RECLAMATION
Managing Water in the West

Bond Quality of Fiber Reinforced Polymer Concrete Strengthening Systems

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Bond Quality of Fiber Reinforced Polymer Concrete Strengthening Systems

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Mission Statements

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian Tribes and our commitments to island communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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1.0 Executive Summary

Fiber reinforced polymer (FRP) sheets were attached to the top face of concrete slabs. The top surfaces of the slabs were prepared using four different surface preparation methods. The methods were: surface grinding, sand blasting, bush hammering, and power washing. Bond strength of the FRP bonded to the concrete surface was measured using two different pull off adhesion testers; the Elcometer 106 device and the PosiTest® Pull-Off Adhesion Tester. In addition several slabs were tested to failure in flexure.

Overall, measured bond strength was higher than the minimums specified by ACI-4402R-10 [1]. However, there is a significant difference in the results from the two pull off adhesion testers. Based on bond strength testing, sand blasting of the concrete surface appears to be the best surface preparation method.

Flexure testing of the concrete slabs, with FRP bonded to one face, results in larger maximum loads; as compared to a plain concrete slab.

2.0 Introduction

A major advancement in the field of concrete technology and repair is the use of fiber reinforced polymers (FRP) to strengthen and protect concrete structures. Very basically, synthetic fiber sheets (generally carbon, glass, or aramid) are impregnated with a polymer and attached (glued) to concrete elements. The technology is rapidly gaining use in strengthening columns, pipelines, walls, beams and floors. Additional strength may be required due to new earthquake loading information, blast proofing of structures, or improving the strength of existing deteriorated concrete structures.

The Bureau of Reclamation (BOR) has been building a variety of concrete structures for over 100 years. Many of these aging structures are in need of rehabilitation or strengthening for a variety of reasons. In many cases the age of the structure drives the need for rehabilitation; however strengthening may be needed due to new seismic loadings, changes in hydraulic loadings or security concerns such as blast resistance capability.

Currently, when we need to strengthen a structure, we add concrete, and/or add steel, or completely rebuild a structure or portions of it. These options are costly due to high construction costs, have losses associated with disruptions of the facility and there is an increase in public disturbance.

BOR is interested in developing and using modern technologies in order to extend the useful life and/or strengthen concrete structures. An attractive alternative to our current practices for strengthening concrete structures may be FRP. Since this is a newer technology, there are a number of issues surrounding its use. The four most common issues surrounding FRP and concrete substrate are bond strength, surface roughness, fiber alignment, and voids/delaminations between the FRP and existing concrete.

This document will focus on the bond strength between the FRP and concrete substrate. In addition, slabs with different FRP systems were tested in flexure. The flexure test will provide a basic understanding of how the FRP systems affect the strength of the concrete, based on different surface preparations.

Some of the recognized benefits of using FRP are:

- High tensile strength
- Low weight
- Corrosion resistance
- Excellent fatigue behavior
- Non-conductive
- Speed of construction
- Minimum or no use of heavy equipment and lifting equipment
- Ability to apply to many non-flat shapes
- Minimum change to dimensions and weight of strengthened elements
- Maintains aesthetics of the structure
- Low cost of construction

Some of the negatives associated with using FRP systems are:

- High material cost
- Creep and shrinkage concerns
- Potential for environmental degradation
- Consistency of material properties
- Global and local buckling
- Requires highly trained specialists
- Lack of standards and design guides
- Limited joining and connection technology

3.0 Background

3.1 FRP Materials

From ACI-440.2R-10, section 3.1:

> Primer – The primer is used to penetrate the surface of the concrete, providing an improved adhesive bond for the saturating resin or adhesive.

Putty Fillers - The putty is used to fill small surface voids in the substrate, such as bug holes, and to provide a smooth surface to which the FRP system can bond. Filled surface voids also prevent bubbles from forming during curing of the saturation resin.

Saturating Resin – The saturating resin is used to impregnate the reinforcing fibers, fix them in place, and provide a shear load path to effectively transfer load between fibers. The saturating resin also serves as the adhesive for the wet lay-up systems, providing a shear load path between the previously primed concrete substrate and the FRP system.

Adhesives – Adhesives are used to bond pre-cured FRP laminate systems to the concrete substrate. The adhesive provides a shear load path between the concrete substrate and the FRP reinforcing laminate. Adhesives are also used to bond together multiple layers of pre-cured FRP laminates.

Protective Coatings – The protective coating is used to protect the bonded FRP reinforcement from potentially damaging environmental effects. Coatings are typically applied to the exterior surface of the cured FRP system after the adhesive or saturating resin has cured

Fibers – Continuous glass, aramid and carbon fibers are common reinforcements used with FRP Systems. Steel fiber mats can be used as well. The fibers give the FRP system its strength and stiffness.

3.2 Tensile Properties

From ACI-440.2R-10, Table A1.1:

Table 3.2.1 – Tensile Properties of Common Fibers used in FRP systems

Fiber Type	Elastic Modulus, 10^3ksi	Ultimate Strength, 10^3ksi
Carbon		
General Purpose	32 to 34	300 to 500
High Strength	32 to 34	550 to 700
Ultra- High Strength	32 to 34	700 to 900
High Modulus	50 to 75	250 to 450
Ultra-High Modulus	75 to 100	200 to 350
Glass		
E-Glass	10 to 10.5	270 to 390
S-Glass	12.5 to 13	500 to 700
Aramid		
General Purpose	10 to 12	500 to 600
High Performance	16 to 18	500 to 600

3.3 Commercially Available Externally Bonded FRP Systems

From ACI-4402R-10, section 2.2:

> Wet lay-up FRP systems consist of dry unidirectional or multidirectional fiber sheets or fabrics that are impregnated on-site with a saturating resin. The saturating resin is used to provide a binding matrix for the fiber and bond the sheets to the concrete surface. Wet lay-up systems are saturated with resin and cured in place and in this sense are analogous to cast-in-place concrete.
>
> Prepregs are a ready-made material made of a reinforcement form and polymer matrix. Passing reinforcing fibers or forms such as fabrics through a resin bath is used to make a prepreg. The resin is saturated (impregnated) into the fiber and then heated to advance the curing reaction to different curing stages. Thermoset or thermoplastic prepregs are available and can be either stored in a refrigerator or at room temperature depending on the constituent materials. Prepregs can be manually or mechanically applied at various directions based on the design requirements.
>
> Pre-cured FRP systems consist of a wide variety of composite shapes manufactured in the system supplier's facility and shipped to the job site. Typically, an adhesive is used to bond the pre-cured flat sheets, rods or shapes to the concrete surface or inserted into slots cut into the wall. The adhesive used to bond the pre-cured system to the concrete surface must be specified by the system manufacturer. Adhesive selection is critical in that the adhesive provides for the proper transfer of load between the surface of the concrete and the cured reinforcement.

3.4 Physical Properties of FRP Systems

From ACI-4402R-10, section 3.2:

> FRP material has a density that is significantly less than that of steel, 75 to 130 lb/ft^3 and 490 lb/ft^3 respectively. This lower density represents lower transportation costs, lower added dead weight to the structure, and overall ease of handling of the material.

3.5 Mechanical Properties and Behavior of FRP Systems

From ACI-4402R-10, section 3.3:

> FRP loaded in direct tension does not exhibit any plastic behavior before rupture. The FRP in tension behaves in a linearly elastic stress-strain relationship until failure, which occurs without adequate warning.
>
> The fibers are the main load-carrying component in the FRP. Tensile strength and stiffness of the FRP system is based primarily on several elements which include type of fiber, orientation of the fibers, and quantity of the fibers.
>
> In bond-critical applications, high temperatures reduce the overall mechanical properties of the polymer and the polymer reduces its ability to transfer the stresses from the concrete to the fiber.
>
> Compressive strengths of bond-critical applications should not be considered due to limited data and research.

The existing concrete should provide the necessary strength to develop the design stresses of the FRP through bond. The tensile strength should be at least 200 lb/in^2 (1.4Mpa). FRP systems should not be used when the concrete substrate has a compressive strength less than 2500 lb/in^2 (17Mpa).

4.0 Test Program

4.1 Test Sample Preparation

Twenty four 2-ft wide by 4-ft long by 6-inch thick concrete test slabs were made. Cylindrical samples were made for compressive and tensile strength testing. Results are shown in Table 5.1.1. The concrete slabs were cured for 28 days and removed from the forms.

Four types of standard surface preparation methods were used to prepare the surface of the slabs. These surface preparation methods were: power washing, bush hammering, sand blasting and grinding. See Figures 1 through 13 for equipment used and finished surface preparation. The bush hammered surfaces were very rough, so epoxy putty was used to smooth the surface before applying the fabric.

Two systems were used for the bond strength test, SikaWrap Hex 103C and Tyfo SCH-41. Three systems were used for the flexural strength test, Wabo® Mbrace CF 530 (labeled as Degussa in the photos), SikaWrap ®Hex 103C and Tyfo® SCH-41. There was insufficient Wabo® Mbrace CF 530 to be used for the bond strength testing. All the fabric fibers were carbon fibers.

After the concrete slab surfaces were prepared, they were inspected to ensure the surface was free of bond inhibiting materials.

For all the systems, prior to placing the fiber sheets, the concrete surface was primed with a base coat of epoxy or epoxy putty. The fiber sheet was then impregnated with the epoxy prior to placement on the concrete slab. For larger projects, the impregnation process is typically accomplished using a mechanically driven fabric saturator. In cases where the application is small, such as this project, hand impregnation is done using a roller prior to fabric placement.

The impregnated fiber sheet was then placed on the concrete test slabs. The material used was uni-directional, therefore placement in a specific orientation must be ensured to maximize tensile strength. The composite slab plus fiber sheet was allowed to cure for several weeks prior to testing. Figures 14 through 28 show the application of the epoxy and fiber fabric to the concrete slabs.

4.2 Bond Strength Test

Two types of test equipment were used to determine the bond strength of the carbon fiber fabric; the PosiTest® Pull-Off Adhesion Tester manufactured by the

DeFelsko® Corporation and the Elcometer® 106 Pull off Adhesion Tester manufactured by Elcometer Instruments Inc. Each piece of test equipment is described in Appendix 3.

