DURABILITY OF FIBRE REINFORCED POLYMER (FRP) WRAPS AND EXTERNAL FRP-CONCRETE BOND

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Abstract

Carbon and glass Fibre Reinforced Polymers (CFRP and GFRP) have proved very effective in restoring and upgrading the performance of concrete structures. However, concerns about the durability of FRP's have been a major obstruction to a rapid growth in their application in concrete structures. For a designer to suggest the application of FRP with the same confidence as the traditional materials, it is vital to know how these new materials perform when exposed to severe environments.

In this paper, selected results from an extensive test program are presented in which the durability of FRP-reinforced concrete was investigated. The environmental parameters to which the specimens were subjected included freeze-thaw cycling, temperature variation, and NaOH solutions with pH 10, pH 12 and pH 13.7 concentrations. Specimens comprised FRP wrapped concrete cylinders and FRP bonded concrete prisms. The tests carried out on the specimens examined the influence of various environmental conditions on the confining effects of FRP wraps and performance of FRP-to-concrete bonds. Results to-date indicate that the exposure to low alkaline environments has minimal effects on the properties tested during this experimental program. High alkaline, freeze-thaw cycles, and temperature cycles seemed to be the environmental conditions with noticeable effects on the bond properties.

1. Introduction

The concrete industry's interest in FRP reinforcements stems from the fact that they do not cause durability problems similar to that of steel corrosion. Although the use of FRP in new and existing concrete structures has demonstrated excellent structural performance, there still exists the need for understanding the long-term durability of FRP in the environments to which the concrete structures are exposed.

In an extensive research program, glass and carbon FRP and FRP-reinforced concrete specimens were subjected to various environmental conditions such as freeze-thaw cycles, UV radiation, temperature variation, NaOH solution with pH 10, pH12 and pH 13.7 concentrations, and moisture to evaluate their effects on material and structural properties of the specimens [1]. This paper reports results from a selected group of specimens and examines the durability of FRP wraps and FRP-to-concrete bonds after exposure to these environments.

2. Experimental Program

2.1 Exposure Environments

The environments to which the specimens were exposed are as follows:

1. Control Environment: 22 ^{o}C and about 50% relative humidity
2. Freeze-thaw: cycling between -18 ^{o}C and +4 ^{o}C submerged in water
3. Temperature variations: 4 cycles/day between -20 ^{o}C and +40 ^{o}C in dry chamber
4. Alkali Solutions: submersion in pH 10, pH 12, and pH 13.7 (nominal pH 14) NaOH solution at 38 ^{o}C

2.2 Materials

The FRP materials used here were from the TYFO™ S Fiberwrap™ System. The properties of the hand wet lay-up composites as provided by the supplier are shown in Table 1. The concrete used for the cylinders and the prisms was made using Ontario Hydro's pre-packaged mix (King Mix No. 4003 July 30/96). The average 28-day strength of the moist-cured 150 mm x 300 mm concrete cylinders was about 35MPa. To obtain a workable and freeze-thaw resistant concrete, super-plasticizer and air entraining admixture were used. The void ratio was measured to be 7.2%.

Table 1: Properties of TYFO™ S Fiberwrap™ System GFRP and CFRP

Property	**Carbon (SCH 41) FRP**	**Glass (SHE 51) FRP**
Ultimate Tensile Strength (N/mm/layer)	850-950	490-560
Rupture Strain (mm/mm)	0.0142	0.0197
Nominal thickness of the Fabric (mm)	1.04	1.24
Weight of the Fabric (grams/m^2)	658	923
Weight of FRP Sheet gr/mm^2/layer	1660	2500
Coefficient of Thermal Expansion/ ^{o}C	-0.5×10^{-6}	7.7×10^{-6}

2.3 Specimens

To study the confining effects of FRP wraps, concrete cylinders, 75 mm in diameter and 150 mm long, were cast from the mix described earlier. The concrete cylinders were moist cured for 28 days at 95% relative humidity and 23°C. They were end-ground until smooth, parallel, and flat end surfaces were obtained. The wall surfaces of the cylinders to be wrapped were cleaned with sandpaper to remove any loose materials. The cylinders were coated with the epoxy and were left to get tacky. Afterwards, Glass/Carbon impregnated fabrics were wrapped onto them with an overlap of 100 mm. The wrapped cylinders were left to cure for seven days and then grouped into control and exposed batches. The exposed cylinders were put into the respective environments and the control specimens were kept at the room condition. The results from 252 wrapped and unwrapped concrete cylinders are summarized here. Each point shown in a graph represents an average value of 3 specimens.

