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## Progress in Durability Study of FRP Materials

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### ABSTRACT

During the past decades, FRP strengthened RC structures have attracted worldwide interest in both application and research. Nowadays, as more and more infrastructures are being suffered from severe corrosions due to harsh and extreme environments, the durability of FRP strengthened RC structures has generally emerged as the most important issue in research. Thus, the paper presents the latest progress in durability study of the FRP materials through an in-depth review and analysis on existing extensive investigations. The time-dependent performances of two types of FRP materials of carbon FRP (CFRP) and glass FRP (GFRP) under severe environments of humidity, high temperature, wet–dry cycles, freeze–thaw cycles, ultraviolet radiation exposure, and natural exposure have been compared and analyzed. The results have finally confirmed the superior corrosion resistance of FRP material, although the performance of GFRP material exhibited a slight deterioration.

### 1. INTRODUCTION

Reinforcement technique of fiber reinforced polymer (FRP) is a kind of reinforcement technology that FRP is adhered on the surface of structure in order to improve the bearing capacity of structure. Because of its feature of convenient construction, short construction period, better durability, little influence on structure appearance and unit weight, and so on, it has been widely used in civil engineering, water conservancy, port, etc. With in-depth application of FRP, the durability of FRP reinforced concrete structure has aroused people's great attention (Wang & Zhao, 2007).

For the assessment of durability of FRP reinforced concrete structure, most of them are realized through the accelerated corrosion method in artificial environment laboratory. Some research institutions adopted the method of outdoor natural aging as well. The method of natural aging really reflects the corrosion over time of the structure, but the corrosion rate is slow and the cost is high. At present, the types of artificial simulation environment are (1) the acid, alkali, and salt solution, (2) the freeze–thaw cycle, (3) dry–wet condition, (4) high and low temperature environment, (5) ultraviolet aging, and (6) the alternate coupling of several kinds of environment. According to the above several kinds of artificial simulation environment, there are two aspects of the durability research direction of FRP reinforced concrete structure: (1) the durability of the material (FRP/adhesive/concrete) and (2) the durability of interfacial bond property (FRP-binder

interface/binder – concrete interface/FRP-concrete interface). In this paper, we will, respectively, elaborate the present situation and progress in the study of the durability of FRP materials in this paper.

### 2. EFFECT OF WATER IMMERSION AGING

Ren, Yao, and Hu (2005) conducted a 30-day immersion test for CFRP and GFRP at room temperature. The test results show that for CFRP under water immersion test, its tensile strength, elastic modulus, and ultimate strain have not been influenced greatly. But for GFRP, the tensile strength and ultimate strain decrease by 10 and 8%, respectively, while the elastic modulus does not change. Thus, it shows that the Glass fiber material after suffering with water immersion test has a certain trend of embrittlement.

Cromwell, Harries, and Shahrooz (2011) have been studied the mechanical performance of CFRP plate, CFRP cloth, and GFRP cloth, respectively, soaking in pure water solution and saline solution. (1) The pure water solution: the test materials are exposed to the test environment which is the pure water with 38°C and relative humidity of 100% for 1000, 3000 and 10,000 h, respectively. The test results show that the tensile strength, elastic modulus, and ultimate strain of CFRP plate, CFRP cloth, GFRP cloth, all tend to be stable. (2) The saline solution: the test materials are exposed to the test environment which is the saline solution with 22°C for 1000, 3000, and 10,000 h, respectively. And the test results show that the tensile strength, elastic modulus, and ultimate strain of CFRP

plate and CFRP cloth are almost constant, while the tensile strength, elastic modulus, and ultimate strain of GFRP cloth reduce with increasing corrosion time.

After Ren et al. (2005) conducted immersion test with alkali solution at room temperature, it is concluded that the stress–strain relationship of two kinds of fiber materials shows a linear change. Alkali environment had great effects on the mechanical performance of GFRP that after soaking in alkali for 30 days, the tensile strength of two kinds of GFRP remains only 1/4 and 1/6, respectively. However, epoxy resin can effectively reduce the alkali erosion to glass fiber. After these two kinds of GFRP impregnating with epoxy resin soaked in the alkali for 30 days, the tensile strength remained 1/2 and 3/4. Alkali environment had bad effects on the mechanical performance of CFRP as well. After soaking in alkali for 30 days, the tensile strength of CFRP falls by one-third. Likewise, epoxy resin can effectively reduce the alkali erosion to carbon fiber that after CFRP impregnating with epoxy resin soaked in the alkali for 30 days, the mechanical performance remains basically constant.

