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Bond durability of basalt-fiber-reinforced-polymer (BFRP) bars embedded in concrete in aggressive environments

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ABSTRACT

Recently, basalt-fiber-reinforced-polymer (BFRP) bars have emerged as a promising alternative to glass-fiber-reinforced-polymer (GFRP) bars. So far, however, BFRP bars have not been incorporated into design standards and specifications. This is due to limited studies and lack of knowledge on the performance of the bars in concrete, in particular, their bond durability when exposed to aggressive environments. This paper presents some results of an extensive research program investigating the bond durability behaviors of BFRP bars in concrete structures and the long-term bond-strength-retention predications of the BFRP bars on the basis of short-term tests results. This research included testing deformed BFRP bars measuring 12 mm in diameter. Pullout specimens were tested with direct tensile loading after being exposed to an alkaline solution (pH 12.9) for 1.5, 3, and 6 months at temperatures of 40 °C, 50 °C, and 60 °C. This paper investigated the effects of alkaline environment, exposure periods, and elevated temperatures on bond strength as well as the degradation mechanism and mode of failure of the BFRP-reinforced specimens. In addition, optical microscopy and scanning electronic microscopy were used to investigate the degradation of BFRP bars tested. The test results indicate an initial increase in the bond strength of the conditioned specimens as the temperature increased compared to their unconditioned specimens. After 1.5 months of exposure, the specimens conditioned at 50 °C and 60 °C, respectively, had bond-strength increases of 25% and 26%, while the specimens conditioned at 40 °C exhibited no noticeable changes (a minor decrease of 4.3%). Nevertheless, the bond strength of the conditioned specimens deteriorated during immersion. The highest bond-strength reductions occurred in the conditioned specimens after 6 months of exposure at 40 °C (a 16% loss), followed by specimens conditioned at 50 °C (7% loss) and 60 °C (5% loss) compared to their counterparts at 1.5 months. Lastly, the long-term bond-strength-retention predications of the BFRP bars after 50 years of service life in dry, moist, and moisture-saturated environments with mean annual temperatures between 5 °C and 35 °C ranged from 71% to 92%.

1. Introduction

Currently, glass and carbon are the fibers used most widely in manufacturing fiber-reinforced-polymer (FRP) composite bars. Basalt fibers, the latest generation of FRP composites, are currently attracting the interest of the research community and construction industry [1]. Basalt fibers are processed from volcanic rock with a melting process similar to that used for glass fibers. Basalt fibers, which are continuous, offer higher tensile strength than E-glass fibers, greater strain at failure than carbon fibers, as well as good resistance to chemical attack, high-corrosion resistance, thermal stability, low water absorption, and high impact and fatigue resistance [2–5].

Recent advances in polymer technology have led to the development of a new generation of FRP reinforcing bars, namely basalt-FRP (BFRP) bars. The use of BFRP bars in construction applications is relatively new. This type of structural material is expected to provide performance comparable or superior to that of glass-FRP (GFRP), while being significantly cost-effective [6–9]. In order for this new material to gain wide acceptance for use in the construction industry and inclusion in FRP standards and guides, its safety, sustainability, and several aspects of its structural and mechanical behaviors require investigation. One of these fundamental aspects is

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the bond-development phenomenon, which is a primary parameter for BFRP's successful application as internal reinforcement in concrete structures [10]. Bar-bond characteristics affect bar anchoring, lap–splice strength, concrete-cover requirement, serviceability, and ultimate states. The long-term bond-strength durability also plays a significant role in the long-term performance of concrete structures incorporating internal FRP reinforcement [11,12].