Each type of equipment measures the force required to pull a specified test diameter of fabric off the substrate, using either mechanical or hydraulic means. This force is in the normal direction to the test sample.

The basic steps for testing bond strength are:

- A one-time use dolly is cleaned and abraded,
- Adhesive is prepared (Araldite®) and applied to the dolly,
- The dolly is then adhered to the fiber fabric and allowed to cure,
- The fiber fabric under the test dolly is separated from the surrounding fabric by cutting or drilling.
- Force is exerted on the dolly until bond failure, or the equipment limit is reached.
- The final force is recorded at bond failure. A valid test result occurs when the fabric is completely removed from the concrete substrate and remains adhered to the adhesive on the dolly.

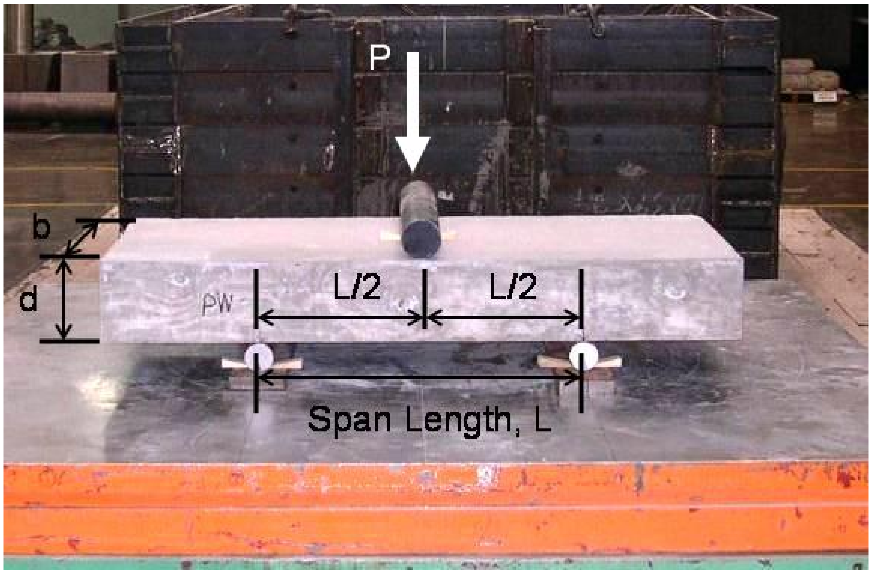
Figures 29 through 37 show the placement of the dolly and general configuration of the testing equipment.

4.3 Flexural Strength of Concrete Test

Testing of the concrete slabs in flexure was based on ASTM C 293-02, "Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Center Point Loading) [2]. The complete test procedure is provided in Appendix 4.

To summarize ASTM C 293-02, a concrete slab is placed on the loading apparatus such that the load P is at the center of the slab. The span length, L is within 2% of three times the depth of the slab. For this report the span length was approximately equal to 2.0 feet. The load P was applied in a continuous constant rate without shocking the slab until failure. A typical testing setup is shown in Figure 4.3.1 below.

Figure 4.3.1: Typical Flexural Strength Test Setup



5.0 Results

5.1 Concrete Material Properties

Six, 6-inch diameter by 12-inch long concrete cylinders were cast from concrete used in the placement of the 24 test slabs. The specimens were cured for 28 days in 100% humidity at 72 degrees Fahrenheit. Specific gravity of the concrete was determined "as is". Compressive strength testing was performed according to ASTM C 39/C 39M - 04 "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens" [3]. The ends of the compressive strength specimens were capped with a sulfur compound to achieve end tolerances according to ASTM C 617 - 98, "Standard Practice for Capping Cylindrical Concrete Specimens" [4]. Splitting tensile strength was performed according to ASTM C 496-04, “Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens” [5].

Test results are shown in Table 5.1.1 below.

The average compressive strength was 4070 lb/in^2 at 28 days.

The average tensile strength was 425 lb/in^2 at 28 days.

Table 5.1.1: Concrete Test Cylinder Break Record

Specimen ID	Compressive Strength, lb/in^2	Tensile Strength, lb/in^2	Specific Gravity
1	4240		2.30
2	3920		2.20
3	4060		2.28
4		430	2.28
5		405	2.29
6		440	2.28

5.2 Bond Pull Off Strength Test Results - Fyfe SCH 41 – TYFO S

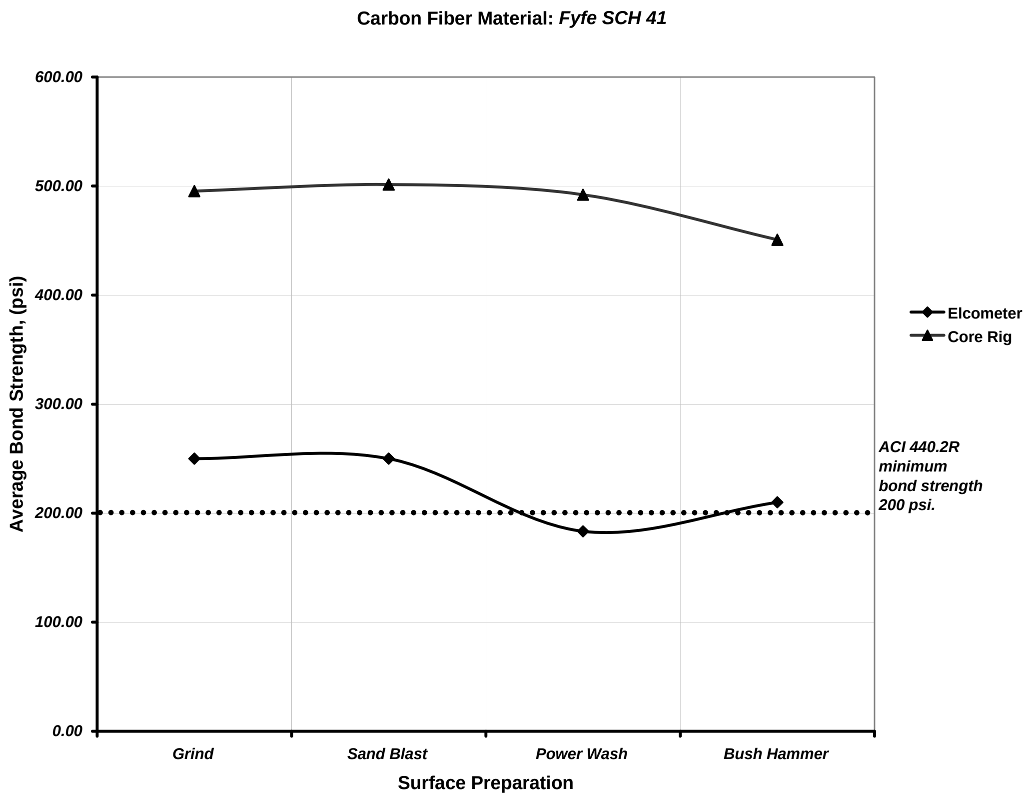
See Figures 38 to 48 & 60 to 70, in Appendix 1. Failure mode refers to where the failure occurred. They were divided into three categories. Failures that occurred at the dolly to fiber interface were labeled as Dolly to Fiber (DF). Failures between the fibers and the concrete were labeled as Fiber to Concrete (FC). Failures that occurred in the concrete were labeled as concrete substrate (C). There were a few cases where the instrumentation reached its capacity before failure occurred. Those results were included in the concrete substrate failure category, since that is likely where the failure would have occurred if the equipment limits had not been reached.

Table 5.2.1: Bond Strength Results

Material: Fyfe TYFO SCH 41 "TYFO S"								
		Failure Mode				Failure Mode		
Surface Preparation	**Elcometer (lb/in^2)**	**C**	**DF**	**FC**	**PosiTest (lb/in^2)**	**C**	**DF**	**FC**
Grinder	200		X		450		X	
	250	X			502		X	
	300	X			534		X	
Grinder (avg)	**250**	**2**	**1**		**495**		**3**	
Sand Blast	300			X	384		X	
	200		X		560*	X		
	250		X		560*	X		
SB (avg)	**250**		**2**	**1**	**501**	**2**	**1**	
Power Wash	250	X			560*,**	X		
	150			X	538		X	
	150		X		378		X	
PW (avg)	**183**	**1**	**1**	**1**	**492**	**1**	**2**	
Bush Hammer	200	X			440		X	
	300		X		416		X	
					496		X	
BH (avg)	**250**	**1**	**1**		**451**		**3**	

Notes:
C = Concrete Substrate DF = Dolly to Fiber FC = Fiber to Concrete
*No failure – equipment limit reached
** No figure

Figure 5.2.2: Average Bond Strength vs. Surface Preparation



Bond strength test results for the Elcometer were generally significantly lower than for the PosiTest unit. The reason for this is unknown. It could be that the area tested is small so that test results are more sensitive to weak zones. However, it is more likely that the process of cutting the fabric around the dolly prior to the test damages the fibers and/or concrete just below the fibers. Since the Elcometer dollies are relatively small, test results may be significantly affected by this cutting.

For the Elcometer tests, there were 4 failures in the concrete, 5 at the folly to fabric interface, and 2 at the fabric to concrete interface. For the PosiTest tests, there were 3 failures in the concrete and 9 failures at the dolly to fabric interface.

