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"Anchorage Of Carbon Fiber Reinforced Polymers To Reinforced Concrete In Shear Applications"

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ABSTRACT

Post installed anchors come in either mechanical anchors that develop their strength purely through mechanical interlock with the base concrete, or bonded anchors that develop their strength by bonding anchor rod to the base concrete. Bonded anchors are either grouted, typically cementitious material, or adhesive, typically a chemical material. This thesis presents a current literature review of post-installed bonded anchors, preliminary testing of adhesive bonded anchors, and details of short term and long-term test setups for future testing. The purpose of this thesis was to develop the test setups that will be used for future testing on anchors.

INTRODUCTION

Concrete is a material used extensively in structural applications across the world, creating a need to anchor other materials. Anchorage to concrete can be accomplished through a piece of steel, such as a threaded rod, bolt, or proprietary anchor, partially embedded in the base concrete and used to connect additional members. Anchorage of this type can be categorized as either cast in place or post installed. Cast in place anchors are embedded in the concrete before it hardens. Advantages of cast in place anchors are their predictable and more reliable behaviour and failure modes, but require a high level of accuracy in their placement to ensure proper alignment as they cannot be moved after the concrete hardens. Post installed anchors typically use proprietary methods to attach to hardened concrete. This allows for freedom in placement to ensure proper alignment, but can be subject to much more variability in performance and capacity of the anchor. Post installed anchors can be categorized as either mechanical or bonded anchors as seen in Figure. Mechanical post installed anchors use friction and mechanical interlock to transfer their load from the anchor rod to the concrete. ACI 318-02 Appendix D was the first edition of anchor design standards in the ACI Building Code Requirements for Structural Concrete. It covered cast in place anchors and post installed mechanical anchors and gave design standards for both. Bonded anchorage systems generally comprise of a steel anchor rod, either threaded or dowel (rebar), and a bonding material.

Anchor Systems

Post installed anchors allow contractors the freedom to put anchors in the proper position after the concrete base member is cast, but their behaviour is less predictable and more susceptible to changes in environmental conditions. Both adhesive and grouted anchors can creep, deform or displace over time due to sustained stress. Creep over a period of sustained load can cause failure in adhesive anchors at loads lower than their short-term static capacity.

