FAMU-FSU
College of Engineering

Department of Civil and Environmental Engineering

MATERIAL PROPERTIES OF BASALT FIBER REBARS

Tested According to ASTM Test Protocols

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A Product Review submitted to the Manufacturer
Rock Rebar Inc.
For the product RockRebar®

Submitted:
May 25, 2019

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Chapter 1

Introduction

It is the goal of this report to summarize the performance evaluation of basalt fiber reinforced polymer (BFRP) rebars. After a long peer-review, BFRP rebars have received industry recognition as reinforcements for concrete in AC-454 (International Code Council Evaluation Services, 2017), and are now considered as a new environmentally friendly, low carbon, "green" and renewable material for the construction industry. However, before any new material is used for infrastructure projects, the physical and mechanical material properties must be completely characterized. In an effort to analyze BFRP rebars for internal concrete reinforcement, the product know as RockRebar® was experimentally tested and evaluated for its performance. To fully characterize the rebar product, the measurements and analyses included: cross-sectional properties, fiber contents, short-term and long-term moisture absorption characteristics, transverse shear strength, apparent horizontal shear strength, tensile strength, elastic modulus, and bond-to-concrete strength. All tested materials were produced on a Basalt World Corp (BWC) Lean Green FRP Rebar Machine™ and produced by the BFRP rebar manufacturer Rock Rebar Inc., who supplied random samples of RockRebar® BFRP rebar. These products were manufactured in Florida, USA, using the RockRebar® proprietary US production Olin epoxy resin and Dixie Chemical cross linker. Representative specimen types, which were analyzed in this research, are shown in Figure 1.1. For the purpose of this report, two different

(a) Rebar size # 3

(b) Rebar size # 5

Figure 1.1: Sample of the tested Rock Rebar Inc. product RockRebar®

rebar sizes were tested, which included # 3, and # 5 rebars.

The results presented in this report were obtained at the FAMU-FSU College of Engineering in the Civil Engineering Materials Laboratory and the High Performance Materials Institute (HPMI) under the supervision of Dr. Raphael Kampmann. All tests were conducted according to the methods described by the American Society for Testing and Materials (ASTM) in line with the relevant test protocols. Data acquisition software, such as LabView and MTS TestWorks was used to collect the raw data with high data rates. The collected raw data were analyzed using R-statistics[1] and R-Studio[2] software packages.

[1] R.app GUI 1.70 (7434 El Capitan build), S. Urbanek & H.-J. Bibiko, R Foundation for Statistical Computing, 2016

[2] Version 1.1.383 2009-2017 RStudio, Inc.

Chapter 2

Cross-Sectional Properties

The effective rebar diameter was measured according to the ASTM D 792-13. Due to the variety of FRP rebars on the market and due to the various surface enhancement features, differently produced rebars deviate from the stated nominal diameter. The Table 2.1 below lists the results of water displacement method according to the ASTM D 792-13 for the tested NoRUst rebar products. According to the Test Standard a minimum of five specimen need to be tested for each rebar type.

Table 2.1: Results from diameter measurements for rebar size # 3 and # 5

Specimen		Specimen Length				Weight				
		L1	*L2*	*L3*	*Average*	*a*	*a + s*	*b*	*s*	ΔM
		cm	*cm*	*cm*	*cm*	*g*	*g*	*g*	*g*	*g*
RockRebar® # 3	Epoxy1	3.13	3.13	3.14	3.13	5.22	13.01	10.36	7.8	2.57
	Epoxy2	3.21	3.21	3.19	3.2	5.32	13.13	10.44	7.81	2.63
	Epoxy3	3.00	3.00	3.00	3.00	5.00	12.81	10.27	7.81	2.46
	Epoxy4	3.23	3.23	3.24	3.24	5.37	13.17	10.48	7.8	2.67
	Epoxy5	3.12	3.11	3.12	3.12	5.18	12.99	10.37	7.81	2.57
RockRebar® # 5	Epoxy1	3.12	3.14	3.12	3.12	13.6	21.4	14.61	7.8	6.8
	Epoxy2	3.12	3.12	3.12	3.12	13.73	21.54	14.69	7.81	6.88
	Epoxy3	3.11	3.1	3.11	3.11	13.64	21.45	14.62	7.81	6.81
	Epoxy4	3.3	3.32	3.29	3.3	14.43	22.24	15.06	7.81	7.26
	Epoxy5	3.1	3.08	3.08	3.09	13.49	21.3	14.51	7.81	6.7

The average of the 1 −inch cut specimen pieces was calculated from three measurements (L1, L2, and L3), taken at 120° increments around the rebar circumference. The measurements representing the weight of the dry sample in the air (a), the specimen together with the fixture (a+s), and the weight of the submerged specimen hanging from the sample holder (b). By subtracting the weight of the dry sample (a) from the specimen together with the fixture (a+s) the weight of the fixture (s) was calculated for each specimen individually. Finally, the weight of the immersed sample ($\triangle M$) was determined by subtracting the weight of the fixture (s) from the weight of the specimen, which was hanging from the fixture (b) in water. The average of the five specific weight measurements of the sample groups for the # 3 rebar sample type was 4.3 g. Likewise, the five # 5 rebar sample types were measured with an average of 6.89 g. The temperature of the distilled water that was used for these tests was measured with 25 °C during the tests. Proper testing is observed at a temperature of 23 °C, wherefore the values were multiplied by a correction factor.

The following Table 2.2 shows statistical results of the effective rebar diameter for the NoRust rebar products. It includes the minimal, maximal, and mean value as well as the standard deviation

Table 2.2: Evaluation for the effective rebar diameter # 3 and # 5

Specimen	Min Value mm	Max Value mm	Mean Value mm	Standard Deviation mm	CoV † %
RockRebar® #3	10.23	10.29	10.25	0.023	0.225
RockRebar® #5	16.65	16.78	16.72	0.052	0.314

† Coefficient of Variation

of each specimen type and its coefficient of variation. The standard deviation quantifies the amount of variation for each data set. In total, the standard deviation of 3 rebar was below 0.023 mm, and the rebar # 5 had a standard deviation of 0.052 mm. The coefficient of variation provides the probabilities of occurrence of different possible outcomes throughout the experiment, which was determined to be below 0.225% for 3 rebar, and for the # 5 rebar was 0.314%. These values were calculated by dividing the mean value by the standard deviation. Therefore, test measurements differ from the mean value by about the coefficient of variation. The nominal rebar diameter for the # 3 is 9.5 mm (3/8 in.), and for the # 5, it is 16 mm (5/8 in.). The effective diameter determination is a method to calculate the exact diameter regardless of the production and the surface treatment, which differs between the different manufacturers and influences the diameter. It can be seen that the mean value of the product for the #3 rebars and for the rebar # 5 were above the nominal diameter by about 1 mm. By calculating further engineering properties like the tensile stress, the choice of the nominal or the effective diameter may significantly influence the results.

Chapter 3

Fiber Content

The fiber content percentage plays a key role in transferring the stresses over entire reinforcement. The tensile stresses are transferred from one fiber to another during stressing. To increase the tensile strength of the rebar, to improve the ductility of the rebar, and to improve the overall quality of rebar production, it is important to understand the resin matrix and determine the fiber to resin ratio.

The procedure for Ignition loss test for cured reinforced resins is explained in this paragraph to describe how the fiber content for the tested FRP rebars was determined. ASTM D 2584 -11(ASTM-International, 2011) outlines this procedure and details the required conditions. The specimen for this procedure were conditioned in a temperature range from 21 °C to 25 °C (70 °F to 74 °F) at a relative humidity between 40 % and 60 %, for at least 40 hours prior to testing. The conditioned sample was then cut to the desired length of 25 mm (1 in.) with a precision of 0.05 mm (0.0019 in.). The weight of the conditioned sample (W_s), was then recorded to the nearest 0.05 g (0.0017 oz.) using an electronic balance. This weight was used as the 100 % reference value for calculating the fiber and resin contents (relative to the initial weight). Likewise, a clean and oven dried crucible was weighed (W_c),to the nearest 0.05 g (0.0017 oz.) to obtain the initial weight of the sample holder. The FRP rebar specimen was transferred to the crucible and the total weight of the specimen and the crucible (W_i), was recorded to the nearest 0.05 g (0.0017 oz.). To burn off all resin, the crucible (of known mass) along with the specimen were exposed to a temperature of 542 °C to 593 °C (1000 °F to 1100 °F) in a muffle furnace until the specimens reached a constant weight. The crucible was then carefully removed from the muffle furnace and allowed to cool down to room temperature, before the cooled crucible including the fibers (and sand for rebars that used surface enhancement made from sand) was weight using a precision electronic balance. This weight was recorded as final weight (W_f). For the rebar products made with sand at the surface for bond enhancement, the weight of the sand (W_s), was recorded and subtracted from the initial weight of the crucible and the specimen to obtain comparable and absolute fiber content percentages. Because fibers (and sand) are not susceptible to loss on ignition, the reduction in weight due to the burning process is equivalent to the weight of resin, and hence, the percentage of fibers was determined through the difference in weight before and after the burning process. For reliability of test results and to obtain representative values for the BFRP rebar product as a whole, the test was repeated five times for specimens taken from different sections of the production lot and the average value was assigned.