5.3 Bond Pull Off Strength Test Results SikaWrap Hex 103C

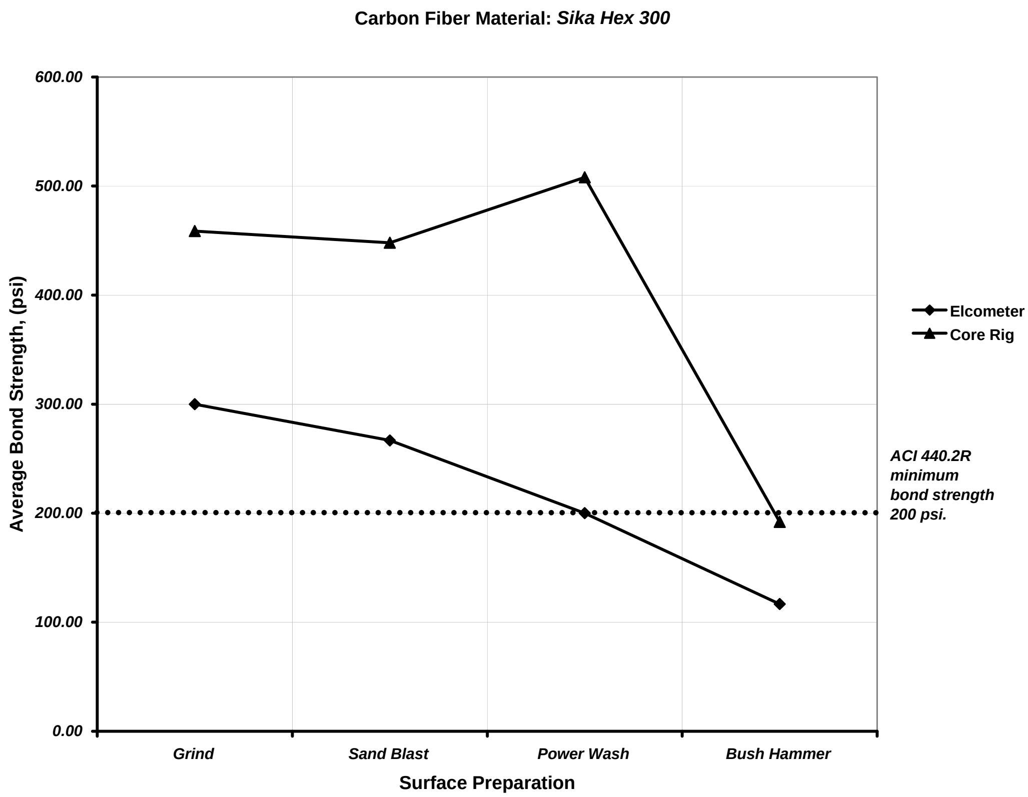
See Figures 49 to 59 & 71 to 81, in Appendix 1. Please note – the card labels in the figures refer to the epoxy used to secure the carbon fiber fabric, and not the carbon fiber itself (SikaWrap Hex 103C)

Table 5.3.1: Bond Strength Results

Material: SikaWrap Hex 103C								
		Failure Mode				Failure Mode		
Surface Preparation	**Elcometer (lb/in^2)**	**C**	**DF**	**FC**	**PosiTest (lb/in^2)**	**C**	**DF**	**FC**
Grinder					256			**X**
	300	**X**			560*	**X**		
	300	**X**			560*	**X**		
Grinder (avg)	**300**	**2**			**459**	**2**	**1**	**1**
Sand Blast	200	**X**			504			**X**
	300	**X**			440	**X**		
	300		**X**		400	**X**		
SB (avg)	**267**	**2**	**1**		**448**	**2**		**1**
Power Wash	200	**X**			544			**X**
	200			**X**	472	**X**		
	200		**X**					
PW (avg)	**200**	**1**	**1**	**1**	**508**	**1**		**1**
Bush Hammer	100	**X**			272	**X**		
	150	**X**			192	**X**		
	100	**X**			112	**X**		
BH (avg)	**117**	**3**			**192**	**3**		

Notes:
C = Concrete Substrate PF = Dolly to Fiber FC = Fiber to Concrete
*No failure – equipment limit reached

Figure 5.3.2: Average Bond Strength vs. Surface Preparation



As above, bond strength test results for the Elcometer were generally significantly lower than for the PosiTest unit.

For the Elcometer tests, there were 8 failures in the concrete, 2 at the dolly to fabric interface, and 1 at the fabric to concrete interface. For the PosiTest tests, there were 8 failures in the concrete, 1failure at the dolly to fabric interface, and 3 at the fabric to concrete interface.

5.4 Flexural Strength of Concrete Test

See Figures 82 through 104, in Appendix 1.

Table 5.4.1: Flexural Strength of Concrete Results

Material	Surface Prep	Max load, (lbs)
Plain Slab	*None*	11,790
Degussa	*Power Wash*	39,748
Degussa	*Sand Blast*	77,681
Degussa	*Bush Hammer*	44,800
SikaWrap Hex 103C	*Power Wash*	43,054
Sikawrap Hex 103C	*Sand Blast*	64,000
SikaWrap Hex 103C	*Bush Hammer*	57,577
SikaWrap Hex 103C	*Grinder Finish*	50,566
TYFO "S"	*Power Wash*	45,856
TYFO "S"	*Sand Blast*	59,626
TYFO "S"	*Bush Hammer*	55,042
TYFO "S"	*Grinder Finish*	52,070

6.0 Conclusions

6.1 Bond Pull off Strength

1. There is a significant difference between test results from the Elcometer 106 (small dolly) and PosiTest Pull of Adhesion Tester (large dolly) for a given surface preparation method and FRP system. The test results from the Elcometer were significantly lower than test results from the PosiTest unit.
2. Average test values from the Elcometer and PosiTest unit for the bush hammer surface preparation fall below the minimum recommended bond strength in ACI-4402R-10 for the Sika material.
3. Not all of the bond tests resulted in failure in the concrete substrate.
4. Sand blasting, grinding, and power wash seem to provide the best surface for applying FRP's, in that order.
5. Bush hammering should not be used for surface preparation in most situations.
6. The PosiTest method tested a larger area and produced results with slightly more consistency
7. The Elcometer tested a smaller area and produced results with somewhat lower consistency.

8. Overall, for the Elcometer tests, there were 12 failures in the concrete, 7 at the dolly to fabric interface, and 3 at the fabric to concrete interface.
9. Overall, for the PosiTest tests, there were 11 failures in the concrete, 10 failure at the dolly to fabric interface, and 3 at the fabric to concrete interface.

6.2 Flexural Strength of Concrete

1. All of the FRP systems provided an increase in the maximum load capability of the concrete slabs as compared to the plain concrete slab.
2. The sand blast method of surface preparation provided the highest overall results.
3. The power wash surface preparation method provided the lowest increase in maximum load capability as compared to the plain concrete slab.
4. The FRP system did not significantly delaminate from the concrete. Localized delamination at the points of maximum cracking was observed and can be seen in the photos.
5. The likely failure mode is shear failure of the concrete. This is based on observation only.

7.0 Recommendations for Future Research

1. This study showed significant differences between the 2 established methods to test bond strength. Increasing the number of materials and tests would likely result in more definitive test results.
2. The reason for the large difference in results between the two types of bond testing equipment should be investigated. From that, determine the best equipment and procedures for evaluating bond strength of FRP systems.
3. The role of existing concrete surface conditions (temperature, relative humidity, and surface moisture of the concrete at the time of installation) should be evaluated as they relate to bond strength.
4. This repair material seems to have several possible uses for Reclamation, particularly in the areas of strengthening existing structures, adding shear capacity, and repairing high-head water transmission pipelines. To this end, a strategic plan should be developed to identify areas and potential partners to study potential uses, design methodologies, and needed research to better define the best ways to use this technology at Reclamation.

References

[1] ACI 440.2R-02, *"Guide for Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures"*, American Concrete Institute, 2002.

[2] ASTM C 293-02 "Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Center Point Loading)", American Society of Testing and Materials

[3] ASTM C 39/C 39M - 04 "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens", American Society of Testing and Materials

[4] ASTM C 617 - 98, "Standard Practice for Capping Cylindrical Concrete Specimens", American Society of Testing and Materials

[5] ASTM C 496-04, "Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens", American Society of Testing and Materials

Appendix 1
Photographs

Figure 1: View of test slabs ready for surface preparation.

Figure 2: Air-powered jack hammer with bush hammer tool attached.

Figure 3: Water blast surface preparation unit.

Figure 4: Sand blast surface preparation unit.

Figure 5: Air-Compressor used to power the jack hammer and the sandblast unit.

Figure 6: Sandblasted surface.

Figure 7: Grinder surface.

Figure 8: Bush hammered surface; note rough texture and exposed aggregate.

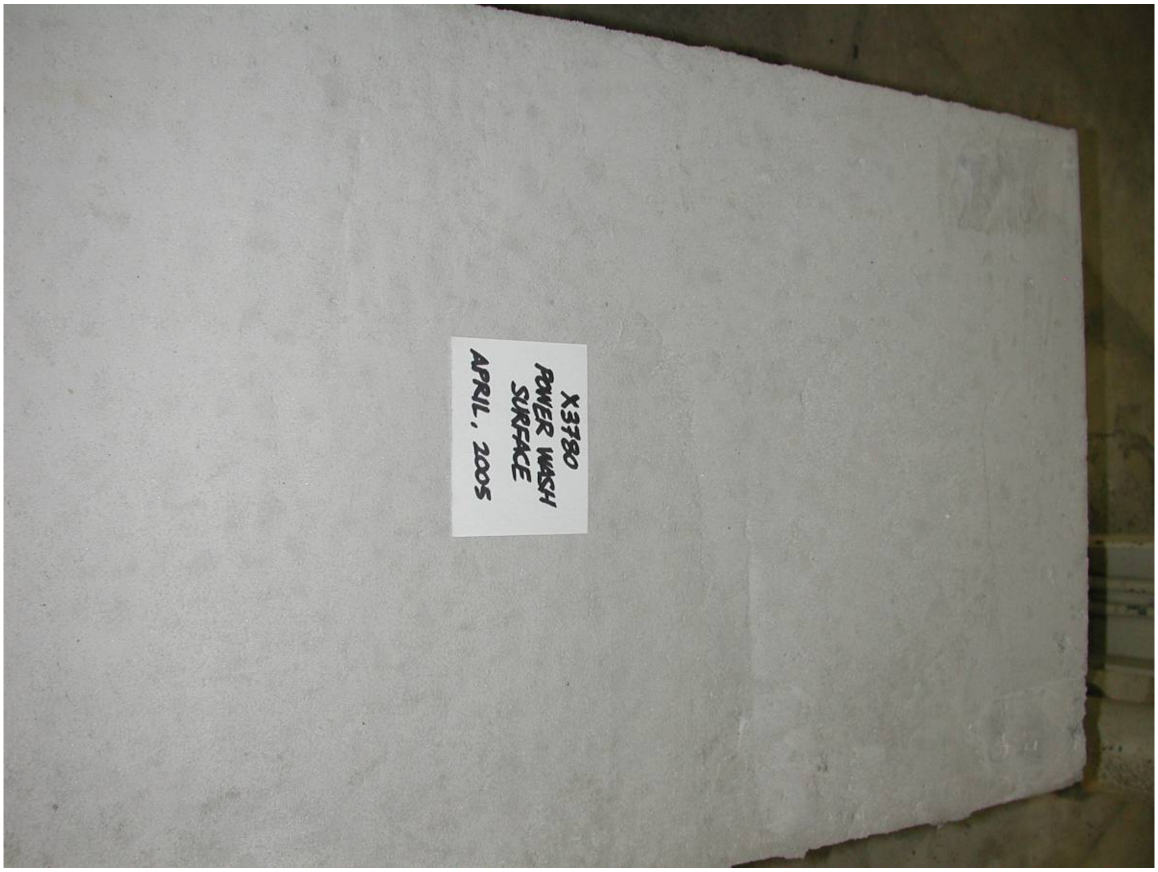


Figure 9: Power washed surface.

