Water permeability, strength and freeze-thaw resistance of crumb rubber-modified permeable concrete brick based on orthogonal test

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Abstract. Permeable concrete brick (PCB), as a new type of pavement material, is commonly used in sidewalks and parks owing to its environmental benefits. Crumb rubber, as an excellent pavement materials modifier, has many advantages in improving freeze-thaw durability of PCB. In this paper, a kind of rubber-modified permeable concrete brick (RMPCB) was prepared. The effects of water-binder ratio, designed porosity and crumb rubber content on compressive strength, split tensile strength, permeability coefficient and freeze-thaw durability of RMPCB were studied. Nine groups of tests were carried out by orthogonal design; range analysis and variance analysis were used to investigate the effect of three factors (water binder ratio, designed porosity and crumb rubber content) on the test results of RMPCB. The results show that porosity is the dominant factor in the properties of permeable bricks. Higher porosity can significantly increase the permeability coefficient of RMPCB, but weaken its strength and freeze-thaw durability. The split tensile strength and freeze-thaw durability of RMPCB are positively affected when crumb rubber content is 4% of the weight of cement. With the increase of water-binder ratio, the compressive strength of RMPCB first increases and then decreases, but the effect of water-binder ratio on other properties is not significant. The optimal water-binder ratio, design porosity and crumb rubber content for RMPCB are 0.30, 15% and 4%, respectively.

Keywords: Permeable Concrete Brick; Crumb Rubber; Mechanical Properties; Permeability; Freeze-Thaw Durability; Orthogonal Test

1. Introduction

As the world economy develops quickly, a growing number of countries have joined the ranks of global urbanization, which has led to many fatal climate problems inevitably such as urban heat island effect [1,2]. Besides, almost all urban surface is covered with concrete and asphalt, which are consisted of impervious materials. High modernization also caused an increase of surface rainwater runoff, resulting in frequent rainfall and flooding disasters. Seeking solutions for the rainwater management appear to be extremely urgent [3,4]. Permeable concrete brick(PCB), as an irreplaceable part of a sponge city, is a new eco-friendly permeable pavement material. It consists of coarse aggregate with a specified size, little or no fine aggregate, cement and water [5]. Owing to its loose and porous structure, PCB has great advantages over traditional pavement materials in noise absorption and alleviating the fragility of urban water environment [6]. Contributed to its superior ecological environment function, it is widely used in parks, sidewalks and parking lots [7].
As the automotive industry has grown by leaps and bounds, millions of tons of waste tires are produced worldwide each year, which bring about a tremendous amount of pollution [8]. The traditional treatment for waste tires is to burn them as fuel or bury them. But burning will cause severe secondary environmental pollution, and burying will lead to the waste of land resources [9]. Many researches have verified that it is a more eco-friendly treatment to smash the waste tires into rubber powders and mix them into the road materials, which could enhance the toughness and freeze-thaw resistance of the pavement structure [10,11].

As a new type of pavement material, quantities of investigations have been done on the mix ratio of permeable bricks. Cai et al. [12] studied the impact of admixture dosage, binder-aggregate ratio, water-binder ratio and gravel gradation on the performance of sand-based permeable bricks, and obtained the optimal mix ratio. The results showed that the compressive strength and permeability coefficient reached 35.6MPa and 3.5×10⁻² cm/s, respectively. According to the mechanical properties and workability of the new permeable brick aggregate, He et al. [13] proposed a new mix ratio design theory derived from the target porosity. A new parameter λ was introduced to represent the ratio of the gravel consumption per unit volume and the close packing density of gravel during the preparation of permeable bricks. The method was found to have a certain significance of reference and the compressive strength of the specimens prepared by this method was up to 35.5 MPa. Liu et al. [14] used steel slag and fly ash to replace basalt aggregate to prepare permeable bricks. The optimal fly ash dosage, steel slag dosage and target porosity were determined to be 30%, 6.5% and 25%, respectively. Luo et al. [15] investigated the effects of the grading, cement, alkali activators content and molding pressure on the properties of permeable bricks through the orthogonal experiments. The compressive strength of prepared permeable bricks exceeded 30 MPa, and the permeability coefficient reached 1.3×10⁻² cm/s.