The measured fiber content results are plotted in the Figure 3.1. The bar chart compares both the bar sizes tested. Each individual bars represents one specimen. The red hatched part of each bar indicates fiber content percentage of the rebar specimen, the blue part represents the resin content percentage and the black part represents sand content percentage. The surface of the rebar specimens were sand coated to increase the bond to concrete. The 100% value of rebars are based on total specimen weight minus the sand content. All the rebar specimen had a minimum requirement of 70% fiber content. Overall, the measured fiber content results show the proper production consistency for all the rebar sizes.

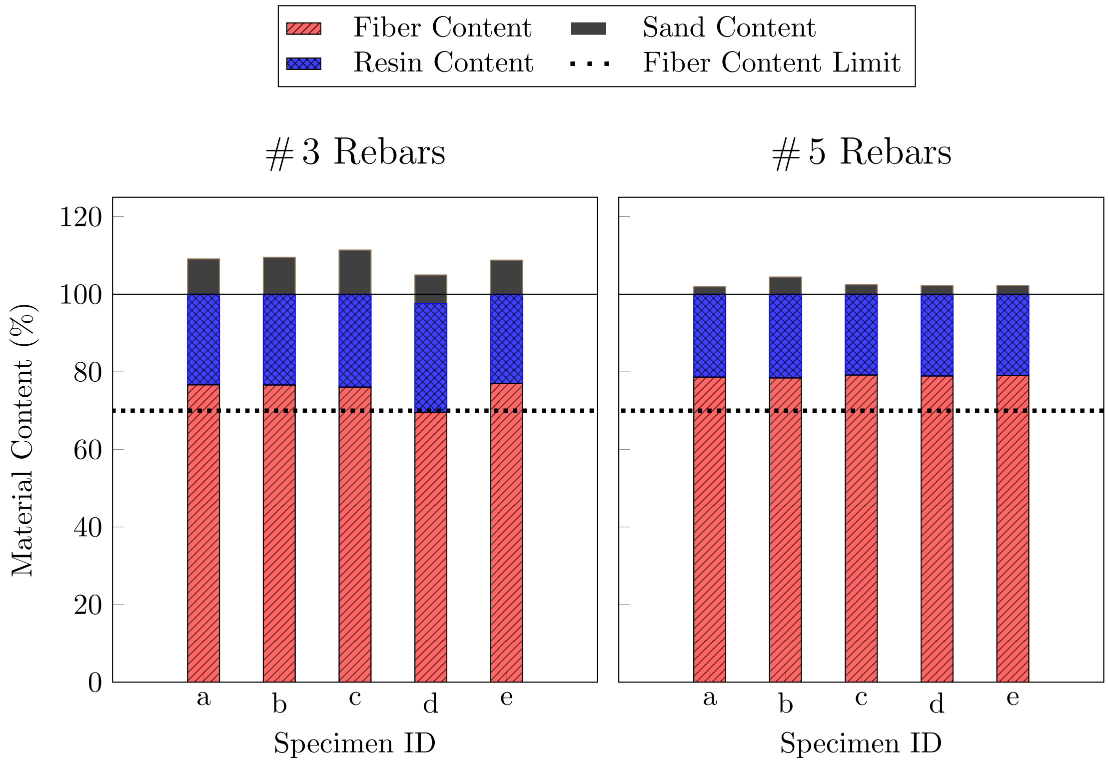


Figure 3.1: Fiber content results of RockRebar® with epoxy resin

Chapter 4

Moisture Absorption

The moisture absorption property is very important because the FRP are used in bridges constructed at bay areas and over the rivers, and the moisture decreases the strength of the structures. The moisture percentage in the FRP has to be continuously monitored to maintain the structural stability. If the rebar absorbs more moisture, the strength bearing capacity decreases and the stability of the structure decreases. The durability and long-term performance of a rebar is dependent on its porosity, and accordingly on its moisture absorption capacity. Specifically the saturation absorption values is important for material acceptance, and it should not exceed 1 %.

The test procedure described in ASTM D 5229(ASTM, 2014) defines the standard method for determining the moisture absorption characteristics of FRP and it is explained in this paragraph to detail how the porosity of the tested rebars was calculated. ASTM D 5229 offers seven different test procedures (A through E,Y, and Z) to assign moisture absorption properties for FRP in different environments. Procedure A is most commonly used, and was therefore, followed as described for this research project as well. Each specimen was first oven dried to eliminate potential moisture entrapped in the pores or at the surface. The dried and conditioned specimens were placed in storage bags to ensure that no moisture got in contact with the specimens. Three diameter measurements were taken at 120° intervals, perpendicular to the longitudinal axis of the FRP rebar, and those measurements were recorded to the nearest 0.001 mm ($\frac{4}{10\,000}$ in.). Then, each specimen was weighted with a precision of 0.05 g (0.0017 oz.) in its dry state and recorded as W_i. The specimens were then submerged in distilled water. The water along with the submerged specimens were stored in a air circulated oven to maintain the temperature of 50 °C (122 °F) throughout the entire duration of the experiment. First weight measurements to record W_1 after water conditioning were taken after two weeks. To obtain additional measurements, the specimens were removed from the water bath in two week intervals (continuous conditioning) and surface dried with a fresh paper towel until no free water remained on the surface of the FRP rebar. The final weight of each specimen (W_f) was measured and recorded to the nearest 0.05 g (0.0017 oz.). This procedure was repeated and weight gains were monitored until three consecutive two-week measurement did not differ by more than 0.02 % from one another. For reliability of test results and to obtain representative values for the BFRP rebar product as a whole, the test was repeated five times for specimens taken from different sections of the production lot and the average value was assigned.

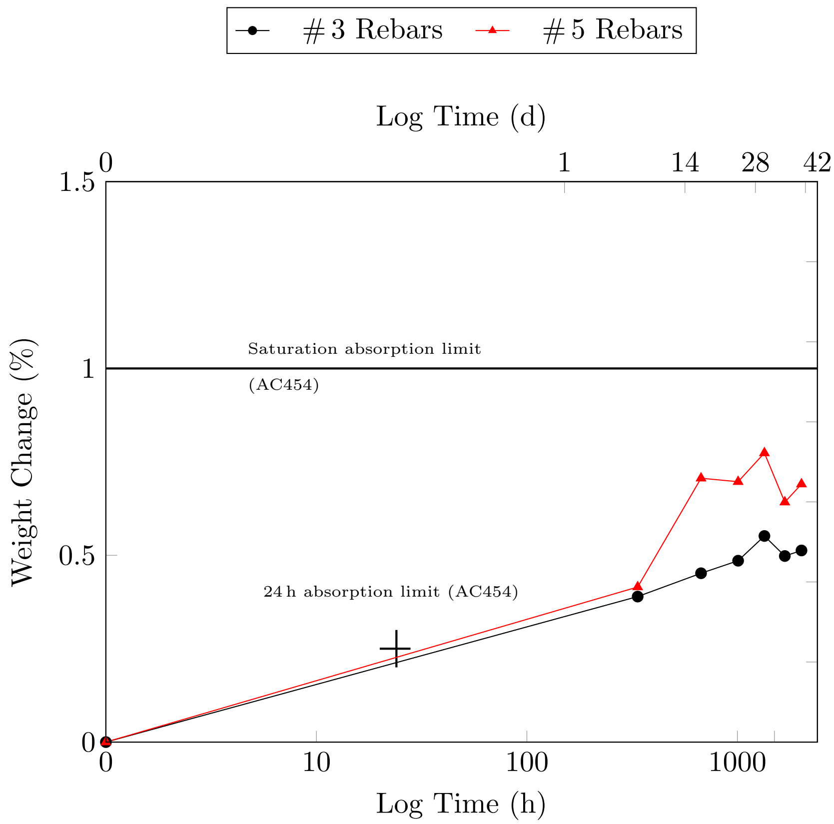


Figure 4.1: Moisture Absorption results of RockRebar® with epoxy resin

Chapter 5

Transverse Shear

The transverse shear strength is an important characteristic if the bars are used as dowels in concrete pavement, stirrups in concrete beams, or as general shear reinforcement elements. ASTM D 7617 (ASTM-International, 2012b) was used in the process of testing and analyzing the data. Before testing, the specimens were conditioned according to the ASTM D 5229 (ASTM, 2014). The conditioned specimen were then cut to length with a minimum length of 225 mm so that they fit in the shear fixture which is a device that produces double shear on the FRP rebar specimen. This fixture has two bar seats, two lower plates, and two guides machined from steel which are connected with two threaded rods using bolts, and nuts. The conditioned and curtailed bars were placed inside the shear test fixture and tested with a displacement rate such that the test continuous for at least 1 minute and a maximum of 10 minutes until the force reaches 70 % of the ultimate load. The transverse shear strength was determined using the ultimate load and the cross sectional area of the specimen as measured per ASTM D 792 (ASTM-International, 2015) (see above).

