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Durability of Concrete Columns Protected by Sustainable Composite Sheets in an Acid Environment

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ABSTRACT

An experimental investigation is conducted to study the durability of axial concrete members confined with carbon fiber reinforced polymer (CFRP) composite sheets in an acid environment. Test specimens such as concrete cylinders and CFRP and epoxy coupons are submerged in a 5% concentration sulfuric acid solution up to 6 weeks and monotonically loaded to failure. The composite is deteriorated primarily because of degradation in its resin matrix, rather than in carbon fibers. The load-bearing capacity of plain concrete is proportionally reduced as an exposure period increases. The capacity of the strengthened concrete, however, decreases up to about 30%, regardless of acid exposure time. Sulfuric acid alters the governing failure mode of the plain and confined concrete specimens.

INTRODUCTION

There are many sources influencing the performance of concrete structures from physical distress to chemical attributes. Concrete structures constructed in industrial regions may be exposed to acid environments, leading to a decrease in their load-bearing capacity. Among many possible acidic conditions such as nitric, acetic, and pentanoic acids, sulfuric acid (H_2SO_4) is of interest for concrete members due to its common occurrence: when sulfuric acid reacts with calcium hydroxide ($Ca(OH)_2$) in concrete, gypsum is created so that the porosity of the concrete increases. Attiogbe and Rizkalla [1988] studied the effect of sulfuric acid on the behavior of concrete having variable covers and compositions. Physical and chemical approaches were taken to examine a change in mass and energy-dispersion spectrum. It was reported that the deterioration of the acid-exposed concrete initiated at a surface level and propagated inward with time. Bassuoni and Nehdi [2007] tested self-consolidating concrete in a sulfuric acid environment, including several parameters: types of cementitious binders, aggregate ratios, and the presence of reinforcing fibers. There was no specific relationship between the loss of mass and the decrease of compressive strength. The inclusion of an organic corrosion inhibitor (amines and esters), a quaternary binder, and hybrid fibers retarded acid damage in concrete. Araghi et al. [2015] investigated the performance of concrete mixed with polyethylene terephthalate particles subjected to sulfuric acid. Findings include that a reduction in load-carrying capacity and concrete mass was reasonably mitigated as the amount of polyethylene terephthalate augmented.

Structural strengthening using carbon fiber reinforced polymer (CFPR) composites has been exploited in the civil structural community for the last two decades [ACI 2007]. CFRP is considered to be a sustainable rehabilitation material because of its superior durability compared with other conventional construction materials, leading to reduced long-term maintenance expenses. Externally-bonded CFRP sheets are frequently used to increase flexural, shear, and axial capacity of deteriorated concrete members. Despite the possible use of CFRP in industrial regions where sulfuric acid may be of concern, no research has been reported to evaluate the behavior of the strengthening system and strengthened members. This paper deals with an experimental program concerning the performance of CFRP-confined axial concrete elements exposed to sulfuric acid.

RESEARCH SIGNIFICANCE

Concrete structures are often constructed for industrial purposes and they may be exposed to acid-induced distress (e.g., wastewater). Although various technical methods have been used to enhance the sustainability of these structures, including the addition of supplementary cementitious materials, effective solutions are still required because calcium hydroxide inside concrete reacts with acid environments. Another challenge is that the load-bearing capacity of existing concrete columns experiencing acid-induced deterioration can be reduced and, consequently, the need for rehabilitation arises. Conventional retrofit approaches such as concrete jacketing may postpone the failure of the structural system, whereas the problem could occur again due to the aforementioned chemical reaction mechanism. This research proposes a retrofit method using CFRP sheets that can extend the service life of acid-damaged concrete members.

EXPERIMENTAL INVESTIGATION

Materials. Concrete was mixed in the laboratory with a specified compressive strength of 20 MPa. The nominal properties of unidirectional CFRP sheets are a tensile strength of 3800 MPa and a modulus of 227 GPa. A two-part epoxy adhesive, consisting of a resin and a harder, has a nominal tensile strength of 55 MPa and a modulus of 3 GPa according to the manufacturer.

Specimens. Concrete cylinders were cast with dimensions of 100 mm in diameter and 200 mm in length and cured for 28 days in a humidity room. The fully cured concrete was wrapped with a single layer CFRP sheet bonded using the epoxy adhesive; then, was further cured for 7 days as recommended by the manufacturer. To examine the effect of acid-induced deterioration on the strengthening system, CFRP and epoxy coupons (15 mm wide by 150 mm long and 5 mm wide by 10 mm thick by 100 mm long, respectively) were made, as shown in figure 1.

