UNIVERSITÉ DE SHERBROOKE

NSERC Industrial Research Chair in Innovative FRP Composites for Infrastructures

Behaviour of Post-Installed GFRP Adhesive Anchors in Concrete

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July 2006

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Notations

h_e : The effective height of the anchor; mm

d_b : GFRP bar diameter; mm

l_e : Effective height (embedment length); mm

τ : Bond stress; MPa

F_u : Maximum load; N

Abstract

This report presents the results of an experimental investigation conducted on the bond behavior of GFRP post-installed adhesive anchors embedded in plain concrete. A total of 90 sand-coated GFRP V-ROD bars of three different diameters; 25.4, 15.9, and 6.35 mm diameter were tested at different embedment lengths ranging from $5d_b$ to $15d_b$ where d_b is the bar diameter. These anchors were installed in large scale plain concrete slabs. The layout of the GFRP adhesive anchors were planned in accordance to the ASTM E-488 96 requirements. The anchors were installed using two different type of adhesives, epoxy based adhesive (HIT RE 500) and cement based adhesive (HIT HY 150). The experimental results indicated the adequate performance of this type of post-installed GFRP adhesive anchors. The capacity of these anchors is achieved at a considerably smaller embedment length.

Keywords

Bond, GFRP, Anchor, Adhesive.

1. Introduction

The resistance to corrosion and chemical attack, high strength-to-weight ratio, and ease of handling of FRP rods make them a better alternative to steel reinforcement in concrete members subjected to severe environmental conditions. The adhesive anchor generally consists of a reinforcing bar inserted into a drilled hole in hardened concrete with a structural adhesive acting as a bonding agent between the concrete and the reinforcing bar (Cook et al. 1992). The post-installed anchors can be driven in almost any desired position in hardened concrete by installing in holes drilled into concrete. These anchors are usually needed for strengthening and rehabilitation of deteriorated concrete structures or even attaching a structural concrete element to an existing concrete structure. The load-transfer mechanism of adhesive anchor is different than that of cast-in-place one. For adhesive anchor, the load is transferred through the adhesive to the concrete along the entire embedded portion of the anchor. This load-transfer depends on the strength of the adhesive-bar bond, the adhesive-concrete bond, and also on the extent to which the adhesive impregnates the concrete surrounding the drilled hole (Cook et al. 1992). Although the use of these post-installed adhesive anchors provides greater flexibility in design and strengthening of concrete members, their behavior is less understood than that of the cast-in-place anchors.

The bond strength of post-installed FRP anchors depends on the mechanical properties of the FRP bars, the adhesive, and the concrete. The high strength and low modulus of elasticity as well as the differences in the properties of the fiber material and the matrix may lead to different bond characteristic from those of steel bars (Wang et al. 1999). Additionally, the behavior of post-installed FRP anchors seems to be more complex because it is dependent on the adhesive-bar interface, adhesive-concrete interface, as well as the surface and material properties.

To experimentally investigate the behavior of GFRP adhesive anchors, an extended experimental program was planned. The program included three different diameters, 6.35 mm, 15.9 mm and 25.4 mm as well as two different types of adhesive; epoxy based (HIT RE 500) and cement based (HIT HY 150). The anchors were tested with different embedment lengths ranging from $5d_b$ to $15d_b$; where d_b is the bar diameter. The details of the test program are shown in Table 1. The FRP bars and the adhesives used in this study were manufactured by Pultrall Inc. (2005) and Hilti Inc. (2005), respectively.

2. Test Specimens

This research includes tension testing of 90 sand-coated GFRP V-ROD adhesive anchors of 6.3 mm, 15.9 mm, and 25.4 mm diameter with two different adhesives. The first adhesive, Type HIT RE 500, is a high strength epoxy based adhesive specially designed for fastening into solid base materials in a wide range of material temperatures ranging from 49^{o}C down to -5^{o}C. It may be also used in underwater fastening for oversize holes up to two times the bar diameter but with a maximum of 76 mm hole diameter. The second type of adhesive, Type HIT HY 150, is a hybrid adhesive consisting of a methacrylate resin, hardener, cement and water. It is formulated for fast curing and installation in a wide range of material temperatures ranging from 40^{o}C down to -5^{o}C (Hilti Inc. 2005). The specifications of these adhesives are shown in Table 1.

