Research Article

Effect of Recycled Aggregate Content on Water Permeability and Pore Structure of Pervious Concrete Pavement

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1. Introduction

With the development of the economy, China is becoming increasingly urbanized. Reconstruction projects also increase sharply, leading to a rapid rise in the amount of construction garbage [1]. The waste concrete accounts for approximately 30%–50% of the total construction waste, which will contaminate land and the surrounding environment without proper precautions [2–5]. Therefore, how to collect and process waste concrete properly has become a major problem. One solution is to transit waste concrete to recycled aggregate (RA) to replace natural aggregate (NA) [6–10]. Applying RA in pervious concrete can utilize the advantages of pervious concrete (such as permeability, water permeability, sound absorption, and heat insulation) and reduce construction waste and the consumption of NA [11, 12].

Pervious concrete has been developed for many years. A great amount of research has been conducted on this topic. John and Nowasell [13] studied the performance change of concrete by using lightweight aggregates to completely replace the traditional fine aggregate components in pervious concrete; Öz (2018) studied the performance of pervious concrete with acidic pumice as the coarse aggregate; Cui et al. [14] used the laboratory test to reveal the mechanism of sediment clogging in the pores of the pervious concrete pavement under stormwater runoff; Zhang et al. [15] used experimental method and numerical simulation to analyze the approximate simulation of stormwater runoff over the pervious pavement. Zhang et al. [16] studied the percolation performance of pervious concrete through CT scanning technology and numerical simulation; Nantasai and Nassiri [17] developed a multiple linear regression model to investigate frost durations at pervious concrete pavement near-surface depths for application in winter maintenance operations.

In many aspects, pervious concrete with the addition of RA outperforms previous concrete without RA. It has been found that when RA in pervious concrete is used appropriately, it can increase the strength and abrasion resistance. In addition, thermal conductivity and sound absorption qualities of concrete can be enhanced as well [18] (Ngohpok...
Many previous studies on RA concrete [19–21] obtained the same conclusion that the mechanical properties of RA concrete are lower than those of the normal concrete and there is a certain relationship between the reduction degree and the amount of RA. Rao et al. [22] discovered that the amount of RA and the size of aggregate particle size had a significant influence on the decrease of strength. Furthermore, Chindaprasirt et al. [23] also came to the same conclusion in their study. However, some studies suggested that when RA is added to concrete, the strength is not substantially different from and even greater than that of the normal concrete [24–27]. (X_his study suggests that when the RA is added to pervious concrete, changes of strength and permeability are uncertain.

(X_here existing research on pervious concrete is seldom focused on RA, so the effect of RA content on the mechanical properties and permeability of pervious concrete is not clear, and the comprehensive performance evaluation of RAPC is lacking.

Therefore, relevant research needs to be carried out. Therefore, this study tested the strength of the specimens with different RA contents. The permeability of Recycled Aggregate Pervious Concrete (RAPC) was evaluated from two aspects, i.e., permeability and water retention. Additionally, CT scanning was used to analyze the internal structure of concrete to obtain a more accurate porosity. This study provides theoretical support for the application of recycled aggregate in pervious concrete.

2. Materials and Methodology

2.1. Raw Materials. The raw materials include PO 42.5R Portland cement, polycarboxylate water-reducer, NA, and RA. The RA used in the experiment was purchased from the local wharf and was obtained through crushing the waste concrete. Both aggregates have a particle size of 0–15 mm, and the gradation of coarse aggregates is shown in Figure 1. The main properties of the aggregate are shown in Table 1.

2.2. Mix Proportions. In this study, the water-cement ratio was 0.258, and the total aggregate volume was constant by replacing the same volume of NA with RA. Five kinds of concrete were recorded as RAPC0, RAPC25, RAPC50, RAPC75, and RAPC100, respectively. Table 2 presents the mixture proportion of RAPC. The W/C ratio was selected with reference to the industry standard “Technical Specification for Pervious Cement Concrete Pavement” (CJJ/T135-2009) of the People’s Republic of China, which specifies that the W/C ratio should be determined by test and range from 0.25 to 0.35. The mix ratio of pervious concrete with different RA contents was designed by the volume method and then mixed according to the calculated mix ratio. The amount of cement or admixture is adjusted appropriately according to the working properties of pervious concrete to obtain the ratio for strength and permeability tests.