Li, Ren, Huang, and Si (2010) had carried on the static tensile test of CFRP sheet and GFRP sheet which had soaked in the alkali solutions of 30, 40, 50, and 60°C, respectively. The test results show that with the increase of aging time, the tensile strength, elastic modulus, and elongation of CFRP sheet and GFRP sheet decreases gradually. And the higher the temperature is, the faster they decrease. Furthermore, by using the modified Arrhenius model to analyze the test results, he also carried out the references for the design strength of fiber reinforced polymer under the action of temperature and alkali solution.

Xiao, Yu, and Qin (2003) had studied the change law of mechanical performance with the time of a kind of high strength fiber composite by accelerated test: the main fiber of fiber composite is Glass fiber, whereas the lateral fiber is Aramid fiber. Besides, the resin matrix is epoxy resin. The study shows first alkaline medium has no effect on the tensile strength of high strength fiber composite basically. Next, although the tensile strength of specimens declined after stored in acidic medium for a short time, the strength rebounded after a relatively long period of time. At last, two kinds of medium have a little influence on the tensile elastic modulus of FRP material. And the change of the biggest elongation and the change of tensile strength of FRP are very similar that the two has a linear relationship basically.

From what has been discussed above, no matter soaking in pure water, seawater, or alkali solution, the change laws of mechanical durability of all kinds of FRP materials are different and the durability of CFRP is better than GFRP.

### 3. EFFECTS OF WET–DRY CYCLES

Xi, Chang, Asiz, and Li (2004) had studied the mechanical performance of CFRP in aqueous solution and brine solution under cyclic drying–wetting. The test results show that the tensile strength and elastic modulus of CFRP decrease by 4 and 27%, respectively, in aqueous solution under cyclic drying–wetting, whereas its tensile strength and elastic modulus decrease by 14.7 and 32% in brine solution under wet–dry cycles. It also shows that for mechanical performance of CFRP, the wet–dry cycles when in brine solution is much more serious than when in aqueous solution.

Specimens were put into 10% NaCl solution by Li (2006), soaking for 8 h. Then, he took them out and dried them at room temperature for 16 h with using fan for ventilation. Taking the procedure above as a cycle, he conducted 50 and 100 times, respectively. The test results show that the cyclic drying–wetting in brine solution has little effect on the strength of both CFRP and GFRP, but the ductility of CFRP decreases, whereas the ductility of GFRP increases. Its effect on the elastic modulus depends on the degree of post cure of resin and the degree of the cyclic drying–wetting in brine solution. It need to further research that there is no relevant test to separate the influence of humidity with the influence of chloride.

### 4. EFFECTS OF FREEZE–THAW CYCLES

CFRP and GFRP were tested for 50 and 100 times of freeze–thaw cycles by Ren, Hu, and Zhao (2003). The time of each cycle is 3 h and the temperature is controlled at  $-17 \pm 2$  and  $8 \pm 2^\circ\text{C}$ . The test results show that the stress–strain relationship of the two kinds of fiber materials showed a linear change after 50 and 100 cycles of freezing and thawing. The tensile strength of CFRP decreased slightly that the tensile strength decrease by 2.1% after 50 freeze–thaw cycles, whereas the tensile strength decrease by 4.4% after 100 freeze–thaw cycles. There is no obvious change in the elastic modulus of CFRP. However, the tensile strength and ultimate strain of GFRP decrease greatly that they both decrease by 10% approximately. Similarly, the elastic modulus change of GFRP was not significant. Since the freeze–thaw cycles test is carried out under water immersion, the effect of freeze–thaw cycles on mechanical performance of FRP can be concluded in combination with the results of pure water immersion test before. Water has no effect on the mechanical performance of CFRP, so the main factor that causes the decrease of the tensile strength of CFRP is the freeze–thaw cycles. For GFRP, the reason for the decrease of the tensile strength is due to the influence of freeze–thaw cycle on the performance of pre-coated binder, the influence

of water on the strength of glass fiber and the influence of freeze–thaw cycles on the mechanical performance of the glass fiber.

Xi et al. (2004) had studied the mechanical performance of CFRP under the freeze–thaw cycles. The test results show that the tensile strength and elastic modulus of CFRP decrease by 10 and 18%, respectively, under the freeze–thaw cycles. Thus, the mechanical performance of CFRP is affected by the freeze–thaw cycles.

