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EVALUATION OF GATORBAR FOR USE IN REINFORCED CONCRETE APPLICATIONS IN HAWAII

for

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Introduction

A review of literature related to the use of Basalt Fiber Reinforced Polymer (BFRP) bars as reinforcement in structural concrete was performed. In particular, this review focused on a number of test programs that evaluate the performance of BFRP bars fabricated by Neuvokas and referred to as "GatorBar". This report presents the results of this assessment.

In the past decade, Fiber Reinforced Polymer (FRP) reinforcing bars have been used extensively in structural concrete applications. The bars consist of continuous fibers embedded in an epoxy or vinylester polymer matrix. To date, the most commonly used fibers were glass, carbon and aramid, referred to as GFRP, CFRP and AFRP, respectively. These reinforcing bars have gained in popularity primarily because of their immunity to corrosion. This leads to far superior durability of FRP reinforced concrete members when compared with concrete reinforced with traditional steel reinforcing bars, particularly in a marine or coastal environment common to the Hawaiian Islands. One major disadvantage of FRP bars has been the cost comparison with traditional steel reinforcing. However, increased production and use of FRP's has led to decreases in the cost of these new materials.

More recently interest has grown in the use of Basalt fibers to create BFRP reinforcing bars (Fiore, et al., 2015). Basalt is a natural inorganic material found in volcanic rocks originating from molten lava. Basalt has a melting temperature between 1500 ^{o}C and 1700 ^{o}C. Once molten, the basalt can be extruded through small nozzles to produce continuous filaments of basalt fiber with diameters ranging from 13 to 20 μm (Patnaik, 2009). BFRP bars have the same advantage of immunity to corrosion as do the other FRP bars. They are also poor conductors of heat and electric current, similar to glass fiber FRP bars. In addition, BFRP can be produced at a cost that is competitive with steel reinforcing bars. This makes them very attractive for use in concrete cast in marine or coastal exposure conditions.

This literature review is intended to provide background to the performance of BFRP when used as reinforcing bars in concrete members. The review covers general aspects of BFRP reinforcing bar performance, and then focuses on the specific BFRP bars produced by Neuvokas Corporation and distributed under the trade name "GatorBar".

General Characteristics of Basalt Fiber Reinforced Polymer (BFRP)

Basalt Fiber Reinforced Polymer (BFRP) reinforcing bars have high tensile strength while being significantly lighter than steel reinforcing bars. The tensile behavior of BFRP bars is linearly elastic with no yield point. Traditional reinforced concrete member design using steel reinforcement cannot be used to design members with BFRP reinforcement. Design of reinforced concrete members with BFRP reinforcing bars should follow the same procedures as outlined in ACI 440.1R design guidelines for glass (GFRP) and carbon (CFRP) reinforcing bars (ACI, 2006).

Compared with reinforcing bars produced with traditional glass (GFRP) and carbon (CFRP) fibers, BFRP reinforcing bars have strength values greater than that of GFRP, but less than CFRP, while the modulus of elasticity is similar to that of GFRP (Elgabbas, et al., 2016). Bending tests performed on concrete beams reinforced with BFRP flexural reinforcement show that the bond between the bars and concrete is adequate to produce a well-distributed flexural crack pattern similar to what is observed in traditional reinforced concrete beams. Because of the relatively low modulus of elasticity of the BFRP bars, the bending stiffness reduces significantly after concrete cracking (Elgabbas, et al., 2016). The performance of BFRP reinforced concrete beams is similar to that observed for GFRP reinforced beams. If BFRP is to be used in beam construction, this low post cracking stiffness must be considered when estimating the beam deflections (Lapko and Urbanski, 2015).

As with other fiber-reinforced polymers, BFRP is a composite of fibers embedded in a polymer matrix. Although elevated temperatures have little effect on the basalt fibers, the polymer will lose strength and stiffness. Lu, et al. (2016) found that at 390°F (200°C), the tensile strength and elastic modulus of BFRP reduced by 37.5% and 31%, respectively, compared with room temperature. When embedded in concrete, the thermal insulation of the concrete cover will help to protect the BFRP, but this strength and stiffness reduction must be considered when designing structural load-bearing members using BFRP.

Wei et al., (2011) performed durability tests on the performance of BFRP and GFRP composites when exposed to a seawater environment. They found that "*the chemical stability of BFRP and GFRP in seawater is nearly the same*." Altalmas et al., (2015) performed bond tests on BFRP and GFRP reinforcing bars after exposure to various environments, including seawater. They conclude that sand-coated bars showed higher bond strength and higher adhesion to concrete than ribbed bars for both fiber types, with no change evident due to seawater exposure.

Performance of GatorBar Reinforcing Bars

GatorBar reinforcing bars are produced by Neuvokas Corporation, Ahmeek, Michigan. Neuvokas has sponsored a number of laboratory tests of the GatorBar physical and mechanical properties and their performance in concrete beams. The technical reports from these tests were reviewed and are summarized in the following sections.

Physical Properties of GatorBar Reinforcing Bars

Two test series were performed under the direction of Prof. Brahim Benmokrane at the University of Sherbrooke in Canada to determine the material properties of GatorBar specimens. These tests were performed during the development phase of GatorBar, and show significant improvement in the material properties from the first series (Cousin and Benmokrane, 2014a) to the second series of tests (Cousin and Benmokrane, 2014b).

Chemical resistance of the basalt fibers sourced from China and Russia was tested through immersion in deionized water, saline solution (10% NaCl), alkaline solution (pH: 12.9) and acidic solution (10% HCl). The report concludes that the "*basalt fibers performed very well and no significant degradation was observed in the four chemical solutions*" (Cousin and Benmokrane, 2014b).