However, there are few researches on rubber-modified PCB. Most of the existing researches are about crumb rubber-modified concrete and crumb rubber-modified pervious concrete. Abdelmonem et al. [16] systematically explored the influence of the incorporation of recycled rubber powder on the performance of high strength concrete. Rubber powder was utilized to replace the clean sand with equal volume, and the dosage was 0%,10%,20%,30%. The results showed that the compressive, tensile and flexural strength of high strength concrete decreased by about 50% as the crumb rubber dosage increased from 0% to 30%, but the impact resistance increases by 83%. Liu et al. [17] prepared rubber modified permeable concrete using rubber of 1-3mm and 40 mesh, and studied the influences of the size of waste rubber particle and rubber content on strength, water permeability, freeze-thaw resistance and ductility. The results show that the performance of fine rubber was better than that of coarse rubber. The flexural strength of the 40-mesh rubber with the content of 8% decreased only by 17.1%, while the flexural strain increased by 42%, and the freeze-thaw durability was also significantly improved. Bonicelli et al. [18] investigated the impact of the particle size of rubber and rubber particle content on the physical and mechanical properties of permeable concrete. The result shows that the performance of coarse rubber is better than that of fine rubber.

Therefore, it is vital significance to study the properties about rubber-modified permeable concrete bricks(RMPCB). In view of the present situation, the influences of water-binder ratio, designed porosity and the crumb rubber content on porosity, permeability coefficient, compressive strength, split tensile strength and loss rate of compressive strength of RMPCB were studied based on orthogonal test, which brought a reference for the application of rubber in permeable bricks.

2. Materials and Methods

2.1. Materials
Portland cement (type P.O), with the strength of 42.5MPa, obtained from Jilin Yatai Cement Co., Ltd. (Jilin, China) was used as the cementitious material and Table 1 and Table 2 presents its physical properties and chemical composition, respectively. Natural basalt coarse aggregate (NBCA), with a single particle size of 4.75-9.5mm was used as the coarse aggregate, whose properties are listed in
Table 3. The crumb rubber was produced by waste tires, whose particle size is 40 mesh. To modify the crumb rubber, sodium hydroxide solution with the mole of 0.25 was employed and Figure 1 presents the specific appearance of crumb rubber [19]. The polycarboxylic acid superplasticizer obtained from Shanxi Qinfen Building Material Co., Ltd. (Shanxi, China) was used to promote the workability of RMPCB, and the dosage was 0.8% of the mass of cement.

Table 1. Physical properties of cement.

| Density (kg/m³) | Specific Surface Area (m²/kg) | Setting Time (min) | Compressive Strength (MPa) | Flexural Strength (MPa) |
|----------------|-------------------------------|-------------------|---------------------------|------------------------|
|                |                               | Initial Setting   | Final Setting             | 3d                     | 28d                    | 3d                     | 28d                    |
| 2960           | 345                           | 190               | 255                       | 22.0                   | 47.9                   | 4.8                    | 7.5                    |

The specific surface area was measured with Blaine method according to the Chinese national standard JTG E30-2005.

Table 2. Chemical composition of cement.

| Materials  | Chemical Composition (%) | LOI (%) |
|------------|--------------------------|---------|
| SiO₂       | CaO                      | Al₂O₃   | Fe₂O₃ | MgO | SO₃ |      |
| Cement     | 23.5                     | 61.3    | 5.8   | 4.6 | 1.8 | 2.6  | 2.3 |

Table 3. The Properties of NBCA.

| Apparent Density (kg/m³) | Bulk Density (kg/m³) | Bulk Porosity (%) | Water Absorption (%) | Needle-Like Particle Content (%) | Crushing Value (%) |
|--------------------------|----------------------|-------------------|----------------------|---------------------------------|-------------------|
| 2826.60                  | 1591.13              | 43.71             | 1.73                 | 12.6                            | 9.9               |

The water absorption is for 24 hours according to the Chinese national standard JTG E42-2005.

Figure 1. Crumb rubber.