Durability of FRP-to-concrete bond was studied using FRP bonded concrete prisms. Each specimen was comprised of two halves cast together and reinforced with the 25 x 262.5 mm FRP laminates (Figure 1). In each half of a specimen a bolt-plate assembly was installed before casting, which provided the means to apply the load without causing direct tension in the concrete. The bolt was 15.8 mm in diameter and 200 mm long and the steel plate was 50 x 50 x 6.25 mm. Concentrically placed plastic pipe sleeves, 150 mm long x 19.4 mm diameter, were used on the bolts to avoid contact between the bolts and the concrete. The ends of sleeves were sealed with silicon caulking. To break the bond between the two halves of the prism, an oiled 1 mm thick by 50 x 50 mm square formica plate was inserted between the two steel end-plates.

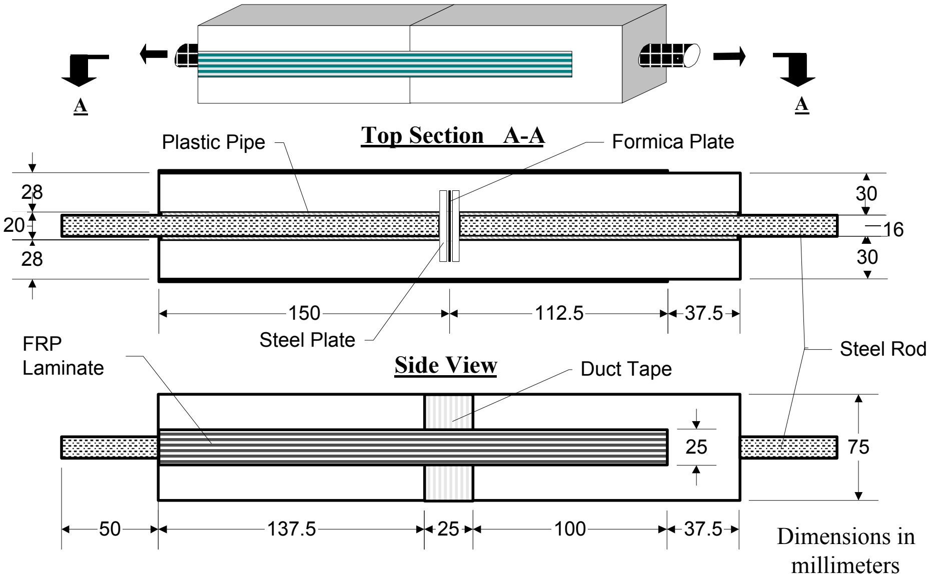

Figure 1: FRP Bonded Concrete Prism

The concrete prisms were moist cured for 28 days followed by one day drying at room temperature. Afterwards, the two side-faces of the prisms where the FRP sheets were to be bonded were sand blasted. At the mid length of the 300 mm long prism, where the two 150 mm long halves were designed to separate, a 25 mm wide smooth surface duct tape was wrapped around the prism section (Figure 1) to break the bond between the FRP and the prism.

Details of FRP applications are available elsewhere [1]. The Prisms were cured for seven days after FRP application, grouped into batches of exposed and control, and placed in the respective environments. The test results from 264 FRP bonded concrete prisms are summarized here. Each point shown in a graph represents an average value of 4 specimens for freeze-thaw and 5 specimens for the other exposures.

3. Results and Discussion

3.1 FRP Wrapped Concrete Cylinders

The concrete cylinders were tested under monotonic compression for their mechanical properties. Axial and circumferential strain values were measured using bonded strain gauges. The chord modulus of elasticity and the energy absorbing capacity of the specimens were calculated. The chord modulus of elasticity was obtained by fitting a straight line through the data points between 10% and 40% of the maximum strength on the stress-strain curve. Figure 2 shows typical stress-strain responses of CFRP and GFRP wrapped and unwrapped concrete cylinders. The wrapped specimens, although very ductile, did not show any post peak stress-strain behaviour. The failure was sudden, especially in Carbon Fibre Reinforced Polymer (CFRP) wrapped cylinders, irrespective of whether the testing was carried out under load control or displacement control. The stress-strain curves for both types of wrapped cylinders were somewhat bilinear with a yield point almost equal to the failure stress of the unwrapped control specimens. This yield point was more pronounced in the case of GFRP wrapped cylinders, in which the stress had a post yield drop resembling ductile steel.

