Experimental Study on the Constitutive Relationship of Epoxy-Coated Reinforcement to Seawater Sea Sand Recycled Concrete

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Abstract. In order to study the constitutive relationship between the seawater sea sand recycled concrete (SSRC) and the epoxy-coated reinforcement (ECR), the pull-out tests were performed. There were totally 24 specimens with different types of concrete (natural aggregate concrete, recycled aggregate concrete and SSRC), strength grades (C20 and C25), bond lengths (3d, 5d and 8d), reinforcement types (ordinary steel bars and ECR) and cover thicknesses (67mm and 42mm). Test results indicated that the bond-slip curve of SSRC to ECR was similar to that of RC and OC, which can be divided into three stages: the micro-slipping, the slipping, and the declining. In the case of SSRC specimen and ECR specimen whose protective layer has a thinner thickness, the curvature of the ascending section of the curve decreased significantly. As to SSRC specimen with a higher strength and ECR with a shorter bonding length, the descending section of the curve tends to be flat. Finally, the expression of the bond-slip constitutive relationship between SSRC and ECR was proposed, which can shed light on theoretical analysis and practical engineering.

1. Introduction
With the rapid development of the construction industry, it will inevitably lead to the shortage of fresh water, river sand and natural aggregate resources, and environmental pollution caused by waste concrete. These problems are particularly severe in the more developed areas along the eastern coast of my country [1]. The use of seawater and sea sand recycled concrete can reduce dependence on natural building materials and damage to the natural ecological environment, which is an effective way to solve the above problems [2]. Sea water and sea sand recycled concrete is concrete made by mixing sea water, sea sand, recycled coarse aggregate, cement and water (including admixtures or admixtures) in a certain proportion, and the sea sand contains mud the amount is low, the fineness is uniform, and in the eastern coastal areas of my country, there are abundant resource reserves [21]. The basic performance of recycled coarse aggregate is similar to that of natural aggregate. If the seawater, sea sand and recycled coarse aggregate can be fully and effectively used to prepare concrete, it can bring huge economic and environmental benefits. Existing research results show that seawater and sea sand recycled concrete can meet the basic requirements of engineering for strength and work ability, and it is a good new green environmental protection material [3].

However, in some design and analysis processes of reinforced concrete structures, it is necessary to apply the bond-slip constitutive relationship between steel bars and concrete, such as the bond element
in nonlinear finite element analysis, to determine the tensile stiffness effect of concrete members after cracking As well as calculating the amount of steel slippage at seismic members and nodes, etc [4], so far, there is no discussion and specific expression about the constitutive relationship between seawater sea sand recycled concrete and epoxy coated steel bars. The theoretical research and application of sand reclaimed concrete have brought great difficulties. In this paper, pull-out tests on 24 bonded slip specimens were conducted to study the different concrete types, design strength levels, bond lengths, types of steel bars and protection the changes in bonding performance between seawater and sea sand recycled concrete and epoxy-coated steel bars under parameters such as layer thickness. The research results provide a solid foundation for the development of China's marine concrete structures.

2. Test Overview

2.1. Raw materials

2.1.1. Ordinary steel bar and epoxy-coated reinforcement. The ordinary steel bars used in the test have the same shape and size as the cross ribs of epoxy-coated steel bars, and their grades are HRB400. The measured mechanical properties of the steel bars are shown in Table 1.

| Rebar type                      | d/mm | S/mm² | T/mm | fy/MPa | fs/MPa | Es/GPa |
|--------------------------------|------|-------|------|--------|--------|--------|
| Ordinary steel                 | 16   | 201.1 | 0    | 570    | 746    | 200    |
| epoxy-coated reinforcement      | 16   | 201.1 | 0.17 | 567    | 739    | 200    |

2.1.2. Mixed water and fine and coarse aggregate. The mixing water of seawater sea sand recycled concrete is sea water, and the fine aggregates are sea sand (Figure 1), all taken from Qingdao Lingshan Bay. The coarse aggregate is recycled coarse aggregate (Figure 2), which is processed from waste concrete from a demolished road (the original concrete has a design strength grade of C25). The mixing water for recycled concrete and ordinary concrete is tap water, the fine aggregate is river sand (Figure 1), and the coarse aggregate of ordinary concrete is gravel (Figure 2). The cement used in the test is 32.5R ordinary Portland cement.

