Deliverable 3

Performance evaluation, material and specification development for basalt fiber reinforced polymer (BFRP) reinforcing bars embedded in concrete

Contract Number BDV30 TWO 986-01
FSU Project ID: 042088

Submitted to:

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02/28/2019

Recommendations

This report aims to provide recommendations for the mechanical and physical requirements of basalt fiber reinforced polymer (BFRP) rebars to assist the Florida Department of Transportation with the implementation process. BFRP rebar technology is still considered new in civil engineering construction in the United States, but it has been successfully used around the world in demonstration and low-risk projects. Before using any new or emerging material in infrastructure projects, the physical and mechanical properties must be evaluated and compared to acceptance criteria. In case of emerging materials, acceptance criteria might not have been fully established yet and research is needed to characterize a variety of products to determine general market quality and to define adequate limiting values. In this report, recommendations for physical properties such as cross-sectional dimensions, fiber content, and moisture absorption properties for BFRP rebars are proposed. In addition, recommendations for mechanical properties, including the apparent horizontal shear strength, the transverse shear strength, and the tensile properties are suggested. These suggestions are the result of experimental material evaluations and accompanying literature reviews. After the relevant material parameters were obtained for three different commercially available BFRP rebar products — and two different sizes (# 3 and # 5) — the results were analyzed and statistically compared and evaluate. Based on the findings, the following recommendations are provided:

Cross Section property The cross-sectional properties were measured according to ASTM D 792 (ASTM-International, 2015b). The cross sectional property is an important characteristics because the true tensile strength of rebar depends on the effective area. The nominal cross sectional area per FDOT specifications, section 932, for # 3 GFRP rebar is 0.11 in., with a minimum measured area of 0.104 in. and a maximum measured area of 0.161 in.. For # 5 rebar nominal cross sectional area, it is 0.31 in., with a minimum measured cross sectional area of 0.228 in. and a maximum of 0.338 in.. All the rebars shall be in the range so as to avoid errors in assumed centroid position for structural resistance calculations, any fit up errors in detailing such as spacing, cover or clearance, and consistency in product approval. It appears that these cross-sectional specification are useful for BFRP rebars as well because the issue of shear lag and load transfer in BFRP rebars is not significantly different from the mechanisms observed in GFRP rebars (Kampmann et al., 2018). Likewise, the production sequence for BFRP rebars and the load transfer is similar to glass fiber based rebars which allows similar definitions for both rebar types.

Fiber Content The experiments and the accompanying mathematical procedures to determine the fiber content percentage of FRP rebars are specified in material standard ASTM D 2584 - 11(ASTM-International, 2011). The fiber content percentage of the rebar plays a key role in the load capacity of the rebar because induced stresses are mostly carried by the fibers in the rebar, while the resin matrix must be stiff enough to transfer the loads between the individual fibers. The minimum fiber content percentage required for GFRP rebars according to FDOT specifications, section 932, which follows ASTM D 2584 -11(ASTM-International, 2011) is 70 %. After careful evaluation on the tested samples, it was seen that two of the three BFRP rebar products exceeded the required minimum criteria by at least 10 %. The third manufactured product exceeded the criteria by 5 %. Further decrease in the fiber content percentage may affect the stress transfer capacity of the rebar. However, it appears reasonable to suggest a minimum fiber content percentage for BFRP rebars to be similar to that for GFRP products. Additional research and analyses are required to establish a strong correlation between fiber content percentage and its effects on the rebar strength to support any modifications to the GFRP specifications specifically for BFRP.

Moisture Absorption of BFRP rebar ASTM D 5229 (ASTM, 2014) details seven different test procedures (A through E,Y, and Z) for estimating moisture absorption properties for FRPs in different environments. Procedure A is most commonly used, and therefore, was followed for this research project as well. The moisture absorption property plays an important role in retaining the strength of rebar and its long-term durability in harsh environments because high moisture absorption values are indicative of a porous rebar which is more prone to degradation. According to FDOT specifications section 932, which follows ASTM D 5229 (ASTM, 2014) section 7.1, the maximum short-term moisture absorption limit for GFRP rebars is 0.25 % by weight. And long-term moisture absorption shall be less than 1 %. After proper evaluation of the tested specimens, it was found that the long-term moisture absorption of BFRP rebars was less than 1 %. As increased moisture absorption property affects the strength and strength retention of FRP rebars, it is reasonable to suggest that the BFRP rebar shall follow the criteria established for GFRP moisture absorption properties. Furthermore, because the microstructure porosity and the moisture absorption of FRP rebars are closely related, SEM analysis of specimen after long-term moisture absorption tests should be conducted to evaluate the rebar properties at the micro level and to define its vulnerability to degradation. New products should be characterized via SEM and the findings and images stored in a data base for comparison to future iterations of specific product lines.