2.2. Orthogonal Experimental Design
Research have shown that the strength, water permeability and freeze-thaw durability of PCB are related to many factors such as water-cement ratio and porosity. Orthogonal experimental design (OED), characterized by efficiency and economy, is a method to study the impact of different factors and levels on the experimental results. Compared with the full tests, OED can get high-quality results with fewer tests. In this paper, in order to comprehensively consider the effects of three factors (water-cement ratio, design porosity and crumb rubber content) at different levels on the mechanical properties, water permeability and freeze-thaw durability and obtain the optimal mix ratio of RMPCB,
OED is selected to be an optimal method, which could greatly reduce the workload and obtain accurate results [20,21]. The orthogonal array made of different factors and levels is the core of OED [22]. The OED table is expressed as \( L_n(t^q) \), where \( L \) stands for OED table, \( n \) represents the number of OED tests, \( t \) stands for the number of levels of each factor and \( q \) is the maximum number of levels of each factor.

In this paper, \( L_9(3^4) \) was chosen for the OED. Three factors (water-binder ratio, designed porosity, and crumb rubber content) were picked as the influencing factors. Every factor has three levels that are presented in Table 4. Table 5 shows the OED table in detail.

Table 4. Different factors and levels of OED.

| Levels | Water-Binder Ratio | Designed Porosity(%) | Crumb Rubber Content(%) |
|--------|-------------------|-----------------------|------------------------|
| 1      | 0.26              | 15                    | 0                      |
| 2      | 0.30              | 20                    | 4                      |
| 3      | 0.34              | 25                    | 8                      |

Table 5. The specific OED table.

| Group Number | Water-binder ratio | Designed porosity (%) | Crumb rubber content (%) | Error | Result |
|--------------|-------------------|-----------------------|--------------------------|-------|--------|
| g1           | 0.26 (1)          | 15 (1)                | 0 (1)                    | 1     | \( r_1 \) |
| g2           | 0.26 (1)          | 20 (2)                | 4 (2)                    | 2     | \( r_2 \) |
| g3           | 0.26 (1)          | 25 (3)                | 8 (3)                    | 3     | \( r_3 \) |
| g4           | 0.30 (2)          | 15 (1)                | 4 (2)                    | 3     | \( r_4 \) |
| g5           | 0.30 (2)          | 20 (2)                | 8 (3)                    | 1     | \( r_5 \) |
| g6           | 0.30 (2)          | 25 (3)                | 0 (1)                    | 2     | \( r_6 \) |
| g7           | 0.34 (3)          | 15 (1)                | 8 (3)                    | 2     | \( r_7 \) |
| g8           | 0.34 (3)          | 20 (2)                | 0 (1)                    | 3     | \( r_8 \) |
| g9           | 0.34 (3)          | 25 (3)                | 4 (2)                    | 1     | \( r_9 \) |

Range analysis is a way to analyze problems by comparing the range value of each factor. As the range becomes greater, the influence degree of factor on test results becomes larger. Formula 1 and Formula 2 show the calculation process of range analysis:

\[
k_{xi} = K_{xi} / 3
\]

\[
R_i = \max \{k_{x1}, k_{x2}, k_{x3}\} - \min \{k_{x1}, k_{x2}, k_{x3}\}
\]

Where, \( K_{xi} \) is the sum of the test index at the level \( i \) of factor \( x \); \( k_{xi} \) is the average value of the \( i \)-th level test index of factor \( x \); \( R_i \) is the range corresponding to factor \( x \).

Variance analysis is a mathematical approach to estimate the accuracy of range analysis and to evaluate the degree of influence of factors on test results through quantitative indexes. The specific calculation method of variance analysis is as the following formulas (3)-(5):

\[
MS_f = \frac{SS_f}{d_f}
\]

\[
MS_e = \frac{SS_e}{d_e}
\]

\[
F = \frac{MS_f}{MS_e}
\]