Testing scheme. The plain and CFRP-confined concrete cylinders were submerged in sulfuric acid (5% concentration) at room temperature, including the CFRP and epoxy coupons (figure 2). It should be noted that the top and bottom surfaces of the confined cylinders were covered by multiple epoxy layers so that the ingress of sulfuric acid was precluded from outside the CFRP-wrapped region. The planned exposure periods varied from 0 to 6 weeks at a 2-week interval. Such a 6-week exposure scheme was determined based on previous research showing a sufficient decrease in concrete mass up to 10%, representing a typical service environment [Bassuoni and Nehdi 2007]. The pH values of the sulfuric acid solution were monitored to ensure that the specimens were exposed to an appropriate condition (figure 3). After achieving the predetermined exposure time, the concrete cylinders were weighted to measure the gain or loss of mass (figure 4) and mechanically loaded until failure occurred using a universal testing machine, as shown in figure 5.

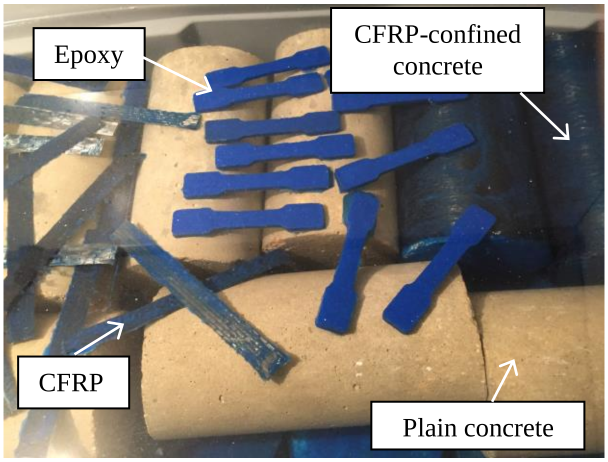


Figure 1. Prepared specimens

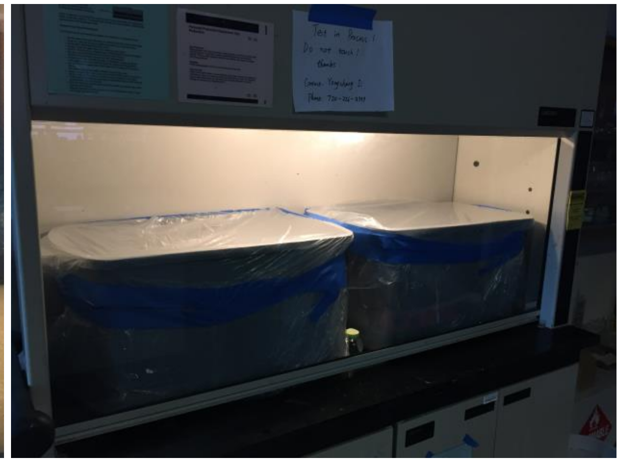


Figure 2. Protected fume hood for conditioning

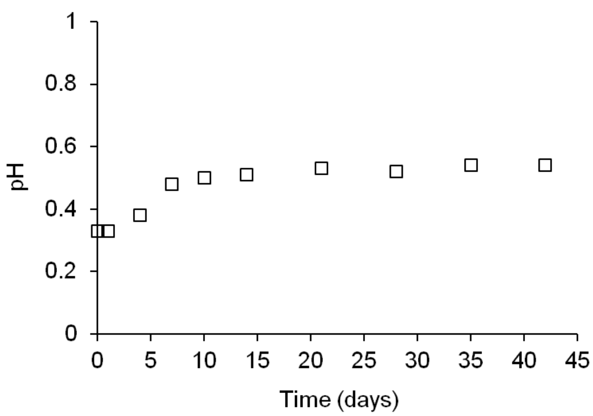


Figure 3. Variation of pH values

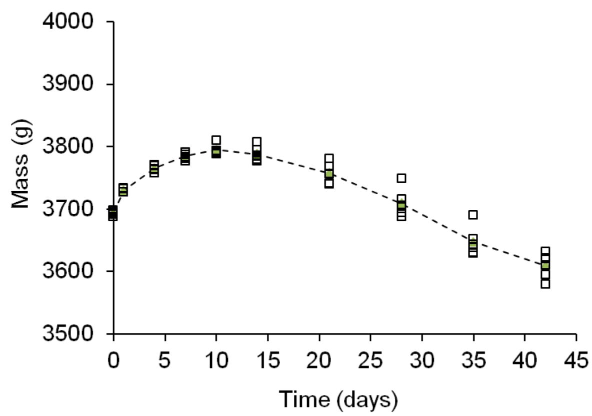


Figure 4. Change in concrete mass

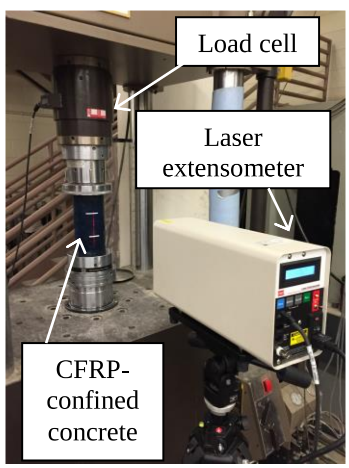
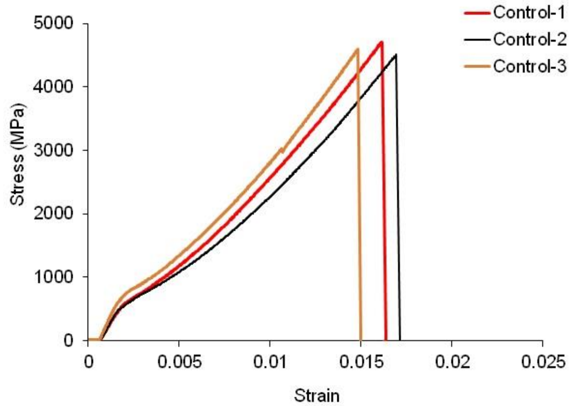
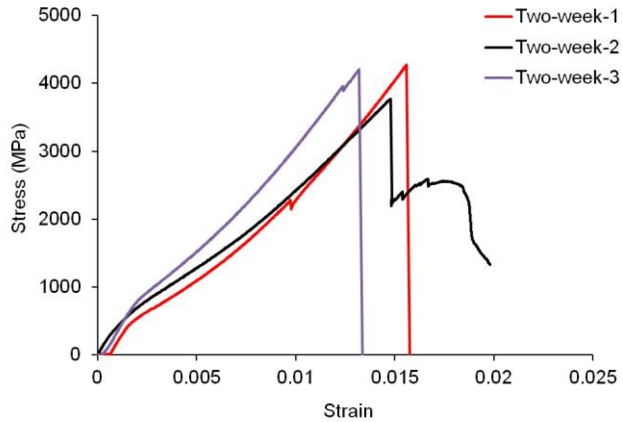


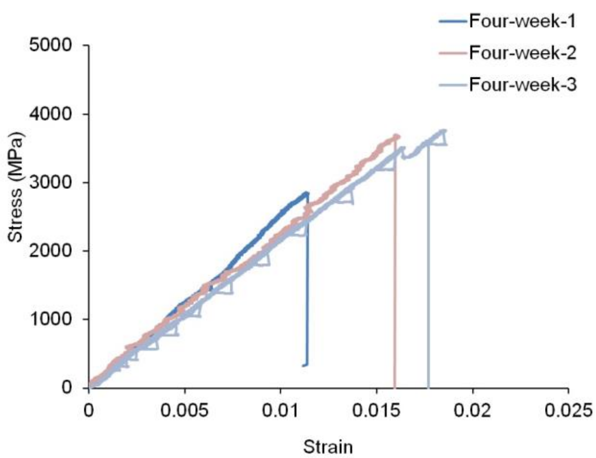
Figure 5. Setup for cylinder testing



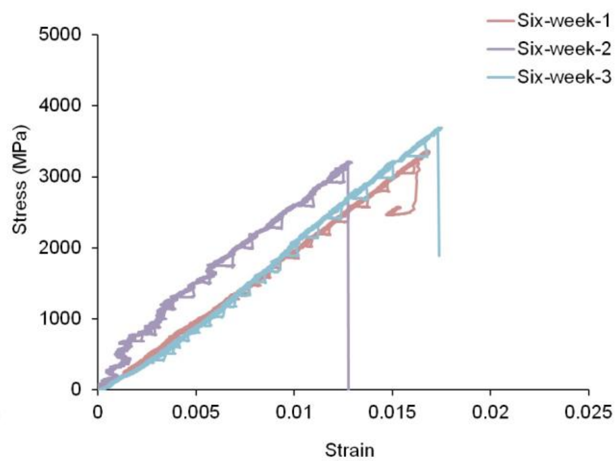
(a)



