Prediction Formula for Absolute Water Consumption of Recycled Coarse Aggregate Concrete

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ABSTRACT: In order to ensure the construction performance of recycled concrete, and the influence of recycled coarse aggregate on water consumption of recycled concrete was studied, and used three kinds of recycled coarse aggregate with different quality to prepare recycled concrete with different replacement rate. Study the influence of recycled coarse aggregate quality and replacement rate on the absolute water consumption of recycled coarse aggregate concrete systemically. The experiment is based on the absolute water consumption of ordinary concrete, puts forward the formula for predicting the absolute water consumption of recycled coarse aggregate concrete based on aggregate quality and replacement rate for the first time. And based on the test date, the error of the prediction formula is compared. The results show that there is a good linear relationship between the absolute water consumption and the replacement rate of recycled coarse aggregate concrete. With the improvement of the quality of recycled coarse aggregate, the absolute water consumption is significantly reduced. According to the experimental data, the maximum calculation error of recycled aggregate concrete is -1.97%, which has high accuracy and good applicability.

1 INTRODUCTION

Compared with natural coarse aggregate, the high water absorption of recycled coarse aggregate is the biggest problem, as a result, the amount of water needed for recycled coarse aggregate concrete is greater than that of ordinary concrete, and there are many factors that affect the water consumption of recycled coarse aggregate concrete. Although some experts and scholars have carried out specific studies on the mix proportion design of recycled concrete, it has not given a strong applicability, high accuracy of recycled concrete water consumption forecast formula. Therefore, it is an urgent problem to establish a formula for predicting the water consumption of recycled concrete based on recycled coarse aggregate quality and replacement rate. It can also provide a theoretical basis for the formation of recycled concrete mix design rules.

But, the amount of water required for the recycled coarse aggregate concrete mixture is related to the quality of the recycled coarse aggregate, the manner of
use, the rate of substitution and so on, it is also affected by the different use conditions of the recycled coarse aggregate. According to the change of the environment of using recycled coarse aggregate, the water consumption of recycled coarse aggregate concrete mixture is divided into three cases:

1) Absolute water consumption: the recycled coarse aggregate in the preparation of recycled concrete in the dry state, at this time, the recycled coarse aggregate has no moisture inside and outside, which is represented by \( W_g \);

2) Additional water consumption: the recycled coarse aggregate is used as a state of natural environment in the preparation of recycled concrete, at this time, the moisture content of recycled coarse aggregate is closely related to atmospheric environment, and the internal or external aggregate may contain some water, which is represented by \( W \);

3) Effective water consumption: the recycled coarse aggregate is used as the dry state of the saturated surface when the recycled concrete is used, at this time, the internal moisture content of the recycled coarse aggregate is saturated, and no external moisture is absorbed, which is represented by \( W_{g0} \).

According to the different state of the recycled coarse aggregate in the preparation of recycled concrete, the relationship between the different water consumption can be obtained as shown in equations (1) and (2).

\[
W_g = W + m_c \omega_c \tag{1}
\]

\[
W_{g0} = W_g - m_c \omega_a \tag{2}
\]

In type: the \( m_c \) indicates the amount of recycled coarse aggregate, and the unit is kg/m\(^3\); the \( \omega_c \) indicates the moisture content of recycled coarse aggregate, \%; the \( \omega_a \) indicates the water absorption of recycled coarse aggregate, \%.

Taking into account the different water content of recycled coarse aggregate in the preparation of recycled concrete, in order to highlight the difference between the recycled coarse aggregate and the natural coarse aggregate, therefore, based on the absolute water consumption of recycled concrete and the absolute water consumption of ordinary concrete, a prediction formula of absolute water consumption of recycled concrete with high precision and wide application is obtained.

2 EXPERIMENTAL RESEARCH

2.1 Materials

The experiment using P·O 42.5 cement produced by Shanshui cement factory, and the natural fine aggregate using grade II river sand, and the natural coarse aggregate using 5~25mm continuous gradation of granite stone produced by Laoshan, and the recycled coarse aggregate or RCA are made up of the waste concrete through simple crushing of the jaw crusher, and then through the particle shaping equipment once or double physical enhancements, and the three kinds of RCA according to the "Recycled Coarse Aggregate for Concrete" (GB/T 25177-2010) for the determination of the performance index, the basic performance index of Table 1, and additive using polycarboxylic acid high performance water reducing agent, and water using tap water.
Table 1. Basic performance indexes of recycled coarse aggregate.