Where, \( SS_f \) represents the sum of squared deviation of each factor, \( d_f \) is the degree of freedom of each factor, \( MS_f \) is the mean square of each factor, \( SS_e \) is the sum of squares of the error, \( d_e \) is the freedom degree of error, \( MS_e \) is the mean square of the error.
2.3. Preparation of RMPCB
Conforming to CJJ/T 135-2009, the volume method was utilized for mix proportion design during the preparation of RMPCB. The specific mix proportion and the dosage of each material is listed in Table 6. The specific preparation steps are as follows: (a) NBCA and crumb rubber were put into the mixer and mixed for 30s; (b) Put 50% of the water into the mixer and mixed for 30s; (c) Cement was put into blender and stir for 30s; (d) Put the remaining water and all the superplasticizer into blender and mix for 1min. After 24 hours, the specimens should be demoulded and transferred to the curing room with a standard condition (95% relative humidity and 20±2°C temperature). For specimens with total porosity, effective porosity, permeability coefficient, compressive strength and split tensile strength, they are required to be maintained under standard condition for 28 days; as for the freeze-thaw cycles tests, specimens are maintained under standard condition for 24 days and then maintained in water with a temperature of 20±5°C for 4 days. Figure 2 shows the surface texture of a prepared RMPCB specimen in group 5.

Table 6. Mix ratio of RMPCB.

| Group Number | Water-Binder Ratio | Designated Porosity (%) | Crumb Rubber Content (%) | Coarse Aggregate (kg/m³) | Cement (kg/m³) | Water (kg/m³) | Crumb Rubber (kg/m³) | Superplasticizer (kg/m³) |
|--------------|-------------------|-------------------------|--------------------------|--------------------------|----------------|--------------|---------------------|--------------------------|
| g1           | 0.26              | 15                      | 0                        | 1559.31                  | 491.70         | 127.84       | 0.00                | 3.93                     |
| g2           | 0.26              | 20                      | 4                        | 1559.31                  | 409.30         | 106.42       | 16.37               | 3.27                     |
| g3           | 0.26              | 25                      | 8                        | 1559.31                  | 326.89         | 84.99        | 26.15               | 2.62                     |
| g4           | 0.30              | 15                      | 4                        | 1559.31                  | 461.29         | 138.39       | 18.45               | 3.69                     |
| g5           | 0.30              | 20                      | 8                        | 1559.31                  | 383.98         | 115.19       | 30.72               | 3.07                     |
| g6           | 0.30              | 25                      | 0                        | 1559.31                  | 306.68         | 92.00        | 0.00                | 2.45                     |
| g7           | 0.34              | 15                      | 8                        | 1559.31                  | 434.42         | 147.70       | 34.75               | 3.48                     |
| g8           | 0.34              | 20                      | 0                        | 1559.31                  | 361.62         | 122.95       | 0.00                | 2.89                     |
| g9           | 0.34              | 25                      | 4                        | 1559.31                  | 288.81         | 98.20        | 11.55               | 2.31                     |

The crumb rubber was added into RMPCB by the weight of the cement.

Figure 2. Surface texture of a prepared RMPCB in group 5.

2.4. Test Methods

2.4.1 Porosity. In this research, the total porosity and the effective porosity of 200 × 100 × 60 mm PCB are tested and calculated by the following equations (6)-(7):

\[ P_t = \left(1 - \frac{m_r - m_w}{V \rho_w}\right) \times 100\% \]  \hspace{1cm} (6)
\[ P_e = (1 - \frac{m_2 - m_1}{V \rho_w}) \times 100\% \quad (7) \]

Where, \( P_t \) and \( P_e \) are total porosity (%) and effective porosity (%), respectively. \( m_1 \) refers to the mass of prepared sample when it is dried (g). \( m_2 \) represents mass of surface dried sample (g). \( m_0 \) refers to the mass of sample when it is immersed in water (g). \( V \) stands for the volume of sample (mm\(^3\)). \( \rho_w \) refers to the density of water (g/mm\(^3\)).

