Investigation of carbonation resistance of recycled aggregate concrete

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Abstract. This paper studied the carbonation resistance of recycled aggregate concrete (RAC) designed by two mix proportion design methods through accelerated carbonation test. The investigated variables include water-cement ratio, replacement ratio of recycled coarse aggregate (RCA), and carbonation time. Based on the test results, the effects of water-cement ratio, replacement ratio of RCA, mix proportion design method, and carbonation time on the carbonation resistance of RAC were analyzed and discussed. The results showed that the mix proportion design method has a significant effect on the carbonation resistance of RAC. The replacement ratio of RCA and the water-cement ratio alternately affected the carbonation resistance of RAC. The replacement ratio of RCA is the major factor affecting the carbonation resistance of RAC. In addition, a carbonation model for RAC considering the effect of the mix proportion design method was proposed. The comparison of the test values and calculated values indicates that the proposed model can properly predict the carbonation depth of RAC.

1. Introduction
Recently, with the rapid growth of the economy and population, more and more buildings and infrastructures are being built. Concrete, as the most widely used building material, is being used heavily, leading to significant consumption of the natural aggregates. Thereby lead to problems that natural aggregates shortage and environmental population. Thus, it is urgent to explore an effective measure to solve the problems. Meanwhile, numerous construction wastes are being generated in the demolition of old buildings [1,2]. The improper disposal of these wastes will cause a series of environmental problems [3]. Recycled aggregate concrete (RAC) is produced with recycled aggregates instead of natural aggregates. The recycled aggregates are made by construction wastes. So, using RAC instead of conventional ordinary concrete in construction can not only alleviate the shortage of natural aggregates but also solve the disposal problems of numerous construction wastes, which accords with the idea of sustainable development.

Previous studies [4,5] have proved that it is feasible to use of RCA in substitution to natural aggregate in production of concrete. Cabral et al. [6,7] observed that the tensile strength, cube compressive strength and elastic modulus of RAC are less than that of ordinary concrete, and the effect of recycled fine aggregate (RFA) on the mechanical properties of RAC is also less than that of RCA. However, Butler et al. [8] pointed out that the RAC splitting tensile strength is similar to ordinary concrete. Lima et al. [9] found that the compressive strength and tensile strength of RAC decrease with the increase of the replacement ratio of RCA. Deng et al. [10-13] found that the quality
of RCA has a significant effect on the mechanical properties of RAC. Kou et al. [14] also observed that the mechanical properties of RAC made from high-quality RCA are not poorer than ordinary concrete. However, some studies [15-17] reported that the compressive strength of RAC would not be affected by the RCA.

The durability is an important property for concrete [18]. Previous studies [19-21] pointed out that as the replacement ratio of RCA increases, the deterioration ratio of mechanical properties of RAC is lower than that of durability properties. Xiao et al. [22] found that the microstructure of RAC is more complex than that of ordinary concrete; because of that, there are more interfacial transition zones (ITZ) in RAC, and the old mortar on RCA has many initial damage microcracks. Otsuki et al. [23] pointed out that due to the effect of the old ITZ and old mortar in RCA, the carbonation depth and the chloride ion permeability of RAC are slightly higher than that of ordinary concrete. Bravo et al. [24] also found that the durability of RAC is poorer than ordinary concrete. But the durability of RAC made from different RCA is significantly different. Faella et al. [25] pointed out that the high porosity of RCA is the major reason causing the poor durability of RAC. Lovato et al. [7, 18, 26-28] found that the carbonation depth of RAC is higher than that of ordinary concrete under the same condition, and the effect of RFA is greater than that of RCA. Silva et al. [18] conducted that the carbonation depth of RAC would be twice as high as that of ordinary concrete when the replacement ratio of RCA reaches to 100%. However, some studies [29-32] found that the carbonation depth of RAC is no worse than that of ordinary concrete.