Table 1: Material Specifications (Hilti 2005)

Adhesive	Compressive Strength (MPa)	Tensile Strength (MPa)	Modulus of Elasticity (MPa)	Bond Strength (MPa)	Absorption (%)	Resistance (Ω/m)
HIT RE 500	82.7	43.5	1493	12.4	0.06	6.6×10^{13}
HIT HY 150	71.8	15.9	7032	Not Specified	0.12	2.0×10^{13}

The Test specimens were divided into three series corresponding to the bar diameter. Each series includes two groups; one for each adhesive type. The test specimens in each group included three different embedment lengths $5d_b$, $10d_b$, and $15d_b$ with five replicate samples each. Table 2 gives the details of the test specimens. The FRP bars were cut to the desired length then steel tubes were installed on the FRP bars (using epoxy grout) at one end keeping the other end free to be driven into the concrete. Each bar is designated by a set of symbols and numbers to be uniquely identified. As an examples for G#25-5D-E4; the first letter G denotes glass, #25 denotes the bar diameter in mm, 5D denoted the embedded length in bar diameter multiplications, E4 denotes the fourth sample out of the five replicates with epoxy adhesive.

Table 2: Details of Test Specimens

Series	**Group**	**Adhesive Type**	**Diameter (mm)**	**Embedment Length Le (mm)**			**No. of Samples**
				5 d_b	**10 d_b**	**15 d_b**	
Series 1	Group I	Epoxy based (HIT RE 500)	25.4 (#8)	127	254	382	3×5=15
	Group II	Cement based (HIT HY 150)	25.4 (#8)	127	254	382	3×5=15
Series 2	Group I	Epoxy based (HIT RE 500)	15.9 (# 5)	79.5	159	238.5	3×5=15
	Group II	Cement based (HIT HY 150)	15.9 (# 5)	79.5	159	238.5	3×5=15
Series 3	Group I	Epoxy based (HIT RE 500)	6.3 (# 2)	31.5	63	94.5	3×5=15
	Group II	Cement based (HIT HY 150)	6.3 (# 2)	31.5	63	94.5	3×5=15

Four Concrete slabs with dimensions of 3450×1750×400 were cast using ready-mixed normal weight concrete (type V, MTQ) on July 2005. Figure 1 shows one of the concrete slabs just after concrete casting. After casting, the concrete slabs were cured with water for 14 days and stored out the laboratory. Layout of the GFRP anchors was made in accordance with ASTEM E 488-96. To install the FRP anchors, holes were drilled using rotary hammer pits. For the epoxy based adhesive (HIT RE 500), the holes were cleaned by wire brushes and compressed water as this type of epoxy performs adequately in moisture whereas they were cleaned by wire brushes and compressed air in case of using the cement based adhesive (HIT HY 150). After cleaning the holes on the inside, the two-component adhesive package was installed in the dispenser then injected into the holes. Consequently, the bars were pushed into the holes in a screwing fashion. The epoxy based GFRP adhesive anchors were installed during the third week of October, 2006 (installed in two slabs) while the cement based GFRP adhesive anchors were installed during the first week of November, 2006 (installed in the other two slabs). The first two slabs were then moved to the laboratory, indoors, to test the anchors during the last week of January 2006. The GFRP adhesive anchors in these slabs were tested during the period of January 27, 2006 to February 10, 2006. The other two slabs were then moved to the laboratory to test the anchors during the last second week of February, 2006. The test of GFRP adhesive anchors in these slabs was completed by March 24, 2006. During the period from installing the adhesive anchors to being tested, the installed specimens were stored in open air. They were subjected to real environmental conditions including wet-dry cycles, freeze-thaw cycles and temperature variation. The concrete cylinders were kept in the same conditions; their compressive strength at testing was 45 MPa. Figures 2 to 5 show the steps of anchor installation.

