Research Article

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Bond behavior of recycled coarse aggregate concrete with rebar after freeze–thaw cycles: Finite element nonlinear analysis

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Abstract: In this article, the bond performance of recycled coarse aggregate concrete with rebar after freeze–thaw cycles is analyzed by the ABAQUS finite element method. The result shows that the finite element simulation value of the ultimate bond strength of recycled aggregate concrete specimens is in good agreement with the experimental value, while the agreement between the finite element simulation value of the peak bond slip of recycled aggregate concrete specimens and the experimental value is low; the bond strength between rebar and recycled aggregate concrete increased with the increase of concrete strength and concrete cover depth; the calculation formula for the bond strength between recycled aggregate concrete specimens with different concrete strengths and different concrete cover depth after freeze and thaw cycles are obtained.

Keywords: recycled concrete, finite element, freeze–thaw cycles, concrete cover depth, concrete strength

1 Introduction

Concrete has become the preferred material for modern engineering structures due to the good working performance, and the bond performance between concrete and rebar is the basis for the two materials to work together [1]. Freeze–thaw damage is one of the important reasons for the degradation of frost resistance and mechanical properties of concrete [2]. The mechanical properties of concrete will also change after freeze–thaw cycles, thus affecting the bond performance between concrete and rebar [3]. The bond performance between concrete and rebar deteriorated after freeze–thaw cycles [4], and the maximum bond strength between concrete and rebar decreased gradually with the increase of the number of freeze–thaw cycles [5], while the slip corresponding to the maximum bond strength increased [6].

In recent years, the rapid development of the construction industry has resulted in a large amount of waste concrete [7]. Waste concrete not only occupies land resources but also pollutes the environment [8]. With the enhancement of people’s environmental awareness, the impact of waste concrete on the environment has attracted more and more attention [9]. At the same time, the natural aggregates required to prepare concrete are decreasing [10]. Therefore, it is necessary to find a new production method to solve the current problems in the construction industry [11]. Recycled aggregate concrete is a new type of concrete that is mixed with waste concrete after crushing, cement, sand, water and admixtures [12]. Recycled concrete technology can not only solve the problem of resource shortage but also realize the sustainable use of resources [13]. However, the poor frost resistance of recycled aggregate concrete leads to poor bond performance between recycled aggregate concrete and rebar [14], which will inevitably affect the application of recycled aggregate concrete in engineering [15]. Therefore, it is necessary to study the bond performance between recycled aggregate concrete and rebar under freeze–thaw environment [16].

The bond strength between recycled aggregate concrete and rebar decreased after freeze–thaw damage [17], while the slip increased [18], which was consistent with the degradation law of the performance between ordinary...
aggregate concrete and rebar. In addition, the recycled aggregate replacement rate, the rebar type and the diameter of the rebar would affect the bond performance between recycled aggregate concrete and rebar under freeze–thaw environment [19]. The bond strength between recycled aggregate concrete and rebar decreased with the increase of the recycled coarse aggregate replacement rate [20]. The bond strength of between recycled aggregate concrete and deformed rebar was greater than that between recycled aggregate concrete and plain rebar after the same numbers of freeze–thaw cycles [21]. The bond strength between recycled aggregate concrete and rebar decreased with the increase of the steel bar diameter [22]. Lu [22] proposed the bond–slip constitutive relationship between recycled aggregate concrete and rebar.

Some scholars have also investigated the performance between ordinary aggregate concrete and rebar under salt–frost cycles [23], and the results show that the degradation degree of bond performance after salt–frost cycles was greater than that after freeze–thaw cycles [24]. Ren et al. [25] and Shang et al. [26] found that the bond strength between recycled aggregate concrete and rebar in seawater after freeze–thaw cycles was lower than that in freshwater, while the bond slip in seawater was larger than that in freshwater. However, the test method would not only consume a lot of materials but also spend a lot of time. Therefore, a new method was needed to study the bond performance of concrete specimens instead of the experimental method.

With the rapid development of computer technology, the method of finite element analysis technology has been widely used in engineering [27]. Scholars have begun to numerically analyze the bond performance between concrete and rebar on the basis of experiments [28]. The rationality of the finite element model could be verified by comparing the finite element simulation results with the experimental results [29]. The three-dimensional nonlinear finite element analysis method and the two-dimensional nonlinear finite element analysis method could better simulate the bond performance between concrete and rebar [30,31]. In recent years, the finite element method was used to investigate the bond performance between recycled aggregate concrete and rebar [32].

However, there are few studies on bond performance between recycled aggregate concrete and rebar after freeze–thaw cycles by the finite element method. Although Fubo [33] investigated the bond performance between recycled aggregate concrete and rebar after freeze–thaw cycles, the important influencing factor of concrete strength was not considered. In addition, the relationship between bar diameter and concrete strength and bond strength could not be established. Therefore, the objective of this study is to investigate the bond performance between recycled aggregate concrete and rebar after freeze–thaw cycles by the finite element method, considering the effects of recycled aggregate concrete strength and concrete cover depth on bond performance, and to establish the calculation formula for the bond strength between recycled aggregate concrete specimens with different concrete strengths and different concrete cover depths after freeze and thaw cycles. This study provides the theoretical basis for the application of recycled aggregate concrete in cold regions.