5.1 Load vs. Displacement

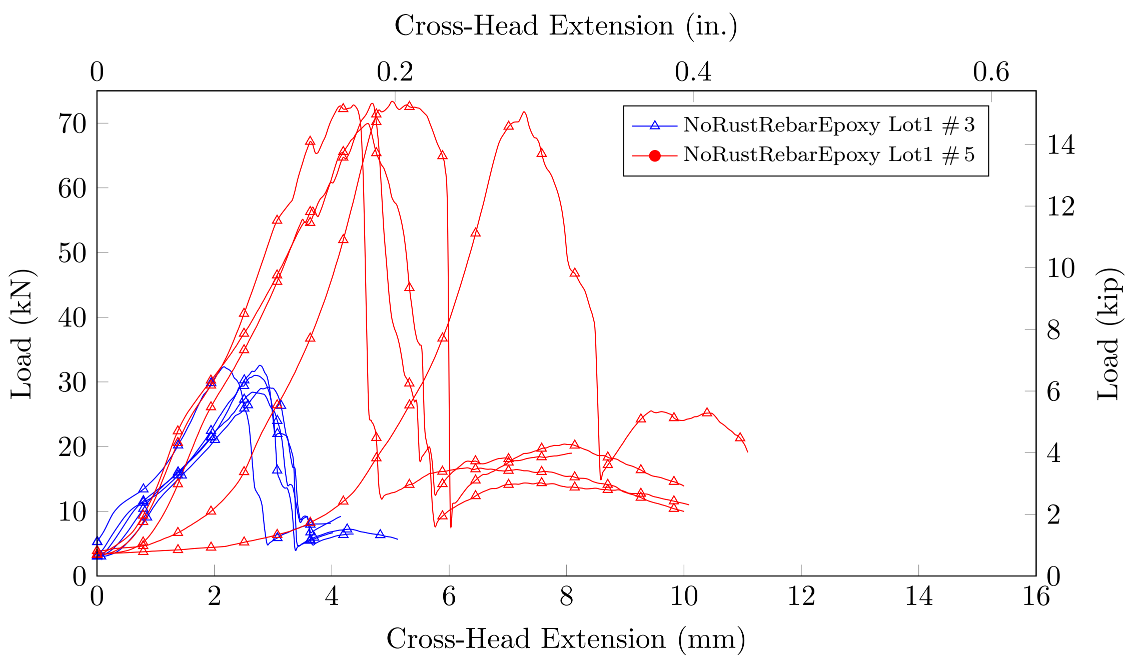


Figure 5.1: Transverse shear test extension vs. load results for RockRebar® Lot 1 # 3, and # 5 rebars with Epoxy resin

5.2 Shear Stress vs. Extension

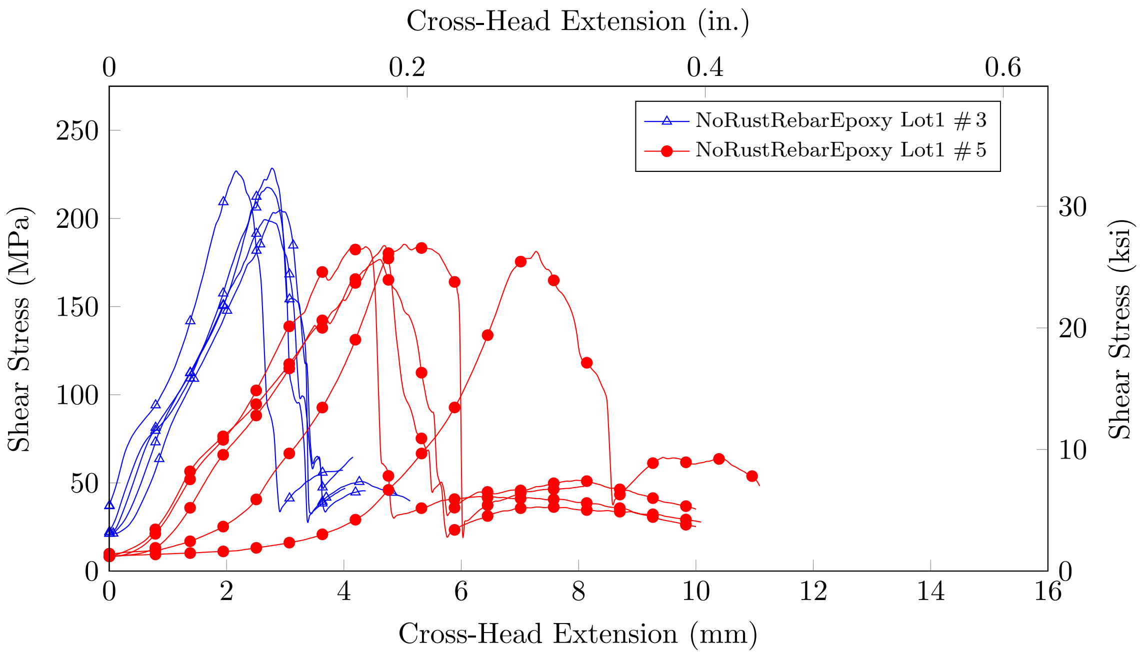


Figure 5.2: Transverse shear stress vs. extension results for RockRebar® Lot 1 # 3, and # 5 rebars with Epoxy resin

5.3 Modes of Failure

The Figure 5.3 in this section shows the pictures of failed BFRP specimen due to transverse shear load.

(a) RockRebar® # 3

(b) RockRebar® # 5

Figure 5.3: Failure pattern for tested rebar after completion of horizontal shear test

5.4 Summary of Transverse Shear Properties

The statistical values of the transverse shear properties for the RockRebar® products are listed in the following Table 5.1.

Table 5.1: Transverse shear test statistical values for each sample group (Imperial Units)

Exposure		Sample Group				Statistical Values				
						Shear Stress				
Age d	T °C	Manuf. Type	Resin Type	Size #	Lot No.	$\wedge$ ksi	$\vee$ ksi	μ ksi	σ ksi	CV %
0	23	RockRebar®	Epoxy	3	1	29.1	33.2	31.4	1.9	6.00
0	23	RockRebar®	Epoxy	5	1	25.7	26.9	26.5	0.5	1.94

Chapter 6

Apparent Horizontal Shear

The FRP rebar products were tested for horizontal shear properties. The horizontal shear test was conducted according to the ASTM D 4475 (ASTM-International, 2012a) standards. This test alone does not suffice for design purposes, but the horizontal shear failure is an indicator for the strength of the resin, and therefore, is a well suited quality control criteria and used for comparison among multiple specimens from the same manufacturer. First, the diameter at the center of the specimen was recorded and the specimens were conditioned at a temperature range from 21 °C to 25 °C and a moisture content between 40 % and 60 % before they were cut to a length of approximately 5 times the diameter. A minimum of 5 specimen were tested per sample. The horizontal shear strength was assessed through a three-point load test over a span length that is short enough to prevent bending failure. The load was applied at the center of specimen with a displacement rate of 1.3 $\frac{\mathrm{mm}}{\mathrm{min}}$ until the shear failure was reached via horizontal delamination (failure of the resin). The ultimate load and the break type were recorded and analyzed.

6.1 Load vs. Displacement

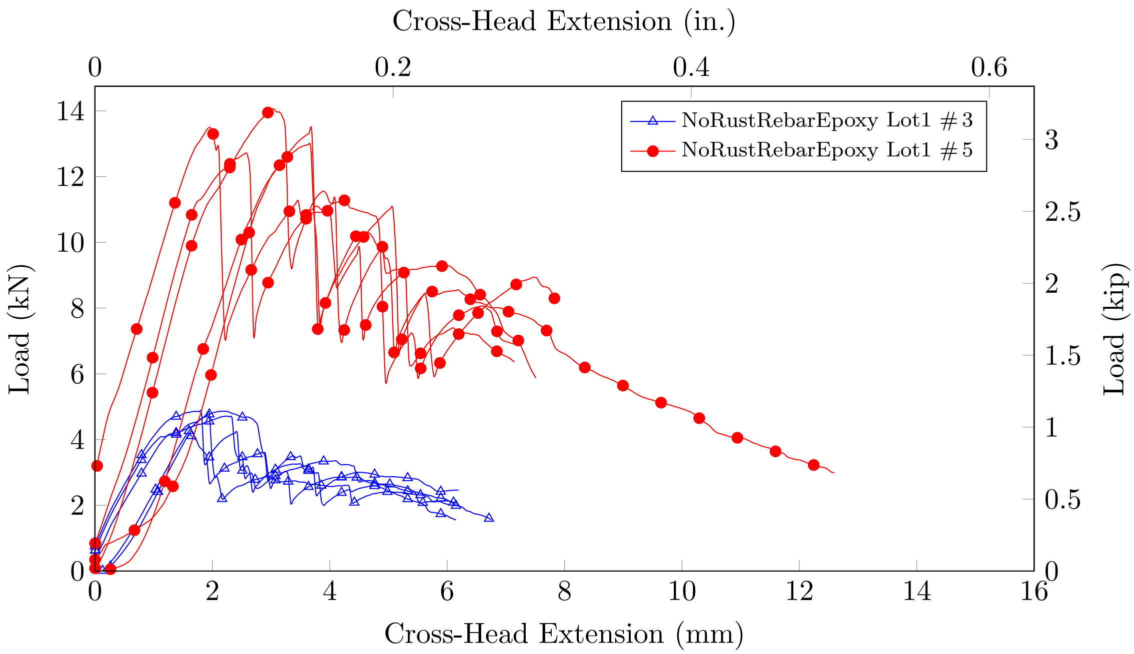


Figure 6.1: Horizontal shear test extension vs. load results for RockRebar® Lot 1 # 3,and # 5 rebars with Epoxy resin