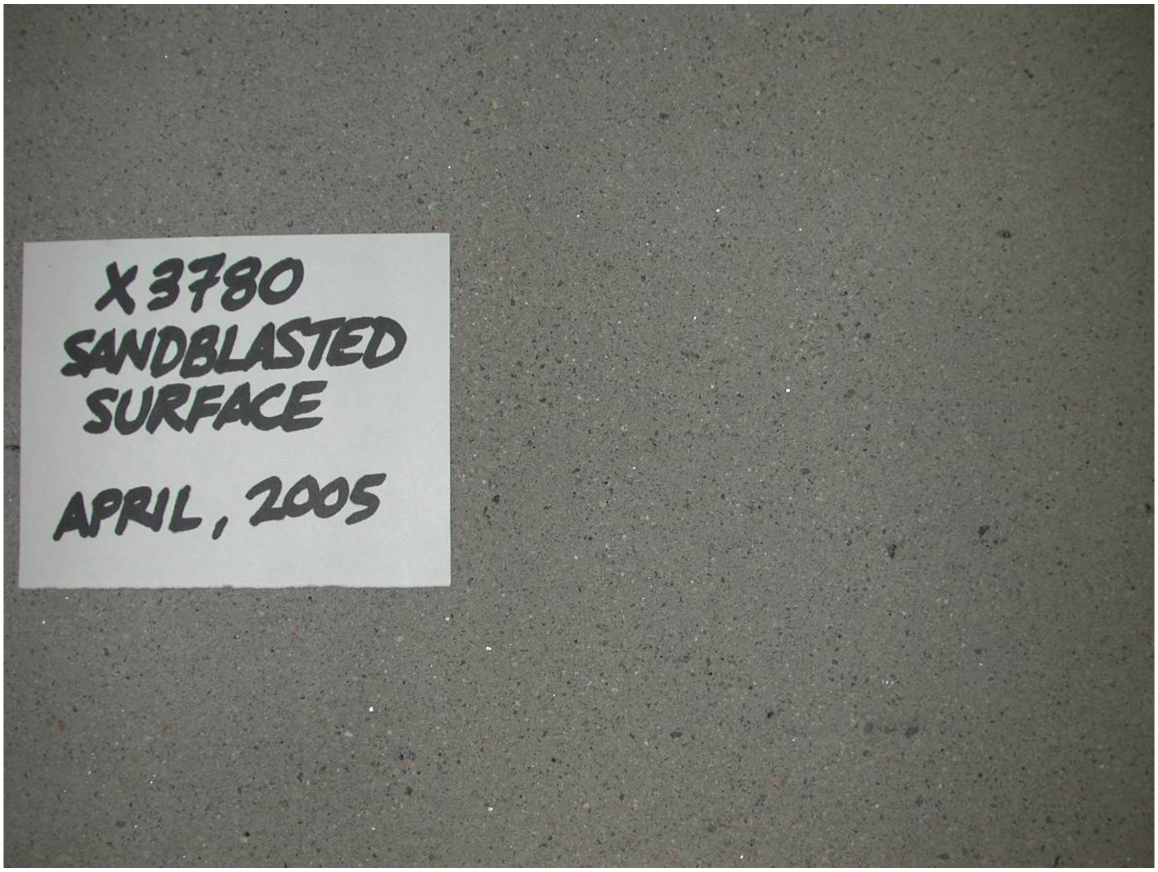


Figure 10: Close-up view of sandblasted surface.

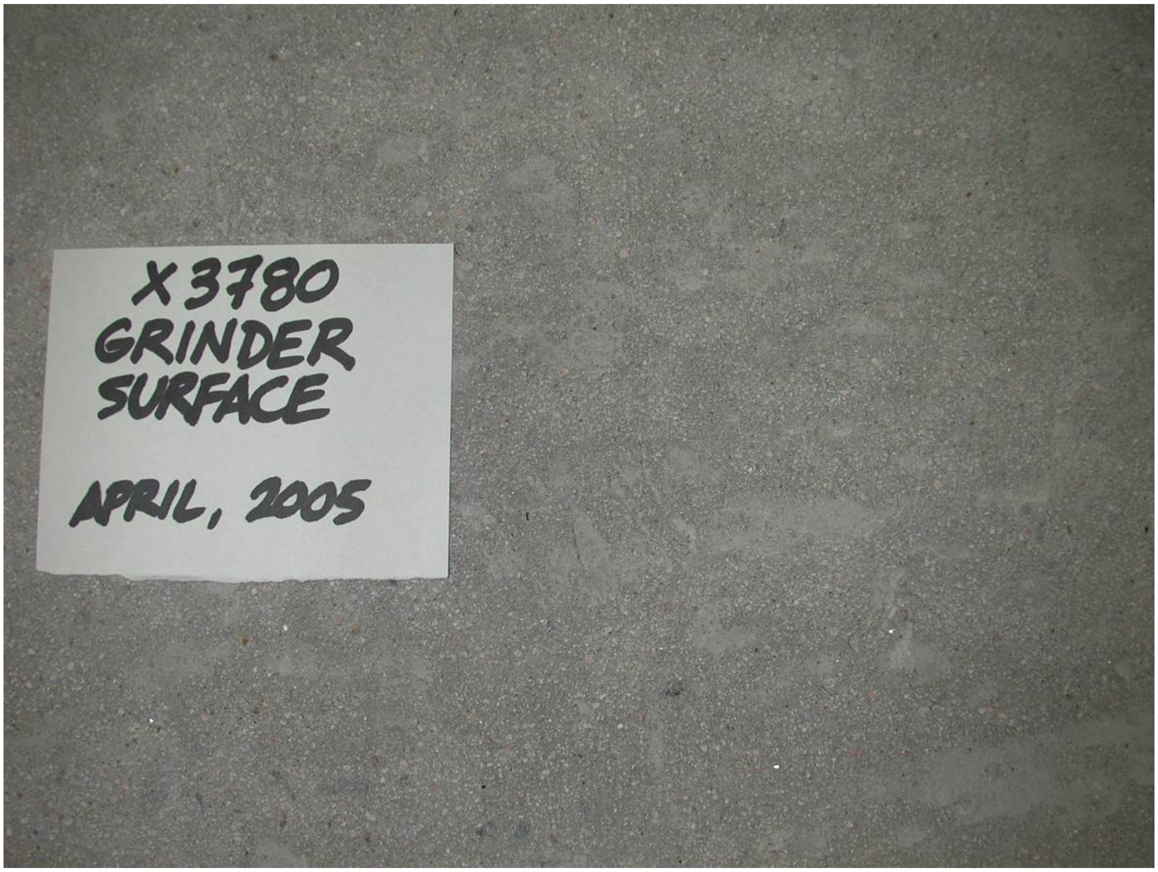


Figure 11: Close-up view of grinder surface.

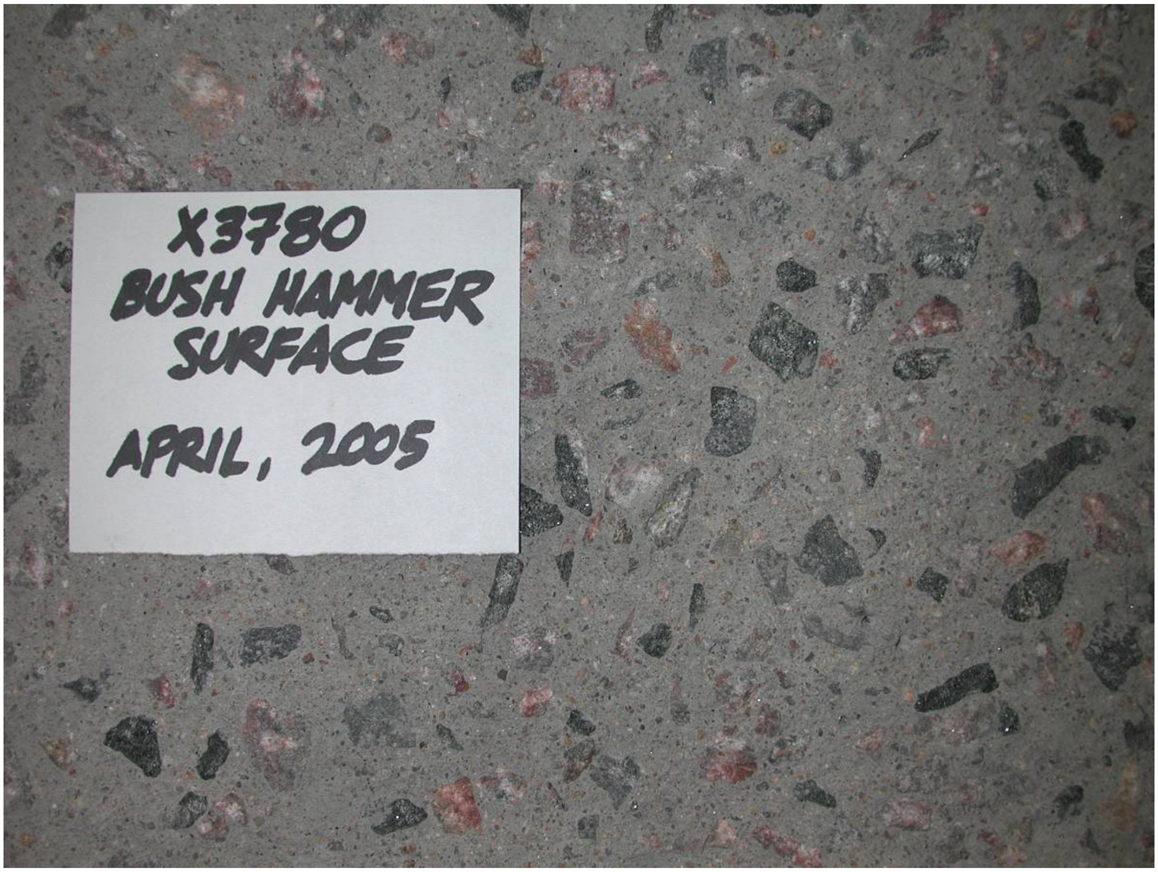


Figure 12: Close-up view of bush hammered surface.