Summarizing the literature mentioned above, it is found that the previous study results on the carbonation resistance of RAC are high discrete, which is the result of used different RCAs and different mix proportion design methods. Although the carbonation resistance of RAC has been studied by some scholars, studies about the effect of mix proportion design method on the carbonation resistance of RAC and prediction model for the carbonation depth of RAC considering the effect of mix proportion design method are rare. Therefore, the present study aims to investigate the carbonation resistance of RAC and establish the corresponding carbonation depth prediction model; the investigated variables include the RAC mix proportion design method, RCA replacement ratio, and water-cement ratio. For this goal, a total of 150 specimens were designed and tested. Based on the test results, the effect of the RAC mix proportion design method, RCA replacement ratio, and water-cement ratio on the carbonation resistance of RAC were analyzed and discussed, respectively. In addition, a RAC carbonation depth prediction model considering mix proportion design method, RCA replacement ratio, and water-cement ratio was established. The results of this study can expand the database of RAC carbonation depth and help to further understand the carbonation resistance of RAC.

2. Materials and testing procedure

2.1. Raw materials

Gumiao Brand P.O 42.5 ordinary Portland cement produced by Huahong Cement Co., Ltd. Guangxi, China was used in this test, and Table 1 listed its main physical properties tested according to GB175 [33]. The mixing water was tap water. The crushed stone from the Gravel Plant in Nanning was used as the natural coarse aggregate (NCA). The RCA used was made from the abandoned concrete collected from Nanning Express Ring Road. The abandoned concrete used in this study has been discarded by the road for a long time and attached with a lot of dust and asphalt. An appropriate amount of sample for this study was collected randomly and transported to the laboratory. After the process of crushing, washing, and sieving, the RCA used in this study was finally obtained and shown in Figure 1. The natural fine aggregate (NFA) used was Yongjiang river sand obtained from the Gravel Plant in Nanning. The physical properties of RCA, NCA, and NFA were tested following the code JGJ 52 [34] and shown in Table 2.
Figure 1. Recycled coarse aggregates.

Table 1. Main parameters of P.O.42.5.

| Ignition loss of cement /% | Sieve residue /% | Normal consistency /% | Setting time /h:min | Flexural strength /MPa | Compressive strength /MPa |
|----------------------------|------------------|-----------------------|---------------------|-----------------------|-------------------------|
|                            |                  |                       | Initial             | Final                 | 3 d                     | 28 d                    |
| 2.23                       | 0.4              | 26.8                  | 2:25                | 3:36                  | 5.42                    | 8.83                    |

Table 2. Physical properties of aggregate.

| Type of aggregate | Bulk density /Kg/m³ | Maximum size /mm | Water absorption /% | Moisture content /% | Crushing index /% | Fineness modulus |
|-------------------|---------------------|------------------|--------------------|---------------------|------------------|-----------------|
| NAC               | 2670                | 31.5             | 1.35               | 0.46                | 13               | -               |
| RCA               | 2545                | 31.5             | 4.32               | 0.68                | 33.52            | -               |
| NFA               | 2610                | 4.75             | 1.04               | -                   | -                | 2.8             |

2.2. Mix proportions

For RAC, there are three commonly used mix proportion design methods. The first one is to design the RAC as same as ordinary concrete. The second one is to design the RAC using pre-absorbent aggregate according to the ordinary concrete design method. The third one is to design the RAC based on the free water-cement ratio. According to previous studies on the mix proportion design of RAC [35-38], it is found that the performance and mechanical properties of RAC designed with different mix proportion design methods are different. In this study, for a better discussion on the effect of both water-cement ratio and RCA replacement ratio on the carbonation resistance of RAC, we designed the RAC specimens with the first and the third mix proportion design methods. The mix proportions used are shown in Table 3, and the additional water used in the third mix proportion design method was calculated by Eq. (1).

\[ AW = m_{RA}(W_{RA} - W_h) \]  

Table 3. Mix proportions.