Figure 1: Concrete Slab after Casting

Figure 2: The Drilling of the Holes

Figure 3: The Two-Component Package

Figure 4: Injection of the Adhesive into the Hole

Figure 5: Installing the Bar

3. Test Set-Up and Procedure

A test set-up, in accordance with the requirements of the ASTM E 488-96, was used (Figure 6). The test bars were pulled using a hydraulic jack connected to a manual pump. Each anchor was instrumented with one LVDT to measure the bar displacement at different loading stages. Not to break it, the LVDT was removed at approximately 80% of the expected failure load. The loading pump and the LVDT were connected to a data acquisition system to continuously record data up to the anchor failure.

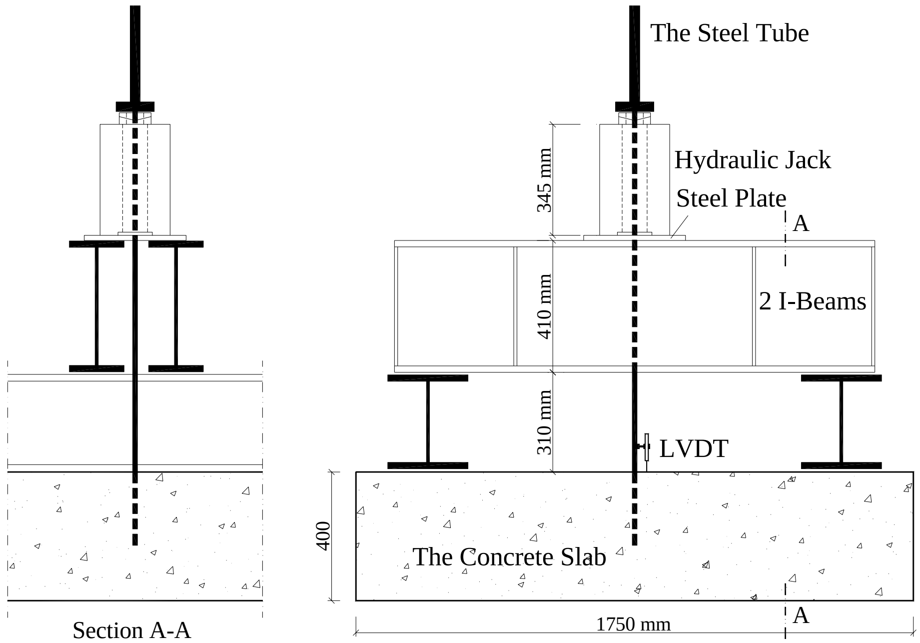


Figure 6: Test Set-up

4. Test Results and Discussion

The test results are presented in Tables 4 to 9 while the failure modes are shown in Figure 2. For bars with small embedment length ($5d_b$), the mode of failure was concrete failure (concrete cone or concrete damage followed by bar pull-out). Additionally, in case of concrete failure, severe damage was observed in the concrete around the anchors. However, for bars with greater embedment lengths ($10d_b$ and $15d_b$), the mode of failure was bar rupture. From the test results, there was no significant difference between anchors with $10d_b$ and $15d_b$ embedment lengths in terms of maximum load and mode of failure. As a result, except for bars of 15.9 mm (#5) diameter installed with epoxy based adhesive, $10d_b$ seems to be enough development length. Gesoglu et al. (2005) conducted an experimental study on the post-installed steel adhesive anchors of 12 and 16 mm diameter with embedment length ranged from $3.3d_b$ to $10d_b$ in normal-strength, high-strength and steel fiber-reinforced concretes. In this study, the steel bar failure of the 16 mm diameter adhesive anchors was achieved at an embedment length of $10d_b$ in normal-strength, high-strength, and steel-fiber reinforced concretes.

Regarding the bars of 15.9 mm diameter, the 10 d_b (178 mm) embedment length was not enough to provide the ample strength of the bars. Increasing the embedment length to 15 d_b (260 mm) enabled achieving the tensile capacity of some bars. The main reason for these bars to have a different mode of failure was referred to the overlapping of the concrete failures from the adjacent bars (bars with 25.4 mm diameter (#8)). Although the spacing between these bars was in accordance to the ASTM –E488-96, it was not enough to prevent the overlapping of the concrete failures. The minimum clearance requirements for ASTM –E488-96 are given in Table 3.