<table>
<thead>
<tr>
<th>Category</th>
<th>SC-RCA</th>
<th>OP-RCA</th>
<th>DP-RCA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle size distribution</td>
<td>Continuous grain size</td>
<td>Continuous grain size</td>
<td>Continuous grain size</td>
</tr>
<tr>
<td>Elongated and flaky particle/%</td>
<td>6</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Apparent density/(kg/m³)</td>
<td>2432</td>
<td>2468</td>
<td>2475</td>
</tr>
<tr>
<td>Packing density/(kg/m³)</td>
<td>1355</td>
<td>1389</td>
<td>1407</td>
</tr>
<tr>
<td>Porosity/%</td>
<td>44</td>
<td>44</td>
<td>43</td>
</tr>
<tr>
<td>Content of impurities/%</td>
<td>0.8</td>
<td>0.5</td>
<td>0.1</td>
</tr>
<tr>
<td>Content of harmful substances</td>
<td>Qualified</td>
<td>Qualified</td>
<td>Qualified</td>
</tr>
<tr>
<td>Alkali aggregate reaction</td>
<td>Qualified</td>
<td>Qualified</td>
<td>Qualified</td>
</tr>
<tr>
<td>Content of fine powder/%</td>
<td>1.9</td>
<td>1.1</td>
<td>0.8</td>
</tr>
<tr>
<td>Content of clay lump/%</td>
<td>0.6</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Water absorption /%</td>
<td>3.7</td>
<td>2.3</td>
<td>1.7</td>
</tr>
<tr>
<td>Crushing index/%</td>
<td>18</td>
<td>15</td>
<td>9</td>
</tr>
<tr>
<td>Soundness/%</td>
<td>8.9</td>
<td>5.7</td>
<td>3.1</td>
</tr>
<tr>
<td>Aggregate type</td>
<td>Class II</td>
<td>Class II</td>
<td>Class I</td>
</tr>
</tbody>
</table>

Notes: the SC-RCA means simple crushing recycled coarse aggregate; the OP-RCA means once physical enhancement recycled coarse aggregate; the DP-RCA means double physical enhancements recycled coarse aggregate.

2.2 Test Plan

Recycled coarse aggregate concrete test use a uniform ratio of 40% of the sand rate. The amount of polycarboxylic acid high performance water reducing agent is 1.2% of the amount of cementitious material. The amount of water used during the test was determined by adjusting the slump of the concrete mixture at (180 ± 20) mm. The effects of the following three factors on the performance of recycled coarse aggregate concrete were also considered in the experiment:

1. The amount of cementitious materials: 300 kg/m³, 350 kg/m³, 400 kg/m³, 450 kg/m³ and 500 kg/m³;
2. The kinds of recycled coarse aggregate: SC-RCA, OP-RCA and DP-RCA;
3. The replacement rate of recycled coarse aggregate: 0, 20%, 40%, 60%, 80% and 100%.

2.3 Test Results and Analysis

The linear regression relationship between the absolute water consumption and the substitution rate of the recycled concrete prepared by three different kinds of recycled coarse aggregate is shown in Fig.1.
It can be seen from Fig.1 that the absolute water consumption of the recycled concrete increases with the increase of the replacement rate of the recycled coarse aggregate, and a good linear relationship is obtained with different amount of cementitious material. The replacement rate of material is one of the important factors affecting the absolute water consumption of recycled concrete. In addition, with the upgrading of recycled coarse aggregate quality, the absolute amount of recycled concrete is reduced, which is in the same amount of cementitious materials and recycled coarse aggregate replacement rate, three kinds of recycled concrete absolute water consumption from less to more are as follows: DP-RCA > OP-RCA > SC-RCA.

### 3 ESTABLISHMENT OF PREDICTION FORMULA FOR ABSOLUTE WATER CONSUMPTION OF RECYCLED COARSE AGGREGATE CONCRETE

#### 3.1 Absolute Water Consumption Forecast Formula Form

Compared with ordinary concrete, the increase of absolute water consumption of recycled coarse aggregate concrete is mainly related to the quality and the replacement rate of recycled coarse aggregate. Therefore, the absolute water consumption of ordinary concrete is used as a reference, and the influence coefficient $\beta_g$ of absolute water consumption is introduced to reflect the effect of the addition of recycled coarse aggregate on the absolute water consumption of recycled concrete. The formula for predicting the absolute water consumption of recycled coarse aggregate concrete is shown in equation (3).
\[ W_{Rg} = W_0 + \beta_g \lambda_g \]  

(3)

In type: the \( W_{Rg} \) indicates the absolute water consumption of recycled coarse aggregate concrete, and the unit is kg/m\(^3\); the \( W_0 \) indicates the absolute water consumption of ordinary concrete, and the unit is kg/m\(^3\); the \( \lambda_g \) indicates the replacement rate of recycled coarse aggregate, \%.  

### 3.2 Calculation of Absolute Water Consumption Influence Coefficient

When the zero point of the linear regression equation of the absolute water consumption and the replacement rate of the recycled coarse aggregate concrete is normalized, the slope gradually decreases with the improvement of the quality of the recycled coarse aggregate. The better the quality of recycled coarse aggregate is, the smaller the effect of the addition of recycled coarse aggregate on the absolute water consumption of recycled coarse aggregate concrete is. So the slope can be defined as all kinds of recycled coarse aggregate concrete absolute water impact coefficient, which is represented by \( \beta_g \).