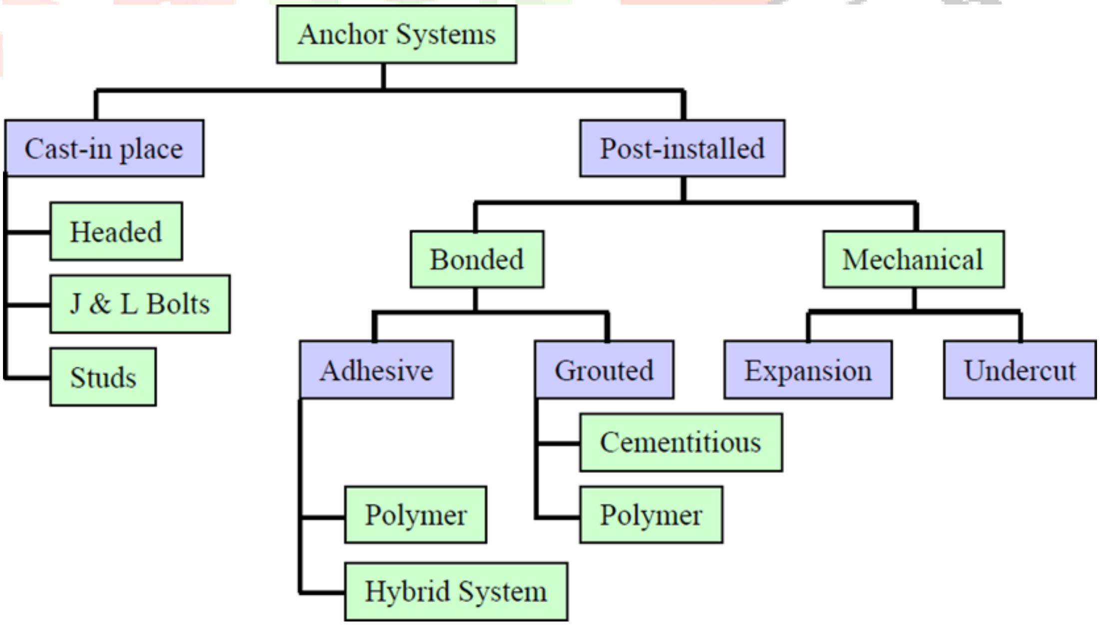


Figure Anchor Systems

Adhesive anchors are known to creep, but their specific capacity under sustained tensile loads is not Clearly understood. This test provides a guide criterion for designers showing maximum load of an Adhesive anchor system when subjected to sustained the varying environmental conditions such as Elevated temperature and humidity.

LITERATURE REVIEW

An adhesive anchor system has a hole less than 50% of the anchor rod diameter. The material used in these anchors is defined by A Class "Organic polymers used in adhesives can include, but are not limited to, epoxies, polyurethanes, polyesters, methyl methacrylate and vinyl esters; or inorganic polymers." Most of the organic polymer's adhesives are contain two parts that require mixing just prior to application. This is typically done with a caulking type gun that mixes the two components as they are installed into the hole. Inorganic adhesive anchors allow for the use of cementations products, typically reserved for grouted anchor applications with a hole diameter of greater than 1.5 times the anchor diameter. Adhesive anchor manufacturers provide a table listing allowable load and ultimate load for their anchor system based on anchor rod diameter, embedment depth, and concrete compressive capacity. Separately they provide a list of hole diameters to use with each acceptable anchor rod diameter.

Creep of adhesive anchors has been a known problem, but the long-term capacity of the anchors under different conditions has only been heavily researched within the past ten years following the 90-tunnel failure. Published research at the time of the accident showed the poor creep performance of adhesive anchors including a warning from James et al. "It should be emphasized that resins used in structural applications can exhibit significant Viscous elastic response to long-term loadings, especially at elevated temperatures." As with most engineering failures, additional guidelines were published in response to the failure.

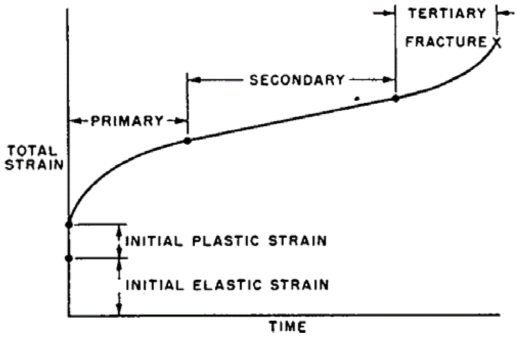


Figure Time and Total Strain Graph

Tertiary Creep (ASTM) Reprinted, with permission, from D2990-09 Standard Test Methods for Tensile, Compressive and Flexural Creep and Creep-Rupture of Plastics, copyright ASTM International. A copy of the complete standard may be obtained from ASTM International, www.astm.org.These loads generally cause failures within four months of application.

The literature review of Cook et al. provides a thorough understanding of adhesive anchor research as of its publishing in 2013. This report had two goals:

- Investigate the influence of various parameters (e.g., type of adhesive, installation conditions, and in-service conditions) on the sustained-load performance of adhesive anchors
- Develop recommended test methods, material specifications, design guidelines, design specifications, quality assurance guidelines, and construction specifications for AASHTO for the use of adhesive anchors in transportation structures.