(b)

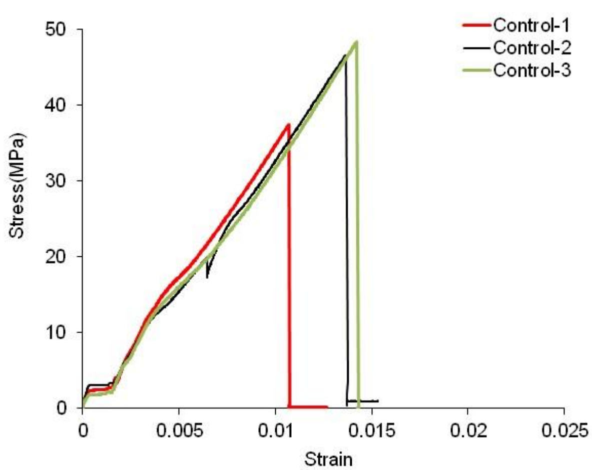


(c)

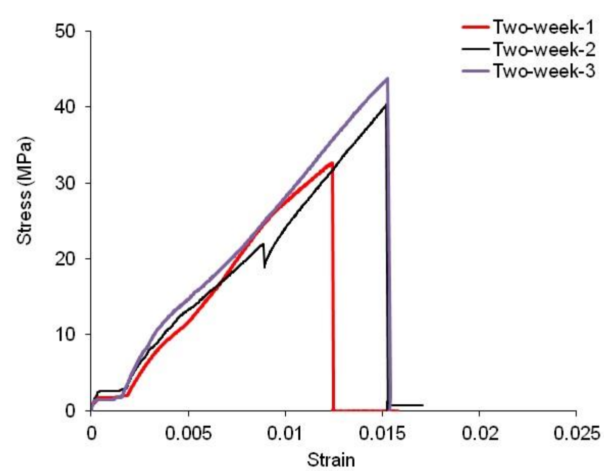


(d)

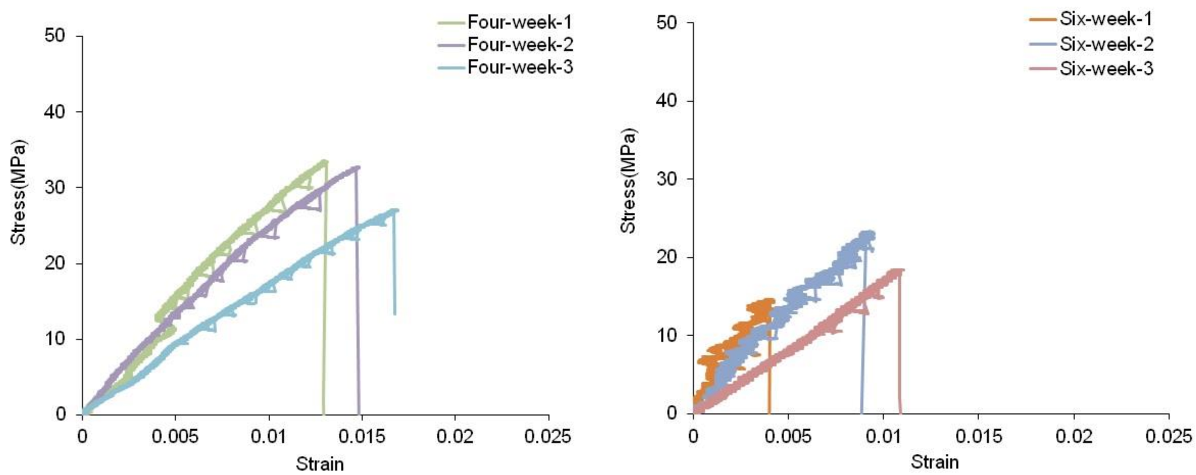
Figure 6. Stress-strain behavior of CFRP exposed to sulfuric acid: (a) 0 week; (b) 2 weeks; (c) 4 weeks; (d) 6 weeks



(a)



(b)



(c) (d)

