Sulfate Environment Influences on the Interfacial Bond Performance between CFRP and Concrete

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Abstract: The potential of Carbon Fiber Reinforced Polymer (CFRP) in the reinforcement of concrete structures has been shown in many studies and practical applications. Some concrete structures are in harsh environment so its reinforcement mechanical properties decrease due to time and environment effect. There are many region where plenty of saline soil, so much SO$_4^{2-}$ ions could permeate into CFRP and concrete structures and cause corrosion. Na$_2$SO$_4$ solution was adopted to simulate the harsh environment and through single shear test to study the interfacial bond properties between CFRP and concrete, and SEM detection technique was adopted to analyse the deterioration mechanism. Three parameters just like concrete surface roughness, concrete compressive strength and specimens corrosion time were studied. As the results indicate: With the increase of the roughness, the interface ultimate load also increases gradually. Bond stress occurred biggest value at 7-day, the interface ultimate load drops greatly at various roughness levels after 30 days at different concrete strength. At 60 days, some crystal structures connecting into bulky crystal and the concrete and the adhesive layer were damaged seriously; lacking of epoxy resin connection, the fiber is weak in integrity, which has great influence on bonding effect of concrete.

1. Introduction

In saline soil and collapsible loess regions of China, cases of sulfate attacking and destroying concrete could be found in cross-sea bridges, undersea tunnels, port wharf and coastal structure under marine environment. Guan Tiancheng$^{[1]}$ studied influences of sodium sulfate solution soaking and solution dry-wet cycle on CFRP and concrete shearing bonding performance by studying 38 CFRP-concrete single shear test strength. Professor Li Weiwen$^{[2]}$ from Shenzhen University studied the mechanical properties of CFRP-concrete bonding interface, the tensile strength of CFRP sheets, the compressive strength and elastic modulus of concrete through accelerated deterioration test with 10% sodium sulfate solution and studied the influences of sodium sulfate solution soaking on CFRP-concrete shearing bonding performance through single shearing test of CFRP-concrete bonding interface. Li Yapeng$^{[3]}$ adopted quick freezing method to conduct freezing and thawing cycles in sodium sulfate solution whose mass fraction is 5%. After freezing and thawing cycles in sodium sulfate solution, with the increase of the times of freezing and thawing, the tensile strength and elastic modulus of CFRP sheet increase also, while the range ability of the elongation is not obvious.
International scholars have conducted abundant studies on sulfate attack\cite{4-7}. Concrete surface roughness has significant influences on interfacial bonding\cite{8}. While implementing studies on interfacial behavior, scholars both at home and abroad have not considered fully the influences of concrete surface roughness on interfacial bonding and studied on deterioration law of interface bonding performance in sulfate environment with the parameters. Therefore, in this experiment, two variables, concrete surface roughness and concrete strength class, are adopted to study the ongoing change of FPR-concrete interface under sulfate attack and focuses are also laid on interface ultimate load, average bonding press and other important performance parameters. Meanwhile, SEM detection technique is adopted to analyze the degeneration mechanism of interface bonding performance.

2. Experimental material and corrosion environmental simulation

2.1 Specimens preparation

The size of the concrete specimens designed in this experiment is 80×80×200mm³, as shown in figure 1. Two types of concrete strength are considered in this experiment (C30, C50) and 3 types of interface roughness are prepared for each concrete strength grade. For each roughness, 3 specimens are in a group. In this experiment, HICOMA-HITEX series carbon fiber sheet manufactured by Nanjing Haituo Composite Material Co., Ltd is adopted and the adhesive is prepared with epoxy AB glue produced of the same factory at the ratio of 2:1. The concrete surface is painted with epoxy and pasted with CFRP sheet. The curing temperature is $20\pm2{^\circ}\text{C}$, 7 days later the experiment starts. Specific material performance is shown in table 1-2.