| Number | Water/Cement | RCA ratio /% | Water /kg | Additional water /kg | Cement /kg | NFA /kg | NCA /kg | RCA /kg | Slump /mm |
|--------|--------------|--------------|-----------|----------------------|------------|---------|---------|---------|-----------|
| R4500  |              | 0            | 209       | 0                    | 465        | 628     | 1161    | 0       | 90        |
| R4503  |              | 30           | 209       | 0                    | 465        | 628     | 813     | 348     | 90        |
| R4505  |              | 0.45         | 209       | 0                    | 465        | 628     | 580.5   | 580.5   | 85        |
| R4507  |              | 70           | 251       | 0                    | 558        | 628     | 348     | 813     | 85        |
| R4510  |              | 100          | 251       | 0                    | 558        | 628     | 0       | 1161    | 80        |
|     |     |     |     |     |     |     |     |     |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| R5500 | 0   | 209 | 0   | 380 | 709 | 1156 | 0   | 95  |
| R5503 | 30  | 209 | 0   | 380 | 709 | 809  | 347 | 95  |
| R5505 | 0.55 | 50  | 209 | 0   | 380 | 709  | 578 | 578 | 95  |
| R5507 | 70  | 251 | 0   | 456 | 709 | 347  | 809 | 90  |
| R5510 | 100 | 251 | 0   | 456 | 709 | 0    | 1156| 90  |
| R6500 | 0   | 222 | 0   | 342 | 772 | 1158 | 0   | 100 |
| R6503 | 30  | 222 | 0   | 342 | 772 | 811  | 347 | 100 |
| R6505 | 0.65 | 50  | 266 | 0   | 410 | 772  | 579 | 579 | 100 |
| R6507 | 70  | 266 | 0   | 410 | 772 | 347  | 811 | 100 |
| R6510 | 100 | 266 | 0   | 410 | 772 | 0    | 1158| 95  |
| F4500 | 0   | 209 | 0   | 465 | 628 | 1161 | 0   | 95  |
| F4503 | 30  | 221.7 | 12.7 | 465 | 564 | 813  | 348 | 95  |
| F4505 | 0.45 | 50  | 230.1 | 21.1 | 465 | 564  | 599 | 599 | 85  |
| F4507 | 70  | 238.6 | 29.6 | 465 | 564 | 356  | 842 | 85  |
| F4510 | 100 | 251.3 | 42.3 | 465 | 564 | 0    | 1198| 85  |
| F6500 | 0   | 222 | 0   | 342 | 772 | 1158 | 0   | 100 |
| F6503 | 30  | 234.6 | 12.6 | 342 | 667 | 811  | 347 | 100 |
| F6505 | 0.65 | 50  | 243.1 | 21.1 | 342 | 667  | 579 | 579 | 95  |
| F6507 | 70  | 251.5 | 29.5 | 342 | 667 | 347  | 811 | 95  |
| F6510 | 100 | 264.2 | 42.2 | 342 | 667 | 0    | 1158| 95  |

Number Description: ‘R’ represents the recycled aggregate concrete designed following ordinary concrete, and ‘F’ represents recycled aggregate concrete designed based on free water-cement ratio. And the first two figures represent its water-cement ratio, and the last two figures represent its RCA replacement ratio, for example, ‘R4510’ represents RAC designed following ordinary concrete, and its water-cement ratio and RCA replacement ratio are 0.45 and 100%, respectively.

2.3. Specimen production and testing methods

2.3.1. Compressive specimens Prepare the concrete according to Table 3 and put it into 150 mm × 150 mm × 150 mm plastic cube molds when the slump of the fresh concrete is between 80 mm and 100 mm. Next, put them on a vibrating table to be shaken and levelled. The vibratory compacted specimens were placed in a standard concrete curing room for 24 hours and then demoulded. The specimens were then placed back in the curing room. Measured the compressive strength of specimens after 28 days following the code GB/T 50081 [39].

2.3.2. Carbonation specimens Carbonized specimens were made with the same method as compressive specimens, whose size was 100 mm × 100 mm × 300 mm and cured for 24h before demoulded. After demoulding, all specimens were sealed with epoxy resin except for the two pressure surfaces leaving for carbonation. Next, all treated specimens were carbonized in a carbonation chamber at a temperature of 20 ± 0°C, a carbon dioxide concentration of 20 ± 3%, and a relative humidity of 70 ± 5%. The carbonation depth of all specimens was tested according to GB/T 50082 [40] at the ages of 3 d, 7 d, 14 d, 28 d, and 56 d, respectively.
3. Test results and discussion

