Durability of Concrete Beams with Bonded FRP Composites made of Flax and Glass Fibers

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DURABILITY OF CONCRETE BEAMS WITH BONDED FRP COMPOSITES MADE OF FLAX AND GLASS FIBERS

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ABSTRACT: Synthetic fibers, such as glass fibers, in the form of fiber-reinforced polymer (FRP) composites have been extensively used for the repair and strengthening of existing concrete structures in the past three decades. As glass fibers come from a non-renewable resource, this research was conducted on flax fibers as a natural plant-based material and a potential replacement to glass fibers. The element of durability is a major concern with natural materials such as flax fibers. In this study, durability tests were conducted in order to investigate the long-term behavior of both glass and flax FRPs externally bonded to concrete beams. A total of 100 plain small-scale concrete beams (75×100×400mm) were prepared and bonded with flax and glass FRPs made of vinyl-ester resin. The test specimens were immersed into water solution and tested after 21, 42, and 63 days. There were also specimens kept in dry conditions and were used as control specimens. The temperature of the solutions were controlled at 20 and 60 °C. Five identical specimens were prepared and tested for each condition. The durability of the bond between the FRP and the concrete were studied under three-point bending. The weight of the specimens and the pH and temperature of the solutions were also observed. In general, the test results showed that the bond strength of the control specimens bonded with flax FRP was 20% weaker than their counterparts with glass FRP in air dry condition. After 63 days in water at 60 °C, the residual bond strength of the specimens bonded with flax FRP was 84% and with glass FRP was 90%; which were compatible with the overall moisture absorption of 2.79% and 2.35%, respectively.

1. Introduction

During the past three decades, synthetic fibers such as glass and carbon fibers have been extensively used for the repair and strengthening of existing concrete structures in the form of fiber-reinforced polymer (FRP) composites. Synthetic fibers are made of non-renewable resources and their production typically emits significant greenhouse gases contributing to global warming. Moreover, it is very difficult to recycle FRP composites made of synthetic fibers (hereafter called synthetic FRPs) at the end of their life span and they are typically sent to landfills, which are filling up fast. Natural fibres extracted from plants (e.g. flax, hemp, jute, and etc.) are good examples of renewable materials and offer several economic, technical, and ecological advantages over synthetic fibres. FRP composites made of natural fibers (hereafter called natural FRPs) have many potentials for recycling and degradation, depends on the type of polymer. The worst case scenario is the incineration of natural FRPs to generate power as well as to reduce their volume significantly to fly ash and bottom ash with many potential applications in concrete industry. Natural FRPs have been extensively researched for the past two decades. Due to the relative large quantity, low cost of raw material, low density, high specific properties, and positive environmental profile; natural fibres have been considered as prospective substitutes to synthetic fibres, specifically glass fibres. Despite of positive characteristics, natural fibres have some negative characteristics. They are highly hydrophilic and their mechanical and physical properties are strongly dependent on the climate, location, and weather; so it is difficult to predict their respective composite properties and failure mechanism. In terms of long-term performance of natural FRPs, there are drawbacks with respect to their durability against moisture and other environmental conditions. The durability of synthetic FRPs externally bonded to concrete structures have been extensively studied, for example see Jia et al. (2005) and Myers (2007). It has been shown that the bond between FRP and concrete can be deteriorated by aging and exposure to environmental conditions. Many parameters including material properties, type of environmental exposure, type of loading, and quality of workmanship can affect the deterioration of the bond (Sen, 2015). As natural fibers are more sensitive than synthetic fibers to moisture, the durability of the bond between natural FRPs and concrete needs to be studied in depth. In this study, durability tests are conducted in order to investigate the long-term behavior of both synthetic and natural FRPs externally bonded to concrete beams. A total of 100 plain concrete beams are prepared and bonded with flax and glass FRPs made of vinyl-ester resin. The test specimens are immersed into water solution and tested after different exposure durations at 20 and 60 °C. The durability of the bond between the FRP and the concrete are tested under three-point bending and compared to control specimens.

2. Experimental Program

The experimental program follows the concept of the accelerated conditioning protocol (ACP) recommended by ACI 440.9R-15 (2015) for FRP-bonded concrete beams. The critical mechanism is considered to be the effect of moisture accelerated by heat on the bond between FRP and concrete. After the aging process, the FRP-bonded beams are tested under a three-point bending. A bond failure mode is typically expected, which is where the fracture surface passes entirely through the FRP-concrete interface and some concrete may remain adhered to the FRP. Durability of this failure mode is mainly dependent on the durability of the polymer, however the FRP's fibers and the concrete substrate have some effect. In fact, the intent of the combined ACP and bond tests is not to test the durability of concrete and/or FRP, but rather to test the durability of the bond between FRP and concrete.