| Specimen | Cement (kg/m³) | Fly ash (kg/m³) | Coarse aggregate (5-20mm) (kg/m³) | Fine aggregate (kg/m³) | Water reduce agent (kg/m³) | Water (kg/m³) |
|----------|----------------|----------------|---------------------------------|-----------------------|--------------------------|---------------|
| C30      | 336            | 59             | 1045                            | 789                   | 3.95                     | 167           |
| C50      | 423            | 47             | 1104                            | 660                   | 6.11                     | 150           |

| Specimen | $f_c$ (MPa) | $f_t$ (MPa) | $E_f$ (MPa) | $t_f$ (mm) | $m_f$ (g/m²) |
|----------|-------------|-------------|-------------|------------|--------------|
| specimen | C30         | 35.0        | 5.3         |            |              |
|          | C40         | 46.0        | 6.4         |            |              |
|          | C50         | 57.5        | 7.4         |            |              |
| CFRP     | 3400        | 2300        | 0.167       |            | 300          |
| Epoxy    | 38          | 2.4×10⁶     | 2.4×10⁶     |            |              |

The concrete test block is cured in the curing chamber for 28 days after the concrete specimens...
are prepared well, then it is taken out at room temperature. 180 days later, the surface of the test block is cleaned with hairbrush and its surface roughness is measured with sand filling method. After the bonding interface is measured, it is painted with epoxy resin glue and pasted externally CFRP sheet. Then roll on it towards one direction with rolling brush many times to roll out the air in it so that the epoxy resin glue could soak completely CFRP. The test blocks are then kept at room temperature of \((20\pm2)\ ^\circ\mathrm{C}\) for 7 days till the epoxy resin is solidified completely, which is kept for CFRP-concrete single shear test.

162 CFRP-concrete single shear test blocks are prepared, the size of each CFRP sheet is \(360\times60\mathrm{mm}^2\), and the bonding area is \(140\times60\mathrm{mm}^2\). The bond method can be seen from figure 2.

![Fig.2 Area of test concrete to be tested](image)

2.2 Corrosion environmental simulation

\(\text{Na}_2\text{SO}_4\) solution adopts saturated solution with the mass fraction of 17.2%. Every three days, all specimens are taken out to be dried with natural air blower. Then they are immersed in the solution vertically for wetting-drying cycle so as to accelerate the erosion rate. The erosion periods are set as 0 day, 7 days, 15 days, 30 days, 45 days, and 60 days. The erosion scene is shown in figure 3.

![Fig.3. The sulphate corrosion environment](image)

After the specimens are kept in the corrosion medium for 7 days, it could be felt that fiber surface of the specimens becomes smoother. Seen from the appearance of the specimens, there is obvious
change in color (becoming milky white), while the appearance of the fiber sheet has no change and no
discoloration is found in the adhesive layer between the fiber sheet and the concrete. From the
appearance, it could be seen that 7 day corrosion has no obvious damage to the fiber sheet and the
epoxy resin. As is shown from figure 4.

Fig. 4 Apparentness of three kinds of roughness of CFRP-concrete specimen at 7 days

3. Experimental process
All the experiments adopted 20t electro-hydraulic servo to load on material testing machine. The
loading device is shown in figure 5. The loading rate was 10mm/min. In the experimental process, the
debond condition of the specimens was observed real-time and the initial debond time is recorded.
After the specimens are debonded, the debond shape of the interface, the ultimate bearing capacity and
the maximum displacement of the interface through the loading equipment were all observed and
recorded.

When the loading reaches 17% of the ultimate load, sounds of "flap" could be heard. Till ultimate
load is reached, a "flap" could be heard suddenly and CFRP is debonded from the concrete sample
without any obvious symptom; Therefore, it is brittle fracture. After single shear fracture of the sample,
there are altogether three fracture modes: the first is tensile failure in the interface between the
adhesive layer and the concrete; the second is the fiber sheet with some debond concrete block; the
third is tearing failure of the fiber sheet. In the experiment, the first mode occurs to 65% of the
specimens; the second occurs to 30% of the specimens and the third occurs to 5% of the specimens.
4. Experimental result analysis and discussion

4.1 Experimental phenomena

![Failure modes of CFRP-concrete specimens](image)

Fig. 6 Failure modes of CFRP-concrete specimens

The damage modes of concrete at different curing ages and strength are similar, so sulfate attaching specimens at C30 of 30-day age is taken as the example. In failure modes, for interfaces f1 and f2, the failure form is tearing a small piece of concrete at the loading end. Failure between FRP and concrete is FRP debonded from the concrete surface, with concrete of certain thickness. While at f0 interface, the main failure mode is FRP debond from surface layer mortar, as is shown in figure 6.