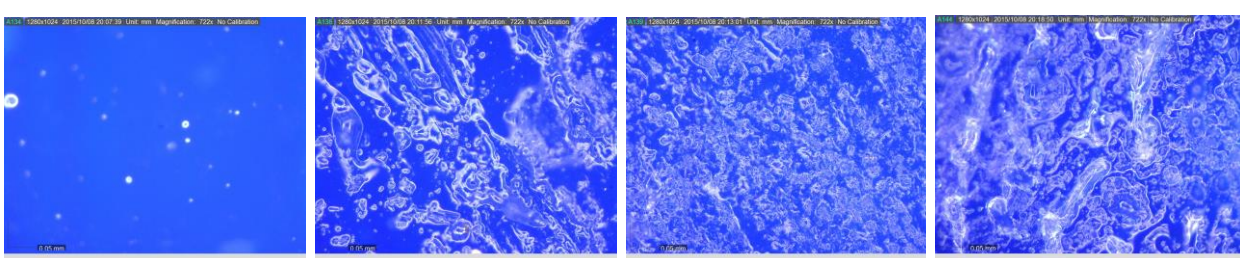
Figure 7. Stress-strain behavior of epoxy exposed to sulfuric acid: (a) 0 week; (b) 2 weeks; (c) 4 weeks; (d) 6 weeks

The load applied and corresponding displacement of each specimen were recorded using a load cell and a non-contacting laser extensometer connected to a computerized data acquisition system. Three specimens were tested per exposure category.

TEST RESULTS

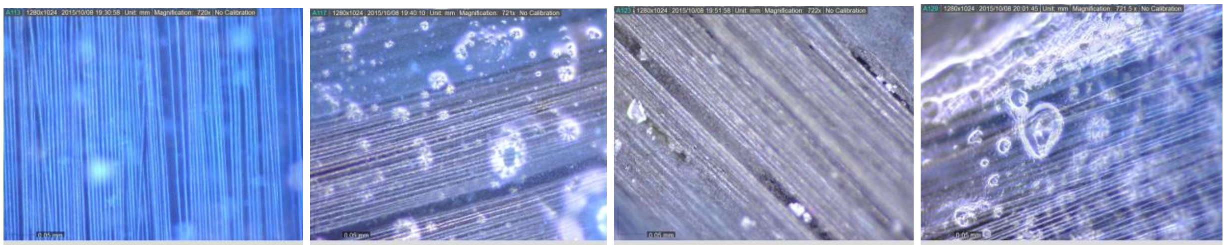
Stress-strain of CFRP and epoxy

Figure 6 reveals the stress-strain behavior of the CFRP sheets submerged in the acid environment. Regardless of exposure time, all coupons showed essentially linear responses, whereas their ultimate strength was influenced by the time. The control specimens exhibited an average failure stress of 4600 MPa (figure 6a), which was 21% higher than that of the manufacturer's nominal strength. This may be attributable to the fact that the manufacture's strength is a guaranteed design value and thus could be conservative. With an increasing exposure period, the CFRP strength was gradually reduced down to 3524 MPa at 6 weeks (figure 6b to d); that is a 23% decrease in strength relative to the control case. The constitutive relationship of the epoxy is provided in figure 7. The stress-strain responses were similar to those of the CFRP with an average strength reduction of 58% between the control category and the one exposed to 6 weeks. These observations point out that the strength of the CFRP composite was degraded by the exposure to sulfuric acid primary due to the deterioration of the epoxy binder, rather than the carbon fibers.



(a) (b) (c) (d)

Figure 8. Microscopic imaging of epoxy: (a) 0 week; (b) 2 weeks; (c) 4 weeks; (d) 6 weeks



(a) (b) (c) (d)

Figure 9. Microscopic imaging of CFRP: (a) 0 week; (b) 2 weeks; (c) 4 weeks; (d) 6 weeks

Microscopic observation

The microscopic images of the epoxy and CFRP before and after the acid exposure are provided in Figs. 8 and 9, respectively, taken by a high-resolution digital optical microscope at a 720 times magnification. The control epoxy specimen (figure 8a) displayed a clean surface with several air bubbles that were captured when the epoxy was cured; on the other hand, those exposed to sulfuric acid demonstrated complex surface wrinkles (figure 8b to d). The images of the CFRP specimens clearly showed that carbon fibers embedded in the epoxy matrix were not damaged by the acid exposure (figure 9) even though some changes in the matrix was noticed.