2.1. Test Matrix

A total of 100 plain concrete beams (75×100×400 mm) were prepared and bonded with flax and glass FRPs made of vinyl-ester resin to be tested under three-point bending. The test parameters are: fiber type (flax vs. glass), environmental aging condition (dry, immersed in water, and freeze/thaw), exposure duration (21, 42, and 63 days) and temperature during exposure (20 and 60 °C). For each case five identical specimens were prepared as shown in Table 1.

Table 1 – Test matrix.

Exposure Duration (days)	**Air Dry**		**Water**		**Freeze/Thaw**
	T=20 °C	**T=60 °C**	**T=20 °C**	**T=60 °C**	**25 Cycles**
0	5	-	-	-	5
21	-	-	5	5	
42	-	-	5	5	
63	5	5	5	5	
Total	100 (50 flax and 50 glass) FRP bonded concrete beams				

2.2. Material Properties

All specimens were constructed with the same concrete mix design containing 1076 kg/m^3 coarse aggregate, 700 kg/m^3 fine aggregate, 207 kg/m^3 water, and 421 kg/m^3 Portland cement type I/II. Maximum aggregate size was 19 mm and the 28-day concrete compressive strength was 45 MPa. For flax FRPs, a 275 g/m^2 stitched unidirectional flax fabric was used. The fabric was made of flax fibers with the density of 1.5 g/cm^3, diameter of 20 µm, tensile strength of 500 MPa, elastic modulus of 50 GPa, and rupture strain of 2% reported by the manufacturer. For glass FRPs, a 955 g/m^2 stitched unidirectional glass fabric was used. For both flax and glass composites, a vinyl ester resin catalyzed with 1.25% methyl ethyl ketone peroxide (MEKP) was used. The resin cured at room temperature for 24 hours and post-cured for 2 hours at 138 °C was reported by the manufacturer to have the tensile strength of 82 MPa, elastic modulus 3.72 GPa, and rupture strain of 7.9%. Five identical tensile coupons of flax and glass

FRPs were prepared and tested with the rate of 2 mm/min (Hristozov et al., 2016). Fig. 1 shows the tensile test results based on nominal thicknesses of 1.0 and 1.5 mm of flax and glass FRP, respectively. The average tensile strength of flax and glass FRPs was 207.42 and 865.35 MPa, respectively. The dotted lines in Fig. 1 show the elastic modulus of flax and glass FRPs with the average values of 21.94 and 37.37 GPa, respectively. As shown in Fig. 1, the behavior of glass FRPs is almost linear up to rupture, however that of flax FRPs is bilinear with a transition zone at strains ranging from 0.002 to 0.003 mm/mm and a secondary slop of almost two-third of the initial slope. The initial linear zone and the nonlinear transition zone can be related to the nonlinear behavior of polymers and the secondary linear behavior can be due to the crimp extension of natural fibers.

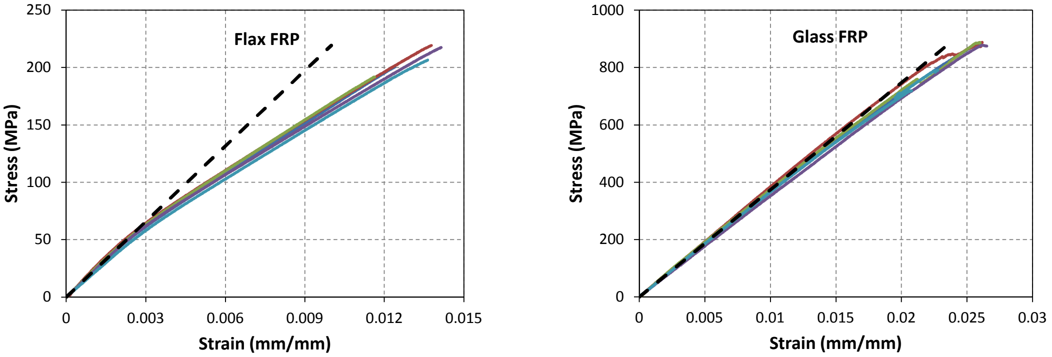


Fig. 1 – Tensile stress-strain curves of flax and glass FRPs.