Horizontal Shear Strength The horizontal shear test was conducted according to ASTM D 4475 (ASTM-International, 2012a) standards. It has been noted that the FDOT specifications does not include minimum horizontal shear strength requirements for rebars made from any fiber material. The horizontal shear failure, however, is an indicator of the resin strength and the resin-to-fiber bonding quality and as such important for the load transfer from fiber to fiber. After a manufacturer survey was conducted — as part of the literature review — to identify common practices in the FRP rebar industry, it has been noted that horizontal shear tests are one of the common quality control methods that producers rely on to ensure production quality and consistency. Accordingly, FDOT Section 932 would benefit from limiting minimum values for the acceptance of FRP rebars. Likewise, it would provide a direct benefit to the manufacturing community and the intersection between FDOT and technology implementation because a quality control parameter could be directly targeted during production — and quickly evaluated. The horizontal shear strength of # 3, and # 5 GFRP rebars appears to range around 6 ksi (c.f. Kampmann et al. (2018)). However, because no specified criteria for the minimum horizontal shear strength has been defined, additional research focusing on this property is recommended.

Transverse Shear Strength ASTM D 7617 (ASTM-International, 2012b) was followed to test and analyze the transverse shear data obtained from BFRP rebar testing. FRP rebars are weak in the transverse direction or perpendicular to the rebar longitudinal axis. According to FDOT specification, section 932, GFRP rebars are required to reach a minimum shear strength of 22 ksi, before rupture. After a careful testing and analysis process, the tested # 3 BFRP rebars sustained shear stresses at failure ranging from 30 ksi to 36 ksi and # 5 rebars sustained a stress range from

26 ksi to 33 ksi. Based on the results obtained in this study, in comparison to other studies (Kampmann et al., 2018), it appears that BFRP rebars are stronger than GFRP rebars in the transverse direction. For simplicity, this research suggests that the minimum transverse shear strength criteria for BFRP rebars should be similar to the criteria defined for GFRP rebars.

Tensile Properties The tensile strength and elastic modulus of BFRP rebars were evaluated based on procedures and methods detailed in ASTM D 7205 (ASTM-International, 2015a) The minimum tensile load requirements for # 3 GFRP rebar according to FDOT specifications, section 932, is 13.2 kip, and for # 5 rebar is 29.1 kip. Based on the findings from this research project and projects targeting glass fiber based rebars (Kampmann et al., 2018), it can be stated that BFRP rebars appear to be measurably stronger in tension with higher elastic moduli — as compared to GFRP rebars. It has been noted that the minimum tensile load sustained by # 3 BFRP rebars is 19.68 kip and that of # 5 rebars is 42.8 kip . The elastic moduli of BFRP rebar were measured with a minimum of 8 ksi. The elastic moduli of GFRP rebar according to Kampmann et al. (2018) was measured to reach average values of approximately 7000 ksi. All tested BFRP rebar strengths superseded the minimum strength criteria for GFRP rebars. A Further detailed testing of a wide range of rebars from several manufacturers is required to fully study the strength properties of rebar and to properly define a minimum required criteria. However, if basalt fiber specific criteria are desirable for the tensile properties, the data in this research suggests that the minimum strength and elastic modulus should be significantly higher for BFRP rebars.

Further Suggestions It is noted that no long-term tests were performed throughout this project and that additional durability analyses for BFRP rebars in extreme environments shall be done. It appears vital because of the unique chemical composition of basalt fibers and the interaction they can potentially undergo in saline-rich and high pH environments. This may be one of the most important aspects for a proper life cycle of concrete structures reinforced with BFRP rebars in aggressive environments (e.g.; bridges in Florida) because of the highly basic conditions in cementitious paste.

Lu et al. (2015) compared virgin to aged, pultruded BFRP plates and rebars to measure the effect of thermal aging (at 135 °C and 300 °C for four hours) on the longitudinal tensile strength and the inter laminar shear properties. It was found that the degradation process of aged rebars immersed in alkaline solution and distilled water accelerated due to thermal aging. Altalmas et al. (2015) studied the bond-to-concrete durability properties of sand coated basalt fiber reinforced polymer (BFRP) rebars and glass fiber reinforced polymer (GFRP) rebars via accelerated conditioning in acidic, saline, and alkaline solutions for 30 days, 60 days, and 90 days. The results showed that the bond strength of rebars immersed in acid solution, alkaline and saline environments in comparison to un-aged rebars reduced and that all rebars failed in inter-laminar shear. Wang et al. (2017) tested tensile strength and Young's modulus properties of BFRP and GFRP rebars exposed to seawater and sea sand concrete (SWSSC). The rebars were exposed to normal SWSSC (N-SWSSC), and high performance SWSSC (HP-SWSSC) at room temperature, 40 °C, 48 °C, and 50 °C for 21 days, 42 days and 63 days. When compared to HP-SWSSC, N-SWSSC was more aggressive on both BFRP, and GFRP bars due to the high alkali ion concentration. In high temperature environments, the GFRP rebars were more durable than the BFRP rebars, because of the different resins. Based on the SEM, 3D X-ray, and CT-results, the resin properties of GFRP bars were more stable in SWSSC conditions than the resin used for the tested BFRP rebars. In research projects conducted by Benmokrane et al. (2017) and Kajorncheappunngam et al. (2002), the longterm durability in alkali environments at accelerated temperatures for rebars made with different resins was evaluated. It was seen that the performance of epoxy resins was comparably good and acceptable.

