Experimental Study of Pervious Concrete Using Recycled Coarse Aggregate

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Abstract. The project aims at studying the effect of water-cement ratio and the replacement ratio of recycled coarse aggregate (RCA) on the physical and mechanical properties of pervious concrete and the correlation between these properties. The research methodology is to replace natural coarse aggregate (NCA) with RCA at four replacement levels of 10, 20, 30 and 40 % and adjust water-cement ratios of 0.25 and 0.30. The total void content, effective void content, cubic compressive strength, splitting tensile strength, water permeability, and abrasion resistance of pervious concrete were tested. The results show that with the increasing of w/c ratio or replacement ratio of RCA, void content and permeability coefficient of pervious concrete increase in a certain degree, but cubic compressive strength, splitting tensile strength and abrasion resistance decrease. Data analysis shows that there are good correlations between relevant performance indicators.

Keywords: Pervious concrete Recycled coarse concrete Void content · Cubic compressive strength · Splitting tensile strength · Permeability coefficient · Abrasion resistance

1. Introduction
With the rapid development of the national economy and the transformation of the old city, lots of natural pervious pavements are constructed to be impervious pavement or fine permeable pavement, resulting in a series of problems, such as hindering rainwater into groundwater, urban heat island effect, rainy night driving glare and longer driving braking distance [1, 2]. In order to effectively alleviate these problems, some researchers put forward the concept of pervious concrete [1, 3-4].

Pervious concrete is a green and high porous concrete made with Portland cement, water, single size or non-continuous grading coarse aggregate, with little or no fine aggregate, and other chemical/mineral admixtures if needed [1, 3-5]. The properties of coarse aggregate [6], cement type [7], mix proportion [8], admixture [9] on the influence of physical and mechanical properties of pervious concrete were studied, and a series of research results were obtained.

With the further study of pervious concrete, it is found that the damage pathway of pervious concrete is always along the transition area between the aggregates, so some scholars have tried to study the physical and mechanical properties of pervious recycled concrete (PRC) with RCA. Güneyisi E et al. [10] studied the influence of RCA substitution rate and w/c ratio on the properties of PRC. Chindapasirt et al. [10] studied the influence of the incorporation of fine aggregate and fly on the mechanical properties of PRC. The results of Barnhouse et al. [12] showed the bond property between aggregate is the key factor, not aggregate property and substitution ratio. But the results of Zhang et al. [13], Yap, S. P et al. [14] and Ngohpok, C et al. [15] showed that properties of RCA have great influence on the properties of PRC. It can be seen from above that the related research on pervious recycled concrete has not yet reached a unified conclusion. In view of this, the effects of water-cement ratio and replacement ratio on the compressive strength, splitting tensile strength,
permeability and abrasion resistance of pervious recycled concrete were tested. And the relationship between the performance indicators were discussed and provided as a reference for similar research.

2. Experimental Study

2.1. Materials
The CEM I 42.5R type of Portland cement made in China was used in all pervious concrete, and the chemical compositions of Portland cement is listed in Table 1.

Table 1. Chemical composition of Portland cement and FA

| Chemical composition (%) | SiO$_2$ | Fe$_2$O$_3$ | Al$_2$O$_3$ | TiO$_2$ | CaO   | MgO   | SO$_3$ | Na$_2$O | K$_2$O |
|-------------------------|---------|-------------|-------------|---------|-------|-------|--------|---------|--------|
| Portland cement         | 19.33   | 3.69        | 5.98        | 0.28    | 60.86 | 3.02  | 3.05   | 0.29    | 0.87   |

The Natural coarse aggregate (NCA) is limestone crushed stone, and the particle size is about 9.5-12mm, close bulk density and water absorption rate are 1498 kg/m$^3$ and 1.48% respectively. The recycled coarse aggregate (RCA) obtained from the laboratory waste test beam were crushed with jaw crusher, sieved, washed. The particle size of recycled concrete ranges from 9.5mm to 12mm, and its close packing density and water absorption rate are 1236 kg/m$^3$ and 1.67% respectively. PCA-lpolycarboxylate high performance water reducing agent was provided by SOBUTE NEW MATERIAL CO., LTD, the water reduction rate is more than 30%. The solid content of the reinforcing modifier is more than 96%, the pH is 6.93, the fineness is 0.25mm, the SiO$_2$ content is 72.47% and the CaO content is 0.63%.