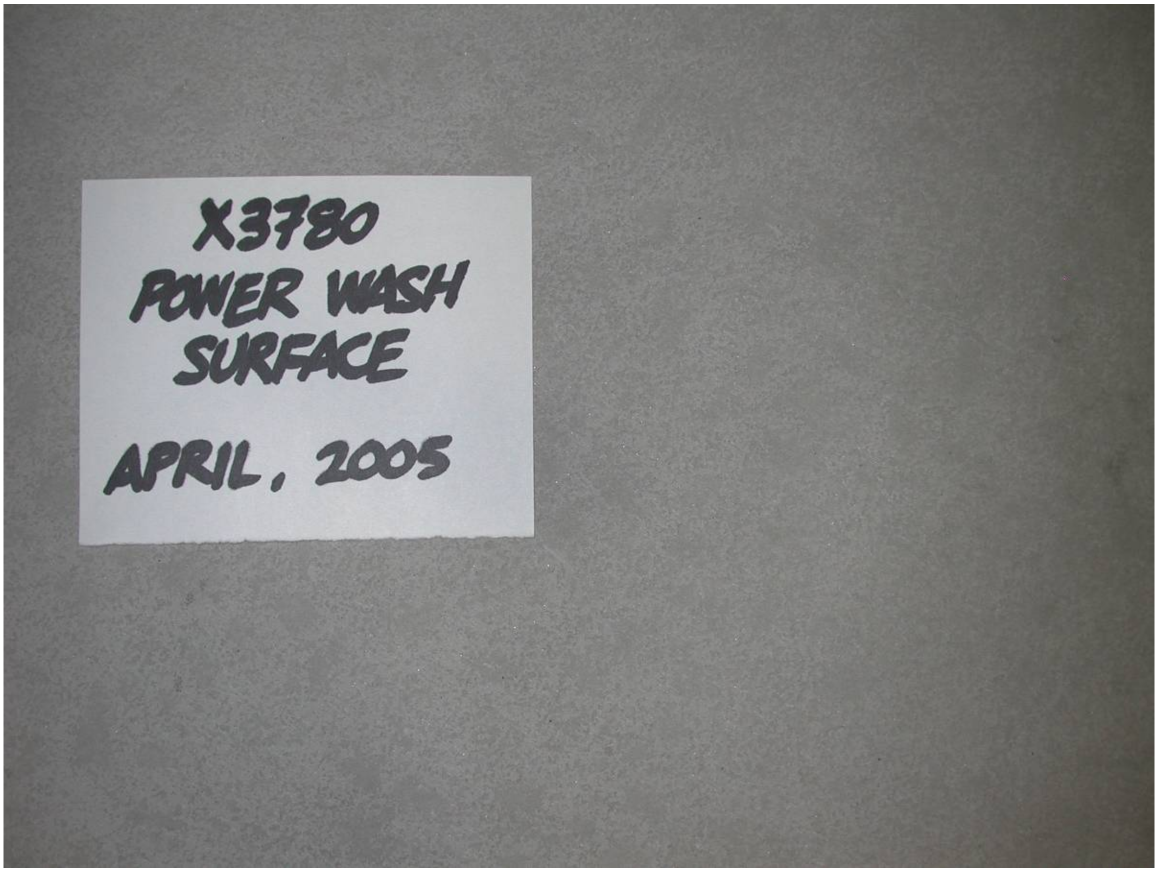


Figure 13: Close-up view of power washed surface.

Figure 14: Preparing materials to apply epoxy putty to rough test slab surfaces.

Figure 15: Measuring “A” and “B” components of epoxy putty.

Figure 16: Mixing epoxy putty with a power drill.

Figure 17: Adding catalyst for epoxy surface primer.

Figure 18: Using drill to mix epoxy primer.

Figure 19: Applying epoxy putty to bush hammered test slab.

Figure 20: Epoxy putty applied to a bush hammered test slab.

Figure 21: Applying epoxy primer to a sandblasted surface test slab.

Figure 22: Completing application of epoxy primer to test slab with a grinder surface.

Figure 23: Saturating carbon fiber mat with epoxy prior to placement.

Figure 24: Applying first layer of carbon fiber overlay test slab (TYP).

Figure 25: Applying the second layer of carbon fiber to a test slab (TYP).

Figure 26: Troweling on a saturation coat of epoxy to the second layer of carbon fiber.

Figure 27: Carbon fiber overlay completed on the grinder surface (foreground) and sandblasted slabs (background).

Figure 28: Completed test slabs.   One slab from each carbon fiber system was used to test in three-point load (tension) tests; the others were used in pull-off testing for bond strength.

Figure 29: Coring one-inch diameter holes in the fabric with a cordless drill for Elcometer adhesion (pull-off) testing.

Figure 50: Applying epoxy to fiber before placing dolly.

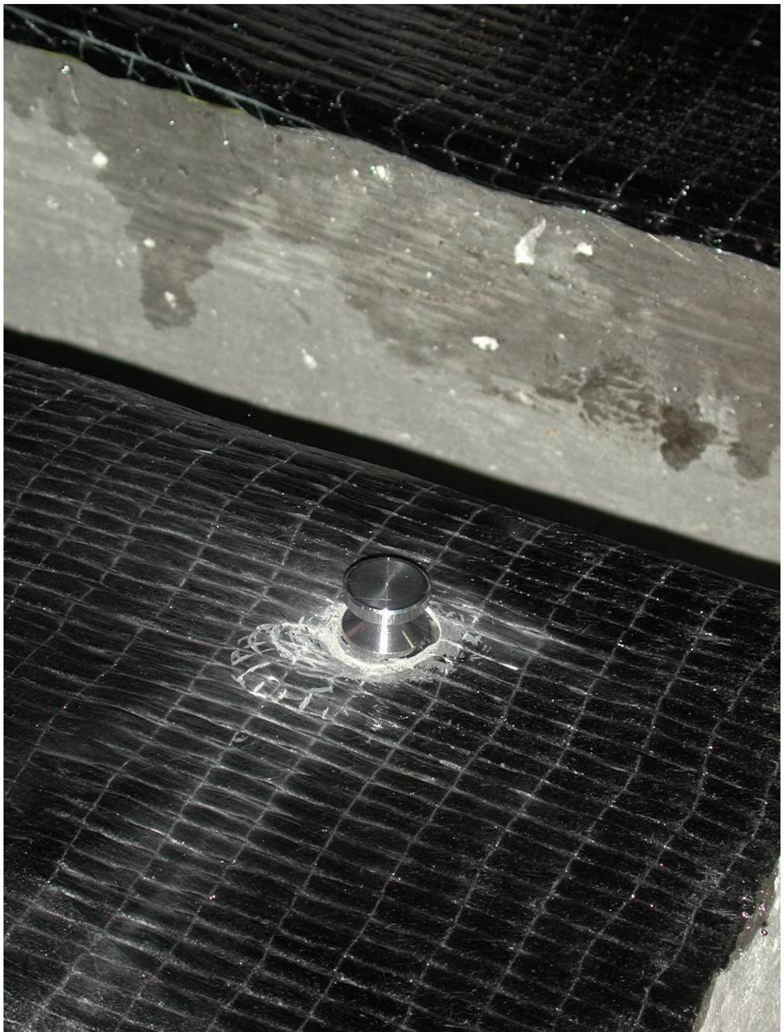


Figure 31: Dolly in place and ready for Elcometer 106 Pull off Adhesion Tester.

Figure 32: Typical Elcometer 106 Pull off Adhesion Tester.

Figure 33: Core drilling machine used to cut 2-1/8" diameter holes for PosiTest adhesion test.

Figure 34: Applying epoxy to the dolly for PosiTest adhesion test.