The report includes a research program of 17 test series with each series investigating the sensitivity of an adhesive anchor's creep capacity to a specified parameter, 16 all started with five short term tests to establish a parameter mean static load (MSL). Each test series then ran a number of sustained load tests on the adhesive that showed the most sensitivity to a given parameter in the short-term test in accordance with AASHTO TP-84 (2010), to develop a stress vs time to failure plot of each parameter. Further information about AASHTO TP-84 (2010) and the stress vs time to failure plot can be found in Chapter 6. These tests were compared against the baseline tests, series 1 and 2, to develop an alpha reduction ratio (parameter MSL/baseline MSL). The alpha reduction ratios for the short term and the long-term tests were then compared with each other to determine if a given parameter had more of an impact on long-term performance than short term performance. The alpha short term was divided by the alpha long term to determine an influence ratio. If this influence ratio was greater than 1 then the parameter had a negative effect on creep. Adhesive only tests were conducted to determine validity in their use to predicted anchor pull-out strength. An adhesive only test was also conducted to determine an adhesive's sensitivity to loading before manufacturers recommended cure time. Alpha reductions were taken at a minimum of 1 because it is not recommended to increase design capacity above a baseline level. For example, the baseline mean static load (MSL) for adhesive B (an epoxy system) was 22.9 kips. The MSL for elevated service temperature (>120°F) was 23.1 kips. This correlates to an alpha reduction factor of 1.01, signifying that there is no statistical difference between the baseline MSL and the elevated temperature MSL. Cook et al. (2013) conclude that the elevated temperature does not affect the short-term capacity of adhesive B. Similarly, the alpha reduction factor calculated between baseline and elevated temperature long term tests was 0.83.

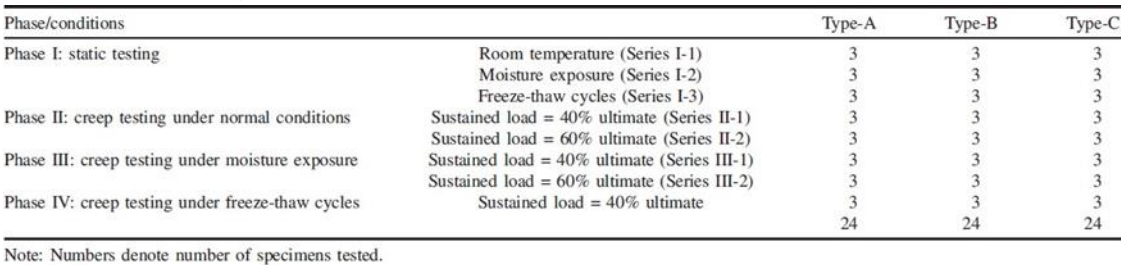
The second goal of Cook et al. (2013) was to recommend changes to AASHTO TP-84 (2010). Those recommendations are to include at least three sustained load levels (instead of two), and to not include the short-term test when constructing the stress versus time-to-failure graph.

Separately, the report made an observation on design values from ACI 355.4 (2011) which uses a reduction factor of 0.75 to relate unconfined tests to confined tests. Cook et al. (2013) found that their unconfined tests compared to confined tests resulted in a reduction factor between 0.37 And 0.53 (Cook et al. 2013).

El Menoufy et al. (2014) investigated the effects of standard temperatures, moisture, and freeze/thaw on adhesive anchors. This research tested three types of adhesives, a fast-setting acrylic based (Named Type A), fast setting epoxy based (Named Type B), and a standard setting epoxy based (Named Type C). The anchors used in this test were 15M deformed steel bars with 0.63 in diameter (16 mm) installed at 4.9 in (125mm). Static tests were conducted in accordance with ASTM E488 (2010). Detailed information on ASTM E488 (2010) can be found in Chapter 6. 72 total pull out tests were conducted (27 Static and 45 Sustained). Static failure was defined as yielding of the 15M bar. This yielding caused a decrease in cross section that caused the adhesive to expand and bond failure began to occur. Table shows the four testing phases and the three environmental parameters considered (normal conditions 73°F ± 7°F (23°C ±4°C), in-service moisture, and freeze/thaw). Test procedures were conducted in accordance with ICC-ES AC308 (2009) for in-service moisture and freeze/thaw. For freeze/thaw and moisture tests, the test specimens' top surfaces were covered with 0.47 in (12mm) deep 2.99 in (76mm) radius volume of water. For freeze/thaw, the sustained load was applied and 50 cycles were conducted by thawing for eight hours at +68°F ±3.6°F (+20°C ±2°C) and freezing for 16 hours at 4°F ±3.6°F (-20°C ±2°C). Most specimens in this research failed after the anchor bar began yielding and results were normalized against the known yield strength of the anchor bar.