2.3. Preparation of Specimens. Excessive vibration will lead the cement slurry to sink to the bottom, thus plugging the pores and affecting the water permeability. According to GBT 50081-2002, the specimen should be prepared by using manual tamping and machine vibration. The mold containing the fresh concrete was placed on the shaking platform and then vibrated two times. The first vibration duration was 10 s and the second vibration was 5 s until the surface was smoothed. After 24 h of curing, the specimen was demoulded and put into water for 28 d.

The cube specimen with a size of $150 \times 150 \times 150$ mm was used for compression and splitting tensile strength tests, and the rectangular specimen with a size of $100 \times 100 \times 200$ mm was used to obtain the tensile strength. For three-point bending and four-point bending tests, a beam with the size of $100 \times 100 \times 400$ mm was used.

When measuring the porosity of pervious concrete, a cylinder with a diameter (D) of 74 mm and height (H) of...
100 mm was used, which was obtained by coring from a concrete block of 150 × 150 × 150 mm. The cylinder with $D = 70$ mm and $H = 150$ mm was used for the permeability test, and the specimen with $D = 110$ mm and $H = 150$ mm was for evaluating the water retention; both were cast in a PVC tube.

2.4. Test Methods

2.4.1. Strength. The compressive strength, splitting tensile strength, three-point bending strength, four-point bending tensile strength, and flexural strength were obtained by using a microcomputer-controlled electro-hydraulic servo universal testing machine (Figures 2(a)–2(c)) and determined according to GB/T 50081-2002. The direct tensile test was carried out on the MTS apparatus (Figure 2(d)). It is difficult to stretch concrete specimens directly, so two steel plates were glued on the ends of the specimen. In this way, the specimen was connected with the steel plate and was loaded through a spherical joint system. The spherical joint can reduce the eccentricity by automatically adjusting the location of the specimen [28]. The experiments above were all controlled by displacement with the rate of 1.6 mm/min.

2.4.2. Porosity. The most common method to measure porosity is to immerse the specimen in water for 24 h and obtain porosity through wet weight and dry weight. In this study, the porosity of RAPC was measured through a new method (Figure 3) and compared with the pore structure of CT scanning. Based on the test results, the porosity obtained from the new method is consistent with other methods, which verified the applicability of the new method. The experimental steps are as follows:

1. The mass error of each specimen was within 0.1 g, and the mass was recorded as initial mass.
2. The specimen was dried in an oven for 24 h at the temperature of 37.8 °C, and the dry mass was recorded as $W_{D}$.
3. The height and diameter of each specimen were measured and recorded.
4. The average height ($H_{avg}$) and average diameter ($D_{avg}$) of each specimen were obtained from step 3.
5. The volume of the specimen ($V_{T}$) was calculated by using the average height ($H_{avg}$) and the diameter ($D_{avg}$).
6. The specimen was immersed underwater for 30 min. After 30 min, knock on the bottom of the container to promote the escape of bubbles in the pervious concrete, and the intensity and frequency of the knock should not cause damage to the specimen or container.
7. The mass of the specimen was measured underwater ($W_{S}$), and a mesh bag was used to hold the concrete.
8. The porosity was calculated as follows:

$$ P(\%) = \left(1 - \frac{(W_{D} - W_{S})/\rho_{w}}{V_{T}} \right) \times 100. \quad (1) $$

In addition, CT technology can detect the material nondestructively and visually display the internal structure. In this study, the pore structure and porosity of RAPC were analyzed by using CT scanning, and the change of the porosity on each slice was calculated through the segmentation of gray values.

2.4.3. Permeability. The permeability test referred to ACI 522R-06 and some research (Neithalath, N., et al., 2004; Neithalath, N., Weiss, J., et al., 2006). In this study, the variable head method was used to measure the permeability coefficient of RAPC. The experimental apparatus is a self-made permeability coefficient measuring instrument (Figure 4), 1 is a filter (supporting the upper part at the same time), 2 represents the specimen, 3 is the plexiglass, 4 is the stop valve, and 5 is the cling film wrapping the specimen (to prevent voids and lateral leakage).