Table 3: Minimum Clearance Requirements for the Test Equipment Supports (ASTM E-488- 96)

Spacing Between Test Supports	Minimum Distance to Edge or Test Frame
2.0 l_e	1.0 l_e

Table 3 test support requirements are not prohibited from being reduced for bonded anchors with embedment lengths equal or grater than 20 times the anchor diameter. However, Hilti (2005) stated that for the steel anchors using HIT RE 500 adhesive, the recommended spacing is 1.5 l_e and a reduction factor is needed when arranging the adhesive anchors at spacing less than 1.5 l_e but it all cases it must not be less than 0.5 l_e.

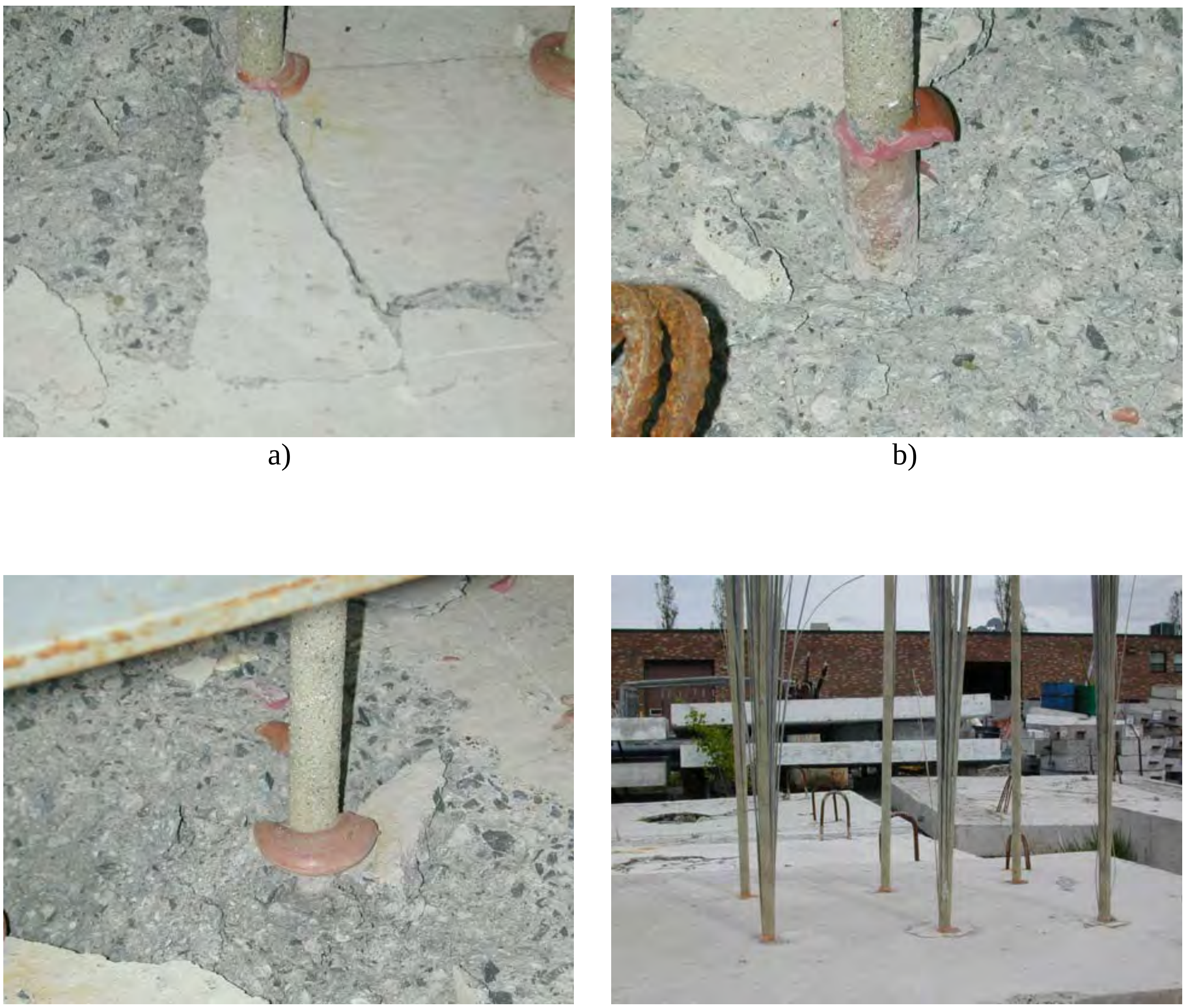
In the current study, the spacing between the GFRP adhesive anchors was kept constant as 1.5 l_e; where l_e is the effective height of the anchor (embedment length).