**2.4.2 Permeability coefficient.** Permeability coefficient is an essential index of PCB. The constant head method was adopted to measure permeability coefficient of RMPCB. The test device is shown in Figure 3. The size of the specimen tested is 100 × 100 × 100 mm\(^3\). In addition, all sides of the specimen were sealed with sealing materials to ensure that water only penetrated from the upper to lower surfaces of RMPCB. The calculation formula of permeability coefficient is as follows (8):

\[ k_T = \frac{Q L}{AHt} \quad (8) \]

Where \( k_T \) is the permeability coefficient of the specimen when water is at a temperature of \( T \) °C (cm/s), \( Q \) represents the total amount of water seeping out in \( t \) seconds (mL), \( L \) stands for the height of prepared sample (cm), \( A \) stands for area of the upper surface of RMPCB (mm\(^2\)), \( H \) corresponds to the water head difference (cm), \( t=300s. \)

![Diagram of Water Permeability Coefficient Test Device](image)

**Figure 3. Water Permeability Coefficient Test Device.**

**2.4.3 Compressive strength.** The compressive strength is tested according to the Chinese standard GB/T 50081-2002. The size of tested specimen is 100 × 100 × 100 mm\(^3\). The value of compressive strength is calculated by formula (9):

\[ F_{oc} = \frac{F}{A} \quad (9) \]

Where, \( F_{oc} \) is the compressive strength (MPa); \( F \) represents the load when the specimen fails (N); and \( A \) is the area under compression of the specimen (mm\(^2\)).

**2.4.4 Split tensile strength.** According to the Chinese national standard GB/T 25593-2010, split tensile strength is measured. 200 × 100 × 60 mm\(^3\) PCB specimens cured for 28 days are used to conduct the test, and the value is calculated as follows (10):

\[ F_s = 0.637 \times k \times \frac{P}{S} \quad (10) \]
where, $F_t$ represents the split tensile strength (MPa), $P$ represents the failure load (N), $k$ refers to the correction coefficient of the thickness of sample, $k=1.00$. $S$ is the area of the failure surface ($\text{mm}^2$).

2.4.5. Freeze-thaw durability. The freeze-thaw durability of RMPCB is evaluated by compressive strength loss rate of RMPCB after 50 freeze-thaw cycles conforming to Chinese national standard JC/T 945-2005. The size of the specimen used in the test is $200 \times 100 \times 60 \text{ mm}^3$. Figure 4 displays the test device of the test. Compressive strength loss rate is calculated as follows:

$$
\Delta R = \frac{R - R_D}{R} \times 100\% 
$$

(11)

Where, $\Delta R$ is the value of compressive strength loss rate of RMPCB after 50 freeze-thaw cycles, $R$ is the compressive strength before freeze-thaw cycles, $R_D$ is the compressive strength after 50 freeze-thaw cycles.

![Figure 4. Freeze-thaw cycles test device.](image)

3. Results and Discussion
Three specimens were used in each group to test the parameters of RMPCB. The freeze-thaw cycle test needs ten specimens in each group. The test results of each group are summarized in Table 7.

| Group Number | $P_t$ (%) | $P_e$ (%) | $k$ (cm/s) | $F_{oc}$ (MPa) | $F_{ts}$ (MPa) | $\Delta R$ (%) |
|--------------|-----------|-----------|------------|---------------|---------------|---------------|
| 1            | 16.6      | 13.6      | 1.113      | 19.5          | 3.9           | 8.21          |
| 2            | 21.7      | 18.2      | 1.319      | 16.8          | 3.3           | 8.33          |
| 3            | 26.9      | 23.7      | 1.610      | 14.3          | 2.7           | 9.09          |
| 4            | 16.2      | 13.5      | 1.078      | 25.6          | 4.8           | 7.03          |
| 5            | 21.3      | 18.1      | 1.271      | 20.2          | 3.1           | 7.43          |
| 6            | 26.9      | 23.4      | 1.554      | 17.4          | 2.7           | 10.92         |
| 7            | 16.2      | 13.1      | 1.033      | 22.7          | 4.1           | 6.61          |
| 8            | 22.1      | 18.8      | 1.336      | 18.9          | 2.9           | 10.58         |
| 9            | 26.7      | 23.3      | 1.522      | 16.5          | 3.4           | 9.70          |

3.1. Orthogonal Experiment Results Analysis

3.1.1 Range Analysis. Table 8 presents the range analysis of the orthogonal tests. The influence of each factor on each test result can be judged according to the range.