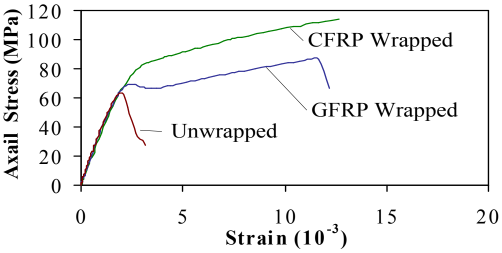

Figure 2: Typical Compressive Stress-Strain Behaviour of FRP Wrapped and Unwrapped Concrete Cylinders

On average one layer of CFRP wrap increased the compressive strength by a factor of about 1.8. This increase in strength with one layer of GFRP wrap was 30% to 40%. The average energy absorbing capacity of the control cylinders increased by a factor of about 14 with CFRP wrap and by a factor of about 11 with GFRP wrap.

Effects of Freeze-thaw Cycles: Figure 3 compares the axial compressive strength of the wrapped and unwrapped concrete cylinders exposed to different number of freeze-thaw cycles with their control counterparts. The strength of exposed unwrapped cylinders dropped by about 15% to 20% with the exposure to 300 freeze-thaw cycles when compared to their unexposed counterparts. The energy absorbing capacity of the unwrapped cylinders also decreased significantly with the increase in the number of freeze-thaw cycles. The modulus of elasticity of unwrapped cylinders on average was only slightly affected by the exposure.

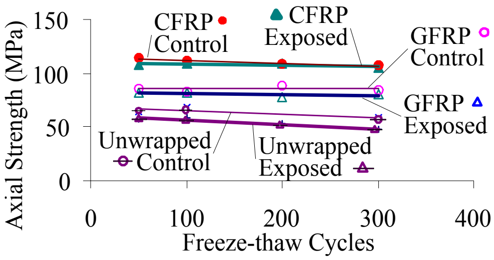

Figure 3: Strength of FRP Wrapped and Unwrapped Concrete Cylinders after Exposure to Freeze-thaw

The exposed GFRP wrapped specimens experienced up to 10% loss in strength when compared to their control partners after exposure to 300 freeze-thaw cycles. However, it should be noted that the scatter in the strength values ranged up to 8%. The energy absorbing capacity was affected slightly by the exposure, but considering the scatter, the effects were negligible. No significant changes were observed in the modulus of elasticity of the GFRP wrapped cylinders due to exposure. The CFRP wrapped cylinders experienced no negative changes in their mechanical properties due to the exposure to the freeze-thaw cycles.

Effects of Temperature Cycling and Alkali Solutions: Figure 4 shows the effects of temperature cycling, and pH 10, pH 12, and pH 13.7 NaOH solutions on the strength of unwrapped cylinders. The strength dropped by 10% to 13% after 7 days of exposure to temperature cycling and alkali solutions. This drop remained almost constant for up to 84 days of exposure to pH 10 and pH 12 solutions. However, the strength of unwrapped concrete cylinders exposed to temperature cycling and pH 13.7 solution dropped by about 20% and 25 %, respectively, after 84 days.

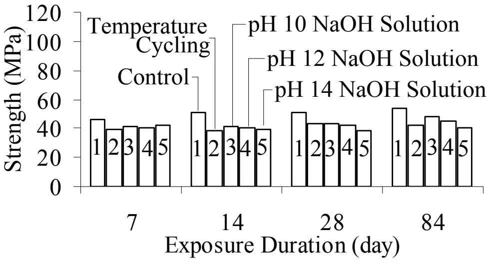

Figure 4: Strength of Unwrapped Concrete Cylinder Exposed to Various Environments

Figure 5 shows the effects of various exposures on the strength of GFRP wrapped concrete cylinders. After 7 days of exposure a slight increase in strength of temperature-cycled specimens was observed when compared to the control specimens. The early increase in strength in NaOH solutions exposed specimens were more pronounced, which can be attributed to the higher temperature (38 ^{o}C) in the exposure chamber. The increases in strength of specimens exposed to pH 10, pH 12, and pH 13.7 solutions were about 14%, 11 %, and 8%, respectively. However, after 84 days, there was only negligible difference between the strength of control and exposed specimens.