At the maximum load of each test, the corresponding bond stress was calculated using the following equation:

$$\tau = \frac{F_u}{\pi \, d_b \, l_e} \qquad (1)$$

where τ is the bond stress (MPa); F_u is the maximum load (N); d_b is the bar diameter (mm) and l_e is the embedded length (mm). Comparing the obtained values listed in Table 3 to the listed one in Table 2, it can be noticed that all of these values are lower than the epoxy adhesive bond capacity reported by the manufacturer. Gesoglu et al. (2005) reported that the maximum bond stress for the $10d_b$ steel anchors was 11.9 MPa for anchors in normal-strength concrete, 12.15 MPa in normal-strength steel fiber reinforced concrete, 12.75 MPa in high-strength plain concrete, and 12.85 MPa in high-strength steel-fiber reinforced concrete.

The test results of series 1 group I was submitted as a conference paper (Ahmed et al. (2006)). This group was selected because it was the first completed one.



a) b)

c) d)

Figure 7: Failure Modes the Test Specimens
a), b), c): Concrete Failure; d): Bar Rupture

Table 4: Test Results of GFRP bars # 8 (25.4 mm) (Epoxy Based Resin HIT RE 500)

Designation	Load (kN)	L (mm)	Stress (MPa)	Maximum Bond Stress (MPa)	Average of Maximum Bond Stress (MPa)	Mode of Failure
G#8-5D-E1	110	(5 d_b) 130	217.20	10.61	10.59 ± 0.50	Concrete
G#8-5D-E2	107		211.27	10.32		Concrete
G#8-5D-E3	105		207.33	10.13		Concrete
G#8-5D-E4	117		231.02	11.28		Concrete
G#8-5D-E5	80.2	This bar was affected by the nearby ones				Concrete
G#8-10D-E1	250	(10 d_b) 254	493.63	12.34	10.85 ± 0.94	Rupture
G#8-10D-E2	211		416.63	10.42		Rupture
G#8-10D-E3	227		448.22	11.21		Rupture
G#8-10D-E4	207		408.73	10.22		Tube slippage
G#8-10D-E5	204		402.80	10.07		Rupture
G#8-15D-E1	199	(15 d_b) 390	392.93	6.40	6.97 ± 0.51	Rupture
G#8-15D-E2	206		406.75	6.62		Rupture
G#8-15D-E3	220		434.40	7.07		Rupture
G#8-15D-E4	231		456.12	7.43		Rupture
G#8-15D-E5	239		471.91	7.68		Rupture
G#8-15D-E6	205		404.78	6.59		Rupture

Table 5: Test Results of GFRP bars # 8 (25.4 mm) (Cement Based Resin HIT HY 150)