In Table 8 and Figure 5a, the designed porosity has the greatest influence on permeability coefficient, then the water-binder ratio, and finally the crumb rubber content. The optimal water-binder ratio, designed porosity and crumb rubber content are 0.26, 25% and 0%, respectively. Figure 5b shows that the designed porosity affects the compressive strength most, then the
water-binder ratio and crumb rubber content. The optimal factor levels are 0.30 for water-binder ratio, 15% for designed porosity and 4% for crumb rubber content. For the split tensile strength of RMPCB in Figure 5c, the influence degree is from the largest to the smallest in order: designed porosity, crumb rubber content and water-binder ratio. The optimal water-binder ratio, designed porosity and crumb rubber content are 0.30, 15% and 4%, respectively. According to the R and K values, it can be seen from Figure 5d, the designed porosity has the greatest effect on the freeze-thaw durability, followed by crumb rubber content. The optimal combination is water-binder ratio 0.30, designed porosity 15% and crumb rubber content 8%.

**Table 8.** Range analysis of RMPCB.

| Index | k (cm/s) | $F_{oc}$ (MPa) | $F_{ts}$ (MPa) | $\Delta R$ |
|-------|---------|---------------|---------------|-----------|
|      | A       | B             | C             | A         | B     | C     | A   | B   | C   |
| K1   | 1.35    | 1.08          | 1.33          | 16.87     | 22.60 | 18.60 | 3.30| 4.27| 3.17| 8.54 | 7.28 | 9.90 |
| K2   | 1.31    | 1.31          | 1.3           | 21.07     | 18.63 | 19.63 | 3.53| 3.10| 3.83| 8.46 | 8.78 | 8.35 |
| K3   | 1.30    | 1.56          | 1.30          | 19.37     | 16.07 | 19.07 | 3.47| 2.93| 3.30| 8.96 | 9.90 | 7.71 |
| R    | 0.05    | 0.48          | 0.03          | 4.20      | 6.53  | 1.03  | 0.23| 1.34| 0.66| 0.50 | 2.62 | 2.19 |

Optimal: A1B3C1 A2B1C2 A2B1C2 A2B1C3

*A is water-binder ratio, B is designed porosity, C is crumb rubber content. A1B3C1 represents that A, B and C take the first level (0.26), the third level (25%) and the first level (0%), respectively. The same is true for A2B1C2 and A2B1C3.

**Figure 5.** K values at different factor levels: (a) Permeability coefficient; (b) Compressive strength; (c) Split tensile strength; (d) Compressive strength loss rate.
3.1.2 Variance Analysis. Table 9-12 show the variance analysis results of each influencing factor on the experimental result. A is water-binder ratio, B is designed porosity, C is crumb rubber content, D is error column. Compared the F value with \(F_{0.01}(2,2)\) and \(F_{0.05}(2,2)\), the influence of certain factors on the test results is judged to be significant or not.

Based on the F value, we can conclude from Table 9 that there is a 99% possibility that designed porosity can significantly affect the permeability coefficient, while water-binder ratio and crumb rubber content have little influence on permeability coefficient. As can be seen from Table 10, the F values of water-binder ratio and designed porosity are both greater than \(F_{0.05}(2,2)\). In other words, the water-binder ratio and the designed porosity have a significant impact on the possibility of not less than 95% of compressive strength. The F value of designed porosity is larger than that of water-binder ratio, which indicates that designed porosity has a greater effect on compressive strength than water-binder ratio. The crumb rubber content has little effect on compressive strength.

We can conclude through Table 11 that the F value of designed porosity is larger than \(F_{0.05}(2,2)\), meaning that the designed porosity has a possibility of 99% and has a significant impact on the split tensile strength. The F value of crumb rubber content is larger than \(F_{0.05}(2,2)\), it means that the crumb rubber content has a significant impact on the split tensile strength with a possibility of 95%. The water-binder ratio has little significant impact on the split tensile strength. The values of designed porosity and crumb rubber content are both greater than \(F_{0.05}(2,2)\) in Table 12, meaning that there is a 95% possibility that the designed porosity and the crumb rubber content have a significant impact on the compressive strength loss rate after freeze-thaw cycle, while the water-binder ratio has little impact on the compressive strength loss rate. The results of variance analysis are almost the same with the results of range analysis.