3.1. Effect of water-cement ratio

3.1.1. RAC designed following ordinary concrete Figure 2 shows the relationship between the carbonation depth and water-cement ratio of RAC designed according to the mix proportion design method of ordinary concrete. It can be seen that the carbonation depth of RAC increases with the increase of water-cement ratio, regardless of the replacement ratio of RCA. The reason is that the greater the water-cement ratio, the more the micropores and defects in RAC. However, under the different RCA replacement ratios, the level of the effect of the water-cement ratio on the carbonation depth of RAC is different. When the RCA replacement ratio is less than 50%, the increasing rate of carbonation depth slows or remains basically unchanged with the increase of water-cement ratio. While the RCA replacement ratio becomes greater than 50%, the increasing rate of carbonation depth increases with the increase of water-cement ratio, and this phenomenon becomes more noticeable when the RCA replacement ratio reaches 100%. This is because the RCA has both negative and positive effects on the carbonation resistance of RAC. On the one hand, the high water absorption of RCA makes the ITZ in RAC more compact, which increases the carbonation resistance of RAC. On the other hand, the initial damage cracks and high porosity of RCA weaken the carbonation resistance of RAC. When the RCA replacement ratio is low, the positive and negative effects of RCA are roughly counterbalanced. But, in the case of a higher RCA replacement ratio, the negative effects of RCA are greater than the positive ones. It can also be noted that as the water-cement ratio increases, both of the carbonization depth and its increasing rate of RAC is lower than that of ordinary concrete. Because of that, the effective water-cement ratio of RAC designed following ordinary concrete is lower than that of ordinary concrete under the same nominal water-cement ratio.

3.1.2. RAC designed based on free water-cement ratio Figure 3 shows the relationship between the carbonation depth and water-cement ratio of RAC designed based on free water-cement ratio. It can be seen that the carbonation depth of RAC also increases with the increase of water-cement ratio. But, compared with the RAC designed following the ordinary concrete, the carbonation depth of RAC designed based on free water-cement ratio is higher.

3.2. Effect of RCA replacement ratio

3.2.1. RAC designed following ordinary concrete Figure 4 shows that when the water-cement ratio is 0.45, the effect of the RCA replacement ratio on the carbonation depth of RAC is insignificant. When the water-cement ratio is 0.55, the carbonation depth of RAC is lower than that of ordinary concrete and decreases with the increase of RCA replacement ratio. When the water-cement ratio is 0.65, the carbonation depth of RAC is also lower than that of ordinary concrete, but first decreases and then increases with the increase of RCA replacement ratio. The reason is that when the water-cement ratio is low, the positive effects of RCA due to its high water absorption and the negative effects of RCA due to its initial damage defects cancel each other out. But when the water-cement ratio is high, the positive effects of RCA is greater than its negative effects. Thus, the carbonation depth of RAC shows a decreasing trend with the increase of the RCA replacement ratio. However, if the RCA replacement ratio is too high, its negative effects will outnumber its positive effects gradually, which causes an increase in carbonation depth.

3.2.2. RAC designed based on free water-cement ratio Figure 5 shows that regardless of what the water-cement ratio is, the carbonation depth of RAC increases with the increase of RCA replacement ratio, and its increasing rate is faster when the water-cement ratio is lower. The reason is that the positive effects of RCA due to its high water absorption were cancelled by the additional water. But the negative effects of RCA due to its initial damage defects still work.
Figure 2. The relationship between the carbonation depth and water-cement ratio of RAC designed following ordinary concrete. (Note: In the legend, the prefix ‘N’ represents the ordinary concrete, i.e. RAC with an RCA replacement ratio of 0%; ‘R’ represents RAC).

Figure 3. The relationship between the carbonation depth and water-cement ratio of RAC designed based on free water-cement ratio. (Note: In the legend, the prefix ‘N’ represents the ordinary concrete, i.e. RAC with an RCA replacement ratio of 0%; ‘R’ represents RAC).
3.3. Effect of mix proportion design method

Figure 6 shows the effect of the mix proportion design method on the carbonation depth of RAC. It can be seen that regardless of what the water-cement ratio is, the carbonation depth of RAC designed following ordinary concrete is much lower than that of RAC designed based on the free water-cement ratio. The higher the RCA replacement ratio, the greater the difference between the carbonation depth of the two types of RAC. The reason is that the effective water-cement ratio of the RAC designed following ordinary concrete is smaller than that of RAC designed based on the free water-cement ratio, and the higher the replacement ratio of RCA, the greater the difference between the effective water-cement ratio of the two types of RAC.

Figure 4. The relationship between the carbonation depth and RCA replacement ratio of RAC designed following ordinary concrete.

Figure 5. The relationship between the carbonation depth and RCA replacement ratio of RAC designed based on free water-cement ratio.