Type A adhesives experienced a decrease in tensile capacity under sustained loading. When compared to the room temperature results of a sustained load at 40% of anchor yield, both moisture and freeze/thaw almost doubled the creep displacement at 90 days. Type B adhesives did not experience a significant difference in creep behavior when compared to normal condition tests due to freeze/thaw. Variable results were achieved under moisture conditions tests with Type B adhesives. Type C experienced little to no creep at room temperature with only slight increase in long term displacements due to moisture. The displacements from the long-term freeze/thaw tests on Type C adhesives were variable, but overall, greater than both room temperature and moisture creep test displacements. The project concluded that epoxy type adhesives exhibited higher ultimate capacities than the acrylic based and that moisture and freeze/thaw has some negative effect on creep capacity. (El Menoufy et al.2014)

Table Test Matrix With permission from ASCE. This material may be downloaded for personal use only. Any other use requires prior permission of the American Society of Civil Engineers.



Phase/conditions		Type-A	Type-B	Type-C
Phase I: static testing	Room temperature (Series I-1)	3	3	3
	Moisture exposure (Series I-2)	3	3	3
	Freeze-thaw cycles (Series I-3)	3	3	3
Phase II: creep testing under normal conditions	Sustained load = 40% ultimate (Series II-1)	3	3	3
	Sustained load = 60% ultimate (Series II-2)	3	3	3
Phase III: creep testing under moisture exposure	Sustained load = 40% ultimate (Series III-1)	3	3	3
	Sustained load = 60% ultimate (Series III-2)	3	3	3
Phase IV: creep testing under freeze-thaw cycles	Sustained load = 40% ultimate	3	3	3
		24	24	24

Note: Numbers denote number of specimens tested.

Table - Test Matrix With permission from ASCE

McDonald (1998) reported pull out capacities of three anchor systems: a polyester resin, an epoxy resin, and a cementitious grout under dry and submerged conditions with both short term and long term (creep) loads applied. This project was specifically concerned with submerged application of anchor systems for use below water level in dams. Submerged tests were conducted by ponding water for 2 weeks then installing the anchors into a completely Submerged hole. 144 anchor systems were tested in static pull out tests and 24 were tested in creep tests. Each anchor system was static tested 18 times dry and 18 times submerged except for adhesive D which was tested 18 times dry and adhesive E which was tested 18 times submerged. Three dry and three submerged creep tests were conducted for each anchor system except for D that was only tested three times dry and E that was only tested three times submerged. No. 6 A36 reinforcement steel bars were used for anchor rods. Five types of bonding materials were tested (A, B, C, D, and E) and the nomenclature is independent for this research. The research reported them all as adhesives even though one of them was a cementitious material. All hole sizes were less than 1.5 times the anchor rod diameter, which equates to adhesive anchors by the most current definitions available. Adhesive A, E-pcon manufactured by ITW, was a two-part ceramic filled epoxy adhesive. Adhesive B, Anchor-It manufactured by Adhesive Technology Incorporated, was "a light paste epoxy adhesive filled with superfine aggregates and hardener component" (McDonald 1998 p. 8). Adhesive C, HEA capsule/C100 manufactured by Hilti Corporation, was a combined application of two vinylester resins mixed together with a caulking type gun. Adhesive D was a two-component vinylester resin packed in a two-chambered plastic cartridge and was also the C100 portion from Adhesive

C. Adhesive D was only used for dry testing due to a strong recommendation from the manufacturer to avoid submerged applications with the product. Adhesive E, Lokset manufactured by Forsoc International Unlimited, was a cementitious compound in a plastic wrapping that, when submerged, allowed a controlled wetting to cure the grout. The hole size for this grouted anchor was 1in (25mm) and the anchor was No. 6 rebar with 0.75in (19mm) diameter. Details about adhesive E can be found in Chapter 4. Static tests were conducted after cure times of 1 day, 3 days, 7 days, 28 day, and 365 days for both dry and submerged conditions.

The experimental plan for this project is to develop test capabilities at UMass Amherst and conduct tests on bonded anchors. This thesis will provide initial test results and a validate test setup. Three trial test series were run for this MS research project to provide troubleshooting for the overall test program and initial data at room temperatures. The environmentally controlled chamber was not built for these tests, and they were run at unregulated ambient air temperature and humidity. Aside from these modifications, AASHTO TP-84 was followed for the testing. Initial experiments were designed to replicate results from tests in Cook et al.