Numerous research efforts have been put into investigating the bond durability of GFRP and CFRP bars in concrete [11–13]. Very few studies, however, have investigated the bond durability of BFRP bars embedded in concrete and subjected to harsh environmental conditions. El Refai et al. [14] investigated the bond durability of sand-coated and helically grooved BFRP bars embedded in concrete. Their work included various accelerated environments, including tap water, seawater, elevated temperature, elevated temperature followed by tap water, and elevated temperature followed by seawater. The authors reported that moister environments caused enhanced adhesion for all specimens at early loading stages. Moreover, exposure to elevated temperatures of up to 80 °C had a minor effect on the bond strength of the tested bars. That notwithstanding, such environments had a harmful effect on the bond strength at later stages depending on the bar material's moisture absorption and its manufacturing quality, regardless of the fiber material. Altalmas et al. [15] conducted a supplemented study on the bond durability of the same sand-coated BFRP bars in concrete exposed to acid, saline, and alkaline solutions for duration of up to 90 days at 60 °C. The study revealed that BFRP specimens immersed in ocean water and alkaline solution for 90 days exhibited a 25% reduction in bond strength compared to 14% for BFRP specimens immersed in an acid solution. In addition, the interlaminar shear between the FRP layers governed the failure of both unconditioned and conditioned pullout specimens. Dong et al. [16] investigated the effect of seawater environmental conditions on bond strength of basalt-vinyl ester (BV), basalt-epoxy (BE), and glass-vinyl ester (GV) FRP bars in concrete for exposures periods of up to 60 days at 40 °C. The test results indicated that, after 60 days in 40 °C seawater, the bond strength of the BV bars and GV bars decreased by 9.1% and 7.1%, respectively, while the bond strength of the BE bars remained essentially unchanged.

The lack of understanding of the bond-durability performance of BFRP bars is a crucial hindrance to their wide acceptance in field applications. It is worth mentioning that BFRP bars have not yet been incorporated into design standards and specifications. An extensive research project is being conducted at the University of Sherbrooke to investigate the short- and long-term performance of BFRP bars under real and simulated harsh environments as a preliminary step in introducing these new bars into FRP codes and materials specifications [7,8,17,18]. This paper presents an experimental investigation aimed at assessing the bond durability of BFRP bars embedded in concrete through accelerated tests in an alkaline solution at different temperatures. This study provides insight into how the bond behaves after long-term environmental conditioning. In addition, the long-term bond-strength retention after 50 years of service in dry, moist, and moisture-saturated environments (based on fib Bulletin 40 [19]) are predicted. The findings of this work will contribute to integrating BFRP bars into North American FRP codes and guides [10,20–23].

2. Experimental work

2.1. Materials properties

2.1.1. BFRP reinforcing bars

BFRP bars with a diameter of 12 mm (nominal cross-sectional area of 113 mm^2) and deformed external surfaces were used in this study, as shown in Fig. 1. These bars are made of continuous longitudinal basalt fibers bound together with a vinyl-ester resin using a pultrusion process. The used basalt fibers are manufactured by ASA.TEC GMBH (Austria) using a mixture of different natural volcanic rocks. The color of the fibers is gold brown, the monofilament diameter is 13–20 μm, and a density of 2.6 g/cm^3 [7]. The physical and mechanical properties of the BFRP bars were determined in accordance with the ACI 440.6 M [20], CSA S807 [21] test methods and the relevant ASTM standards. In addition, the physical and mechanical properties of representative BFRP bars were compared to the minimum requirements for FRP bars, as mentioned in ACI 440.6 M [20] and CSA S807 [21]. Table 1

Fig. 1. BFRP bar 12 mm in diameter used in this investigation.

Table 1
Physical and mechanical properties of BFRP bars 12 mm in diameter.

Test	Property	12-mm	Specified limit	
			ACI [20]	CSA [21]
Physical	Cross-sectional area (mm^2)	125	N/A	N/A
	Fiber content by weight (%)	81.5	55% (by vol.)	70 (by wt.)
	Transverse CET (× 10-6 °C-1)	22.1	N/A	40
	Density (gm/cm^3)	2.09 ± 0.02	N/A	N/A
	Moisture uptake (%)	0.13 ± 0.006	<1	1.0 (D2)[a]; 0.75 (D1)[a]
	Cure ratio (%)	98.0 ± 0.001	N/A	93 (D2)[a]; 95 (D1)[a]
	Tg (°C)	117.0 ± 2.65	100	80 (D2)[a]; 100 (D1)[a]
Mechanical[b]	Ultimate tensile strength (f_{fu}) (MPa)	1706 ± 40	–	–
	Modulus of elasticity (E_f) (GPa)	62.1 ± 5.6	39.3 GPa	40.0 GPa
	Ultimate tensile strain (ε_u) (%)	2.52 ± 0.2	>1.2%	>1.2%
	Ultimate transverse shear strength (τ_u) (MPa)	272 ± 18	>124 MPa	>160 MPa
	Ultimate interlaminar shear strength (S_u) (MPa)	68 ± 4.9	–	–
	Bond strength (τ_{max}) (MPa)	15.48 ± 0.4	>9.6 MPa	>8 MPa

[a] D1 and D2 classifications can be found in CSA [21].
[b] The mechanical properties were calculated using the nominal cross-sectional area.