2 Finite element model

2.1 Recycled aggregate concrete model

SOLID element in finite element ABAQUS could better simulate the performance of recycled aggregate concrete [34]. SOLID element was an eight-node hexahedral solid element. Each node could be divided into three degrees of freedom along the direction of the spatial coordinate system, and the displacement in each direction could bear the tension pressure along this direction. The size of a recycled aggregate concrete model was 150 mm × 150 mm × 150 mm, as shown in Figure 1.

Uni-axial compressive stress–strain constitutive relation of recycled aggregate concrete after freeze–thaw cycles proposed by Wu et al. [12] is expressed as follows (n is the number of freeze–thaw cycles, e_c is the ultimate

![Figure 1: Recycled aggregate concrete model.](image-url)
stress, $\sigma_c$ is the peak strain and $a$ is the parameter to be determined in the ascending branch of the stress–strain curve:

$$y = \begin{cases} 
ax + (3 - 2a)x^2 + (a - 2)x, & x \leq 1 \\
\frac{x}{B(x - 1) + x}, & x \geq 1 
\end{cases}$$

$$B = -9 \times 10^{-6}n^3 + 0.0024n^2 - 0.1689n + 4.2712,$$

$$x = \frac{\varepsilon}{\varepsilon_c}, \quad y = \frac{\sigma}{\sigma_c}. \quad (1)$$

The cube compressive strength $f_{cu}$ of recycled aggregate concrete could be assigned according to the corresponding experimental data. The elastic modulus ($E_c$), the uni-axial compressive strength ($f_c$) and the uni-axial tensile strength ($f_{sp}$) of recycled aggregate concrete are given as follows [35]:

$$E_c = \frac{10^5}{2.8 + 40.1/f_{cu}}, \quad (2)$$

$$f_c = 0.76f_{cu}, \quad (3)$$

$$f_{sp} = 0.24f_{cu}^{0.65}. \quad (4)$$

The cubic compressive strength in ref. [33] was brought into formulas (2–4), and the basic performance indicators of recycled aggregate concrete were obtained, as presented in Table 1.

### 2.2 Rebar model

Considering the setting of the spring element at the interface between the concrete and the rebar, the truss element was selected in the ABAQUS software to simulate the rebar in the concrete, in which the section size of the rebar was set by editing the section in the ABAQUS software. The rebar model is shown in Figure 2.

The stress mode of the rebar simulated in this article is a uni-axial stress state, and the constitutive relation was relatively simple. Therefore, the double-line model was selected for analysis, as shown in Figure 3. The material properties of the rebar were assigned based on the experimental data in ref. [34], and the basic performance indicators of rebar are presented in Table 2.

### Table 1: Basic performance indicators of recycled aggregate concrete

| Concrete strength grade (MPa) | Freeze–thaw cycles (times) | Uni-axial compressive strength (MPa) | Uni-axial tensile strength (MPa) | Elastic modulus (GPa) | Poisson’s ratio |
|------------------------------|---------------------------|-------------------------------------|---------------------------------|----------------------|----------------|
| 40                           | 0                         | 33.97                               | 2.84                            | 27.05                | 0.20           |
| 50                           | 50                        | 32.60                               | 2.76                            | 26.78                | 0.20           |
| 100                          | 100                       | 28.96                               | 2.56                            | 26.00                | 0.20           |
| 150                          | 150                       | 26.98                               | 2.44                            | 25.45                | 0.20           |
| 200                          | 200                       | 26.14                               | 2.39                            | 25.22                | 0.20           |
| 30                           | 0                         | 26.37                               | 2.41                            | 25.28                | 0.20           |
|                              | 50                        | 25.00                               | 2.32                            | 24.89                | 0.20           |
|                              | 100                       | 21.36                               | 2.10                            | 23.66                | 0.20           |
|                              | 150                       | 19.38                               | 1.97                            | 22.87                | 0.20           |
|                              | 200                       | 18.54                               | 1.91                            | 22.51                | 0.20           |
| 20                           | 0                         | 18.47                               | 1.91                            | 22.47                | 0.20           |
|                              | 50                        | 14.97                               | 1.67                            | 20.68                | 0.20           |
|                              | 100                       | 10.94                               | 1.36                            | 17.91                | 0.20           |
2.3 Model assembly and meshing

After establishing the recycled concrete model and the steel bar model, the two models were assembled to make the rebar located in the center of the specimen, as shown in Figures 4 and 5, respectively. Then, the specimen was meshed, and the same mesh size was selected for the concrete element and the rebar element to ensure that the nodes of the concrete element and the steel element were coincident, as shown in Figure 6.