(2009) and Cook et al. (2013) conducted at the University of Florida. Test apparatus for both short term and long-term tests were designed and fabricated for this project and final test setups are detailed in this chapter. The short term set ups conformed to ASTM E488 (2010), and, by definition, to AASHTO TP-84 (2009) and ACI 355.4 (2011). The long term set ups conformed to ASTM E1512 (2007), AASHTO TP-84 (2009), and ACI 355.4 (2011). The test set ups detailed in this chapter are the final designs to be used for future testing.

Test and Results

Short Term Tests

Short term test apparatus conforms with ASTM E488 (2010) standard and is replicated from Cook et al. (2013). The 5/8 in (16mm) anchor rod being tested passes through the confining sheet, the steel confining plate, and through an 11/16 in (17.5 mm) diameter hole at the bottom of the non-rigid coupler where it is secured with a ASTM A194 2H heavy hex nut. Two ASTM A500 grade B HSS8x3x1/4 x 8 in (203mm) long are placed on either side of the non-rigid coupler parallel to each other. The loading rod is secured to the top of the non-rigid coupler with a ASTM A194 2H heavy hex nut, passing between the HSS sections, through a 10 in x10 in x1 in thick (254 mm x 254 mm x 25 mm thick) steel plate with a 2-3/4in (70mm) diameter hole, through the centre hole hydraulic jack, and through the centre hole load cell and secured with an ASTM A194 2H heavy hex nut. A tensile load of 5% of the estimated anchor strength is initially applied in order to bring all members into full bearing. The load is then increased at a rate that causes failure after one minute, but before three minutes. A constant load rate is applied within the limits of the hydraulic pump. Data (load, line pressure and displacement readings) is collected at a sampling rate of one sample every 0.5 seconds, exceeding ASTM E488 (2010) section 7.7. Load and displacement are measured for all short-term tests.

Long-Term Tests

Long-term tests conform to AASHTO TP-84 (2010) and are replicated from Cook et al. (2013). Three long-term test setups are on loan from the University of Florida and were used to start this project. An additional 20 long term test set ups were ordered for the remainder of the project. Plans can be seen in Figure and Figure and the non-rigid coupler details in Figure. The anchor rod passes through the confining sheet and confining plate the same as the short-term tests. On top of the confining plate is a steel frame that contains a set of Standard Car Truck Company D2 inner and D2 outer springs used to maintain load. Initial testing was conducted on springs on loan from University of Florida. The two-railroad car suspension wire steel springs (large and small) seat within each other and are wound opposite to avoid torsion during loading. The small spring (D2 inner) fits inside the large spring (D2 Outer) when used in parallel, Figure. The large springs are approximately 5.5 in (140 mm) in diameter by 8.25 in (209 mm) in uncompressed length with a 1-7/32 in (40 mm) wire diameter, maximum load of 15.959 kips (70.99 kN) at 6-5/8in (168 mm) height, and 9.8 kips/in (17.2 kN/cm) stiffness. The small springs are approximately 3in (76mm) in diameter by 8.25 in (209 mm) in uncompressed length with an 11/16in (17.5mm) wire diameter, maximum load of 5.386 kips (23.96 kN) at 6-5/8 in (168 mm) height, and 3.3 kips/in (5.8 kN/cm) . When used in parallel the maximum load is 21.345 kips (94.95kN) and stiffness is 13.1 kips/in (22.9 kN/cm). The stiffness of each spring individually and both in parallel will be measured as part of future testing prior to using in a sustained load test. An example spring calibration is shown in Figure. This spring has a stiffness of 12.56 kips/in (22kN/cm); lower than the listed spring stiffness of 13.1 kips/in (22.9 kN/cm). The springs are housed in a two piece spring retainer unit, Figure. The top piece is a 1/2 in x 10 in x 10 in (12.7 mm x 254 mm x 254 mm) plate with 1.5 in (31.8 mm) center hole and four 1 in (25.4 mm) corner holes spaced 7 in (177.8 mm) center to center welded to a 2.5. The 5/8 in (16mm) anchor rod being tested passes through the confining sheet, the steel confining plate, and through an 11/16 in (17.5 mm) diameter hole at the bottom of the non-rigid coupler where it is secured with a ASTM A194 2H heavy hex nut. The loading rod is secured to the top of the non-rigid coupler with a ASTM A194 2H heavy hex nut, passes through the springs in a steel frame, through the center hole hydraulic jack, through the center hole load cell and secured with an ASTM A194 2H heavy hex nut on top. A tensile load of 5% of the creep load is initially applied in order to bring all members into full bearing. The load is then increased at a rate that reaches the creep load after one minute, but before three minutes. A constant load rate is applied within the limits of the hydraulic pump. Data (load, line pressure and displacement readings) is collected at a sampling rate of one sample every 0.5 seconds during loading, exceeding ASTM E488 (2010) section 7.7. Load is measured during compression of the spring and displacement is measured at rate that starts at 0.5 seconds per sample during loading, then every one minute for the next 24 hours, then every hour until failure. Variations for Test Series 0a, 0b, and 0c are described in Chapter 8. In order to pre-load the springs and bring them up to the calibrated tension for the long term applied load, a load system is placed above the top plate of the spring retainer unit. A jack chair, center hole hydraulic jack and load cell are stacked to allow for tensioning of the springs. The springs are compressed with the hydraulic jack to the desired force measured by the load cell (and cross referenced to hydraulic pressure and load cell calibration factor). An ASTM A194 2H heavy hex nut within the jack chair secures the springs at the compressed distance and the hydraulic jack and load cell are removed for pre-loading the other long-term specimens. Sustained load is maintained through the compression of the spring. The sustained load does not need to be monitored if the load lost at maximum anchor creep displacement is less than one percent of the sustained load according to AASHTO TP-84. For example, a maximum creep displacement of 0.1 in (2.54 mm) causes a loss of 1.1 5kips (5.11 kN) in a spring with stiffness of 11.5 kips/in (14 kN/m). This is a loss of 5% if the sustained load was 23 kips (28kN); requiring the spring to be recompressed every .02 in(.25 mm) during the test. The compression of the spring would be measured by the displacement of the anchor system (displacement of the anchor-strain of the anchor rod = change in spring compression)