Table 9. Variance analysis of permeability.

| Factors | SS   | df  | MS   | k          | F          | \(F_{0.05}(2,2)\) | \(F_{0.01}(2,2)\) | Significance |
|---------|------|-----|------|------------|------------|------------------|------------------|--------------|
| A       | 0.005| 2   | 0.003| 1.667      | 19.000     | 99.000           | -                |
| B       | 0.356| 2   | 0.178| 118.667    | 19.000     | 99.000           | **               |
| C       | 0.002| 2   | 0.001| 0.667      | 19.000     | 99.000           | -                |
| D       | 0.003| 2   | 0.002| /          | /          | /                | -                |

Table 10. Variance analysis of compressive strength.

| Factors | SS   | df  | MS   | \(F_{0c}\) | F          | \(F_{0.05}(2,2)\) | \(F_{0.01}(2,2)\) | Significance |
|---------|------|-----|------|-----------|------------|------------------|------------------|--------------|
| A       | 26.780| 2   | 13.390| 22.187    | 19.000     | 99.000           | *                |
| B       | 65.007| 2   | 32.504| 53.858    | 19.000     | 99.000           | *                |
| C       | 1.607 | 2   | 0.804 | 1.331     | 19.000     | 99.000           | -                |
| D       | 1.207 | 2   | 0.604 | /         | /          | /                | -                |

Table 11. Variance analysis of split tensile strength.

| Factors | SS   | df  | MS   | \(F_{0s}\) | F          | \(F_{0.05}(2,2)\) | \(F_{0.01}(2,2)\) | Significance |
|---------|------|-----|------|-----------|------------|------------------|------------------|--------------|
| A       | 0.087 | 2   | 0.044| 4.350     | 19.000     | 99.000           | -                |
| B       | 3.167 | 2   | 1.584| 158.350   | 19.000     | 99.000           | **               |
| C       | 0.747 | 2   | 0.374| 37.350    | 19.000     | 99.000           | *                |
| D       | 0.020 | 2   | 0.010| /         | /          | /                | -                |

Table 12. Variance analysis of compressive strength loss rate.

| Factors | SS   | df  | MS   | \(\Delta R\) | F          | \(F_{0.05}(2,2)\) | \(F_{0.01}(2,2)\) | Significance |
|---------|------|-----|------|-------------|------------|------------------|------------------|--------------|
| A       |      |     |      |             |            |                  |                  |              |
| B       |      |     |      |             |            |                  |                  |              |
| C       |      |     |      |             |            |                  |                  |              |
| D       |      |     |      |             |            |                  |                  |              |
3.2. Influencing Factors Analysis

3.2.1 Permeability coefficient. For the permeability, the effective porosity of RMPCB is the dominant factor. Figure 6 shows the connection between effective porosity and permeability coefficient. It can be seen that the effective porosity is in a positive linear correlation with the permeability coefficient, with a linear correlation coefficient of 0.9371. Figure 7 displays the connection between the permeability coefficient, designed porosity and water-binder ratio. It can be seen that the permeability coefficient changes little with the increase of water-binder ratio when the designed porosity is at a constant level. Figure 8 indicates that the content of crumb rubber can hardly affect the permeability coefficient.

** means factor is very significant. * means factor is significant. - means factor is little significant.

|   |   |   |   |   |
|---|---|---|---|---|
| A | 0.437 | 2 | 0.219 | 1.392 | 19.000 | 99.000 | - |
| B | 10.366 | 2 | 5.183 | 33.013 | 19.000 | 99.000 | * |
| C | 7.627 | 2 | 3.814 | 24.290 | 19.000 | 99.000 | * |
| D | 0.314 | 2 | 0.157 | / | / | / | - |

Figure 6. Connection between effective porosity and permeability coefficient.

Figure 7. Connection between permeability coefficient, designed porosity and water-binder ratio.