Designation	Load (kN)	L (mm)	Stress (MPa)	Maximum Bond Stress (MPa)	Average of Maximum Bond Stress (MPa)	Mode of Failure
G#8-5D-C1	120	(5 d_b) 127	236.94	11.85	12.49 ± 0.91	Concrete
G#8-5D-C2	133		262.61	13.13		Concrete
G#8-5D-C3	91.3	This bar was affected by the nearby ones				Concrete
G#8-5D-C4	92.5	This bar was affected by the nearby ones				Concrete
G#8-5D-C5		This bar was not installed				---
G#8-10D-C1	236	(10 d_b) 253	465.98	11.70	11.62 ± 1.64	Rupture
G#8-10D-C2	188		371.21	9.32		Rupture
G#8-10D-C3	265		523.25	13.13		Rupture
G#8-10D-C4	249		491.66	12.34		Rupture
G#8-10D-C5		This bar was not installed				---
G#8-15D-C1	213	(15 d_b) 378	420.57	7.07	7.09 ± 0.80	Rupture
G#8-15D-C2	196		387.01	6.50		Rupture
G#8-15D-C3	204		402.80	6.77		Rupture
G#8-15D-C4	255		503.50	8.46		Rupture
G#8-15D-C5	200		394.91	6.63		Rupture

Table 6: Test Results of GFRP bars # 5 (15.9 mm) (Epoxy Based Resin HIT RE 500)

Designation	Load (kN)	L (mm)	Stress (MPa)	Maximum Bond Stress (MPa)	Average of Maximum Bond Stress (MPa)	Mode of Failure
G#5-5D-E1	60.3	(5 d_b) 95	304.81	12.73	11.29 ± 1.74	Pull-Out
G#5-5D-E2	54.6		275.99	11.53		Pull-Out
G#5-5D-E3	62		313.40	13.09		Pull-Out
G#5-5D-E4	48.1		243.14	10.16		Pull-Out
G#5-5D-E5	42.4		214.33	8.95		Pull-Out
G#5-10D-E1	112	(10 d_b) 178	566.14	12.62	11.47 ± 1.14	Pull-Out
G#5-10D-E2	85.1		430.16	9.59		Pull-Out
G#5-10D-E3	106		535.81	11.95		Pull-Out
G#5-10D-E4	101		510.54	11.38		Pull-Out
G#5-10D-E5	105		530.76	11.83		Pull-Out
G#5-15D-E1	116	(15 d_b) 260	586.36	8.95	8.40 ± 1.19	Rupture
G#5-15D-E2	86.4		436.74	6.67		Pull-Out
G#5-15D-E3	121		611.64	9.34		Rupture
G#5-15D-E4	112		566.14	8.64		Pull-Out
G#5-15D-E5	This bar was destroyed during the test setup					---

Table 7: Test Results of GFRP bars # 5 (15.9 mm) (Cement Based Resin HIT HY 150)

Designation	Load (kN)	L (mm)	Stress (MPa)	Maximum Bond Stress (MPa)	Average of Maximum Bond Stress (MPa)	Mode of Failure
G#5-5D-C1	64.4	(5 d_b) 95	325.53	13.60	15.20 ± 1.28	Pull-Out
G#5-5D-C2	71.0		358.89	14.99		Pull-Out
G#5-5D-C3	73.4		371.03	15.50		Pull-Out
G#5-5D-C4	79.1		399.84	16.70		Pull-Out
G#5-5D-C5	This bar was destroyed during the test setup					---
G#5-10D-C1	122	(10 d_b) 190	616.69	12.88	12.56 ± 0.31	Rupture
G#5-10D-C2	119		601.53	12.56		Rupture
G#5-10D-C3	116		586.36	12.25		Rupture
G#5-10D-C4	116		586.36	12.25		Pull-Out
G#5-10D-C5	122		616.69	12.88		Rupture
G#5-15D-C1	126	(15 d_b) 248	636.91	10.19	10.16 ± 0.12	Rupture
G#5-15D-C2	127		641.96	10.27		Rupture
G#5-15D-C3	124		626.80	10.03		Rupture
G#5-15D-C4	This bar was destroyed during the test setup					---
G#5-15D-C5	This bar was destroyed during the test setup					---

Table 8: Test Results of GFRP bars # 2 (6.35 mm) (Epoxy Based Resin HIT RE 500)