4.2 Experimental data analysis and discussion

4.2.1 Influences of roughness on interface ultimate load

![Ultimate load - time curve based on the parameter roughness](image)

Fig. 7 Ultimate load - time curve based on the parameter roughness

It could be seen from figure 7 that roughness has significant influences on interface ultimate load. With the increase of the roughness, the interface ultimate load also increases gradually. In 0-60 days period, concrete with the same strength at the same age could increase about 5.7%-24.6%, with the maximum added value 24.6%. It is worth mentioning that all the maximum strength points appears at 7-day. Especially, it could be found that the interface ultimate load drops greatly, shows high-speed downswing at various roughness levels after 30 days at different concrete grades.

4.2.2 Influences of roughness on average interface bonding shear stress

There are total 3 different roughness. Take C30 and C40 concrete specimens as the example, the
relations between the average interface bond strength and the erosion age changes are shown in figure 8.

![Graph showing average bond strength over time for different roughness](image)

**Fig. 8 Average bond strength as the time changed for different roughness**

4.3 Analysis of interface bonding mechanism based on SEM technology

![SEM images of sample microstructures](image)

(a) Na$_2$SO$_4$ crystal grows  (b) crystal grow to sheet  (c) Fiber destroyed

(d) Epoxy resin deterioration  (f) Concrete deterioration

**Fig. 9 Microstructure of materials at 60days under sulfate erosion**

From figure 9, it could be found that at the 60th day crystal develops highly, with some crystal structures connecting into bulky crystal and the concrete and the adhesive layer being damaged seriously; lacking of epoxy resin connection, the fiber is weak in integrity, which has great influence on bonding effect of concrete. Moreover, it could be seen from figure 10 (a) and (b) that crystal is easily to generate at the place where there are more flaws. This is caused by "bordering" effect. Based on the principle of molecular dynamics, sodium sulfate ions could cause regional concentration gradient and the ions could flow from high concentration area to low concentration area, so plenty of Na$^+$ and SO$_4^{2-}$ ions would flow towards sharp corner and boundary region. Generation and extension of cracks are the start of acceleration of structure failure, which is even irreversible; therefore, it is necessary and strictly to control concrete beam cracks for civil engineering structure under severe
environment, which is of great and active significance.

5. Conclusion and Recommendations

Na$_2$SO$_4$ solution was adopted to simulate the harsh environment and through single shear test to study the interface bond properties between CFRP and concrete. Totally three parameters are collected, which are concrete surface roughness, concrete compressive strength and specimens corrosion time. Some important conclusions are as follows:

(1) Roughness has significant influences on interface properties. With the increase of the roughness, the interface ultimate load also increases gradually.

(2) Bond stress occurred biggest value at 7-day, and the interface ultimate load drops greatly, showing high-speed downswing at various roughness levels after 30 days at different concrete strength.

(3) From 0 to 60th day crystal develops highly, at 60days some crystal structures connecting into bulky crystal and the concrete and the adhesive layer being damaged seriously; lacking of epoxy resin connection, the fiber is weak in integrity, which has great influence on bonding effect of concrete.

(4) The present work confirmed again the important effects of roughness on the interface between CFRP and concrete. Some other further works need to be done. The CFRP-concrete specimens should go through harsh environment such as high temperature, freeze–thaw cycles, seawater and alkaline solution, etc., as many elements in this research remain researched.

Acknowledgments:
The authors gratefully acknowledge the support received from Liaoning Province Natural Science Foundation of China (Grant No.20180551197) and Technology Applied Projects of Liaoning Provincial College of Communications (Grant No. lnccjyky201817, Grant No. lnccjyky201818).

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