2.3. Specimen Fabrication

As shown in Fig. 2, the concrete were poured into custom-made wooden forms with five cells to make 75×100×400 mm plain small-scale concrete beams. When concrete curing was completed, the beam specimens were saw cut on a form finished face at mid span to a depth of 50 mm (i.e., half of the 100 mm side) based on ACI 440.9R-15. The same surface was also roughened with a concrete surface grinder to enhance the bonding of concrete and FRP. Then, the specimens were dried for a period of 48 hours in a circulating-air oven at a temperature of 50 °C. After a minimum 5 hours cooling in room temperature, a single layer of glass FRP sheet or two layers of flax FRP sheets (75 mm wide × 200 mm long) were applied on the roughened surface. The 3 mm wide saw cut provided two identical bond lengths for the bonded FRP from the beam mid-span. After the FRP cured for 7 days at room temperature, the specimens were pre-conditioned for a period of 48 hours in a circulating-air oven at a temperature of 50 °C. The purpose pre-conditioning was to ensure the resin was cured completely as well as to measure weight of the specimen at dry condition. After weighing, the specimens were ready to be aged in different environmental conditions.

2.4. Environmental Conditioning

The beam specimens bonded with FRPs were immersed into tap water and were kept at two different temperatures, i.e. at the room temperature and in a circulating-air oven at with 60 °C as planned in Table 1. The water containers were sealed to control evaporation. In addition, similar specimens were kept in an air dry condition in oven and room temperature for comparison. For room temperature cases, the air dry specimens were kept on a dry shelf and the rest were immersed into water containers in the lab. The mechanical tests were conducted at 63 days (1500 hours) after the environmental conditionings started. Five identical specimens were prepared and tested. The specimens were taken out of water surface dried and weighed. The temperature and pH of the solutions were also measured. The average pH of the solution at 60 °C during the same period of 63 days was 11.45 with standard deviation of 0.03.

2.5. Test Setup

The specimens were oven dried prior to testing. A universal testing machine was used to perform a three-point bending test as shown in Fig. 2. The tests were displacement controlled with the rate of 0.5 mm/min. The specimens were tested with a simply supported span of 300 mm with 50 mm overhang at each end.

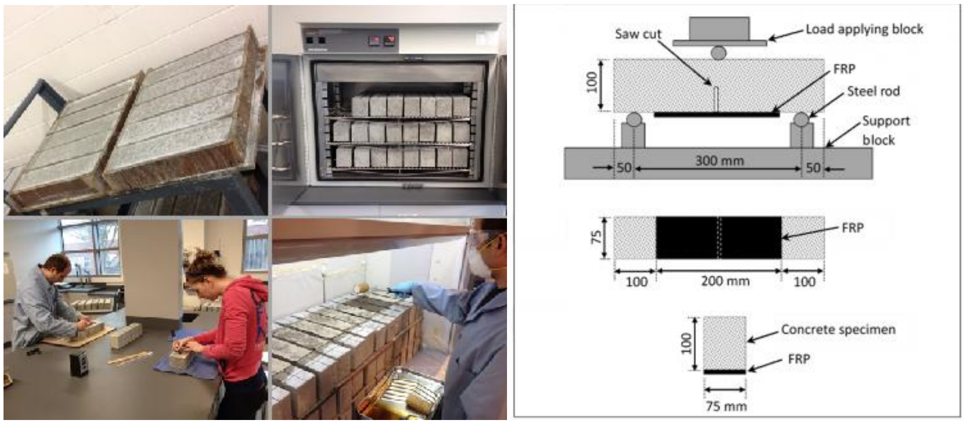


Fig. 2 – Specimen preparation and test set-up

3. RESULTS AND DISCUSSIONS

3.1. Weight Change

The weight change of glass and flax FRP bonded concrete beams is compared in order to understand the difference in water absorption. This can help understand the difference in long-term mechanical properties of the two materials. When flax FRP bonded specimens were placed in the solutions for different durations there was usually a weight gain due to the water absorption by both concrete and FRP materials. Fig. 3 shows the variation in weight gains of the specimens at 60 °C after 63 days immersing in the water. The weight gains were calculated based on oven dry weight and saturated surface dry weight of each specimen. The weight gains are the average of five identical specimens and the bars shown in Fig. 4 represent a standard deviation lower and higher than the average values. The weight gain is measured as follows:

$$M_t = \frac{W_t - W_d}{W_d} \times 100 \qquad (1)$$

where M_t is the percentage of weight gain at the time t, W_d is the weight of the dry specimen at time t=0 and W_t is the weight of the saturated surface dry specimen at time t. As shown in Fig. 3(a), the weight gain percent of flax FRP bonded specimens immersed in water at 60 °C for 63 days was 2.79±0.75%. As shown in Fig. 3(b), the weight gain percent of glass FRP bonded specimens immersed in at 60 °C after 63 days was 2.35±0.32%. By comparing Fig. 3(a) and 3(b), it can be seen that the effect of temperature on the weight gain of both flax and glass FRP bonded specimens had the same trend, however the weight gain in glass FRP bonded specimens is lower than flax FRP bonded specimens. Overall, the average weight gains of flax and glass FRP bonded specimens were 2.79% and 2.35%, respectively. This is compatible with the hydrophilic nature of natural fibers.