Figure 6. The comparison of the carbonation depth of RAC designed by the two mix proportion design methods. (Note: ‘F’ denotes the RAC designed based on free water-cement ratio; ‘R’ denotes the RAC designed following ordinary concrete, and the last two numbers denote the carbonation time).
3.4. Relationship between carbonation depth and time.

Figure 7 illustrates the relationship between the carbonation depth of RAC and carbonation time. It can be seen that the carbonation depth of RAC increases with the increase of carbonation time. Sagoe et al. [41] pointed out that the carbonation depth of RAC is a power function related to the carbonation time (Eq. (2)), and the majority of scholars believe that the exponent of the power function is 0.5. After fitting the test data using the power function Eq. (2), it is found that the power exponent is between 0.30 and 0.46, and the adjusted correlation coefficient R² is between 0.75 and 0.98, which indicates that Eq. (2) can well describe the relationship between the carbonation depth and carbonation time.

\[ X_c = \alpha t^\beta \]  

Where: \( \alpha, \beta \) are undetermined coefficient.

Figure 7. The relationship between the carbonation depth of RAC and carbonation time.

(a) RAC designed following ordinary concrete  
(b) RAC designed based on free water-cement ratio

3.5. Gray correlation analysis

As the carbonation process of RAC is affected by many factors and associated with uncertainty, it can be considered as a gray system [42], which means that the primary and secondary relationship of the effect of various factors on the RAC carbonation resistance can be analyzed by the gray correlation analysis. In this paper, an improved gray relational algorithm [43] was used to analyze the test data, and the calculation results are listed in Table 4. As shown in Table 5, when RAC designed following ordinary concrete, the correlation of water-cement ratio and RCA replacement ratio to the carbonation depth of all ages specimens are positive and negative, respectively. It indicates that the water-cement ratio is positively correlated with the carbonation depth of RAC, while the RCA replacement ratio is negatively correlated with the carbonation depth of RAC. When RAC designed based on the free water-cement ratio, both of the correlation of water-cement ratio and RCA replacement ratio to the carbonation depth of all ages specimens are positive. It indicates that both of the RCA replacement ratio and water-cement ratio are positively correlated with the carbonation depth of RAC. These conclusions are consistent with these conclusions of the qualitative analytical conclusions obtained above. The value of \( \gamma_p/\gamma_C \) is all greater than 1, which indicates that for the two mix proportion design methods of RAC, the replacement ratio of RCA is the primary factor that influences the RAC carbonation depth, and the water-cement ratio is the subordinate factor. Figure 8 shows the relationship between the correlation (or relative correlation) and carbonation time. It can be seen that for the two mix proportion design methods of RAC, the correlation of water-cement ratio to RAC carbonation depth changes very little with the increase of the carbonation time, which means that the effects of water-cement ratio on the carbonation depth of RAC in different carbonation times are basically the same. When RAC designed following ordinary concrete, the relative influence of water-cement ratio and RCA replacement ratio on the carbonation depth of RAC first decreases and then increases with the increase of the carbonation time. However, when RAC designed based on the free water-cement ratio, the opposite trend is shown.
4. Recycled aggregate concrete carbonation model

4.1. Establishment of the carbonation model

Chinese Standard "Standard for durability assessment of concrete structures" [44] gives the ordinary concrete carbonation model. However, the microstructure of RAC is more complicated than that of ordinary concrete, and the influential factors of RAC are also more than that of ordinary concrete. Thus, the carbonation model of ordinary concrete is not suitable for RAC. According to the previous analysis, the carbonation depth of RAC is a power function relationship with the carbonation time. The results of this study and some other studies [45-47] also indicate that all of the RCA replacement ratio, water-cement ratio, mix design method are significantly affect the RAC carbonation resistance. Thus, taking these factors into account, a correcting model Eq. (3) based on this standard is obtained.

\[
x_c = K_R a K_c K_{\rho} K_{\gamma} T^{0.25} R^{1.5} (1 - R) \frac{A}{K_p f_{cu}} + B \right)^C
\]

Where: \( K_R = \alpha \gamma + \beta; \ K_{C2} = \frac{C_{C2}}{C_{C1}} \); corner area take \( K_{\rho} = 1.4 \), non-corner area take \( K_{\rho} = 1.0 \); under pressure take \( K_{\gamma} = 1.0 \), under tension take \( K_{\gamma} = 1.7 \); \( A, B, C \) are undetermined coefficient.

