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Durability under freeze–thaw cycles of concrete beams retrofitted with externally bonded FRPs using bio-based resins

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HIGHLIGHTS

- Effect of freeze–thaw (FT) cycles on RC beams retrofitted with bio-based resin FRP laminates.
- Effect of FT cycles on tensile characteristics of bio-based resin FRP coupons.
- Fully bio furfuryl alcohol resin and a partially bio epoxidized resin were investigated.
- 300 FT cycles over seven months at a temperature range of +6 to −27 °C were applied.
- No reductions in ultimate strengths of beams after FT exposure.

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ABSTRACT

This study examined the effects of freeze–thaw (FT) cycles on the flexural performance of reinforced concrete beams strengthened with externally bonded fibre-reinforced polymer (FRP) laminates fabricated using bio resins. Six large-scale beams including three retrofitted with bio resin-FRP, two with epoxy-FRP, and one control beam, were tested. A fully bio furfuryl alcohol (FA) resin derived from corn cobs and sugar cane, and a partially bio epoxidized pine oil (EP) resin, were investigated. Additionally, 40 FRP tension coupons fabricated with the bio resins and the epoxy resin were tested to assess the effect of FT cycles on their tensile properties. Specimens were exposed to 300 FT cycles over a period of seven months at a temperature range of +6 to −27 °C. The study showed that this aggressive FT regime did not have a negative effect on the ultimate capacities of the beams or the coupons. In fact, all the conditioned beams had peak loads between 7 and 17% higher than their unconditioned counterparts, which may be attributed to the additional curing of concrete during the thawing phase of the FT cycles by submersion in water. The FT conditioned beams with the FA and the EP resin FRPs had 22 and 25% higher yield loads and 25 and 31% higher ultimate loads, respectively, compared to the FT conditioned unstrengthened beam.

1. Introduction

There is a growing need to rehabilitate aging infrastructure, particularly in environmentally challenging regions where infrastructure is exposed to extreme temperatures, moisture and chlorides. Rehabilitation and strengthening of concrete structures using externally bonded fibre reinforced polymers (FRP) has proven to be an effective method since the 1980s [1]. In fact, FRPs present many advantages over traditional rehabilitation methods – they have a high strength-to-weight ratio, are easy to install and are corrosion-resistant [1]. Externally bonded and near-surface mounted FRPs can be used to increase the load-carrying capacity of reinforced concrete structures [31,35,7,26,8,5], but are often exposed to harsh environmental conditions like freeze–thaw (FT) cycling. Differential thermal expansion of the FRP laminate, the adhesive bond line and the concrete substrata may cause localized stresses. Therefore, it is important to study the effects of FT cycling on both the mechanical properties of FRP laminates and the overall retrofitted concrete system. Dutta [12] studied the effect of FT cycling on glass-FRP (GFRP) laminates and found reductions in tensile strengths up to 10% after 150 cycles. Li et al. [19] found that the mechanical properties of basalt-FRPs (BFRPs) and GFRPs were not significantly affected by FT cycling but that the tensile strength and modulus of carbon-FRP (CFRP) were reduced by 16% and 18%, respectively after 90 cycles. Di Ludovico et al. [20] found a 9% reduction in the strength of CFRP laminates after 210 FT cycles. They also found that this reduction could be lessened by using innovative formulated epoxy systems. Nardone et al. [24] found no significant reduction in the mechanical properties of CFRP lam-

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inates after 30 and 80 FT cycles but found that after 210 cycles the tensile strength and ultimate strain were reduced by 9% and 13%, respectively. Shi et al. [27] found a 12% and 14% reduction in tensile strength for CFRP and GFRP laminates, respectively, after 200 FT cycles. However, they found that the cycling had negligible effects on the mechanical properties of BFRP and C-B-FRP hybrid laminates. As we can see from these studies, the mechanical properties of FRP laminates seem to be affected by FT cycling but the degree of which depends on the materials and characteristics of the FRP laminate.

The failure of reinforced concrete beams retrofitted with externally bonded FRPs is often governed by debonding of the external reinforcement [35]. Many studies have focused on the bond behavior of this system (Chen and Teng [10] among many others). A number of studies found that FT cycling had little to no adverse effects on externally bonded FRPs bonded to concrete [17,6,18,11]. Some studies, however, found more significant reductions in strength due to FT cycling. Chajes et al. [9] examined the effects of 100 FT cycles on concrete beams with external aramid, glass and graphite FRPs and found strength reductions up to 27%. Grace and Singh [16] found that the load capacity of reinforced concrete beams with externally bonded CFRP was reduced by 13% after 700 FT cycles. A study by Silva and Biscaia [29] found that small scale beams externally reinforced with GFRP had a 31% decrease in ultimate load capacity after 1000 h of FT cycling. Subramaniam et al. [32] performed a direct shear test to study the effect of FT cycling on the bond between concrete and FRP and found that there was a reduction in strength up to 17% after 300 cycles.