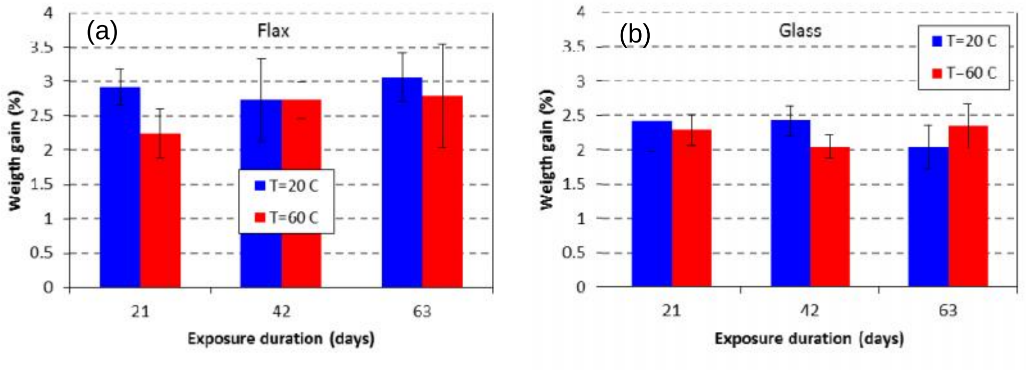
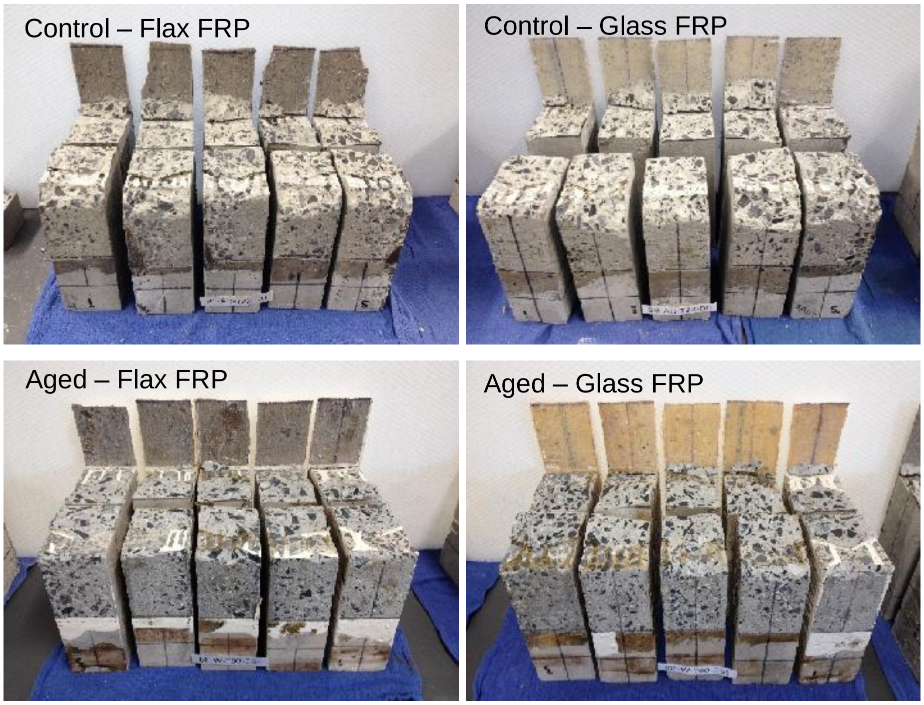


Fig. 3 – Variation in weight gain of concrete beam specimens bonded with (a) flax and (b) glass FRPs immersed in water.

3.2. Failure Mode

The specimens were tested under three-point bending with a span of 300 mm. The load and mid-span deflection of each specimen were measured up to the failure. As shown in Fig. 4, typical failure mode was a brittle debonding of the FRP from the concrete at the interface, not in concrete. For control specimens (i.e., no aging), some cement paste remained locally adhered to the FRP, however for aged specimens less cement paste left on FRP after debonding failure. It shows that the ageing process affected the bonding polymer more than the concrete.