To better simulate the bond performance between recycled aggregate concrete and rebar, a double-spring connecting element was set at the interface surface between recycled aggregate concrete and rebar, and the Spring2 element was selected as the connecting element and modified to a nonlinear element [33]:

"Spring, elset = Springs/Dashpots-1-spring, nonlinear."

3 Results and discussion

3.1 Comparison of finite element analysis results and test results

3.1.1 Comparison of bond strength

The finite element simulation results of the ultimate bond strength ($\tau_c$) of C20 recycled aggregate concrete specimens were compared with the experimental results ($\tau_e$) in the literature [33], as presented in Table 3.

It is presented in Table 3 that the bond strength decreased with the increasing number of freeze–thaw cycles, and the maximum error rate of the finite element simulation value was 18%. It can be seen that the finite element simulation value was in good agreement with the

| Freeze–thaw cycles | $\tau_c$ (MPa) | $\tau_e$ (MPa) |
|-------------------|---------------|----------------|
| 0                 | 16.21         | 15.22          |
| 50                | 13.77         | 12.37          |
| 100               | 9.58          | 7.99           |
experimental value, which proved the rationality of the finite element simulation in terms of bond strength of recycled aggregate concrete with rebar.

3.1.2 Comparison of peak bond slip (slip corresponding to ultimate bond stress)

The finite element simulation results of the peak bond slip ($s_c$) of C20 recycled aggregate concrete specimens were compared with the experimental results ($s_e$) in the literature [33], as presented in Table 4.

It is presented in Table 4 that the peak bond slip increased with the increasing number of freeze–thaw cycles, and the maximum error rate of the finite element simulation value was 43%. It can be seen that the agreement between the finite element simulation value and the experimental value was low. The reason may be that the double-spring connecting element cannot reflect the slip between the recycled aggregate concrete and the rebar, so only the bond strength was analyzed in the following analysis.

3.2 Influence of concrete strength on bond strength

The influence of concrete strength on bond strength between the rebar and the recycled aggregate concrete and with different concrete strengths after freeze and thaw cycles is shown in Figure 7. It can be seen that the bond strength between the rebar and the recycled aggregate concrete increased with the increase of the concrete strength. The reason is that the frost resistance of concrete increases with the increase of the concrete strength, and the loss rate of the concrete strength decreases after freeze–thaw cycles, which leads to the decrease of bond damage.

The ultimate bond strengths between the rebar and the recycled aggregate concrete and with different concrete strengths after freeze and thaw cycles were fitted as follows:

$$\tau_u = -0.0308n + 17.638, \quad R^2 = 0.8345, \quad (5)$$

$$\tau_u = -0.0318n + 16.986, \quad R^2 = 0.9069, \quad (6)$$

$$\tau_u = -0.0723n + 15.475, \quad R^2 = 0.9853. \quad (7)$$

3.3 Influence of concrete cover depth on bond strength

The ultimate bond strength of the recycled aggregate concrete specimens with different concrete cover depths after freeze and thaw cycles, as shown in Figure 8. It can be seen that the bond strength between the rebar

| Freeze–thaw cycles | $s_c$ (mm) | $s_e$ (mm) |
|--------------------|------------|------------|
| 0                  | 0.928      | 0.65       |
| 50                 | 1.310      | 0.95       |
| 100                | 1.569      | 1.12       |

Table 4: The comparison of calculation results ($s_c$) and experiment results ($s_e$)
and the recycled aggregate concrete increased with the increase of rebar diameter. Su et al. [34] also obtained similar conclusions that the bond strength after salt frost cycles increased with the increase of concrete cover depth.

The ultimate bond strengths of the recycled aggregate concrete specimens with different concrete cover depths after freeze and thaw cycles were fitted as follows:

\[
\begin{align*}
\text{c = 67 mm: } & \tau = -0.0308n + 17.638, \quad R^2 = 0.8345, \\
\text{c = 77 mm: } & \tau = -0.0227n + 17.784, \quad R^2 = 0.7764, \\
\text{c = 87 mm: } & \tau = -0.0136n + 18.002, \quad R^2 = 0.9547.
\end{align*}
\]

4 Conclusions

1) The finite element simulation value of the ultimate bond strength of recycled aggregate concrete specimens was in good agreement with the experimental value.

2) The agreement between the finite element simulation value of the peak bond slip of recycled aggregate concrete specimens and the experimental value was low.

3) The bond strength between rebar and recycled aggregate concrete increased with the increase of concrete strength and concrete cover depth.

4) The calculation formula for the bond strength of recycled aggregate concrete specimens with different concrete strengths and different concrete cover depths after freeze and thaw cycles were obtained.

Although this study cannot accurately predict the peak slip of recycled aggregate concrete and rebar after freeze–thaw cycles, it can accurately predict the bond strength of recycled concrete and steel bars after freeze–thaw cycles, which can promote the application of recycled aggregate concrete in engineering.

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