The calculation of the permeability coefficient is as follows:

$$ k = \frac{aL}{At} \ln \left( \frac{h_{1}}{h_{2}} \right), \quad (2) $$

where $L$ is the height of the specimen, $A$ is the cross-sectional area of the specimen, ($h_{1}$, $h_{2}$) is the water level difference, $a$ is the cross-sectional area of the variable head pipe, and $t$ is the time for the water level to drop.

2.4.4. Water Retention. Water can evaporate from the surface of the cylinder; thus, the bottom of the PVC pipe was wrapped by the cling film and pasted with Vaseline to block the water leakage [29]. The experimental steps are as follows:

1. The specimen was immersed in water for 24 h to make pores be filled with water and then was taken out to be weighed. Moisture on the surface of the specimen was wiped to obtain the mass $M_{0}$.
2. The specimen was sealed at the bottom and placed in a standard curing room with the temperature and relative humidity of 20°C and 80%, respectively, and the mass was weighed after 1 h, 3 h, 5 h, and every 24 h until the tenth day (Figure 5).

The formula of water retention is as follows:

$$ K = \frac{m_{S} - m_{D}}{V}, \quad (3) $$

where $K$ is water conservation (g/cm$^3$), $m_{S}$ and $m_{D}$ are the wet and dry mass (g), and $V$ is the volume of the specimen (cm$^3$).

3. Experimental Results

3.1. Strength. In this section, the mechanical properties of pervious concrete with different RA contents were tested, including compressive strength, splitting tensile strength, flexural tensile strength, and uniaxial tensile strength. The
test results showed that the mechanical properties of RAPC decreased with the increase in RA contents.

Three samples were used for each loading condition. Considering the small deviation of the results, the average value was used for discussion. The strength of RAPC is shown in Table 3.

3.1.1. Compressive Strength. The damage pattern of RAPC under uniaxial compression is shown in Figure 6. The effect of different RA content on the compressive strength is presented in Table 3, from which it can be found that the compressive strength decreased with increasing RA content. The compressive strength of RAPC0 was 44.996 MPa, and
the compressive strength of RAPC25 decreased to 32.723 MPa. RAPC0 contains no RA, and its coarse aggregate is all NA. From the aggregate properties in Table 1, it can be seen that the crushing value of NA is small, which indicates its strong resistance to crushing and high strength, so the compressive strength of RAPC prepared with NA is higher. In addition, the cementation between RA and cement matrix is weak, and damage occurs in this weak zone. In addition, RA obtained from waste concrete contains a large number of microcracks, which leads to a lower strength. Moreover, RA has better water absorption than NA, which means that RA can absorb much water in concrete, and thus the rest of the water is inadequate to make the cement complete hydration. The uniform mortar layer can not be formed on the surface of aggregate. Under normal circumstances, the compressive strength of pervious concrete is 5–20 MPa [30]. The experimental results manifest that although the compressive strength of RAPC decreased with the increase in RA, it is still within the normal range, so RAPC can satisfy the strength requirements of sidewalks and bicycle lanes.

3.1.2. Splitting Tensile Strength. The damage pattern of RAPC under splitting tension is shown in Figure 7. From Table 3, it can be found that with the increase in RA, the splitting tensile strength exhibited a significant downward trend. When the NA is completely replaced, the splitting tensile strength decreased from 2.382 MPa to 1.373 MPa (loss rate is 42%), which is mainly due to the increase in porosity. In addition, the cementation of RA and cement matrix is very weak, which leads to a significant reduction in splitting tensile strength. When the NA was partially replaced, the fracture surface of the specimen penetrated the RA.

3.1.3. Flexural Tensile Strength. The three-point bending strength and four-point bending strength of RAPC0 were 2.543 MPa and 3.318 MPa, respectively. However, with the increase in RA, the three-point bending strength and four-point bending strength of RAPC exhibited a significant downward trend, which decreased to 1.324 MPa and