Externally bonded FRPs are traditionally made with synthetic resins derived from unrenewable resources like petroleum. There is a growing push for more sustainable building materials. In the case of FRPs, this can be achieved by replacing synthetic resins with bio-based or partially bio-based resins. Limited work has been carried out on the use and durability of these systems. A study by Eldridge and Fam [13] looked at the effects of environmental aging in saltwater at elevated temperatures on GFRP laminates fabricated with a furfuryl alcohol (FA) bio-resin and a conventional epoxy (E). They found that the specimens fabricated with the Fa resin had up to a 39% lower strength retention compared to the specimens fabricated with epoxy. McSwiggan and Fam [22] studied the effects of environmental aging in saltwater at elevated temperatures on CFRP laminates fabricated with a FA bio-based resin, an epoxidized pine oil (EP) partially bio-based resin and a conventional epoxy resin. The maximum strength losses for the FA, EP and E resins were 19%, 8% and 10%, respectively. Another study McSwiggan et al. [23] studied the effects of environmental aging in saltwater baths at elevated temperatures on the bond between concrete and externally bonded CFRPs using the previously mentioned three resins. The study found that the bond between the FA resin and concrete is not reliable in 'bond-critical' applications such as flexural retrofitting, even at room temperature. However, prefabricated FRP plates made with the FA resin are quite reliable when bonded to concrete using epoxy paste. The reductions in bond strength after 240 days of conditioning did not exceed 15% for any of the resin types.

Previous durability studies on bio resin FRPs focused on conditioning in salt solutions at high temperature. The present study investigates the effects of aggressive FT cycling on the tensile properties of bio resin FRPs and large-scale reinforced concrete beams with externally bonded FRPs fabricated with the FA and the EP bio resins and the conventional E resin. After exposure to 300 FT cycles for seven months, at air temperatures ranging from +13 to −25 °C, to achieve target temperatures at the concrete core in accordance with ASTM C666-97 (ASTM 1997), all the specimens were tested to failure at room temperature. The tension coupons were compared to control counterparts kept at room temperature and also tested in this study, while the beams were compared to identical unconditioned reinforced concrete beams tested to failure at room temperature by McSwiggan and Fam [21].

2. Experimental program

The following section presents the experimental program for the both the FRP tension coupon tests and the large-scale reinforced concrete beam tests.

2.1. Materials

2.1.1. Carbon fibres (C):

A 0.64 kg/m^3 unidirectional carbon fibre fabric was used. The manufacturer reports typical test values for mechanical properties including a tensile strength of 4000 MPa, a tensile modulus of 230 GPa and an ultimate strain of 1.7%. It is commercially available under the name Tyfo® SCH-41 [15].

2.1.2. Glass fibres (G)

A 2.55 kg/m^3 unidirectional glass fibre fabric was used. The manufacturer reports typical test values for mechanical properties including a tensile strength of 3240 MPa, a tensile modulus of 72.4 GPa and an ultimate strain of 4.5%. It is commercially available under the name Tyfo® SHE-51A [15].

2.1.3. Conventional epoxy resin (E)

A low viscosity epoxy resin was used. The manufacturer reports typical test values for mechanical properties including a tensile strength of 72.4 MPa, a tensile modulus of 3.18 GPa and an ultimate elongation of 5%. It is commercially available under the name Tyfo® S [15].

2.1.4. Conventional epoxy paste

An epoxy paste with a tensile strength of 24.8 MPa, a design tensile modulus of 4.5 GPa and an ultimate elongation of 1% was used. It is commercially available under the name Sikadur® 30 [28].

2.1.5. Epoxidized Pine Oil resin blend (EP)

A low viscosity epoxy resin blend, partially derived from oil extracted from pine tree sap, was used. The manufacturer reports typical test values for mechanical properties including a tensile strength of 58.9 MPa, a tensile modulus of 2.64 GPa and an ultimate elongation of 6% [15].

2.1.6. Furfuryl alcohol resin and catalyst (FA)

A low viscosity furfuryl alcohol based ($C_5H_6O_2$) bio resin was used. It is derived from sugar cane and corn cobs and is commercially available under the name QuaCorr®1001 [25]. It has a specific gravity of 1.22, a viscosity of 300–600 cps, a gel time of 18–24 min at 25 °C, and a flash point of 75.6 °C. P-Toluenesulfonic acid monohydrate 97.5% was used to cure this resin at a dosage of 3% by weight.

2.1.7. Concrete

Concrete with a design 28-day compressive strength of 35 MPa was used. The maximum aggregate size was 19 mm. The cylinder strength was measured in accordance with ASTM 39 (2015) [2] and was found to be between 28 MPa and 36 MPa at the time of testing with an average strength of 34 MPa.

2.1.8. Steel reinforcement

15 M and 10 M steel longitudinal reinforcing bars with a yield strength of 430 MPa were used. Tension tests were performed by