6.2 Shear Stress vs. Displacement

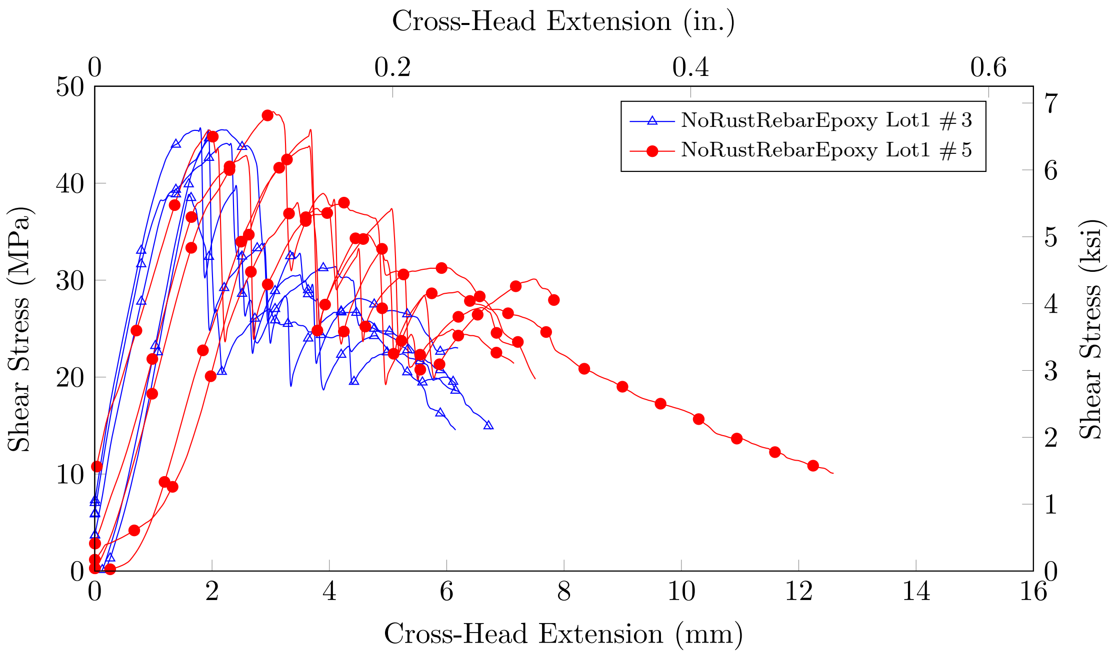


Figure 6.2: Horizontal shear stress vs. extension results for RockRebar® Lot 1 # 3, and # 5 rebars with Epoxy resin

6.3 Modes of Failure

Figure 6.3 shows the failed BFRP specimen after completion of the horizontal shear test.

(a) RockRebar® # 3

(b) RockRebar® # 5

Figure 6.3: Failure pattern for tested rebar after completion of horizontal shear test

6.4 Summary of Horizontal Shear Properties

The statistical values of the horizontal shear properties for the RockRebar® products are listed in the following Table 6.1.

Table 6.1: Horizontal shear test statistical values for each sample group (Imperial Units)

Exposure		Sample Group				Statistical Values				
						Shear Stress				
Age d	T °C	Manuf. Type	Resin Type	Size #	Lot No.	$\wedge$ ksi	$\vee$ ksi	μ ksi	σ ksi	CV %
0	23	RockRebar®	Epoxy	3	1	5.8	6.7	6.4	0.4	5.90
0	23	RockRebar®	Epoxy	5	1	6.2	6.9	6.5	0.3	3.89

Chapter 7

Tensile Strength Tests

The rebars were tested according to the ASTM D 7205 to evaluate the tensile properties. ASTM describes a specific test method with a specimen preparation in which the rebar are anchored via steel pipes at both ends. Because of the low shear strength of FRP rebars, this method is necessary to prevent the rebar from failing in shear before reaching the ultimate tensile strength. The grips of the testing machine would lead to a shear failure of the specimen. The anchors are potted with expansive grout which transfers the force from the testing machine to the rebar via friction between the rebar, the grout, and the anchor. The dimensions of the anchors relate to the rebar diameter and the free specimen length between the anchors is normally described in ASTM with 40 times the rebar diameter.

7.1 Results Load vs. Displacement

The following graph in Figure 7.1 illustrate the test results for the # 3 RockRebar® with epoxy resin.

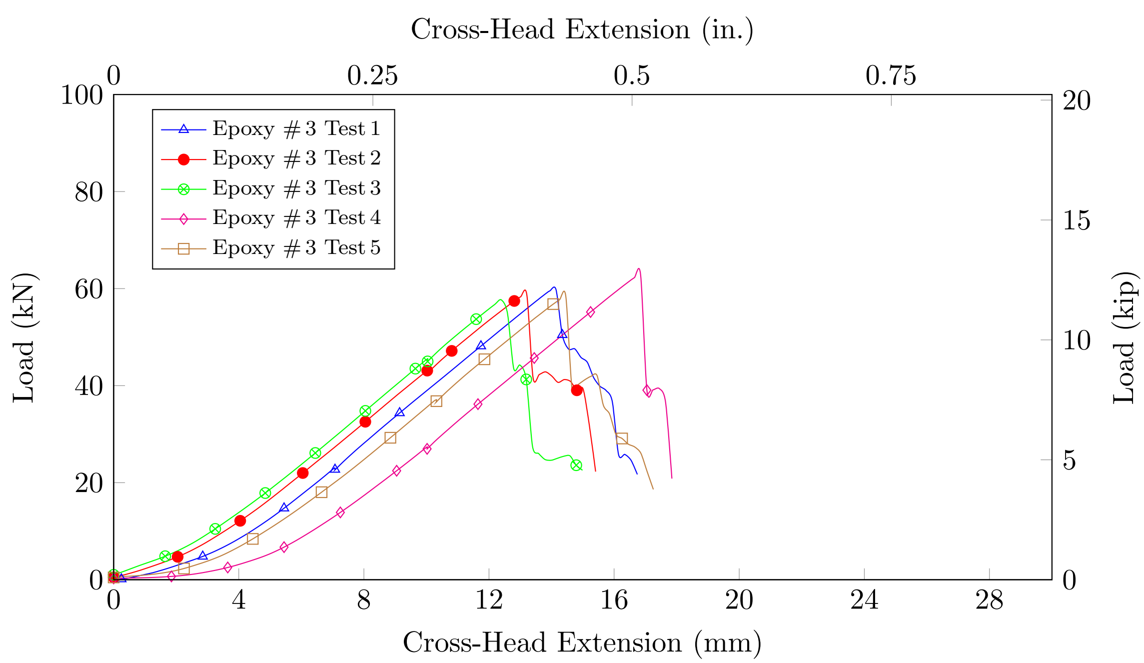


Figure 7.1: Tensile test results for RockRebar® # 3 with Epoxy resin

The specimens reached a linear characteristic around 10 kN until the peak load. The common behavior after the maximum load was overcome was a stepwise loss of load with little inclines until the next loss of load occurred. With increasing cross-head extension in the post-failure region, the load decreased slightly, but then stagnated or even regained some strength throughout further extension, multiple times, until the specimen failed completely.

The Figure 7.2 illustrates the load vs. cross-head displacement for the # 5 rebar.