### Table 3: The strength of RAPC.

| Specimen type | Compressive strength (MPa) | Splitting tensile strength (MPa) | Three-point bending strength (MPa) | Four-point bending strength (MPa) | Direct tensile strength (MPa) |
|---------------|---------------------------|---------------------------------|-----------------------------------|---------------------------------|-------------------------------|
| RAPC0         | 44.996 (σ = 1.039)        | 2.382 (σ = 0.089)               | 2.543 (σ = 0.075)                 | 3.318 (σ = 0.101)               | 2.301                         |
| RAPC25        | 32.723 (σ = 1.256)        | 2.062 (σ = 0.094)               | 1.865 (σ = 0.106)                 | 2.704 (σ = 0.116)               | 2.250                         |
| RAPC50        | 29.861 (σ = 1.291)        | 1.936 (σ = 0.109)               | 1.771 (σ = 0.116)                 | 2.508 (σ = 0.113)               | 2.131                         |
| RAPC75        | 21.365 (σ = 1.634)        | 1.775 (σ = 0.111)               | 1.736 (σ = 0.129)                 | 2.059 (σ = 0.129)               | 1.400                         |
| RAPC100       | 15.324 (σ = 1.985)        | 1.373 (σ = 0.121)               | 1.324 (σ = 0.125)                 | 1.681 (σ = 0.134)               | 1.201                         |

σ represents the overall standard deviation.
3.1.4. Uniaxial Tensile Strength. The uniaxial tensile strength of RAPC decreased with increasing RA content, and the greater the RA content was, the faster the tensile strength decreased. When RA was less than 50%, the loss of strength was relatively small (Figure 9). Meanwhile, the elastic modulus also exhibited a downward trend.

3.2. Porosity

3.2.1. A New Method. A cylinder of $D=74$ mm and $H=100$ mm was used to obtain the porosity. The relationship between porosity and the amount of RA is shown in Figure 10, and it can be seen that the porosity increased from 2.70% to 13.43% when RA increased from 0% to 100%.

As can be seen from Table 2, the content of RA with a particle size of 9.6~15 mm is more than that of NA in this study. When NA was replaced, the amount of coarse aggregate with a size less than 9.6 mm decreased, which means the reduction of small aggregate. Therefore, micropores in concrete gradually disappeared and larger pores were formed, and the porosity of the specimen increased with increasing RA.

3.2.2. CT Scanning. The cross section and longitudinal section of RAPC under CT scanning are shown in Figure 11, and the pore structure of the specimen was also analyzed. The instrument can scan the object continuously, obtain data according to the X-ray absorption and transmissivity of different materials, and collect the cross-sectional image in an arbitrary direction through model reconstruction.

Due to the difference of density between air and RAPC, there is a large discrepancy in the two materials’ X-ray attenuation coefficient at the interface between the specimen and air, causing heavy shadows and poor image quality at both ends of the specimen that cannot be used for analysis. Therefore, it is necessary to screen out the useable cross-sectional image. 2~4 images were removed at each end, and 150 cross-sectional images with a layer space of 0.67 mm were obtained. By using the Philips medical image processing station ISP6.0, the screened cross-sectional images were reconstructed by VR and MRP.

After the reconstruction, 120 cross-sections with a thickness of 0.67 mm were selected. One layer was taken out every six layers along with the height of the sample, and thus 20 cross-sections were obtained. CT value is equivalent to the ratio of the difference between the attenuation coefficient of the material and the absorption of water and the attenuation coefficient of water and then multiplied by an indexing factor. The CT value reflects the density of the material, and the higher the CT value is, the greater the gray values are, and the larger the density is. The dark portion of the image represents the pores and the air, while the gray and white portions represent the aggregate. Within these sections, the size and distribution of pores in each layer can be seen clearly. The maximum length of the narrow pore is 30 mm (generally 10~20 mm), and the maximum diameter of the round pore is about 10 mm (generally 2~7 mm). The narrow and long pores are mainly distributed at the edge or around the center of the sample.

The CT value threshold segmentation method was used to distinguish between the aggregate and the pore. The CT value ranges from −1024 to +3071, and each pixel in the cross section corresponds to a determined CT value. Among these values, the CT value of the pore is −500, the CT value of the aggregate is over 1000, and thus the segment with a CT value greater than 500 was considered to be the aggregate, and the segment less than 500 was considered to be the pore.

The porosity of each layer can be obtained from the ratio of the pixels of pores and the pixels of the whole cross section, and the porosity of RAPC (5 samples labeled as 1~5) along with the height was obtained (Figure 12). The porosity in the middle layers (5-15 layers) had small fluctuation, generally less than 10%, indicating that the pore distribution in the middle of the specimen was uniform. The porosity fluctuation at both ends of the specimen was more than 10%, indicating that the pores distributed unevenly at both ends of the specimen. In addition, the porosity of each layer increased with increasing RA content.