In summary, the freeze–thaw cycle has no significant effect on the performance of FRP materials. Whether it is CFRP or GFRP, the resin matrix can still be solidified in low temperature or moisture under the freeze–thaw cycles. The modulus of elasticity is improved and the freeze–thaw resistance is enhanced, so that the elastic modulus and the freeze–thaw resistance of FRP composites are improved. However, in the curing process of FRP, there are inevitably some defects such as micropores between the fiber and the resin matrix. Then, the intrusion of water and the temperature of the ascending and descending make the fiber and the resin matrix separated, so the freeze–thaw resistance of FRP composites decreases. Besides, the freeze–thaw resistance of GFRP is stronger than that of CFRP under the freeze–thaw environment because the moisture absorption of GFRP is stronger than that of CFRP.

## 5. EFFECTS OF NATURAL AGING

Yang, Yue, Guo, Zhao, and Cai (2006) have studied the natural aging performance of CFRP under different conditions. The test studied the natural aging of two kinds of CFRP and two kinds of epoxy resin in Northwest China and North China with the natural aging time of 0.5, 1, and 2 years. The first CFRP sheet, after 2 years of natural aging in the northwest region, had not resulted in a reduction of the tensile strength because of the environmental impact, whereas the environmental impact of North China led to a small decline in tensile strength. The tensile strength of the second CFRP sheets decreased slightly due to the influence of the environment after 2 years of natural aging in Northwest China and North China. In summary, considering the factors of environmental conditions, the environmental impact of the northwest region on the CFRP is less than that of the North China region. Preliminary analysis shows that this is mainly because the impact of humidity change on the durability of CFRP is greater than the impact of temperature.

The study on the durability of FRP materials with natural aging needs a long time to be explained, so there are few research results in natural aging at present. Despite all this, natural aging is more close

to the engineering practice that the results of the study are more valuable for the promotion and application of FRP. So, it is significant to vigorously carry out research work in this area.

## 6. EFFECTS OF ULTRAVIOLET AGING

Gu and Yang (2010) had studied the durability of basalt fiber sheet under ultraviolet radiation. The test results show that the tensile strength and elongation of basalt fiber sheet decrease with the time of ultraviolet radiation but the drop is slight. The elastic modulus of basalt fiber sheet change little with the aging time, so it can be concluded that the ultraviolet radiation has not much effect on the elastic modulus of basalt fiber sheet.

In fact, the ultraviolet rays of the sun can destroy the typical covalent bond in the FRP material and turn the polymer into a free radical in order to cause light degradation of the material. The effect of oxygen on the resin is also induced by ultraviolet radiation, which causes the aging of the composite. Despite the great influence of ultraviolet radiation on the durability of FRP materials, there are relatively few research results of this area due to the reason of equipment and so on.

## 7. EFFECTS OF DAMP HEAT AGING

Ren et al. (2005) has conducted a 1000-h of damp heat aging test for CFRP and GFRP. The aging environment is 38°C, and the relative humidity is 98%. The test results show that the tensile strength, elastic modulus, and ultimate strain of CFRP all do not change significantly. In other words, the damp and hot environment has no significant effect on the mechanical performance of CFRP. However, the tensile strength, elastic modulus, and ultimate strain of GFRP decrease in different degrees after the damp heat aging test. Different from the pure water immersion and the freeze–thaw cycle, the modulus of elasticity of GFRP sheet decrease in damp and hot environment, which proves that the mechanical performance of glass fibers were affected by the damp and hot environment and CFRP has better resistance to damp heat aging than GFRP.

It can be seen that the humidity and damp heat aging conditions have little impact on the durability of FRP materials, while hot air of the damp and hot environment has a great influence on FRP materials. Moisture promotes interfacial damage and softens the epoxy matrix, and in result the bond between fiber and matrix becomes weak. After the damp heat aging test, the carbon fiber cloth has a tendency of embrittlement. Besides, CFRP has better resistance to damp heat aging than GFRP.

## 8. CONCLUSION

The paper presents the latest progress in durability study of the FRP materials through an in-depth review and analysis on existing extensive investigations. The performances of two types of FRP materials of carbon FRP (CFRP) and glass FRP (GFRP) under severe environments of humidity, high temperature, wet-dry cycles, freeze-thaw cycles, ultraviolet radiation exposure, and natural exposure have been compared and analyzed. The results reveal that both CFRP and GFRP have the superior corrosion resistance although GFRP material exhibited a slight deterioration.

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