Wei et al. (2011) studied degradation of basalt fiber-epoxy resin and glass fiber-epoxy resin composites in seawater. Wei et al. (2011) found that the bending and tensile strength decreased with increase in immersion time. The chemical stability of BFRP rebars can be improved by lowering the Fe^{+2} ions in basalt rock and durability of rebar in seawater can be increased.

Two of the three tested rebar types for this research included rebars made with epoxy resins. The mechanical performance of the rebars made from epoxy resin was higher than the rebars made from other resin. Most basalt rebar manufacturers across the globe uses epoxy resin in the manufacturing processes. It appears that epoxy resins are suitable for the production of basalt FRP rebars and that such constituent materials should be considered in future updates of standard specifications (Florida Section 932). However, additional research with a focus on physical and mechanical properties in response to chemical durability for rebars made with different resins should be conducted.

Comparing this research to a previous study (Kampmann et al., 2018), it can be seen that the maximum strain and elongation of BFRP rebars surpasses the maximum strains of glass fiber based rebars. Likewise, the elastic lengthening of BFRP tendons is higher than that of steel (Thorhallsson and Jonsson, 2012; Pearson et al., 2013) and it might be beneficial to evaluate basalt fiber materials for the use of prestressing tendons.

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(continued..)

SP4 General provisions: Composite fibre-reinforced polymer bars should be used for reinforcement of concrete structures:
- during the construction of facilities of the road and transportation, city engineering infrastructure..., and other structures used in aggressive environments.

SP5.2.1 FRP bars meeting the requirements of GOST 31938 are:
- glass fibre reinforced polymer (GFRP);
- basalt fibre reinforced polymer (BFRP);
- carbon fibre reinforced polymer (CFRP);
- aramid fibre reinforced polymer (AFRP);
- hybrid fibre reinforced polymer (HFRP).

SP5.2.4 Table 1: Rf < 800 MPa (116 ksi); Ef > 50 GPa (7.25 ksi) for both GFRP & BFRP
SP5.2.6: Partial material safety factor for ULS = 1.2 if COV < 0.1; 1.5 if 0.1<COV<0.15 ==> (phi=0.83 or 0.67);
SP5.2.6 Table 2: ULS Env. Reduction CE=0.8 (outdoors); = 0.7 for GFRP.
SP5.2.7 Table 3: SLS sustained loading CE*Cs= 0.4; = 0.3 for GFRP.
SP5.2.10 Shear reinf. (bending radius of stirrups not less than 6db) Rfw=0.004Ef, but not greater than 0.5Rf or 300 MPa (43 ksi)
SP6.2.6: SLS crack widths: 0.7 mm (0.028 in.) – at short-term crack opening; 0.5 mm (0.02 in.) – at long-term crack opening.

Comparisons with selected requirements from CAN/CSA 807-19 (Public Review Copy)
1.2 This Standard covers FRPs comprised of (a) E-CR glass, carbon, aramid or basalt fibres; and (b) isophthalic polyester, vinylester, or epoxy resins.
8.4 GTS = 95% characteristic strength
8.5 Ef = 95% characteristic stiffness. Alternatively, when the COV of the modulus of elasticity is smaller than 5%, the mean value of the test results shall be used.
8.4 Durability- FRPs with a high durability shall... be made with vinylester or epoxy.
Table 1B, Basalt & Glass Rebar Min. Strength (MPa)
- Grade I: 6M-10M 750; 13M & 15M 650; 20M 600; 22M & 25M 550; 30M 500; 32M & 36M 450;
- Grade II: 13M-25M 800;
- Grade III: 13M-25M 1000;

Table 2A, Modulus of Elasticity (straight bars) Grade I, II, III:
- Basalt - 50, 60, 70 MPa
- Glass - 40, 50, 60 MPa

Design Requirements will be in CAN/CSA S6-19. (To be advised by Prof. B.enomokrane)
S6-xx: Partial material safety factor for ULS = 1.2 if COV < 0.1; 1.5 if 0.1<COV<0.15 ==> (phi=0.83 or 0.67);
S6-xx Table 2: ULS Env. Reduction CE=xx (outdoors); = xx for GFRP.
S6-xx Table 3: SLS sustained loading CE*Cs= xx; = xx for GFRP.
S6-xx Shear reinf. (bending radius of stirrups not less than 6db) Rfw=0.004Ef, but not greater than xxx or xx MPa
S6-xx: SLS crack widths: 0.7 mm (0.028 in.) – at short-term crack opening; 0.5 mm (0.02 in.) – at long-term crack opening.
S6-xx: SLS Bond factor Kb = xx
S6-xx: Fatigue factor CE*Cf = xx