![River sand](image1.png) ![Sea sand](image2.png)

Fig 1. Fine aggregates of experimental.
2.1.3. Mix ratio

Table 2. Concrete mix ratio and mechanical properties.

| Concrete type | Concrete grade | Water/(kg·m⁻³) | Cement/(kg·m⁻³) | Sea sand/(kg·m⁻³) | River sand/(kg·m⁻³) | Recycled coarse aggregate/(kg·m⁻³) | Water-cement ratio | $f_{cm}$/MPa |
|---------------|----------------|----------------|----------------|------------------|---------------------|-----------------------------------|-------------------|-------------|
| SSRC          | C20            | 202.4          | 374.8          | 701.3            | 0                   | 1361.4                            | 0.54              | 23.6        |
|               | C25            | 160.0          | 340.4          | 740.8            | 0                   | 1148.7                            | 0.47              | 27.2        |
| RC            | C20            | 202.4          | 374.8          | 0                | 701.3               | 1361.4                            | 0                 | 19.1        |
| OC            | C20            | 202.4          | 374.8          | 0                | 701.3               | 1361.4                            | 0.54              | 26.2        |

3. Loading equipment and systems

The pull-out test loading equipment consists of two parts. 1) MTS-SANS universal testing machine (range 400kN, Figure 3a). 2) Rigid loading frame, which is composed of 4 high-strength screws and 2 30mm thick steel plates (Figure 3b). The loading is carried out by displacement control, the loading rate is 0.3mm/min, the sampling frequency is 5Hz, and an electronic extensometer is arranged at the free end of the specimen to obtain the relative slip data between the steel bar and the concrete.

(a) MTS-SANS    (b) Loading rack

Fig 3. Test loading system.
4. Results and Analysis

4.1. Bond strength
The bonding strength of the specimen is calculated according to formula (1). The measured bonding strength of seawater and sea sand recycled concrete epoxy-coated steel bars is shown in Table 3.

\[ \tau_{\text{max}} = \frac{P_{\text{max}}}{\pi dl_a} \]  

(1)

It can be seen from Table 3 that the failure mode of the specimen is mainly pull-out failure. The bonding strength increases with the increase of the concrete strength and the thickness of the protective layer, and decreases with the increase of the bonding length. Different factors such as concrete type and steel bar type affect the bonding the influence of strength is significant, as shown below.

| Specimen number | Concrete type | Strength level | Rebar type | la | C/m | Destructive mode | Pmax/kN | max/MPa | u,c/MPa | max/ u,c |
|-----------------|---------------|----------------|------------|----|-----|------------------|---------|----------|---------|----------|
| S3dC20E-67      | SSRC          | C20            | ECS B      | 3  | 67  | pullout          | 24.16   | 10.02    | 12.78   | 0.78     |
| S5dC20E-67      | SSRC          | C20            | ECS B      | 5  | 67  | pullout          | 37.58   | 9.55     | 9.48    | 1.01     |
| S8dC20E-67      | SSRC          | C20            | ECS B      | 8  | 67  | Pull-out-split   | 41.15   | 6.40     | 7.61    | 0.84     |
| S3dC20E-42      | SSRC          | C20            | ECS B      | 3  | 42  | pullout          | 20.56   | 8.53     | 7.56    | 1.13     |
| S5dC20E-42      | SSRC          | C20            | ECS B      | 5  | 42  | Pull-out-split   | 17.25   | 4.30     | 5.60    | 0.76     |
| S5dC20O-42      | SSRC          | C20            | OSB        | 5  | 67  | pullout          | 43.41   | 10.80    | 10.71   | 1.01     |
| S3dC25E-67      | SSRC          | C25            | ECS B      | 3  | 67  | pullout          | 37.90   | 15.72    | 14.38   | 1.09     |
| S5dC25E-67      | SSRC          | C25            | ECS B      | 5  | 67  | pullout          | 45.95   | 11.43    | 10.66   | 1.07     |
| R5dC20E-67      | RC            | C20            | ECS B      | 5  | 67  | Pull-out-split   | 32.54   | 8.09     | 7.50    | 1.08     |
| R5dC20O-67      | RC            | C20            | OSB        | 5  | 67  | pullout          | 35.48   | 8.83     | 8.48    | 1.04     |
| O5dC20E-67      | OC            | C20            | ECS B      | 5  | 67  | pullout          | 45.95   | 11.44    | 10.27   | 1.11     |
| O5dC20O-67      | OC            | C20            | OSB        | 5  | 67  | pullout          | 53.88   | 13.41    | 11.60   | 1.16     |