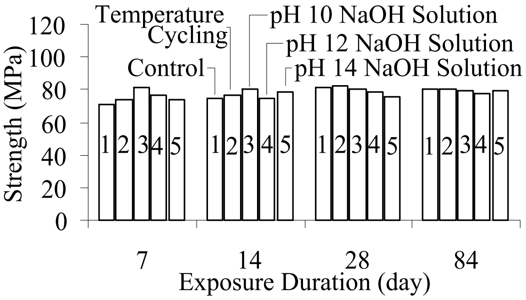

Figure 5: Strength of GFRP Wrapped Concrete Cylinders Exposed to Various Environments

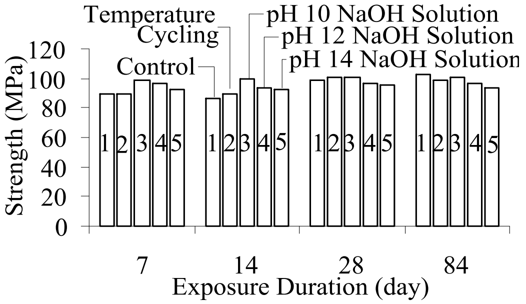

Figure 6: Strength of CFRP Wrapped Concrete Cylinders Exposed to Various Environments

Figure 6 shows the effects of various exposures on the strength of CFRP wrapped concrete cylinders. After 7 days of exposure to NaOH solutions, the strength of specimens was observed to be 3% to 10% higher than that of the control specimens, which can be attributed to the higher temperature (38 ^{o}C) in the exposure chamber. However, the difference in strength between the exposed and control specimens reversed as the duration of exposure extended and after 84 days the strength values of CFRP wrapped specimens exposed to temperature cycles and pH 10 solutions were slightly lower than that of the control specimens. The CFRP wrapped specimens exposed to pH 12 and pH 13.7 NaOH solutions experienced 7% and 10% loss in strength, respectively, when compared to the control specimens.

3.2 FRP Bonded Concrete Prisms

The FRP-bonded concrete prisms (Figure 1) were used to study the durability of the bond between the FRP and the concrete as affected by exposure to different environments. The specimens were tested by applying tension at the ends of the embedded bolts. Pulling apart the bolts caused the FRP-Concrete interface to shear. The bond failure took place at the epoxy-concrete interface. In some specimens, small chips of concrete broke off from the surface of the concrete. The average lap shear strengths of the unexposed CFRP- and GFRP-bonded specimens were about 3.10 MPa and 2.30 MPa, respectively. The reason for a lower GFRP-to-Concrete lap shear strength than that of CFRP-to-Concrete can be partly attributed to the texture of the particular fabric used in this study. The weft in CFRP fabric is very fine and gives the fabric a flat surface, where the GFRP fabric is woven with much thicker Kevlar weft and the fabric surface is very wavy. This can result in lesser GFRP area available to the bond. The epoxy may be too fluid to stay in place and fill the wavy gaps under the sheet. The voids under the GFRP strips could be seen in the tested specimens. Another possible reason can be the stiffness of the fabrics. The GFRP has a lower modulus of elasticity and, thus, deforms more under the same load than the CFRP. This can force the epoxy in the bond to deform more and reach its shear failure strain much quicker under the GFRP than the CFRP.

The FRP panels on each side of the specimens had two bonded lengths, i.e. 100 mm (the short leg) and 137.5 mm (the long leg). The difference of length was aimed to cause failure on the instrumented short leg. However, C-clamps were also used on the long legs to avoid failure there. From the mechanical properties of FRP it was determined that the 100 mm lap length between FRP and concrete was not enough for the FRP to develop its full strength. The failure was thus forced at the interface.

The slip of the specimens was measured by mounting linear voltage differential transducers (LVDTs) on the short leg of specimens. The LVDTs recorded the amount of the slip between the FRP panel and the concrete block in millimetres. Figure 7 shows typical lap shear stress versus lap slip responses of the tested specimens. Each curve displays an elastic range followed by a plastic range.