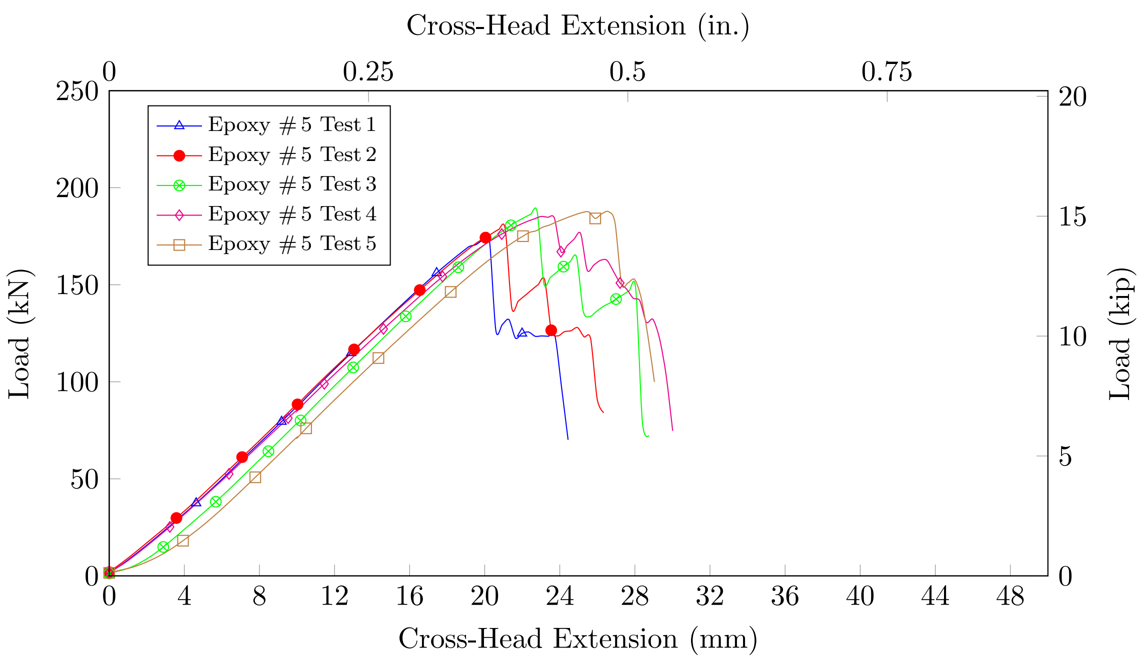


Figure 7.2: Tensile test results for RockRebar® # 5 with Epoxy resin

Similar to the graph in the previous figure, the maximum load level of all tested specimen shown are within similar ranges. All specimen show similar behavior with a small variance of the maximum reached extension. Similar to the other rebar types, the specimens displayed a post-failure behavior in which the load displacement curve recovered and held load again, before the load dropped further. During testing, it was observed that after the maximum load was reached, the rebars delaminated and flared out more and more, as these load-drops occurred (ultimately producing the failure patterns detailed in Section 7.2).

7.1.1 Stress vs. Strain Behavior

The following figures show the relevant (according to ASTM) stress-strain behavior of the tested rebars.

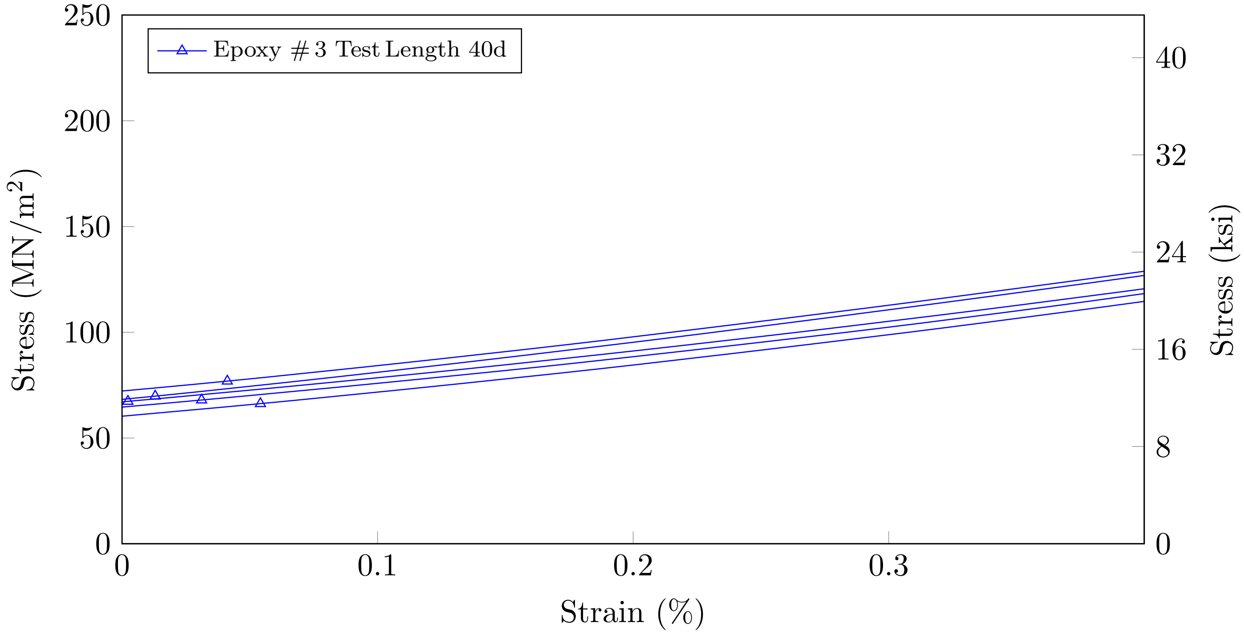


Figure 7.3: Tensile stress vs Strain behavior of RockRebar® Lot 1 Epoxy rebar size 3

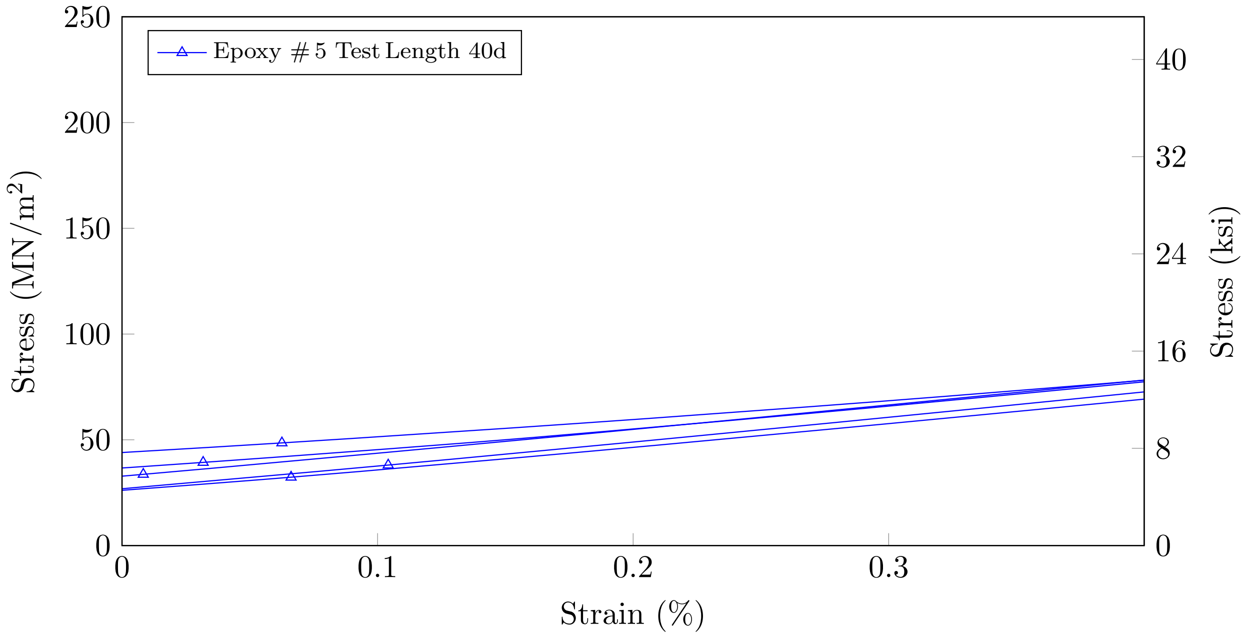


Figure 7.4: Tensile stress vs Strain behavior of RockRebar® Lot 1 Epoxy rebar size 5

7.2 Modes of Failure

According to ASTM D 7205, three different failure modes may occur during a tensile strength test. The first and expected one is the tensile rupture outside of the anchor pipes. Due to insufficient sample preparation or test procedure issues, two more failure modes may occur. The rebar could slip out of the anchor (rebar slippage) or the anchor could slip out of the fixture/grips (anchor slippage). Nevertheless, the last two described failure modes lead to unusable results when defining the material characteristics. However, for this research project, no specimen failed due to rebar or anchor slippage. Hence, tensile rupture of the BFRP rebar was the recorded failure mode for each bar that was tested.

Figure 7.5 and 7.6 show the failed specimens of the # 3 rebar and the # 5 rebar.

Figure 7.5: RockRebar® # 3, final failure pattern after tensile test

Figure 7.6: RockRebar® # 5, final failure pattern after tensile test

All the specimens failed in a similar manner. After the peak load was reached a bundle of outer fibers failed and brushed out over the entire free specimen length. After the first load-drop, this behavior continued at each additional sudden load drop until delamination reached the center of the rebar, and the specimen eventually separated into two parts along the rebar axis.

7.3 Summary of Tensile Properties

The statistical values of the tensile strength properties of the RockRebar® products are listed in the following Table 7.1.