2.2. Mix Proportions
In order to considering the effect of water-cement ratio and the replacement ratio of RCA on mechanical and permeable properties of pervious concrete, two water-cement ratios (0.25, 0.3) and four replacement ratios (10, 20, 30, and 40%) were considered. The principle of replacing RCA was by weight to keep the aggregate-cement ratio constant.

The specific mix proportions of pervious concrete are shown in Table 2. In the table, PC and PRC are used to represent pervious concrete and pervious recycled concrete, PRC25-20 shows the water-cement ratio of 0.25, RCA replacement rate of 20%.

Table 2. Mix Proportions of Pervious Concrete (kg/m$^3$)

| Mix ID   | Water-cement ratios (W/C) | Mix Proportions/(kg/m$^3$) | Cement | Natural coarse aggregate | Recycled coarse aggregate | Water | SP | RM |
|----------|---------------------------|-----------------------------|--------|-------------------------|--------------------------|-------|----|----|
| PC25     | 0.25                       |                             | 490    | 1470                    |                          | 125   | 4.9| 49 |
| PRC25-10 | 0.25                       |                             | 490    | 1323                    | 147                      | 125   | 4.9| 49 |
| PRC25-20 | 0.25                       |                             | 490    | 1176                    | 294                      | 125   | 4.9| 49 |
| PRC25-30 | 0.25                       |                             | 490    | 1029                    | 441                      | 125   | 4.9| 49 |
| PRC25-40 | 0.25                       |                             | 490    | 882                     | 588                      | 125   | 4.9| 49 |
| PC30     | 0.30                       |                             | 454    | 1470                    |                          | 134   | 4.5| 45.4|
| PRC30-10 | 0.30                       |                             | 454    | 1323                    | 147                      | 134   | 4.5| 45.4|
| PRC30-20 | 0.30                       |                             | 454    | 1176                    | 294                      | 134   | 4.5| 45.4|
| PRC30-30 | 0.30                       |                             | 454    | 1029                    | 441                      | 134   | 4.5| 45.4|
| PRC30-40 | 0.30                       |                             | 454    | 882                     | 588                      | 134   | 4.5| 45.4|
2.3. Test Molding Process and Maintenance
In order to prevent the cement slurry from sinking to the lower half of the mold, avoid clogging the bottom of specimens and avoid the loss of cement slurry between the upper aggregates. The specific vibration process was designed and as follows: vibrating three times along the height of the specimen, each vibration with an iron rod vibrated 20 times, and the test piece surface was manually compacted and flattened. All tests were demolded after 24 hours of standard maintenance and continue to be cured.

2.4. Test Specimens and Methods
The cubic specimens with 100-mm dimensions were used for void content test, cubic compressive strength test, splitting strength test and permeability coefficient test, and the 150×150×75mm prism specimens were produced for abrasion test.

The cubic compressive strength and splitting tensile strength of pervious concrete were conducted according to Standard for Test Method of Mechanical Properties on Ordinary Concrete (GB / T50081-2002) [16], and the loading rate was controlled at 0.4MPa and 0.04MPa respectively.

The pores of large porosity pervious concrete can be divided into two types, the continuous effective pores allow water penetrate the entire test specimen, which is called the effective pore or continuous pore. The effective void content test test is strictly in accordance with the test method recommended in Technical Specification for Application of Pervious Recycled Aggregate Concrete (CJJ/T253-2016) [17].

Permeability of pervious concrete is generally expressed by permeability coefficient, according to reference [18], a self-made apparatus (Fig.1) which was made of four transparent plexiglass adhesives is used to test permeability coefficient.

According to Darcy’s law, the permeability coefficients \( k \) can be calculated by the following equation:

\[
k = \frac{a \times L}{A \times t} \ln \left( \frac{h_0}{h_1} \right)
\]

Where \( k \), \( a \), \( L \), \( A \), \( t \), \( h_0 \) and \( h_1 \) are the coefficient of permeability (mm/s), the cross-sectional area of the tube (mm²), the length of the specimen (mm), the average cross-sectional area of the specimen (mm²), the average time taken for the head to fall from \( h_0 \) to \( h_1 \) (s), initial water head (mm), and the final water head (mm), respectively.