Control – Flax FRP

Control – Glass FRP

Aged – Flax FRP

Aged – Glass FRP

Fig. 4 – Typical failure of control specimens and specimens aged in 60 ^{O}C water for 63 days

3.3. Load-Deflection Behavior

Figure 5 shows the load-deflection behavior of control specimens (i.e., no aging). Fig. 6 presents the load-deflection behavior of beam specimens bonded with flax and glass FRPs after 63 days immersion into 60 °C water solution. After the immersion, the specimens were tested with a similar test setup of the control specimens. Keeping the specimens in high temperature for a longer period of time does have a degradation effect on the bond strength. The figures show the behavior of specimens with a duration of 63 days in high temperature. Increasing the temperature along with the duration of immersion decreases the bond strength. The results show that the specimens bonded with flax FRPs aged in 60 °C water are 10% stronger than their counterparts aged in 20 °C water. The result seems in contradiction with the common belief about accelerated aging in water at high temperature. The authors believe that the effect of resin curing at high temperature should be also considered. That is why a set of specimens were kept in 60 °C air dry condition. The results also show that the strength of the control specimens bonded with flax FRP was 20% weaker than their counterparts with glass FRP. The results show that the peak load of the specimens aged in water does not indicate a significant reduction compared to the control specimens, regardless of the aging duration and temperature.

4. Conclusion

In this study, durability tests were conducted in order to investigate the long-term behavior of both synthetic and natural FRPs externally bonded to concrete beams. The test parameters were fiber type (flax vs. glass), environmental aging in water exposure duration 63 days. The durability of the bond between the FRP and the concrete were tested under three-point bending and compared to control specimens. Five identical specimens were prepared and tested for each condition. The weight of the specimens and the pH and temperature of the solutions were also observed. The solutions at higher temperature were more inclined to gain alkalinity from concrete.The average weight gains of flax and glass FRP bonded specimens were 2.79% and 2.35%, respectively. Typical failure mode was a brittle debonding of the FRP from the concrete at the interface. In general, the test results showed that the bond strength of the control specimens bonded with flax FRP was 20% weaker than their counterparts with glass FRP. After 63 days in 60 °C water, the residual bond strength of the specimens bonded with flax and glass FRPs was 72% and 80% with respect to their counterpart specimens kept in 60 °C air dry condition, respectively; which are compatible with the overall moisture absorption of the specimens.

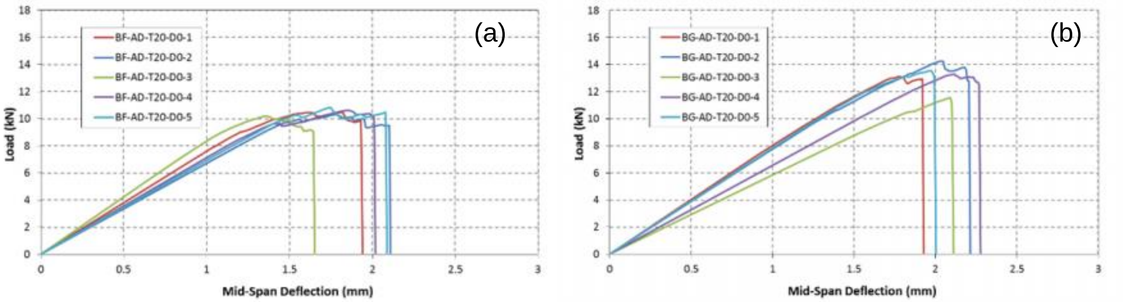


Fig. 5 – Load-deflection of control specimens bonded with: (a) flax FRP; and (b) glass FRP.

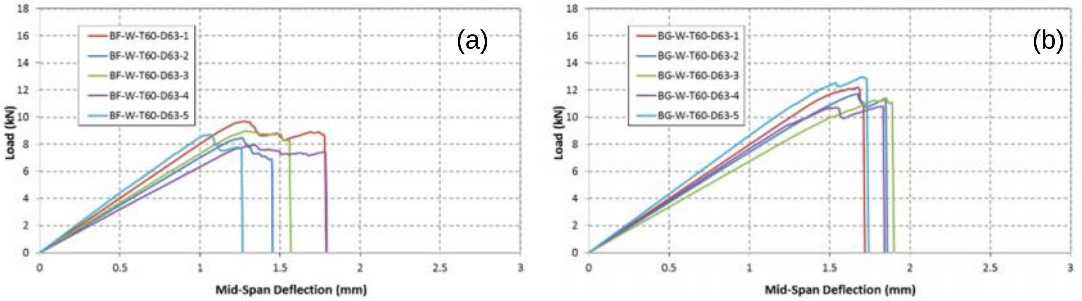


Fig. 6 – Load-deflection of specimens exposed to 60 °C water for 63 days: (a) flax and (b) glass

5. Acknowledgements

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