Bonding Materials

Final tests will be conducted on three adhesives. All three adhesives meet ICC-ES 308 standards.

Adhesive A– Adhesive A is the same adhesive used in test series 0b. This adhesive is a combination of Bisphenol A and Bisphenol F epoxy resins with fillers and m-xylene diamine and aliphatic polyamine hardeners.

Adhesive B– Adhesive B is a Bisphenol A/Epichlorohydrin (Epoxy Resin) with a Di-methaneamine hardener.

Adhesive C– Bisphenol A and Bisphenol F epoxy resins with amine hardeners. The listed uncracked bond stress is 2,148 psi (14.7MPa) and should have a static capacity of 13 kips (58 kN) for this research.

Table Bonding Materials Used per Test Series

Experiment	Description	Conditions	Anchor Cure Time	Load	% Static Load	Failure
0b-1	Static Test	Indoor	7 days	25.5 kips		Steel
0b-2	Static Test	Indoor	7 days	28.5 kips		Steel
0b-3	Static Test	Indoor				
0b-4	Static Test	Indoor				
0b-5	Creep Test	Indoor			90%	
0b-6	Creep Test	Indoor			90%	
0b-7	Creep Test	Indoor			80%	
0b-8	Creep Test	Indoor			80%	
0b-9	Creep Test	Indoor			70%	
0b-10	Creep Test	Indoor			70%	

Test Series0c

Test series 0c was a grouted anchor with a cementitious bonding material. This test series was installed into preliminary concrete specimens chosen that were rectangular prisms 16 in x 16 in x 12 in deep (406 mm x 406 mm x 305 mm deep) created with fabricated wood removable forms, Figure . This specimen size was used in Cook, et al. (2013) and cook, et al. (2009) and was chosen as the starting point for this research. These specimens weighed approximately 270lbs (1.2 kN). For transport, 1/2 in (12.7 mm) inner diameter PVC pipe was cast 4 in (102 mm) from the bottom of the specimens. This allowed for handling using #3 reinforcing bars. Three of these blocks were cast for initial testing and used in test series 0c using Sakrete High Strength Concrete Mix, a ready-mix product, and each 80 lb bag (0.355 kN) was mixed with 3.5 quarts