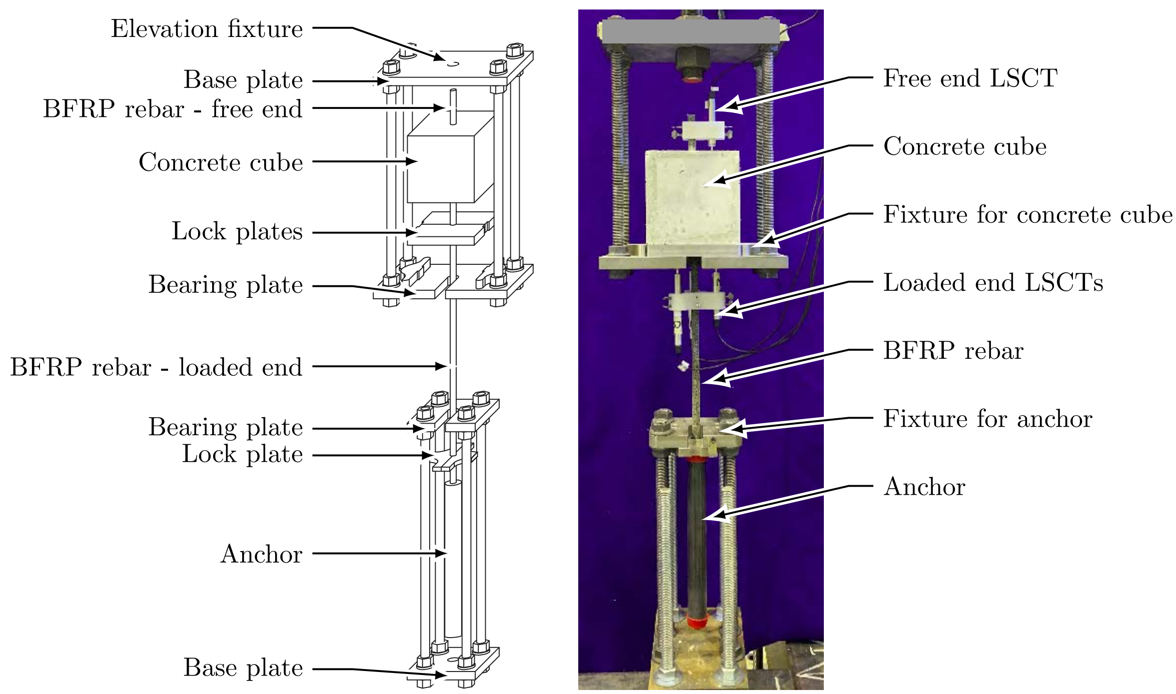
Table 7.1: Tensile strength test statistical values for each sample group (Metric Units)

Exposure		Sample Group					Statistical Values									
							Tensile Strength					Elastic Modulus				
Age d	T °C	Manuf. Type	Resin Type	Size #	Lot No.	FreeSpecimenLength Times Dia	$\wedge$ MPa	$\vee$ MPa	μ MPa	σ MPa	CV %	$\wedge$ MPa	$\vee$ MPa	μ MPa	σ MPa	CV %
0	23	RockRebar®	Epoxy	3	1	40d	819.4	883.2	839.2	26.4	0.03	48	53	50	2	0.0
0	23	RockRebar®	Epoxy	5	1	40d	881.3	950.8	925.3	29.9	0.03	52	55	53	1	0.0

Chapter 8

Bond-to-concrete Strength

The bond-to-concrete properties of the rebars were evaluated via pullout testing according to ASTM D7913 (ASTM International, 2014). For repeatability, a minimum of five specimen per sample group were tested. The bond strength experiments were conducted under standard laboratory conditions within (23 ± 2) °C [(73 ± 5) °F] and (50 ± 10) % relative humidity, using a 300 kN (66 kip) hydraulically controlled load frame. To properly apply the pullout force to the specimen, the test fixtures shown in Figure 8.1 were designed and used. Before installing the LSCTs, which



(a) Concept (b) In Laboratory

Figure 8.1: Experimental Setup

were needed to measure the rebar slip at both ends, an initial seating load of 272 kN (600 lbs.) was applied to generate sufficient stiffness in the system. The force was continuously applied and without shock via a displacement rate of $0.75\,\frac{\text{mm}}{\text{min}}$ ($0.03\,\frac{\text{in.}}{\text{min}}$), all values were recorded with 1000 Hz until the measured force decreased significantly (more than 50 %) and the slippage at the free end of the bar measured at least 2.5 mm (0.1 in.). After each test was completed, the concrete block was split open to analyze the failure mode and to measure the precise bond length of each specimen.

While the raw data was recoded in LabView software with high data rates, it was written to file at 10 Hz (using appropriate filters). For efficient data analysis and data presentation, the high-speed data was filtered and reduced using R-statistics[1] and R-Studio[2] software packages. The graphs presented in this report display the filtered and reduced data, which was verified to match the original raw high-speed data. However, all reported numerical values are based on the raw data and were calculated before any filter was applied.

8.1 Bond Stress vs. Slip at Free End

The bond stress τ_{max} (MPa or lbs./in.^{2}) for a circular bar diameter d (mm or in.) is given by Equation 8.1, in which F represents the recorded pullout load (N or lbs.) and L is the accurately measured bond length (mm or in.).

$$\tau_{max} = \frac{F}{d\pi L} \qquad [in\text{MPa } or \text{ psi}] \tag{8.1}$$

This formula was used to determine the bond behavior development and is the basis for the following graphs; Figures 8.2 and 8.3 depicts the measured bond stresses of the rebars relative to the rebar slip at free end. Graphs in Figure 8.4 portrays bond stresses vs slip at free end of the rebars of both the sizes. For clarity, the post failure measurements (at the onset of the 50 % load drop) were removed from these graphs. All tested specimens failed at the rebar-concrete interface in bond rupture, without splitting the concrete open or without tensile failure. The strength capacity and the failure behavior of the BFRP rebar-concrete interface were affected by the surface enhancement features.

[1] R.app GUI 1.70 (7434 El Capitan build), S. Urbanek & H.-J. Bibiko, R Foundation for Statistical Computing, 2016

[2] Version 1.1.383 2009-2017 RStudio, Inc.