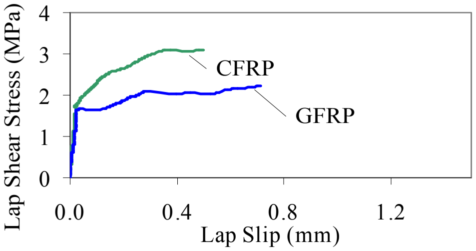

Figure 7: Typical Shear Stress-Slip Behaviour of FRP Lap Bonded Concrete Prisms

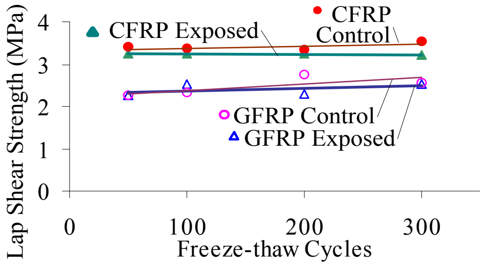

Figure 8: Lap Shear Strength of FRP Bonded Concrete Prisms Exposed to Freeze-thaw Cycles

Effects of Freeze-thaw Exposure: Figure 8 compares the effects of freeze-thaw on lap shear strength of the GFRP and CFRP bonded concrete prisms. On average the lap-shear strength of GFRP specimens dropped only slightly due to the freeze-thaw exposure when it is compared to the strength of control specimens. Due to the wide scatter, it is difficult to evaluate the effect of freeze-thaw exposure on the lap shear rigidity and lap shear slip. The effect, however, seems minimal.

The effect of freeze-thaw on the CFRP-to-Concrete bond is slightly more severe than that on the GFRP bonds. The average lap shear strength of CFRP bonded specimens dropped by about 5% due to the freeze-thaw exposure. The lap shear rigidity and lap shear slip values, due to wide scatters, were not used to evaluate the effect of freeze-thaw exposure.

Effects of Temperature Cycling and Alkali Solutions: Figure 9 compares the effects of temperature cycling, and pH 10, pH 12, and pH 13.7 NaOH solutions on the lap shear strength of GFRP-to-Concrete. At the early stages of exposure drops of about 10% to 14% were observed in the bond strength of all exposed specimens when compared to control specimens. As the duration of the exposure progressed, the difference in strength of specimens exposed to pH 10 and pH 12 solutions and the control specimens disappeared. However, the temperature cycles exposed GFRP specimens lost about 15% of their bond strength and the pH 13.7 NaOH solution exposed specimens lost about 5% of their strength.

Figure 10 shows that at the early stages of the exposure the CFRP-to-concrete bond strength increased, possibly due to the higher temperatures of exposure. However, as the exposure duration progressed, the control specimens gained strength and the strength of exposed specimens did not change much. A large scatter was observed in the data for this series of tests.

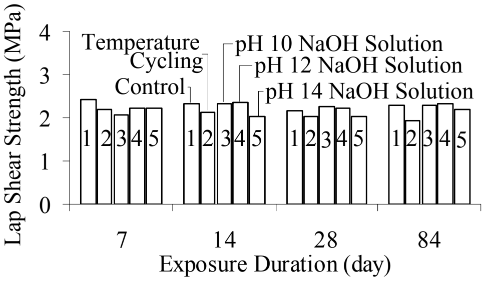

Figure 9: Lap Shear Strength of GFRP Bonded Concrete Prisms Exposed to Various Environments

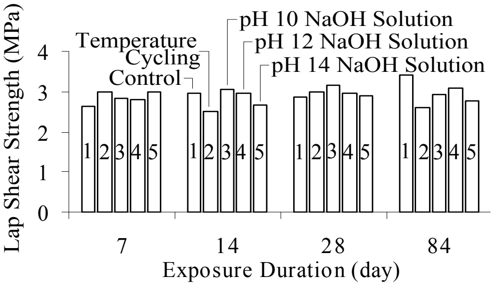

Figure 10: Lap Shear Strength of CFRP Bonded Concrete Prisms Exposed to Various Environments

4. Conclusions

Glass and Carbon FRP wrapped concrete cylinders and externally reinforced concrete prisms were subjected to freeze-thaw cycles, temperature variations (-20°C to +40°C), and alkaline environment (pH 10, pH 12, and pH 13.7 NaOH solutions). The effects of environmental conditions on the long-term performance of FRP wraps and FRP-concrete bonds were studied. Results so far indicate outstanding resistance of both CFRP and GFRP wraps to the exposed conditions. GFRP- and CFRP-to-concrete bonds performed well in resisting the effects of low alkaline environments. However, the bond strength was adversely affected by high alkalinity and freeze-thaw and temperature cycles in both materials.

5. Acknowledgments

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6. References

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