10%, 12%), polypropylene fiber volume ratio (factor C: 1%, 2%, 3%); L9 (3³) orthogonal table is used to carry out a 3-factor 3-level orthogonal test design.

The test for continuous porosity and permeability coefficient of pervious concrete are carried out in accordance with Appendix A of the specification [9,10].
Table 4  Mix proportion of pervious concrete units: kg/m³

| Group | Cement  | Sand  | Coarse aggregate | water | FDN  | SF   | MK   | PP |
|-------|---------|-------|------------------|-------|------|------|------|----|
| PC-1  | 318.94  | 103.72| 1496.95          | 107.51| 3.58 | 10.75| 28.67| 1  |
| PC-2  | 311.77  | 103.72| 1496.95          | 107.51| 3.58 | 10.75| 35.84| 2  |
| PC-3  | 304.61  | 103.72| 1496.95          | 107.51| 3.58 | 10.75| 43   | 3  |
| PC-4  | 311.77  | 103.72| 1496.95          | 107.51| 3.58 | 17.92| 28.67| 2  |
| PC-5  | 304.61  | 103.72| 1496.95          | 107.51| 3.58 | 17.92| 35.84| 3  |
| PC-6  | 297.44  | 103.72| 1496.95          | 107.51| 3.58 | 25.09| 28.67| 1  |
| PC-7  | 304.61  | 103.72| 1496.95          | 107.51| 3.58 | 25.09| 35.84| 1  |
| PC-8  | 297.44  | 103.72| 1496.95          | 107.51| 3.58 | 25.09| 43   | 2  |
| PC-9  | 290.27  | 103.72| 1496.95          | 107.51| 3.58 | 25.09| 43   | 2  |

3. Test results and analysis

3.1. Orthogonal test range analysis

The orthogonal test range analysis table is obtained as shown in Table 5.

Table 5  Ranges of the orthogonal experiment

| Index                        | Range analysis | A   | B   | C   | Influence weight | Optimal mix ratio |
|------------------------------|----------------|-----|-----|-----|------------------|-------------------|
| 28d Compressive strength/MPa | k1             | 18.33| 20.10| 20.60| A>B>C            | A3B2C2            |
|                              | k2             | 20.03| 22.51| 20.80|                  |                   |
|                              | k3             | 23.73| 19.48| 20.70|                  |                   |
|                              | R              | 5.40 | 3.03 | 0.20 |                  |                   |
| Continuous porosity/%        | k1             | 16.93| 16.71| 15.85| C>A>B            | A1B1C1            |
|                              | k2             | 16.21| 16.48| 16.80|                  |                   |
|                              | k3             | 16.07| 16.02| 16.56|                  |                   |
|                              | R              | 0.87 | 0.69 | 0.95 |                  |                   |
| permeability coefficient/mm/s| k1             | 2.90 | 2.41 | 2.51 | A>B>C            | A1B2C2            |
|                              | k2             | 2.51 | 2.80 | 2.69 |                  |                   |
|                              | k3             | 2.36 | 2.55 | 2.57 |                  |                   |
|                              | R              | 0.54 | 0.39 | 0.18 |                  |                   |

According to the range analysis of the 28 days compressive strength of the pervious concrete specimens in Table 5, some conclusions have been obtained: (1) The content of SF has the most significant impact on the 28 days uniaxial compressive strength of pervious concrete, followed by MK, and the content of polypropylene fiber has the least impact on the compressive strength; (2) As the amount of SF increases, the compressive strength continues to increase. This is because the fineness of silica fume is smaller than that of cement. These fine particles are wrapped around the cement mortar. SiO₂ in SF can produce pozzolanic effect and micro-aggregate filling effect with free lime and high-alkali hydrated calcium silicate to produce low-alkali hydrated calcium silicate, hydrated calcium aluminate and ettringite with higher strength and better stability. This improves the bonding force of the cement paste to the aggregate and improves the interface strength between the aggregate and the cementitious materials. (3) When the content of MK was increased from 8% to 10%, the compressive strength increased by 13.67%, but when the content was increased to 12%, the strength decreased by 4.84%. However, when the mixing amount exceeds 10%, the amount of cement will be reduced. As a result, the workability of the pervious concrete mixture is poor, the area of the cement package is reduced, the hydration rate is reduced which leads to the insufficient hydration. The bonding ability of the cement slurry is also reduced, which leads to the extremely weak bonding surface between the aggregate and the slurry and eventually decrease the strength; (4) With the addition of polypropylene fiber, the
The extreme difference analysis results of the continuous porosity of pervious concrete in Table 5 show that the factors affecting the continuous porosity of pervious concrete in order are PP fiber (C) > SF (A) > MK (B). It also can be obtained that the factors that affect the permeability coefficient of pervious concrete in order are SF (A) > MK (B) > PP fiber (C).