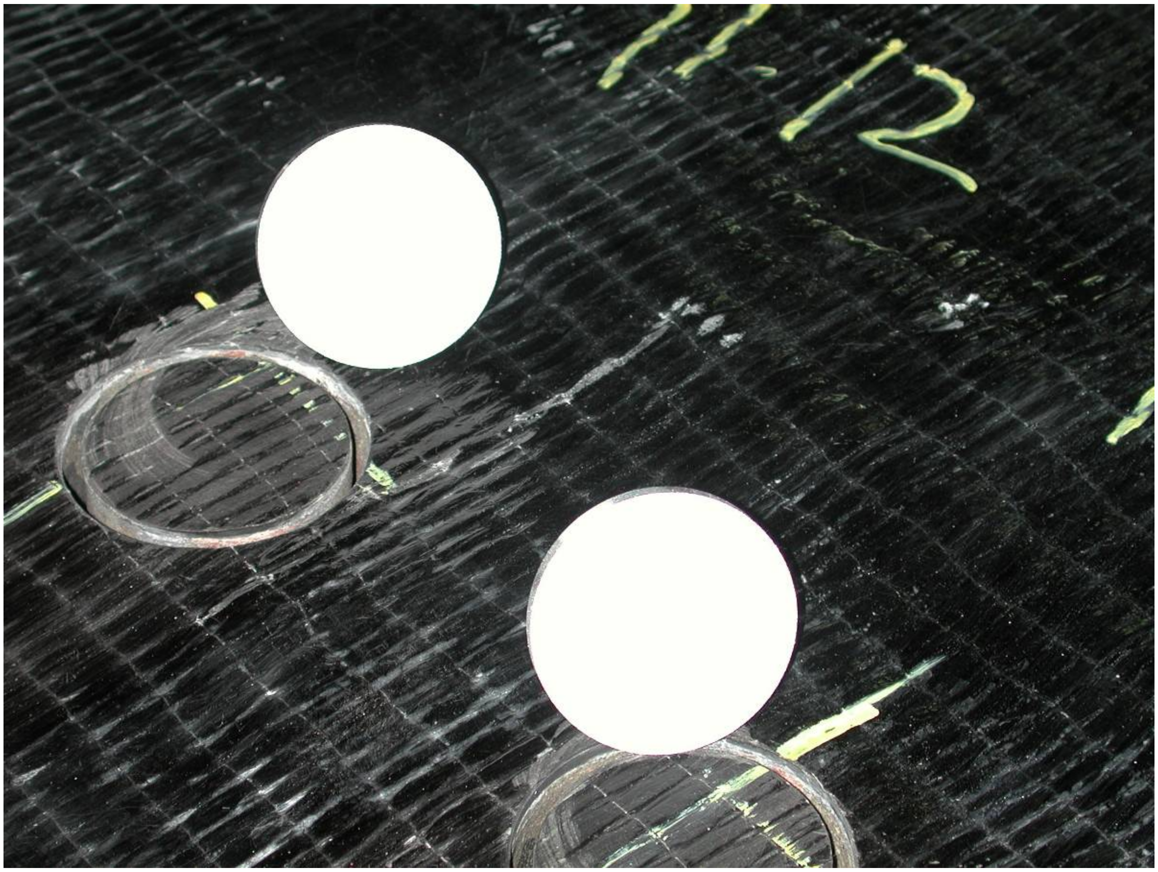


Figure 35: Dollies (2-1/8" diameter) for PosiTest adhesion test. White color caused by reflection of light off of abraided surface.

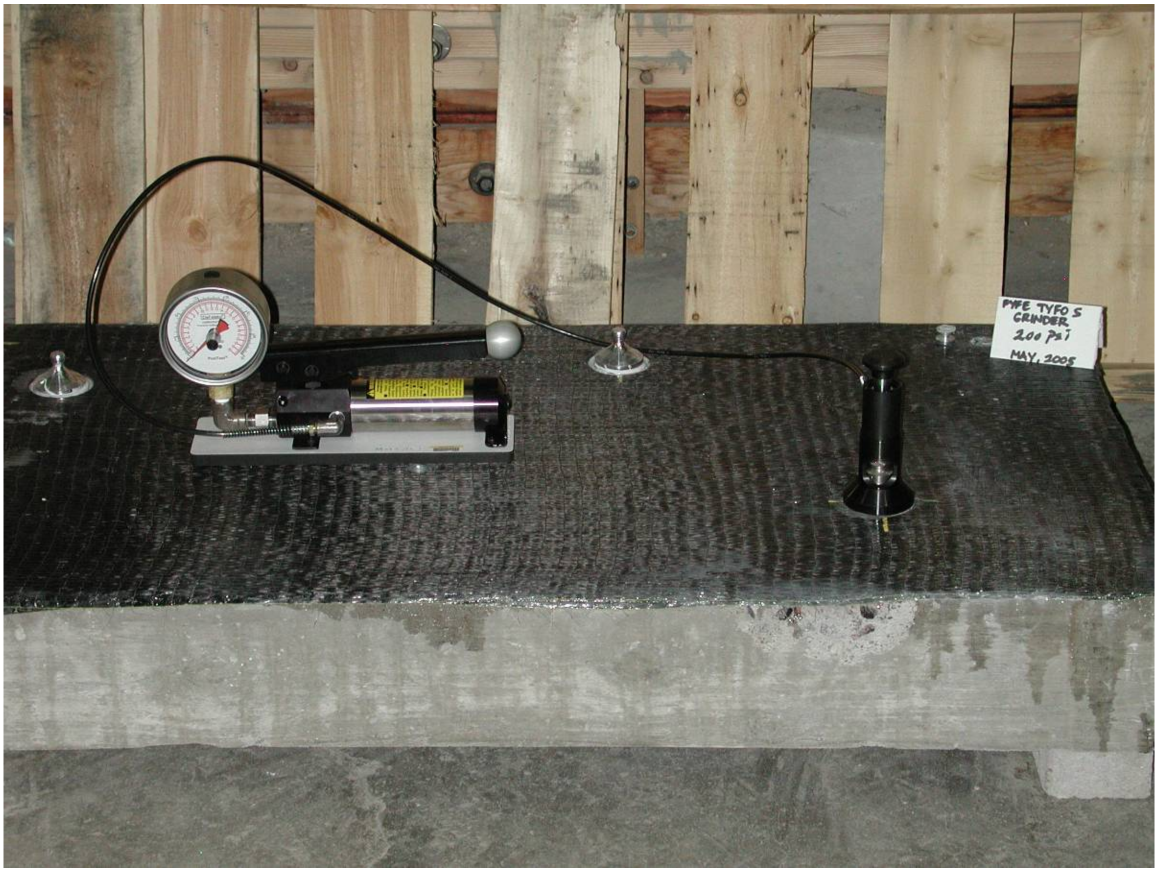


Figure 36: Pull test set-up for PosiTest adhesion dollies.

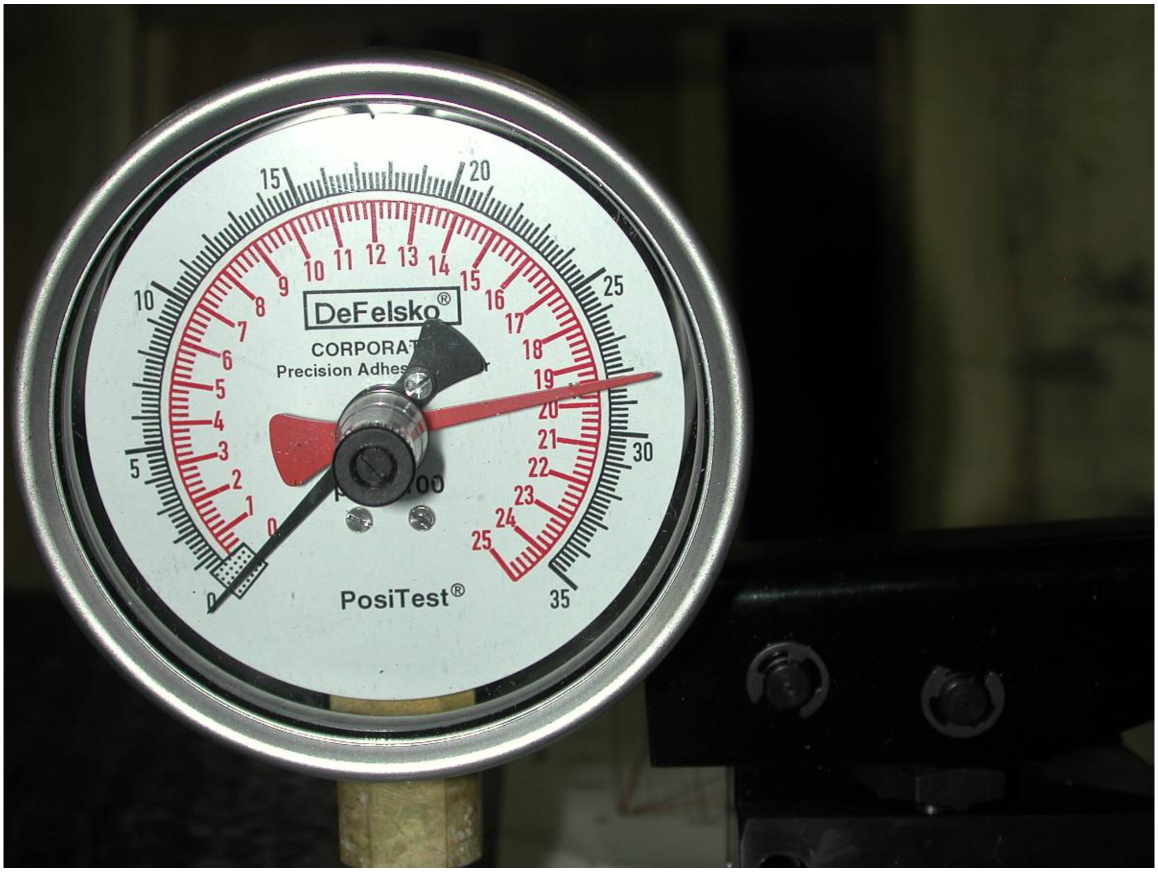


Figure 37: Gauge face on PosiTest adhesion tester

Figure 38: Failure mode – dolly to fiber bond failure mode.

Figure 39: Concrete substrate failure mode.

Figure 40: Concrete substrate failure mode.

Figure 41: Fiber to concrete substrate failure mode.