The abrasion resistance of pervious concrete is usually expressed by the mass loss of abrasion on unit area, and the equation was used to calculate mass loss of abrasion on unit area according to Test Methods of Cement and Concrete for Highway Engineering (JTG E30-2005) [19].
3. Results and Discussions

3.1. Effective Void Content

The effective void content of pervious concrete versus replacement ratio of RCA is plotted in Fig. 2. The effective void content of pervious concrete at w/c ratio of 0.25 were lower than that of pervious concrete at w/c ratio of 0.3. The main reason is that the lower the water-cement ratio, the less the amount of cement and the less the grout on the surface of the coarse aggregate, and then improves the effective void content of PRC. When the replacement ratio of RCA was decreased from 0 to 40% at the same w/c ratio, the effective void content was increased from 14.78 to 15.32% and 15.39 to
16.03% at w/c ratios of 0.25 and 0.3. The main reason is that cracks formed during the crushing of RCA caused more micro pores in the bonding area, and the irregular and angular shapes of RCA hindered the compaction of the test piece and formed more pores. As the replacement ratio of RCA increased, the unfavorable effects became more pronounced, which caused the effective void content increase.

![Figure 3a. Cubic compressive strength versus replacement ratio of RCA](image)

![Figure 3b. Relation-ship between cubic compressive strength and effective void content](image)

3.2. Cubic Compressive Strength
The relationship between the cubic compressive strength and the replacement ratio of RCA is shown in Fig.3a. The cubic compressive strength at w/c ratio of 0.3 was lower than that of pervious concrete at w/c ratio of 0.25, and the ratio between them were about 94.3, 96.7, 97.6, 93.9 and 92.0%, respectively. The greater the w/c ratio means the lower amount of cement paste and lower filling rate of the interstices zone between the aggregates particles, easier to segregate, so the cubic compressive strength of pervious concrete decreased. Increasing the replacement ratio of RCA from 0 to 40% decreased the cubic compressive strength from 23.51 to 21.36MPa and 22.18 to 19.66MPa at w/c ratios of 0.25 and 0.3, respectively. In the process of crushing, the mechanical properties and modulus of elasticity of cement mortar around RCA are lower than NCA, so the bonding performance between the RCA and the cement paste are decreased. The greater the replacement ratio, the more obvious the
adverse effect, and then the cubic compressive strength is decreased. Since the strength of concrete has a great relationship with its compactness, the relationship between cubic compressive strength and effective porosity is studied. The experimental data shows that the relationship between them is more suitable with a power function, and the R-square value of 0.9177, which reflects the good correlation between the two, as shown in Fig.3b.

3.3. Splitting Tensile Strength
The relationship between the splitting tensile strength and the replacement ratio of RCA under different w/c ratios is given in Fig.4a. The splitting tensile strength of pervious concrete at w/c ratio of 0.25 has lower splitting tensile strength, and are about 90.1, 88.9, 90.4, 84.1 and 88.5% of that of specimens at w/c ratios of 0.3, respectively. Increasing the replacement ratio of RCA from 0 to 40% decreased the splitting tensile strength from 1.82 to 1.48MPa and 1.64 to 1.31MPa for the pervious concretes at w/c ratios of 0.25 and 0.3, respectively. The main reason is may be that old mortar around RCA affect the bonding properties between RCA and cement slurry, which lead to weakening of interfacial transition zone and forma weak links inside PRC. As the replacement ratio of RCA increases, the above adverse effects further concentrate and result in a further decrease in splitting tensile strength.

Through the analysis of experimental data, it is found that the cubic compressive strength increases with the increasing of the splitting tensile strength, and the relationship between them given by data fitting is shown in Fig.4b. The R-square value of 0.8694 shows that the correlation is better. Although there is a notable discreteness, the formula basically reflects the relationship between these two performance indexes.