Based on the difference of density between the aggregate and the pore, the specimen was 3D reconstructed and the aggregate was extracted. Figure 13(a) shows the aggregate, Figure 13(b) shows the pore, and Figure 13(c) presents the whole specimen.

The volume of the voids is $V_j$, the height of the specimen is $H$, the area of the cross section is $S$, and the volume of the specimen is $V = S \times H$. The porosity is

$$n = \frac{V_j}{V}. \quad (4)$$

The porosity obtained from the new method was compared with that obtained from CT scanning, as shown in Figure 14. It is obvious that the porosity growing trends were

Figure 7: Damage pattern of RAPC under splitting tension.
Figure 8: Damage pattern of RAPC under bending flexural tests.

Figure 9: Stress-strain curves of RAPC under uniaxial tension. (a) RAPC0; (b) RAPC25; (c) RAPC50; (d) RAPC75; (e) RAPC100.
similar, but the porosity obtained from CT scanning was slightly higher than that obtained from the suggested method. The suggested method cannot detect the unconnected pores which cannot be passed by water and air, while CT scanning can accurately measure all pores, including connected pores and unconnected pores.

3.3. Pervious Properties

3.3.1. Permeability. The relationship between the permeability coefficient and RA content is shown in Figure 15; it can be seen that the permeability coefficient increased with increasing RA, which is consistent with the results obtained by Güneyisi et al. [11]. This indicates that the addition of RA is beneficial to the enhancement of permeability.

The porosity of the specimen increased with increasing RA content; it can be seen that the permeability coefficient is positively correlated with porosity. With the rise of the porosity, the connected pores and the water flow capacity increased, and thus the permeability coefficient was elevated. This result is consistent with that of Güneyisi et al. [11].

3.3.2. Water Retention. Figure 16 shows the relationship between water retention and evaporation time of RAPC; it can be seen that the evolution of water retention of RAPC is similar. The water retention initially decreased gently and then declined rapidly with the evaporation time elapsed.
Based on the water retention after 216 h of evaporation, the relationship between water retention and RA content is shown in Figure 17. When RA content increased from 0% to 50%, the water retention initially increased and then decreased to 1.56 g/cm³. When RA content exceeded 50%, the water retention increased gradually.

4. Conclusion
Based on the above tests, the influences of RA content on the mechanical properties and permeability of RAPC were discussed.
(1) The compressive strength, splitting tensile strength, bending flexural strength (i.e., three-point bending and four-point bending), and uniaxial tensile strength of RAPC decreased by 65.94%, 42.36%, 47.94%, 49.34%, and 47.81% when RA content raised from 0% to 100%, which is due to the weak cementation between RA and cement matrix, a large number of microcracks and defects in RA, and the inadequate hydration of cement.

(2) Two methods of measuring porosity were compared. The porosity increased from 2.70% to 13.43% with increasing RA; this is because the amount of aggregate in NA with a size less than 9.6 mm decreased, leading to the disappearance of micropores and the formation of large pores. The same result was obtained through CT scanning, which was more accurate than the laboratory method.

(3) The increase in RA led to the increase in porosity. In addition, RA contains microcracks and defects, which makes it easier for water to flow through. Therefore, the addition of RA can improve the permeability of RAPC. The water retention after 216 h of evaporation increased with increasing RA content, and the addition of RA manifested a positive influence on water retention.

(4) The compressive strength decreased by 8.7% when the RA content increased from 25% to 50%, but it met the strength requirement of C30. The compressive strength decreased by 28.5% when the RA content increased from 50% to 75%, and it did not meet the strength requirement of C30. The permeability of RAPC 50 increased by 59.1% compared with RAPC 25. The choice of RA content should consider the mechanical properties and permeability. Therefore, RAPC 50 is a suitable choice.

Although the mechanical properties of RAPC were weakened, they can still meet the requirements of practical engineering. Such recycling can save resources, consume construction waste, and protect the environment. RAPC can absorb much water due to its high water permeability and water retention, which is beneficial to the growth of vegetation and the construction of a sponge city [15, 31–34].

Data Availability
The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest
The authors declare that they have no conflicts of interest.

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