According to the previous analysis, the rule of carbonation resistance of RAC with the RCA replacement ratio of less than 50% and more than 50% are different. So, the authors use Eq. (2) to fit the test data with a replacement ratio of RCA subdivided by 50%. The undetermined parameters and the recommended \( K_p \) values in the RAC carbonation depth prediction model are shown in Table 5. As shown in Table 6, the predictive values agree well with the test value. It indicates that the established carbonation model can effectively model the carbonation resistance of RAC.

Table 4. Correlation.

| Age/d | RAC designed following ordinary concrete | RAC designed based on free water-cement ratio |
|-------|-------------------------------------------|-----------------------------------------------|
|       | \( \gamma_c \) | \( \gamma_\rho \) | \( |\gamma_\rho / \gamma_c| \) | \( \gamma_c \) | \( \gamma_\rho \) | \( |\gamma_\rho / \gamma_c| \) |
| 3     | 0.114 | -0.674 | 5.926 | 0.095 | 0.767 | 8.107 |
| 7     | 0.126 | -0.339 | 2.691 | 0.094 | 0.770 | 8.216 |
| 14    | 0.119 | -0.261 | 2.190 | 0.095 | 0.769 | 8.085 |
| 28    | 0.128 | -0.410 | 3.213 | 0.096 | 0.766 | 7.941 |
| 56    | 0.125 | -0.554 | 4.429 | - | - | - |

Table 5. Model parameters and the \( K_p \) recommended values.

| Replacement ratio | \( \alpha \) | \( \beta \) | \( A \) | \( B \) | \( C \) | \( K_p \) |
|-------------------|-------------|-------------|--------|--------|--------|--------|
|                   | P1 | P2 | P3 |
| Not more than 50% | -0.517 | 102.939 | 4.989 | -0.144 | 0.383 | 1.00 | 0.89 | 0.571 |
| Greater than 50%  | 0.794 | 35.712 | 5.294 | -0.136 | 0.426 | 1.00 | 0.92 | 0.517 |

Table 6. Comparison of the predictive values and the test values.

| Number | 7d | 28d |
|--------|----|-----|
|        | Test value/E | Model value/LM | LM/E | Test value/E | Model value/LM | LM/E |
| R4500  | 1.83 | 1.59 | 0.87 | 2.67 | 2.71 | 1.02 |
| R4503  | 2  | 1.96 | 0.98 | 4.17 | 3.34 | 0.80 |
| R4505  | 1.5 | 0.76 | 0.51 | 2.67 | 1.30 | 0.49 |
|   |   |   |   |   |   |
|---|---|---|---|---|---|
| R4507 | 2.17 | 0.92 | 0.42 | 4.00 | 1.65 | 0.41 |
| R4510 | 0.83 | 1.29 | 1.55 | 1.50 | 2.32 | 1.55 |
| R5500 | 4.33 | 5.27 | 1.22 | 7.50 | 8.97 | 1.20 |
| R5503 | 5.33 | 4.75 | 0.89 | 6.50 | 8.08 | 1.24 |
| R5505 | 3   | 3.49 | 1.16 | 4.17 | 5.94 | 1.43 |
| R5507 | 2.67 | 2.55 | 0.96 | 5.50 | 4.61 | 0.84 |
| R5510 | 1.5  | 2.05 | 1.37 | 2.50 | 3.71 | 1.48 |
| R6500 | 8.83 | 8.38 | 0.95 | 16.50 | 14.25 | 0.86 |
| R6503 | 6    | 5.67 | 0.95 | 11.33 | 9.65 | 0.85 |
| R6505 | 4.33 | 5.29 | 1.22 | 10.50 | 8.99 | 0.86 |
| R6510 | 4.33 | 4.57 | 1.06 | 8.50  | 8.26 | 0.97 |
| R6510 | 6.33 | 5.16 | 0.82 | 11.50 | 9.32 | 0.81 |
| F4500 | 1.83 | 3.08 | 1.68 | 2.67  | 5.23 | 1.96 |
| F4503 | 2.5  | 2.95 | 1.18 | 7.50  | 5.02 | 0.67 |
| F4505 | 3.8  | 4.03 | 1.06 | 8.60  | 6.86 | 0.80 |
| F4507 | 6.88 | 5.17 | 0.75 | 10.48 | 9.34 | 0.89 |
| F4510 | 7.95 | 7.14 | 0.90 | 12.20 | 12.88 | 1.06 |
| F6500 | 8.83 | 10.62 | 1.20 | 16.50 | 18.07 | 1.10 |
| F6503 | 10   | 9.10 | 0.91 | 16.80 | 15.47 | 0.92 |
| F6505 | 11.1 | 8.65 | 0.78 | 17.11 | 14.72 | 0.86 |
| F6507 | 12.72 | 10.32 | 0.81 | 20.04 | 18.62 | 0.93 |
| F6510 | 14.08 | 13.50 | 0.96 | 20.54 | 24.37 | 1.19 |
| E1   | 10.1 | 13.73 | 1.36 | 16.50 | 23.34 | 1.41 |
| E2   | 9.5  | 7.73  | 0.81 | 17.00 | 13.15 | 0.77 |
| E3   | 12.2 | 7.69  | 0.63 | 22.00 | 13.07 | 0.59 |
| E4   | 16.2 | 8.95  | 0.55 | 26.00 | 16.15 | 0.62 |
| E5   | 10.4 | 12.27 | 1.18 | 17.10 | 22.14 | 1.29 |
| D1   | 10.4 | 12.27 | 1.18 | 17.10 | 22.14 | 1.29 |
| D2   | 14.7 | 15.93 | 1.08 | 23.10 | 28.75 | 1.24 |
| D3   | 7.3  | 12.06 | 1.65 | 29.20 | 21.77 | 0.75 |
| D4   | 6.3  | 11.92 | 1.89 | 25.80 | 21.52 | 0.83 |