According to the above analysis, the optimal mix ratio of pervious concrete is 7% silica fume (SF), 10% metakaolin (MK), and 2% PP fiber, namely A3B2C2.

### 3.2. Freeze-thaw durability of pervious concrete

In order to further study the frost resistance and durability of the pervious concrete with the optimal mix ratio obtained by the orthogonal test, 36 cube specimens of 100mm×100mm×100mm and 3 prisms of 100mm×100mm×400mm were prepared as described in the previous section. The cube specimens are used to determine the continuous porosity, water permeability and compressive strength after freezing and thawing, and the prism specimens are used to determine the mass loss and relative dynamic modulus of elasticity (RDME) after freezing and thawing.

Figure 1 shows the relationship between the mass loss rate of pervious concrete and the number of freeze-thaw cycles. It can be seen that after freezing and thawing, the quality of the pervious concrete specimens shows a decreasing trend, and the mass loss rate gradually increases as the number of freezing and thawing cycles increases. This is because the pervious concrete itself is a porous skeleton, with few bonding points and a thin bonding layer, which results in a weak transition zone between the aggregate and the slurry. Freezing and thawing causes cracking and misalignment of the weak surface of the aggregate and its surrounding cemented paste, and the surface aggregate gradually peels off, resulting in a gradual decrease in quality.

Figure 2 illustrates the scatter plot and fitting curve diagram of RDME of pervious concrete under different freeze-thaw cycles. It reveals that, at the beginning of the freeze-thaw cycle (0-40 times), the RDME did not change significantly. With the increase of freeze-thaw cycles, the RDME showed a trend of first slowly decreasing and then rapidly decreasing. When the number of freeze-thaw cycles reaches 100 times, the RDME has been reduced to less than 60%. The relationship between RDME and the number of freeze-thaw cycles shows a convex downward trend. A quadratic polynomial was used to fit the relationship between the RDME of pervious concrete and the number of freeze-thaw cycles. It can be seen that the RDME has a good correlation with the number of freeze-thaw cycles, and the correlation coefficient is above 0.94.
3.3. Compressive strength and continuous

Figure 3 shows the scatter plot and fitting relationship curve between the compressive strength and the number of freeze-thaw cycles. It is noticed that at the beginning of the freeze-thaw cycle (0-40 times), the compressive strength declines to a small extent, but as the number of freeze-thaw cycles increases, the compressive strength degradation speed gradually increases. This is because the pervious concrete specimen mainly relies on the "interlocking" effect among the aggregates and the bonding ability between the aggregate and the cementitious paste to bear and transfer the load. The freeze-thaw cycle causes dislocation and bursting at the bonding surface of the aggregate and the slurry. The surface aggregate is peeled off and there are obvious microcracks, which make the overall compactness of the specimen decrease, resulting in a gradual decrease in compressive strength. The exponential function is used to fit the relationship between the compressive strength and the number of freeze-thaw cycles. It can be seen that the curve shows a convex downward trend, and the correlation coefficient is above 0.94.

![Figure 3](image1.png)  
**Figure 3** Relationship between compressive strength and freeze-thaw cycles

![Figure 4](image2.png)  
**Figure 4** Relationship between continuous porosity and freeze-thaw cycles

Figure 4 shows the continuous porosity scatter diagram and fitting curve of pervious concrete subjected to different freeze-thaw times. It can be seen that with the increase of the number of freeze-thaw cycles, the continuous porosity basically shows an exponential trend of increasing. When the number of freeze-thaw cycles reached 80, the continuous porosity increased by 1.38 times compared with that without freeze-thaw cycles. When the number of freeze-thaw reaches 120 times, the continuous porosity increases by 1.63 times. At this time, the surface of pervious concrete test block was observed, and there were obvious penetrating microcracks between slurry and aggregate. It shows that in the process of freeze-thaw cycle, the degree of porosity deterioration in the pervious concrete gradually increases, and part of the semi-closed pores also gradually expand into interconnected pores, which leads to the increase of continuous porosity.

4. conclusion

(1) The content of silica fume has the most significant impact on the 28-day cube compressive strength of the pervious concrete, followed by MK, and the content of polypropylene fiber has the least impact on the compressive strength. As the content of silica fume increases, the compressive strength continues to increase; when the content of metakaolin is increased from 8% to 10%, the compressive strength increases by 13.67%, but when the content increases to 12%, the strength decreases 4.84% instead, which indicates that excessive incorporation of metakaolin has an adverse effect on strength.

(2) Under the premise that all test results meet the performance of pervious concrete, the optimal combination design for 28-days compressive strength is 7% silica fume, 10% MK, and 2% fiber.

(3) The freeze-thaw durability test results based on the optimal mix ratio of the pervious concrete obtained by the orthogonal experiment show that the mass loss rate, and continuous porosity of the
pervious concrete gradually increase with the increase of freeze-thaw cycles. The relative dynamic elastic modulus and the average compressive strength gradually decreases with the increase of freeze-thaw cycles.

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