![Figure 4a. Splitting tensile strength versus replacement ratio of RCA](image-url)
Figure 4b. Relationship between cubic compressive strength and splitting tensile strength

3.4. Water Permeability

The relationship between permeability coefficient and replacement ratio of RCA is given in Fig. 5a. When the replacement ratios of RCA were 0, 10, 20, 30 and 40%, the permeability coefficient at w/c ratio of 0.3 were 14.5, 13.0, 17.6, 17.5 and 23.4% higher than that of specimens at w/c ratio of 0.25. The specimen with lower w/c ratio has thicker cement slurry thickness and higher pore fill rate, which all make pervious concrete difficult to form unobstructed vertical permeable approach and decrease the permeability performance. When the replacement ratio of RCA increased from 0 to 40%, the permeability coefficient increased from 5.93 to 6.92 mm/s and 6.79 to 8.54 mm/s at w/c ratios of 0.25 and 0.3, respectively. The higher the replacement ratio is, the higher the content of irregular RCA is, the less likely to be compacted, so the permeability coefficient of PRC is improved. In the literature [1], it is reported that the permeability coefficient values ranged from 1.4 to 12.2 mm/s is acceptable for pervious concrete, and the permeability coefficient values in this study are from 5.93 to 8.54 mm/s, which can satisfy engineering requirements.

The relationship between effective porosity and permeability coefficient is given in Fig. 5b. It can be seen from Fig. 5b that with the increasing of the effective porosity, the permeability coefficient of pervious concrete also increases. The relationship is more suitable to be expressed by power function, the R-square value of 0.9353 indicates the correlation is very good, and the scatter is smaller. The relationship is consistent with the conclusions of some literatures [11, 13, 20-21]. From the above, the mechanical properties and water permeability performance of pervious concrete need to be balanced by the mix design and be further considered to meet the needs of different practical projects.
3.5. Abrasion Resistance
The abrasion resistance of pervious concrete is generally expressed in terms of the abrasion depth or the mass loss of abrasion on unit area, and the abrasion of pervious concretes by mass loss on unit area versus replacement ratio of RCA is shown in Fig. 6a. The higher the w/c ratio, the greater the loss of abrasion quality per unit area, indicating that its wear resistance has decreased, which is mainly due to the decrease in the bonding performance or the strength of the cement slurry between the aggregates with the increase of the w/c ratio. Further, with the increase of replacement ratio of RCA from 0 to 40%, the values of abrasion loss per unit area increased from 14.656 to 15.344 kg/m² and 15.096 to 15.847 kg/m² at w/c ratios of 0.25 and 0.3, respectively. In addition to the lower abrasion resistance of RCA, waste cement mortar around RCA decrease cohesion force between RCA and coarse aggregate or cement paste.
Figure 6a. Abrasion (by mass loss on unit area) of pervious concrete to replacement ratio of RCA

Figure 6b. Relationship between effective void content-abrasion and cubic compressive strength-abrasion of pervious concrete

The relation between effective void content- abrasion and cubic compressive strength- abrasion (by mass loss on unit area) of pervious concrete are shown in Fig.6b. It can be seen from Fig.6b that with the increasing of abrasion resistance, the cubic compressive strength increases, but the effective void content decreases. The R-square values of 0.9328 R-square values of 0.9578 indicates that the relationship between them can be expressed by a power function, and the dispersion is small. Combined with the above analysis, it is concluded that changing the w/c ratio or replacement ratio of RCA would affect the mechanical properties, the effective porosity and permeability coefficient, so attention should be paid to the w/c ratio and the replacement ratio of RCA.

4. Conclusions
Based on the results mentioned above, following conclusions can be summarized:

The effective void content values increased with the increasing of replacement ratio of RCA or w/c ratio.

The cubic compressive strength decreased from 23.51 to 19.66 MPa with the replacement ratio of
RCA or w/c ratio increasing, and the R-square value of 0.9177 indicated that there is a good relation between cubic compressive strength and effective void content.

Splitting tensile strength was affected by w/c ratios or the replacement ratio of RCA, the relationship between cubic compressive strength and splitting tensile strength can be expressed by power function.

The permeability coefficient from 5.93 to 8.54 mm/s were acceptable for pervious concrete. The permeability coefficient with higher w/c ratio or replacement ratio of RCA was higher. It is found that the permeability coefficient increases with the increasing of effective void content, and the power function relationship between them is proper by R-square value of 0.9353.

Abrasion resistance of PRC decreased with the increasing of the replacement ratios of RCA or w/c ratios, and R-square value of 0.9328 and 0.9578 indicate that the relationship between abrasion-effective void content and abrasion-cubic compressive strength can be well expressed by power function and the dispersion is small.

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