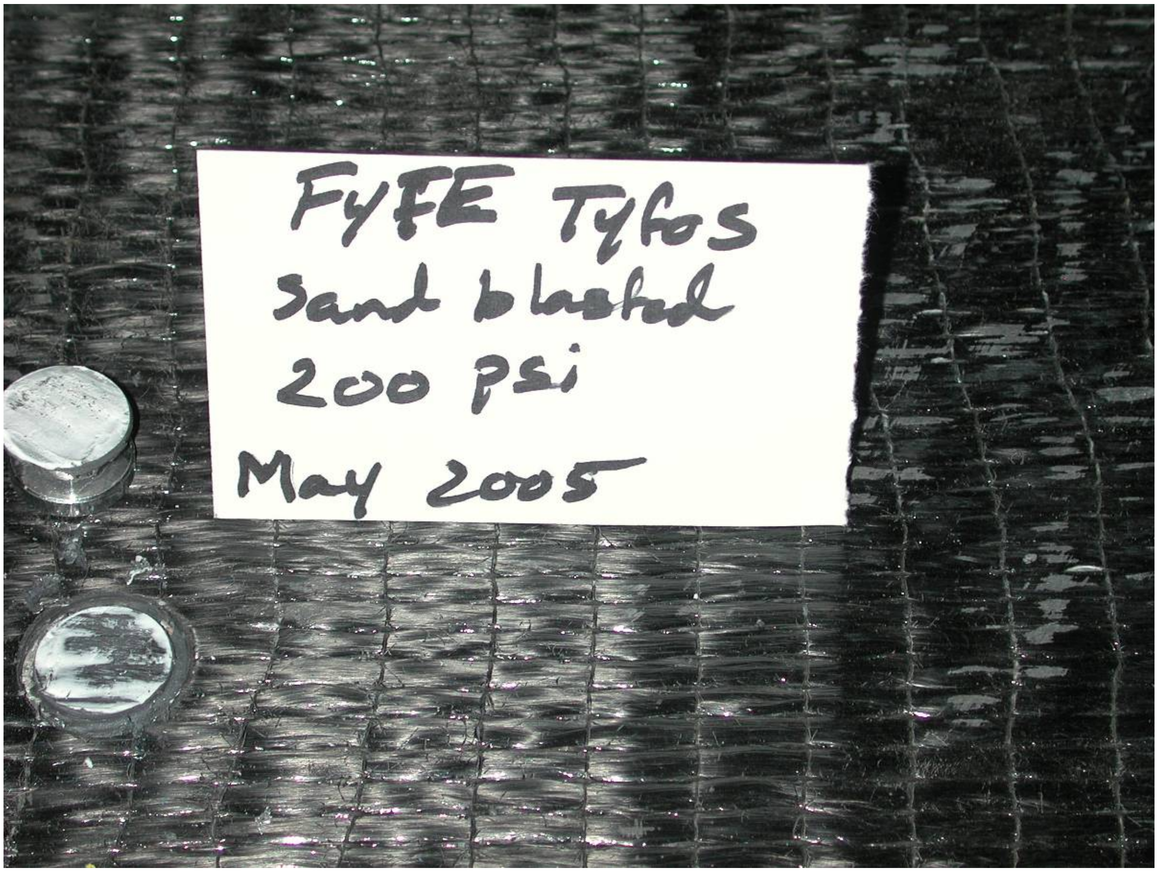


Figure 42: Dolly to fiber failure mode.

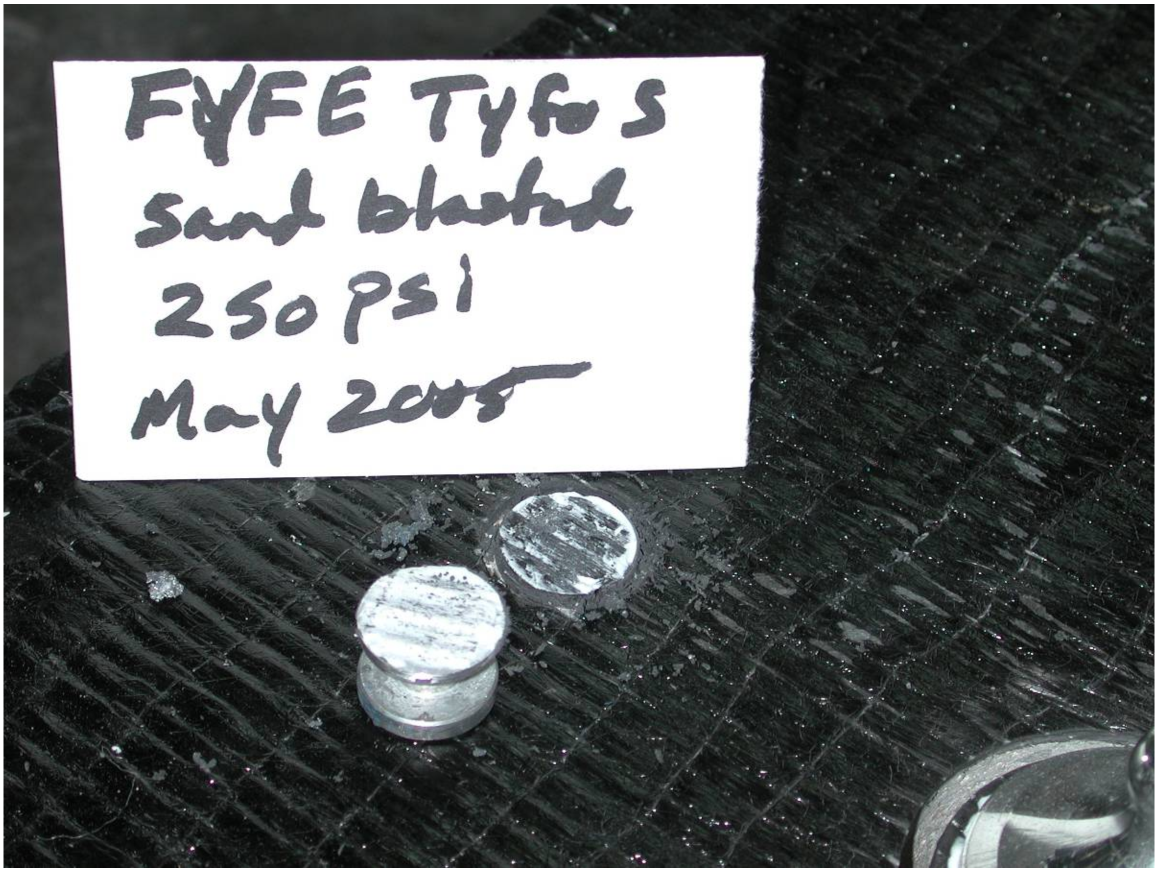


Figure 43: Dolly to fiber failure mode.

Figure 44: Fiber to concrete substrate failure mode.

Figure 45: Dolly to fiber failure mode.

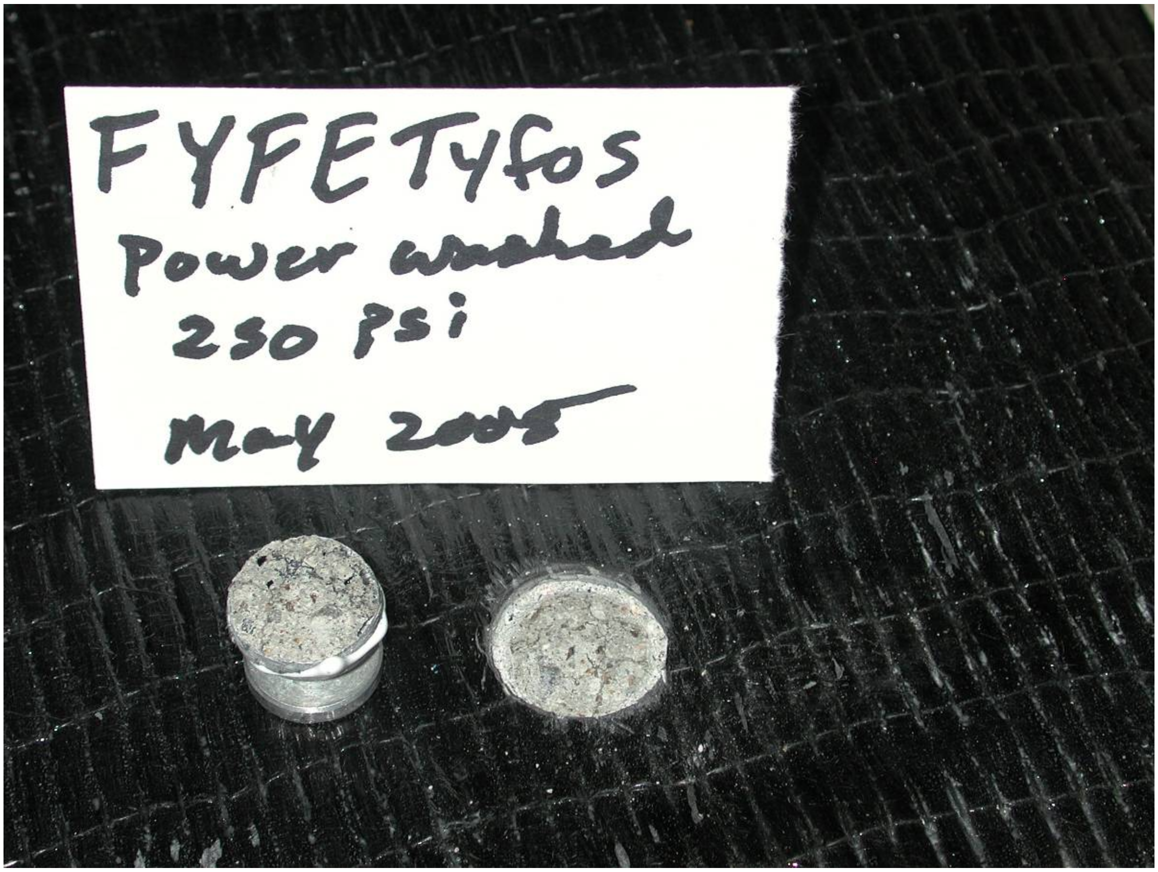


Figure 46: Concrete substrate failure mode.

Figure 47: Concrete substrate failure mode.

Figure 48: Dolly to fiber failure mode.

Figure 49: Concrete substrate failure mode.

Figure 50: Concrete substrate failure mode.

Figure 51: Concrete substrate failure mode.

Figure 52: Concrete substrate failure mode.

Figure 53: Dolly to fiber failure mode.

Figure 54: Concrete substrate failure mode.