Note: la is the bonding length, C is the thickness of the protective layer, d is the diameter of the steel bar, ECR and OSB represent epoxy-coated steel and ordinary steel respectively. The specimens are named after the rule of "concrete type + bonding length + concrete strength + steel bar type + thickness of protective layer".

4.2. Bond-slip curve
The average bonding stress-free end slip curve (\(\tau-s\)) of each group of specimens is shown in Figure 4. Analyzing the above curve, it can be found that the \(\tau-s\) curve changes under the influence of different factors, and can be roughly divided into three stages: micro-slip section, slip section and descending section.
1) Micro-slip section. At the beginning of loading, elastic-plastic slight slippage occurred at the loading end, and there was no slippage at the free end. At this time, the bonding stress is mainly the chemical bonding force. As the pulling force increases, the slippage also increases. The slope of the $\tau$-s curve remains almost unchanged, almost an oblique straight line passing through the origin.

2) Sliding section. As the load increases, the free end begins to slip, and the chemical bonding force is gradually replaced by the steel bar bite force and frictional resistance. With the gradual increase of the external load, significant slippage appeared at the free end, and the growth rate of the bonding stress slowed down. The slope of the $\tau$-s curve gradually decreases.

3) The descending section. After reaching the peak point, slippage develops rapidly. The surface crack growth of the specimen is obvious. After the concrete cracked, the specimen was destroyed and quit work. The slope of the $\tau$-s curve becomes negative and gradually expands.

![Fig 4. Measured average bond stress ($\tau$)-free end slip ($s$) curve.](image)

According to the test results and through a lot of comparative analysis, it is found that the ascending section of the bond-slip curve between seawater sea sand recycled concrete and epoxy-coated steel reinforcement can be adopted by Haraji [5] for plain concrete, and the descending section can be adopted or adopted. Professor Zhenhai [6] aimed at the equation of the concrete compression constitutive decline section, the specific formula is as follows,

$$
\tau = \begin{cases} 
\frac{(s/s_u)^\beta}{s/s_u}, & s/s_u \leq 1 \\
\frac{s/s_u}{\lambda(s/s_u - 1)^2 + s/s_u}, & s/s_u > 1 
\end{cases}
$$

(2)

In formula (2): $\tau$ and $s$ respectively represent the average bond stress and free end slip value; $\tau_{max}$ are the bond strength; $s_u$ are the free end slip value corresponding to the bond strength.
Fig 5. Comparison of adhesion-slip test curves and fitted curves.
The calculation curve is in good agreement with the test curve, indicating that the form of formula (2) can be used to calculate the whole process of adhesion-slip between seawater and sea sand recycled concrete and epoxy-coated steel bars.

5. Conclusion
1) The adhesion-slip curve can be divided into slight slip section, slip section and descending section. When seawater sea sand recycled concrete, epoxy-coated steel bars and protective layer thickness are small, the curvature of the ascending section of the curve is significantly reduced; while when seawater sea sand recycled concrete with higher strength and epoxy-coated steel bars with a smaller bonding length are used, the descending part of the curve tends to be flat.

2) Based on the regression analysis of the test data, the formula for calculating the bond strength between the epoxy-coated steel bar and the seawater and sea sand recycled concrete is deduced, and the measured value is in good agreement with the calculated value. It is recommended that the dimensional bonding-slip curve between seawater and sea sand recycled concrete and steel bars be calculated according to formula (1).

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