(3.3 L) of water. Two 4 in (101 mm) diameter cylinders were tested and the average 28-day compressive strength was 4,561 psi (31.44 MPa). Five anchors were installed into one of the blocks for use in determining static capacity. The other two blocks had only one anchor each for creep tests. The 5/8 in (15.9 mm) diameter B7 threaded anchor rod was used for this test series. The embedment depth was 6 in (152.4 mm) by suggestion of the manufacturer because previous testing with this product has yielded high variation at embedment depths less than 6 in (152.4 mm). The hole diameter for this test series was 1 in (25.4 mm) because 1 in (25.4 mm) samples were donated and require installation in a hole with at least 1 in (25.4 mm) diameter hole. Hole drilling methods described in test series 0b were followed. Hole cleaning for this product required initially removing most of the dust with compressed air. After the dust was removed, the holes were filled with water and allowed to sit for 10 minutes, Figure (far left). After 10 minutes, the water was removed with compressed air, Figure (middle left). The compressed air was sprayed along the sides of the hole for the entire depth to remove as much excess water as possible. The cementitious bonding material is contained in a permeable capsule (cartridge) sock. The sock was soaked in water for 1.5 minutes, and then placed into the hole with excess material to the side. The anchor rod was pushed through the sock, Figure (middle right), to the bottom of the hole and excess cementitious bonding material was wiped away, Figure far right photo.

Figure Concrete Specimens for Test Series 0c

Figure Test Series 0c Installation Photos.

The anchors were allowed to cure for a minimum of 28 days before testing. The results from the five static tests were averaged and creep tests were conducted at 90% of the static capacity.

Test Series Results

Three preliminary test series were run as part of this thesis. The purpose of these test series was to validate equipment and procedures for future testing. Test Series 0a resulted in a final design for the non-rigid coupler and the height of the short term and long-term tests to account for the non-rigid coupler. Test series 0b resulted in improved installation techniques and higher capacity threaded rod. Test series 0c resulted in experience with cementitious anchor. Chapter 9 has recommended future work based on results from these three-test series.

Test Series Results Test Series0a

Experiment 0a-1 was the first experiment run in the series and for this project. This experiment resulted in a bond failure at the concrete/adhesive bond line with a shallow concrete cone. These results were exactly what was expected and were promising for future testing. The load for this test was not measured directly, but an analog pressure gauge was monitored during loading. The pressure reached approximately 2,000psi (13.8MPa) before failure. This equates to 8 kips (35.6 kN) of force. This test series showed that the FRP epoxy was capable of developing high enough bond stresses for testing and that the short-term test apparatus could apply loads properly. Figure shows the bond failure. This failure only occurred because the adhesive was tested prior to fully curing. Test 0a-2 was a static test on fully cured adhesive and resulted in steel failure of the anchor rod.

Figure Experiment 01 failure photos

Conclusions

Many lessons were learned from Test Series 0a. The data from this test series is not valid for comparing performance of adhesive anchor systems, but it is valid to show the functionality of the designed test apparatus. It also led to changes in testing procedures for Test Series 0b and 0c. Test 0a-1 shows that the short-term test set up is capable of applying a failure load to an anchor. Tests 0a-2 and 0a-3 led to a new design for the non-rigid coupler. Test 0a-4 shows that a sustained load can be applied to an anchor and that the load and displacement can be measured. Test 0a-4 also shows the need to take care when aligning a long-term test set up to avoid non-vertical displacements of the spring. Overall, Test series 0a shows that sustained load experiments produce expected results. Lessons from this test series were applied to Test Series 0b and0c.

Test Series 0b lead to a re-design of the non-rigid coupler with a hole 1/16 in (1.59 mm) larger than nominal anchor diameter used in testing. The failure of the B7 threaded rod lead to future research using the higher capacity ASTM A354 GR BD threaded rod. This test series also showed a potential need to measure displacement of the anchor from a different point than the non-rigid coupler. Future researches will investigate methods of measuring displacement from the top of the anchor rod instead of at the non-rigid coupler.

Test set ups discussed in Chapter 7 are a result of a thorough literature review and preliminary experiments and represent the main conclusion of this MS research project.

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