Designation	Load (kN)	L (mm)	Stress (MPa)	Maximum Bond Stress (MPa)	Average of Maximum Bond Stress (MPa)	Mode of Failure
G#2-5D-E1	10.6	($5\ d_b$) 30	334.88	17.72	18.78 ± 3.36	Pull-Out
G#2-5D-E2	13.0		410.70	21.73		Concrete
G#2-5D-E3	13.0		410.70	21.73		Concrete
G#2-5D-E4	8.16		257.80	13.64		Pull-Out
G#2-5D-E5	11.4		360.16	19.06		Concrete
G#2-10D-E1	17.1	($10\ d_b$) 75	540.23	11.43	16.57 ± 3.51	Pull-Out
G#2-10D-E2	27.7		875.11	18.52		Rupture
G#2-10D-E3	31.0		979.37	20.73		Rupture
G#2-10D-E4	25.3		799.29	16.92		Pull-Out
G#2-10D-E5	22.8		720.31	15.25		Pull-Out
G#2-15D-E1	26.9	($15\ d_b$) 95	849.84	14.20	13.79 ± 1.14	Rupture
G#2-15D-E2	28.5		900.39	15.05		Rupture
G#2-15D-E3	22.8		720.31	12.04		Rupture
G#2-15D-E4	25.3		799.29	13.36		Rupture
G#2-15D-E5	26.9		849.84	14.20		Pull-Out

Table 9: Test Results of GFRP bars # 2 (6.35 mm) (Cement Based Resin HIT HY 150)

Designation	Load (kN)	L (mm)	Stress (MPa)	Maximum Bond Stress (MPa)	Average of Maximum Bond Stress (MPa)	Mode of Failure
G#2-5D-C1	9.79	($5\ d_b$) 30	309.29	16.37	20.71 ± 5.64	Pull-Out
G#2-5D-C2	13.0		410.70	21.73		Concrete
G#2-5D-C3	8.16		257.80	13.64		Pull-Out
G#2-5D-C4	16.3		514.96	27.25		Concrete
G#2-5D-C5	14.7		464.41	24.57		Concrete
G#2-10D-C1	24.5	($10\ d_b$) 75	774.02	16.38	16.25 ± 3.13	Rupture
G#2-10D-C2	26.0		821.41	17.39		Rupture
G#2-10D-C3	31.0		979.37	20.73		Rupture
G#2-10D-C4	18.8		593.94	12.57		Pull-Out
G#2-10D-C5	21.2		669.76	14.18		Pull-Out
G#2-15D-C1	22.0	($15\ d_b$) 95	695.04	11.61	14.20 ± 1.86	Rupture
G#2-15D-C2	27.7		875.11	14.62		Rupture
G#2-15D-C3	26.9		849.84	14.20		Rupture
G#2-15D-C4	31.8		1004.64	16.79		Rupture
G#2-15D-C5	26.1		824.57	13.78		Rupture

5. Summary and Conclusion

An experimental study on the behavior of GFRP post-installed adhesive anchors was conducted using sand-coated GFRP V-ROD bars driven into plain concrete slabs using epoxy based adhesive with different embedment lengths (5, 10, and 15 times the bar diameter). The installed specimens were left out the laboratory for five months. During this period, the specimens were subjected to real environmental conditions as wet-dry cycles, freeze-thaw cycles and temperature variation. Based on the test results the following conclusions can be drawn:

1. Although the anchor installation was performed according to the recommendations of ASTM E-488-96, the corresponding ASTM spacing was not sufficient to prevent the overlapping of the concrete failure at smaller embedded depths.
2. There is no significant difference between the anchors with $10d_b$ and $15d_b$ embedment length in terms of capacity and mode of failure for most of the tested specimens.
3. The $10d_b$ embedment length for the sand-coated GFRP V-ROD bars seems to be enough to provide ample strength of the GFRP bars.
4. The used epoxy adhesive functioned properly in wet and partially submerged conditions provided that the holes are clean and free of loose sand or concrete particles.
5. The cement based adhesive provided a short setting time. So, it may be more appropriate in lower temperatures as the epoxy based adhesive showed longer setting time at low temperatures.
6. Due to the lateral weakness of the GFRP bars with 6.35 mm diameter, great attention should be focused on adjusting the bar alignment.
7. When the failure of the FRP adhesive anchors is expected to occur due to concrete failure, it is highly recommended to keep the bar spacing greater than the 1.5 times the effective height of the anchor (embedment length).

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