Figure 8. Connection between permeability coefficient, designed porosity and crumb rubber content.
3.2.2 Compressive strength. The relationship between total porosity and compressive strength is depicted in Figure 9. When the total porosity increased from 16.2% to 26.9%, the compressive strength decreased from 25.6 MPa to 14.3 MPa, which is consistent with the trends reported in other literature [14,23]. Figure 10 shows the connection between compressive strength, water-binder ratio, and designed porosity. It can be concluded that when the designed porosity is fixed, as the water-binder ratio increases, the compressive strength increases first and then decreases. This is because when the water-binder ratio is too low, the fluidity of slurry in the RMPCB is poor and the cement cannot be well hydrated, thus resulting in low compressive strength of RMPCB. However, when the water-cement ratio is excessive, the concrete has great fluidity but is easy to isolation, which leads to uneven composition and structure of RMPCB and reduces the compressive strength. There is no obvious correlation between the crumb rubber content and compressive strength.

![Figure 9](image1.png) **Figure 9.** Connection between total porosity and compressive strength.

![Figure 10](image2.png) **Figure 10.** Connection between compressive strength, designed porosity and water-binder ratio.

3.2.3 Split tensile strength. As can be depicted from Figure 11, the split tensile strength decreases as the total porosity increases. When the total porosity increases from 16.2% to 26.9%, the split tensile strength of RMPCB decreases from 4.8 MPa to 2.7 MPa. Similar conclusions have been drawn by other scholars in relevant research [23-25]. Figure 12 shows the relationship between split tensile strength, designed porosity and crumb rubber content. It can be observed that when the designed porosity is unchanged, the split tensile strength increases as the crumb rubber content increases. However, when the crumb rubber content continues to increase, the split tensile strength begins to decrease. This is because of the reaction of NaOH solution with zinc stearate on the surface of crumb rubber.

![Figure 11](image3.png) **Figure 11.** Connection between total porosity and split tensile strength.

![Figure 12](image4.png) **Figure 12.** Connection between split tensile strength, designed porosity and content of crumb rubber.
rubber, which increases the hydrophilicity of crumb rubber, and improves the adhesion between rubber and cement matrix, thus increasing the split tensile strength of permeable bricks. However, too much crumb rubber will result in the decrease of structural strength. This is because of the hydrophobicity of rubber powder. When the crumb rubber content is at a high level, the hydration reaction inside of RMPCB will become worse, weakening the bonding force between the gravel and cement paste. The water-cement ratio had no significant impact on the split tensile strength.

3.2.4 Loss rate of compressive strength. Figure 13 shows the connection between compressive strength loss rate, designed porosity and crumb rubber content. It can be seen that with the increase of the crumb rubber content, the compressive strength loss rate decreases with the designed porosity fixed. When the crumb rubber content increases from 0% to 8%, the loss rate of compressive strength decreases from 10.58% to 7.43%, which means that the freeze-thaw resistance of RMPCB is greatly enhanced. With the crumb rubber content fixed, the loss rate of compressive strength increases as the designed porosity increases, which indicates that the increase of porosity is not conducive to the freeze-thaw durability of RMPCB. There is no significant connection between water-binder ratio and compressive strength loss rate.

![Figure 13. Connection between compressive strength loss rate, designed porosity and content of crumb rubber.](image)

4. Conclusions
The influences of water-binder ratio, designed porosity and crumb rubber content on the mechanical properties, water permeability and freeze-thaw durability of RMPCB were studied by OED in this paper. OED results analysis and influencing factors analysis were adopted to analyze the experimental results. Derived from the experimental results, conclusions can be drawn as follows:

- Effective porosity mainly affects the water permeability of RMPCB. The permeability coefficient of RMPCB enhances significantly as the effective porosity increases. The water-binder ratio has little impact on permeability coefficient.
- The compressive strength, split tensile strength of RMPCB are negatively correlated with the porosity. The compressive strength and the split tensile strength decrease with the increase of designed porosity.
- The compressive strength of RMPCB first increases and then decreases with the increase of water-binder ratio. There is no obvious correlation between the crumb rubber content and the compressive strength.
- The incorporation of crumb rubber greatly improves the freeze-thaw durability of RMPCB. When the crumb rubber content increased from 0% to 8%, and the loss rate of compressive strength decreased by 29.77%. However, the split tensile strength of RMPCB will be slightly reduced if excessive rubber is added.
Based on the above research, considering the water permeability, mechanical strength and freeze-thaw resistance comprehensively, the optimal water-binder ratio, designed porosity and crumb rubber content for RMPCB were 0.30, 15% and 4%, respectively.

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