Both the basalt fibers and the polymer matrix are not electrically conductive. In addition, they will not corrode in the presence of chlorides or other corrosive environments. They are therefore well suited to marine and coastal applications where corrosion of reinforcing steel presents a significant durability and maintenance concern.

Physical properties were assessed during both test series. This included tests of fiber content, transverse coefficient of thermal expansion, water/moisture absorption, cure ratio, glass transition temperature (T_g), wicking, and microscopy analysis. The test results were compared with the ACI 440.6M-08 "*Specification for Carbon and Glass Fiber-reinforced Polymer Bar Materials for Concrete Reinforcement*" (ACI, 2008).

In the first study, it was found that the test specimens satisfied the ACI requirements for fiber content and cure ratio, but some specimens did not meet the specified values for thermal expansion, absorption and glass transition temperature (Cousin and Benmokrane, 2014a). In addition, optical and scanning electron microscopy identified voids and other defects in the bars.

After further product development, the second study was performed on new GatorBar specimens (Cousin and Benmokrane, 2014b). All specimens tested in the second study met or exceeded the ACI specifications. Fiber content was an average of 75.5% compared with the ACI required minimum of 70%. The average absorption for the test specimens was 0.70%, which satisfies the ACI maximum limit of 1%. The average glass transition temperature was 232^{o}F (111^{o}C) which exceeds the ACI required minimum of 212^{o}F (100^{o}C). The optical and scanning electron microscopy performed in the second study shows a reduction in voids and other defects in the bars. The study concludes that the tested GatorBars satisfy the ACI requirements for glass fiber content, water absorption and glass transition temperature (Cousin and Benmokrane, 2014b).

The final phase of testing showed that immersing the GatorBars in an alkaline solution at 140^{o}F (60^{o}C) for 21 days did not affect the interlaminar shear strength or the bar microstructure (Cousin and Benmokrane, 2014b).

Mechanical Properties of GatorBar Reinforcing Bars

Mechanical tests of 3/8" diameter BFRP bars produced by Neuvokas Corp. were performed at Michigan Technological University (Fraley, 2016). The average results for the five specimens tested in this study are listed in Table 1. These tests were performed as part of a successful trial application of GatorBar reinforcement in curb and gutter sections on the Quincy Street reconstruction project in Hancock, Michigan (Jansson, 2017). Jansson reports that "*Performance of the curb and gutter sections utilizing GatorBar were similar to those sections with conventional steel reinforcement, with no cracks noted*."

Table 1: Average Tensile and Shear Test Results for Neuvokas Corp. GatorBar BFRP bars and Aslan GFRP and CFRP bars, for comparison.

Bar Type	Bar Diameter (in.)	Average tensile strength (ksi)	Average tensile modulus (ksi)	Average strain at failure	Average shear strength (ksi)
GatorBar BFRP	0.375	163.4	6,885	0.0237	28.8
Aslan 100 GFRP[1]	0.375	120	6,700	0.0179	22.0
Aslan 200 CFRP[2]	0.375	315	18,000	0.0175	N/A

[1] Hughes Brothers, Inc., 2011a; [2] Hughes Brothers, Inc., 2011b

Also shown in Table 1 are typical mechanical properties for GFRP and CFRP reinforcing bars produced by Hughes Brother, Inc. under the trade name "Aslan FRP". The basalt bars have 30% greater tensile strength than GFRP with a similar modulus of elasticity.

Bond Strength for GatorBar in concrete

In order for FRP bars to work effectively as reinforcement for concrete members, it is critical that sufficient bond strength be developed along the interface between the bar and the surrounding concrete. Glass and basalt fiber reinforced bars use a similar bond enhancement by means of a sand coating epoxied to the exterior of the bar.

Bond tests were performed at the University of Nebraska, Lincoln, on behalf of Neuvokas Corp. Three bond test programs were performed under the direction of Prof. George Morcous. The first two studies investigated the pullout bond strength of GatorBar bars (Morcous and Tawadrous, 2015a and b), while the third study involved flexural beam tests to determine the bond-dependent coefficient of GatorBar bars (Morcous, 2016). The conclusion of all of these bond test programs was that the GatorBar BFRP bars with the primary exterior coating provide better bond with the concrete than deformed steel reinforcing bars of the same size. They also meet the bond requirements of the ACI 440K subcommittee for use in reinforced concrete applications.

Recommended use of GatorBar BFRP bars

Based on the literature review on basalt fiber-reinforced polymer bars, and the test results of GatorBar BFRP bars produced by Neuvokas, Inc., the following recommendations are made regarding the use of GatorBar reinforcement in concrete applications in Hawaii.

1) GatorBar reinforcing bars can be used in all reinforced concrete applications where GFRP or CFRP reinforcing bars are currently used.
2) If GatorBar reinforcing bars are to be used as flexural reinforcement in concrete beams, walls or columns, careful attention must be paid to the anticipated deflection of the member under load.
3) GatorBar reinforcing bars are particularly suited for use in concrete exposed to a marine or coastal environment because they will not corrode.
4) The use of GatorBar reinforcing bars in slab-on-grade applications will work effectively to limit crack size and distribute cracking in the same way as deformed steel reinforcing bars.
5) As with GFRP and CFRP reinforcing bars, Gatorbar cannot be bent in the field, but must be fabricated with the necessary bends in place. Therefore, applications that require only straight bars present a particular advantage for Gatorbar reinforcing.

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