Considering the large dispersion of recycled coarse aggregate concrete tests, the average absolute water method is adopted (That is, when the replacement rate of recycled coarse aggregate is the same, the average value of absolute water consumption of recycled coarse aggregate concrete under five kinds of cementitious materials). The linear regression relationship between the average absolute water consumption and the replacement rate of the obtained recycled coarse aggregate concrete is shown in Fig.2. After conversion, the influence coefficient of the absolute water consumption of recycled concrete prepared by SC-RCA, OP-RCA and DP-RCA was 26.62, 19.18 and 15.76, respectively.

![Figure 2. Relationship between average absolute water consumption and replacement rate of recycled coarse aggregate concrete.](image)

### 3.3 The Relationship between Absolute Water Consumption Coefficient and Aggregate Quality

The influence coefficient of recycled aggregate concrete is related to the quality of recycled coarse aggregate, it is mainly expressed in the apparent density, water absorption rate and crushing index of recycled coarse aggregate. The linear regression results between the absolute water consumption coefficient of the three kinds of recycled coarse aggregate concrete and the performance indexes of the recycled coarse aggregate are shown in Table 2.
Table 2. Linear regression results between absolute water consumption coefficient and quality of recycled coarse aggregate.

<table>
<thead>
<tr>
<th>Category</th>
<th>Linear regression equation</th>
<th>Correlation coefficient $(R^2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_g-\rho_0$</td>
<td>$\beta_g=-0.238\rho_0+604.5$</td>
<td>0.949</td>
</tr>
<tr>
<td>$\beta_g-\omega_a$</td>
<td>$\beta_g=540.9\omega_a+6.635$</td>
<td>0.999</td>
</tr>
<tr>
<td>$\beta_g-Q_e$</td>
<td>$\beta_g=111.6Q_e+4.900$</td>
<td>0.696</td>
</tr>
</tbody>
</table>

Notes: the $\rho_0$ means apparent density of recycled coarse aggregate, and its unit is kg/m$^3$; the $\omega_a$ means water absorption of recycled coarse aggregate by decimals; the $Q_e$ means crushing index of recycled coarse aggregate by decimals.

3.4 Establish the Prediction Formula of Absolute Water Consumption of Recycled Coarse Aggregate Concrete

It can be seen from Table 2 that there is a linear relationship between the absolute water consumption coefficient of three kinds of recycled aggregate concrete and the performance indexes of recycled coarse aggregate concrete, the correlation is from large to small: $\omega_a>\rho_0>Q_e$. Therefore, it is possible to express the absolute water consumption coefficient of recycled coarse aggregate concrete by using the water absorption rate of recycled coarse aggregate. And bring the relationship between the two into the formula, the formula for predicting the absolute water consumption of recycled coarse aggregate concrete is obtained, as shown in equation (4).

$$W_{RG} = W_0 + (540.9\omega_a + 6.635) \lambda_g$$  \hspace{1cm} (4)

3.5 Error Analysis of Absolute Water Consumption Prediction Formula of Recycled Coarse Aggregate Concrete

In order to verify the accuracy and applicability of the absolute water consumption of recycled coarse aggregate concrete (shown in equation 4), the calculated values of the absolute water consumption of the three kinds of recycled coarse aggregate concrete are compared with the measured values. The error distribution is shown in Fig.3.
Figure 3. Comparison of experimental strength and calculated strength of recycled coarse aggregate concrete.

It can be seen from Fig.3 that there are some errors between the calculated values of the absolute water consumption and the measured values of the three kinds of recycled coarse aggregate concrete. After calculation, the total error range of absolute water consumption forecast formula of recycled aggregate concrete: (-1.97,1.63), the calculation error is small, the absolute water consumption of recycled coarse aggregate concrete calculated by equation (4) is closer to the measured value. It can be concluded that the absolute water consumption forecast formula of recycled coarse aggregate concrete based on recycled coarse aggregate quality and replacement rate has higher accuracy and better applicability, and it can be used to guide the establishment of mix proportion design of recycled coarse aggregate concrete.

4 CONCLUSIONS

(1) Compared with ordinary concrete, it is very complex to determine the water consumption of recycled coarse aggregate concrete. According to the different state of recycled coarse aggregate, the absolute water consumption of recycled concrete is better to show the differences between ordinary concrete and recycled coarse aggregate concrete.

(2) The absolute water consumption of recycled concrete increases with the increase of recycled coarse aggregate replacement rate. And the higher the quality of recycled coarse aggregate, the absolute water consumption of recycled coarse aggregate concrete is relatively reduced. The influence coefficient of absolute water consumption is from small to large: DP-RCA > OP-RCA > SC-RCA.

(3) The influence coefficient of absolute water consumption of recycled aggregate concrete is closely related to aggregate quality, the correlation is from large to small: water absorption > apparent density > crushing value.

(4) The calculation error of absolute water consumption forecast formula of recycled aggregate concrete based on recycled coarse aggregate quality and replacement rate is small, the maximum error is only -1.97%. It has high precision and good applicability.
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REFERENCES