### 4.2. Verification of the carbonation model

To verify the carbonation model established above, the experimental data of literature [46] and [47] were selected. After calculating, it is found that the adjusted correlation coefficient between the predictive values and test values is $R^2=0.959$, which verifies the rationality and effectiveness of the carbonation model established above for RAC.
5. Conclusions
This study investigated the carbonation resistance of RAC designed by two mix proportion design by accelerated carbonation test. The effects of carbonation time, mix proportion design method, RCA replacement ratio, and water-cement ratio on the carbonation resistance of RAC were analyzed and discussed. Based on the test results and discussions, the conclusions can be drawn as follows:

The carbonation depth of RAC increases with the increase of water-cement ratio, and the carbonation depth of RAC with a higher water-cement ratio is more sensitive to the RCA replacement ratio than that of RAC with a lower water-cement ratio.

The effect of RCA replacement ratio on the RAC carbonation resistance is not always monotonous, which is influenced by the water-cement ratio and mix design method. When the RAC is designed following ordinary concrete and the water-cement ratio is lower, the RAC carbonation depth varies little with the RCA replacement ratio, but when the water-cement ratio is higher, the RAC carbonation depth decreases with the increase of the RCA replacement ratio. When the RAC is designed based on the free water-cement ratio, the carbonation depth of RAC increases with the increase of the RCA replacement ratio.

The mix proportion design method of RAC affected its carbonation resistance. The carbonation resistance of RAC designed following ordinary concrete is better than that of RAC designed based on the free water-cement ratio.

The RCA replacement ratio is the primary factor that influences the carbonation resistance of RAC regardless of its mix proportion design method.

The carbonation depth of RAC has a power function relationship with the carbonation time, and its power exponent is between 0.30 and 0.46.

A carbonation model for RAC considering the effect of the RCA replacement ratio and mix proportion design method was established. The established model can properly predict the carbonation depth of RAC.

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6. Appendix A

| Notations | Description |
|-----------|-------------|
| $AW$ | the additional water (Kg) |
| $m_{RA}$ | the mass of RCA (Kg) |
| $W_{a}$ | the water content of RCA (%) |
| $W_{Ra}$ | the water absorption of RCA (%) |
| $X_c$ | the carbonation depth |
| $K_{RA}$ | the influence coefficien of RCA replacement ratio |
| $K_{co2}$ | the influence coefficient of carbon dioxide concentration |
| $K_{ij}$ | the influence coefficient of position |
| $t$ | is the carbonation time |
| $\gamma$ | is replacement ratio of RCA |
| $C_0$ | is the volume of carbon dioxide |
| $R$ | is relative humidity |
| $T$ | is environment temperature |
| $K_p$ | is the influence coefficient of mix design method |
| $f_{cu}^{RC}$ | is the average compressive strength of RAC |

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