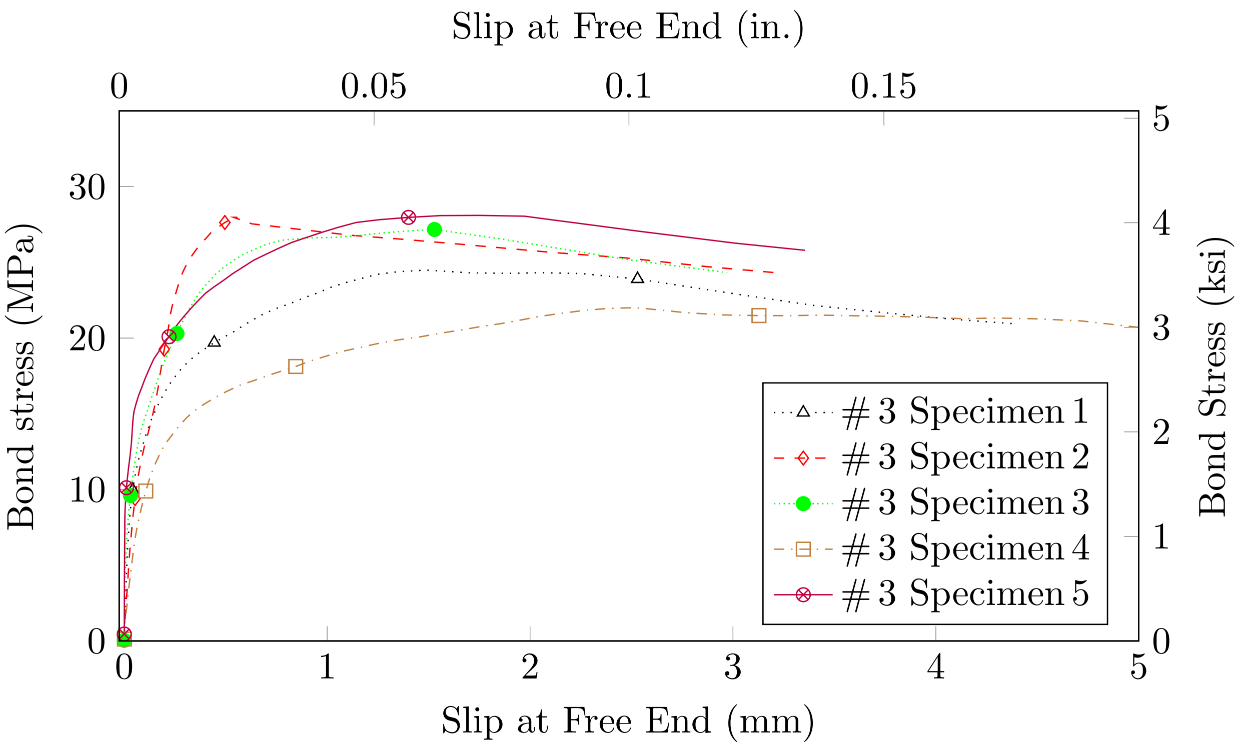


Figure 8.2: Free end slip behavior of the tested RockRebar® # 3

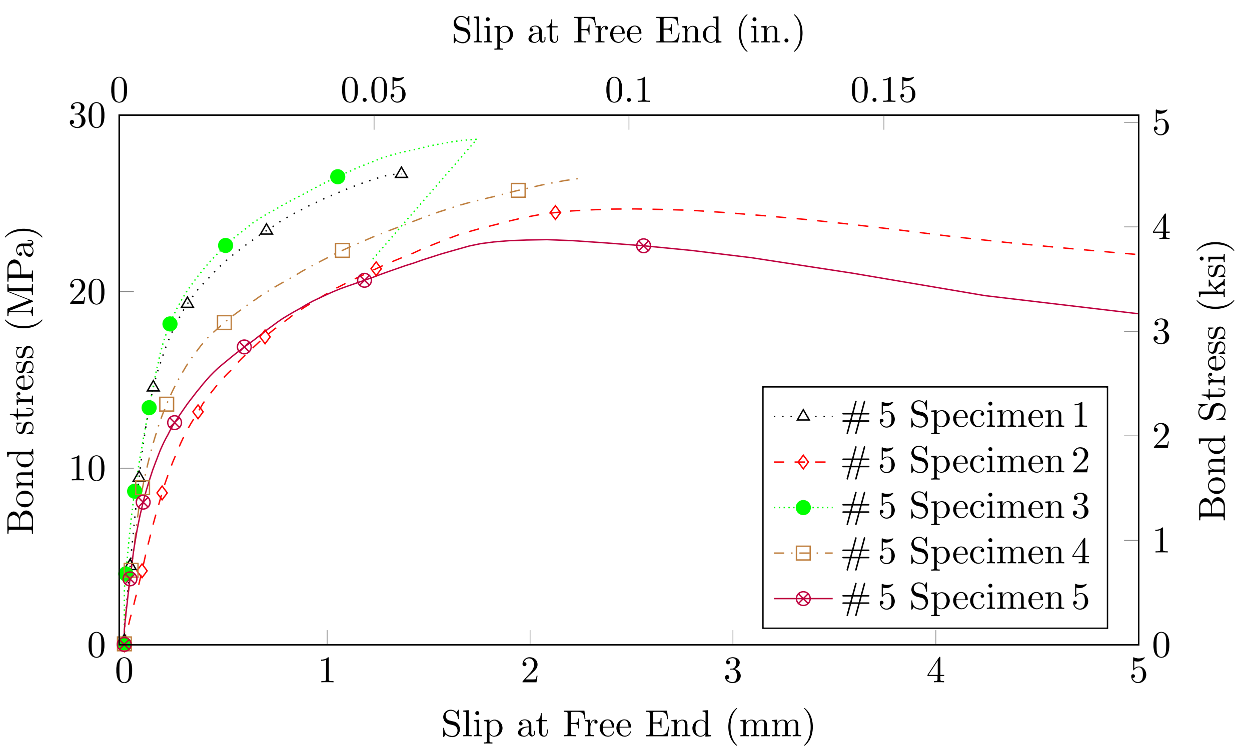


Figure 8.3: Free end slip behavior of the tested RockRebar® # 5

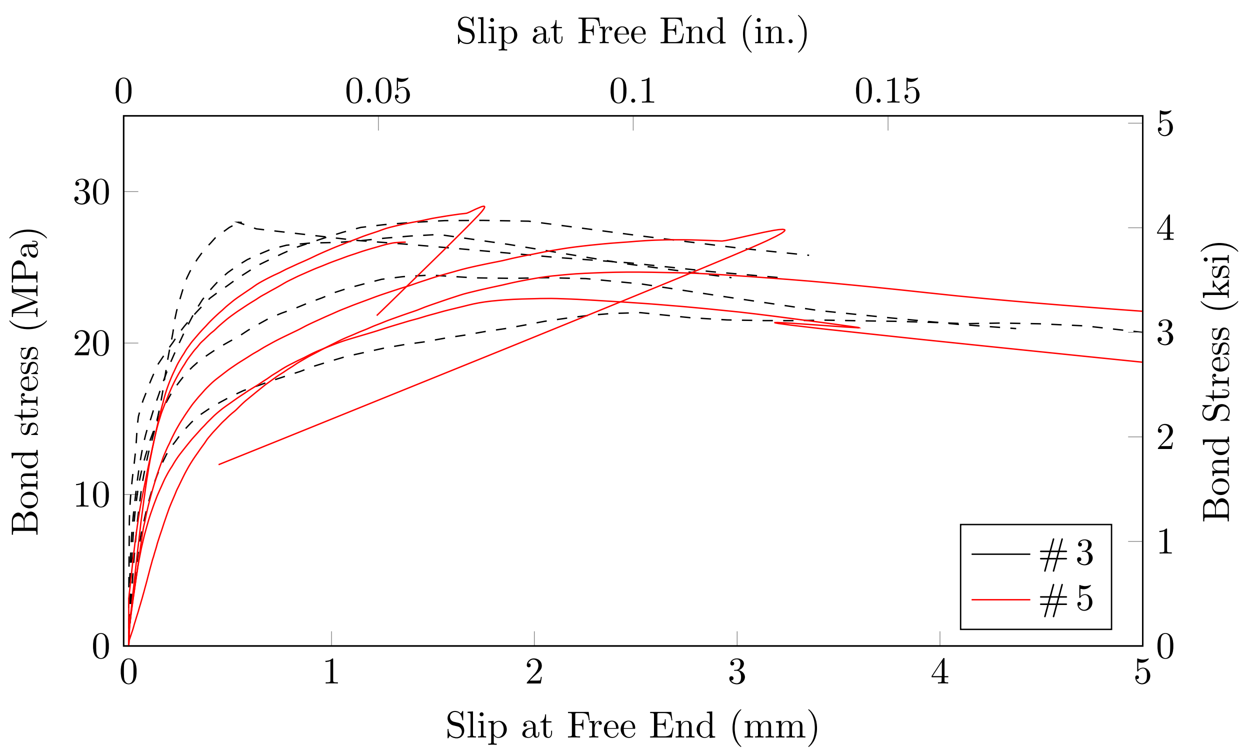


Figure 8.4: Free end slip behavior of the tested RockRebar® # 3 and # 5

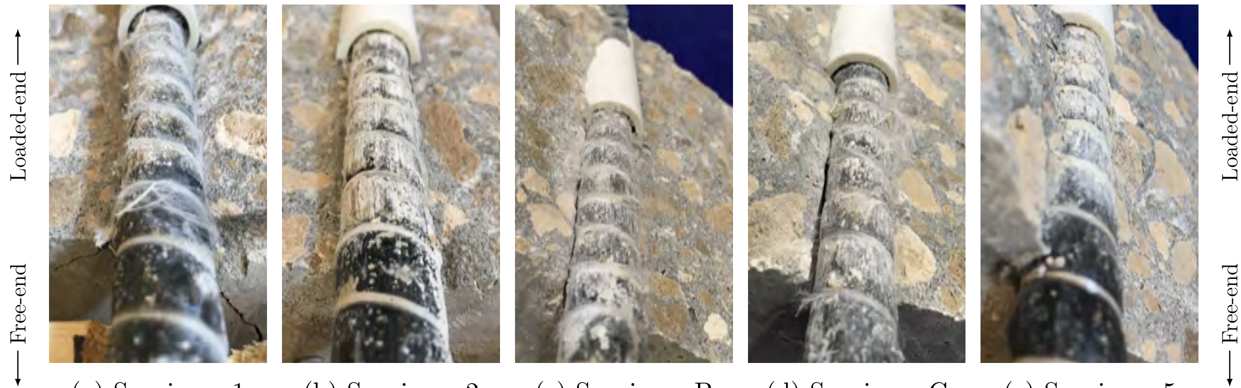
8.2 Modes of Failure

After the pullout tests were completed, the concrete blocks were split in half to further evaluate the failure mode by analyzing the surface of the rebar and the concrete. Figure 8.5 and 8.6 depict the different failure modes as they were observed after pullout testing. It was noted that the rebar

(a) Specimen 1 (b) Specimen 2 (c) Specimen 3 (d) Specimen 4 (e) Specimen 5

Figure 8.5: Overview rebar surface after testing RockRebar® # 3

surface was significantly damaged at the loaded end, and only the sand layer was pulled off from the concrete and the surface deformed slightly, but the helical wraps remained in place. Close to the unloaded end, the surface layer of the rebar did not peel off, and most parts of the sand-coated layer remained well-adhered to the bar.



(a) Specimen 1 (b) Specimen 2 (c) Specimen B (d) Specimen C (e) Specimen 5

Figure 8.6: Overview rebar surface after testing RockRebar® # 5

8.3 Summary of Bond-to-concrete Strength

For numerical comparison and concluding values, Table 8.1 lists the maximum bond stress ($\wedge$), the minimum bond stress ($\vee$), the average bond stress (μ), the standard deviation (σ), and the coefficient of variation (CV) for each individual test sample.