Load-bearing capacity of concrete

Figure 10 summarizes the average ultimate stress of the plain and CFRP-confined concrete cylinders. The specimens without CFRP showed a noticeable capacity drop of 35.2%, 46.7%, and 53.3% for the 2-, 4-, and 6-week exposure periods, respectively, compared with the control capacity. It is postulated that the leaching of calcium hydroxide has resulted in such a strength decrease, while refined chemical analysis may be required in follow-up research to confirm this hypothesis. For the case with CFRP-confinement, a relatively consistent capacity decrease was observed, irrespective of acid exposure time: 29.3%, 31.5%, and 36.4% for the 2-, 4-, and 6-week exposure periods, respectively, relative to the control. This fact implies that sulfuric acid deteriorated the composite jacket to a certain extent; however, the CFRP was still effective in preserving the axial capacity of the confined concrete members.

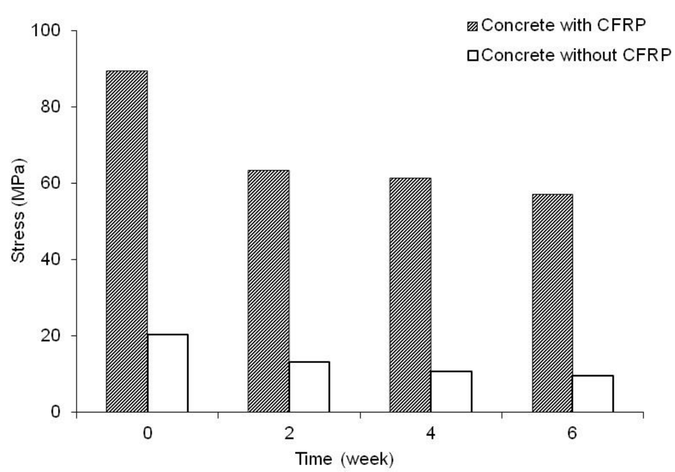


Figure 10. Summary of load-carrying capacity

Failure mode

The failure mode of the plain concrete specimens is presented in figure 11. The cylinders exposed to 0 and 2 weeks failed by a typical diagonal tension crack, while the color of the concrete surface was not the same due to the acid exposure (figure 11a and b). The failure pattern changed when the cylinders experienced more acid in a manner that a vertical crack took place (figure 11c and d) because of the disintegrated cementitious binder (i.e., stress transfer inside the concrete was not effective so the cylinders collapsed when loaded). Another thing to note is that the binder was dissolved by the acid and, thereby, coarse aggregate was visible. Such a trend was more pronounced with an increase in exposure time. The failure of the CFRP-confined concrete is displayed in figure 12. The control cylinder showed a relatively insignificant rupture of the CFRP sheet, as shown in figure 12(a); however, the ones submerged in sulfuric acid revealed that a significant portion of the CFRP fractured (i.e., more than 50% of the covered region) and the core concrete explosively failed (figure 12b to d). The similar failure modes among the 2- to 6-week-exposed specimens can explain the insignificant variation of the load-carrying capacity discussed in the previous section.

(a) (b) (c) (d)

Figure 11. Failure mode of plain concrete: (a) 0 week; (b) 2 weeks; (c) 4 weeks; (d) 6 weeks

(a) (b) (c) (d)

Figure 12. Failure mode of CFRP-confined concrete: (a) 0 week; (b) 2 weeks; (c) 4 weeks; (d) 6 weeks

SUMMARY AND CONCLUSION

This paper has discussed the deleterious effect of sulfuric acid on the performance of CFRP-confined concrete members loaded in axial compression. Ancillary testing was reported to examine the deterioration of the confining system consisting of CFRP sheets and an epoxy adhesive. The following conclusions are drawn:

- The strength degradation of the bonding agent was much more pronounced than that of the CFRP when exposed to sulfuric acid up to 6 weeks, corroborated by the mechanical testing and microscopic observations.
- The plain concrete specimens revealed a significant capacity drop up to 53.3% and the drop rate was proportional to the exposure period. The CFRP-confined concrete also showed a strength decrease, while its drop level was not as significant as that of the unconfined counterparts and was relatively consistent at about 30%.
- The acid exposure altered the failure mode of the plain concrete from an obvious diagonal crack to a vertical crack due to the deteriorated cement binder. The degree of CFRP-rupture in the confined cylinders was related to the extent of acid exposure.

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