Table 8.1: Bond-to-concrete strength test statistical values for each sample

Exposure		Sample Group				Statistical Values				
Age d	T °C	Manuf. Type	Resin Type	Size #	Lot No.	$\wedge$ ksi	$\vee$ ksi	μ ksi	σ ksi	CV %
0	23	RockRebar®	Epoxy	3	1	3.20	4.08	3.77	0.38	0.10
0	23	RockRebar®	Epoxy	5	1	3.33	4.16	3.77	0.32	0.08

8.4 Acceptance Criteria

While acceptance criteria for basalt FRP rebars are not fully established yet, criteria for other fiber based rebars have been developed. One of the most established composite rebar materials is the glass fiber reinforced polymer (GFRP) rebar. For reference, the data in the tables 8.2 and 8.3 shows the acceptance criteria for (GFRP) rebars. The results obtained by testing BFRP rebars

Table 8.2: Acceptance criteria for GFRP rebar # 3

			FDOT 932-3/2017	AC454	ASTM D 7957
Test Method	Test Description	Unit	Criteria	Criteria	Criteria
ASTM D 792	Measured Cross Sectional Area	in.^{2}	0.104 – 0.161	0.104 – 0.161	0.104 – 0.161
ASTM D 2584	Fiber Content	% wt.	$\geqslant 70$	$\geqslant 70$	$\geqslant 70$
ASTM D 570	Moist. Absorption short term @50 °C	%	$\leqslant 0.25$	$\leqslant 0.25$	$\leqslant 0.25$
ASTM D 570	Moist. Absorption long term @50 °C	%	$\leqslant 1.0$	n/a	$\leqslant 1.0$
ASTM D 7205	Min. Guaranteed Tensile Load	kip	$\geqslant 13.2$	$\geqslant 13.2$	$\geqslant 13.2$
ASTM D 7205	Min. Guaranteed Tensile Strength	ksi	n/a	n/a	n/a
ASTM D 7205	Tensile Modulus	ksi	$\geqslant 6,500$	$\geqslant 6,500$	$\geqslant 6,500$
ASTM D 7205	Max. Strain	%	n/a	n/a	n/a
ASTM D 7617	Min. Guaranteed Transverse Shear	ksi	$\geqslant 22$	$\geqslant 22$	$\geqslant 19$
ASTM D 4475	Horizontal Shear Stress	ksi	n/a	$\geqslant 5.5$	n/a
ACI440. 3 R,B.3	Bond-to-concrete strength	ksi	$\geqslant 1.1$	$\geqslant 1.1$	$\geqslant 1.1$

are compared to GFRP rebar acceptance criteria because BFRP acceptance criteria are yet to be developed. Accordingly, the listed criteria (while established for glass) serve as reference points and are used for comparison and initial benchmark data. Tables 8.4 and 8.5 demonstrate that both RockRebar® sizes met or exceeded the acceptance criteria.

Table 8.3: Acceptance criteria for GFRP rebar # 5

			FDOT 932-3/2017	AC454	ASTM D 7957
Test Method	Test Description	Unit	Criteria	Criteria	Criteria
ASTM D 792	Measured Cross Sectional Area	in.^{2}	0.288 – 0.388	0.288 – 0.388	0.288 – 0.388
ASTM D 2584	Fiber Content	% wt.	$\geqslant 70$	$\geqslant 70$	$\geqslant 70$
ASTM D 570	Moist. Absorption short term @50 °C	%	$\leqslant 0.25$	$\leqslant 0.25$	$\leqslant 0.25$
ASTM D 570	Moist. Absorption long term @50 °C	%	$\leqslant 1.0$	n/a	$\leqslant 1.0$
ASTM D 7205	Min. Guaranteed Tensile Load	kip	$\geqslant 29.1$	$\geqslant 32.2$	$\geqslant 29.1$
ASTM D 7205	Min. Guaranteed Tensile Strength	ksi	n/a	n/a	n/a
ASTM D 7205	Tensile Modulus	ksi	$\geqslant 6,500$	$\geqslant 6,500$	$\geqslant 6,500$
ASTM D 7205	Max. Strain	%	n/a	n/a	n/a
ASTM D 7617	Min. Guaranteed Transverse Shear	ksi	$\geqslant 22$	$\geqslant 22$	$\geqslant 19$
ASTM D 4475	Horizontal Shear Stress	ksi	n/a	$\geqslant 5.5$	n/a
ACI440. 3 R,B.3	Bond-to-concrete strength	ksi	$\geqslant 1.1$	$\geqslant 1.1$	$\geqslant 1.1$

Table 8.4: Comparison of RockRebar® # 3 performance to GFRP rebar acceptance criteria

			Per diameter		FDOT 932-3/2017		AC454		ASTM D 7957	
Test Method	Test Description	Unit	Nom.	Exp.	Criteria	✓/✗	Criteria	✓/✗	Criteria	✓/✗
ASTM D 792	Measured Cross Sectional Area	in.^{2}	0.11	0.40	0.104 – 0.161	✓	0.104 – 0.161	✓	0.104 – 0.161	✓
ASTM D 2584	Fiber Content	% wt.	75.17	75.17	$\geqslant 70$	✓	$\geqslant 70$	✓	$\geqslant 70$	✓
ASTM D 570	Moist. Absorption short term @50 °C	%	0.2	0.2	$\leqslant 0.25$	✓	$\leqslant 0.25$	✓	$\leqslant 0.25$	✓
ASTM D 570	Moist. Absorption long term @50 °C	%	0.55	0.55	$\leqslant 1.0$	✓	n/a	n/a	$\leqslant 1.0$	✓
ASTM D 7205	Min. Guaranteed Tensile Load	kip	13.4	13.4	$\geqslant 13.2$	✓	$\geqslant 13.2$	✓	$\geqslant 13.2$	✓
ASTM D 7205	Min. Guaranteed Tensile Strength	ksi	121.7	105.2	n/a	n/a	n/a	n/a	n/a	n/a
ASTM D 7205	Tensie Modulus	ksi	7306	6313	$\geqslant 6,500$	✓	$\geqslant 6,500$	✓	$\geqslant 6,500$	✓
ASTM D 7205	Max. Strain	%	1.66	1.66	n/a	n/a	n/a	n/a	n/a	n/a
ASTM D 7617	Min. Guaranteed Transverse Shear	ksi	29.1	n/a	$\geqslant 22$	✓	$\geqslant 22$	✓	$\geqslant 19$	✓
ASTM D 4475	Horizontal Shear Stress	ksi	5.75	n/a	n/a	n/a	$\geqslant 5.5$	✓	n/a	n/a
ACI440. 3 R,B.3	Bond-to-concrete strength	ksi	3.20	2.64	$\geqslant 1.1$	✓	$\geqslant 1.1$	✓	$\geqslant 1.1$	✓

Table 8.5: Comparison of RockRebar® #5 performance to GFRP rebar acceptance criteria

			Per diameter		FDOT 932-3/2017		AC454		ASTM D 7957	
Test Method	Test Description	Unit	Nom.	Exp.	Criteria	✓/✗	Criteria	✓/✗	Criteria	✓/✗
ASTM D 792	Measured Cross Sectional Area	in.^{2}	0.307	0.65	0.288 – 0.388	✓	0.288 – 0.388	✓	0.288 – 0.388	✓
ASTM D 2584	Fiber Content	% wt.	78.4	78.4	$\geqslant 70$	✓	$\geqslant 70$	✓	$\geqslant 70$	✓
ASTM D 570	Moist. Absorption short term @50 °C	%	0.18	0.18	$\leqslant 0.25$	✓	$\leqslant 0.25$	✓	$\leqslant 0.25$	✓
ASTM D 570	Moist. Absorption long term @50 °C	%	0.77	0.77	$\leqslant 1.0$	✓	n/a	n/a	$\leqslant 1.0$	✓
ASTM D 7205	Min. Guaranteed Tensile Load	kip	41.2	41.2	$\geqslant 29.1$	✓	$\geqslant 32.2$	✓	$\geqslant 29.1$	✓
ASTM D 7205	Min. Guaranteed Tensile Strength	ksi	137.9	121.0	n/a	n/a	n/a	n/a	n/a	n/a
ASTM D 7205	Tensile Modulus	ksi	7749	6989	$\geqslant 6,500$	✓	$\geqslant 6,500$	✓	$\geqslant 6,500$	✓
ASTM D 7205	Max. Strain	%	1.78	1.78	n/a	n/a	n/a	n/a	n/a	n/a
ASTM D 7617	Min. Guaranteed Transverse Shear	ksi	25.7	n/a	$\geqslant 22$	✓	$\geqslant 22$	✓	$\geqslant 19$	✓
ASTM D 4475	Horizontal Shear Stress	ksi	6.22	n/a	n/a	n/a	$\geqslant 5.5$	✓	n/a	n/a
ACI440. 3R,B.3	Bond-to-concrete strength	ksi	3.33	2.89	$\geqslant 1.1$	✓	$\geqslant 1.1$	✓	$\geqslant 1.1$	✓

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