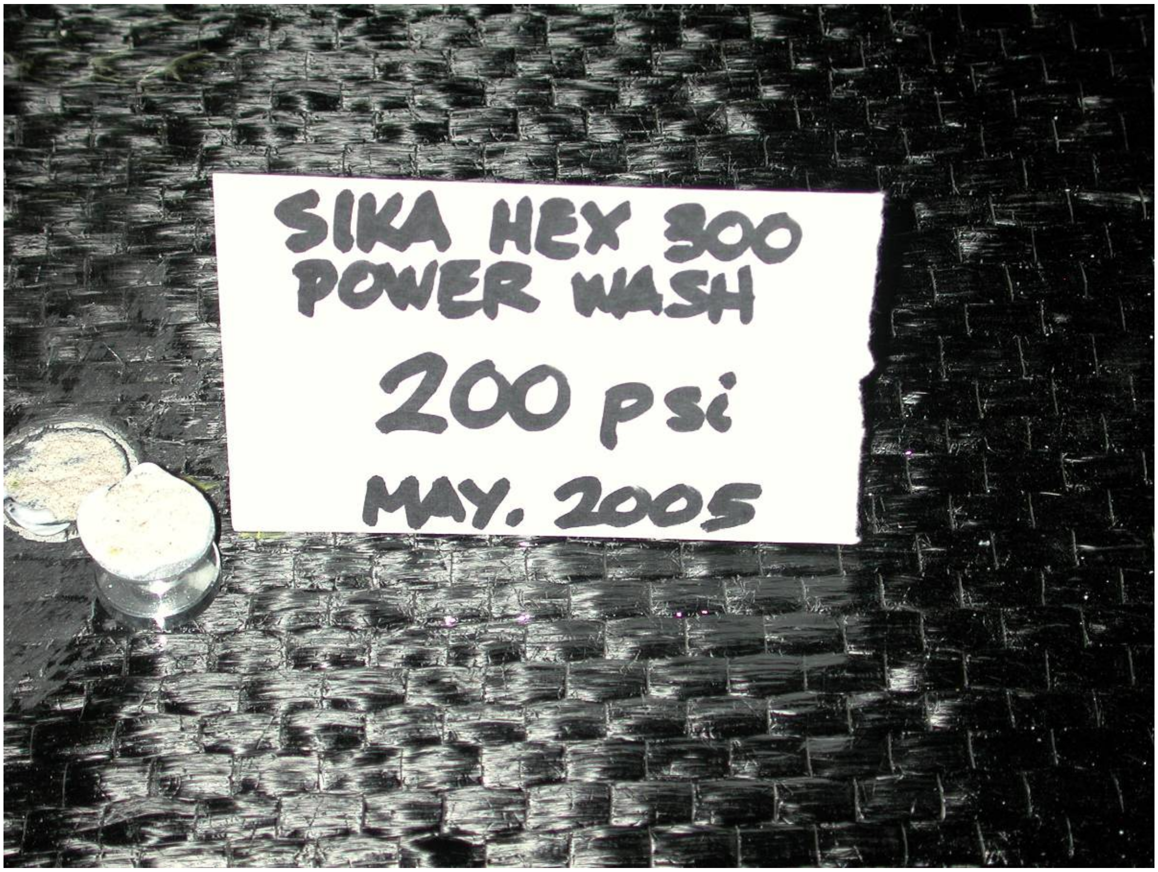


Figure 55: Fiber to concrete substrate failure mode.

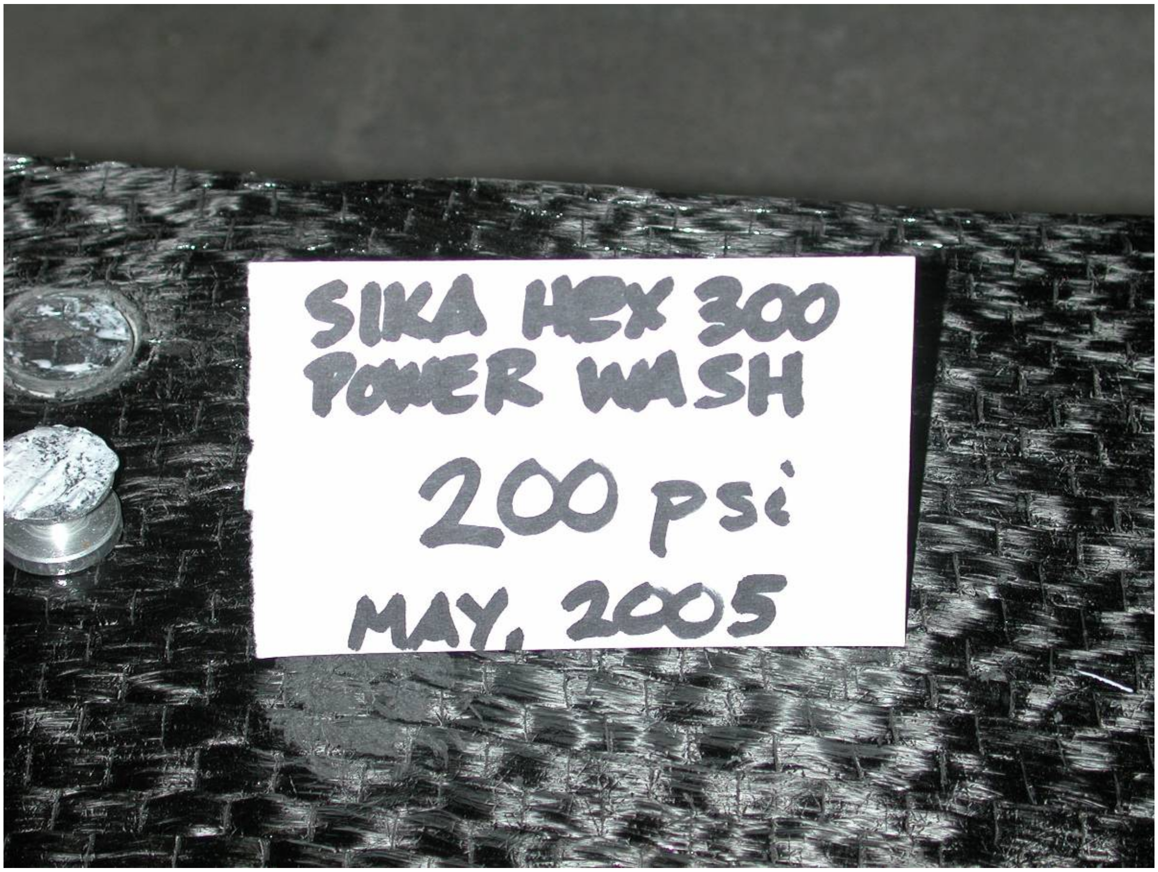


Figure 56: Dolly to fiber failure mode.

Figure 57: Concrete substrate failure mode.

Figure 58: Fiber to concrete substrate failure mode.

Figure 59: Concrete substrate failure mode.

Figure 60: Dolly to fiber failure mode.

Figure 61: Dolly to fiber failure mode.

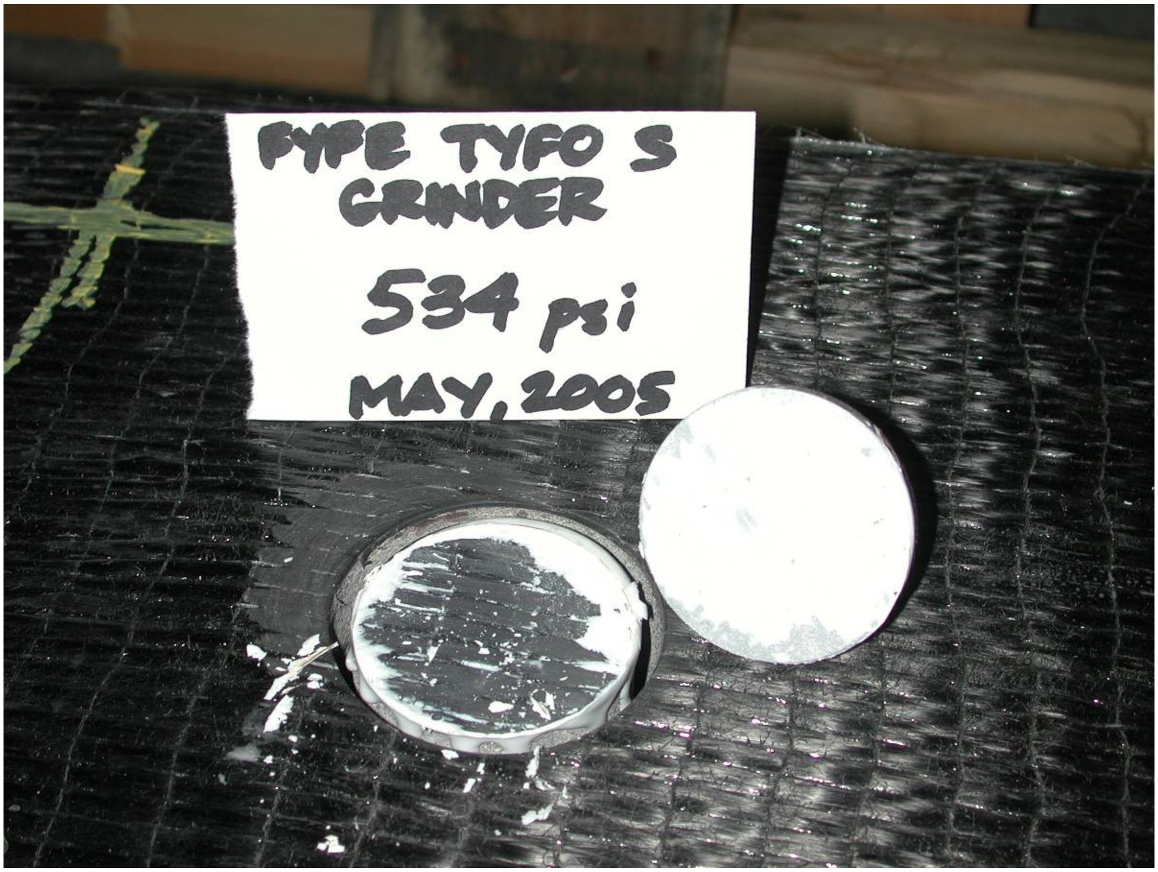


Figure 62: Dolly to fiber failure mode.

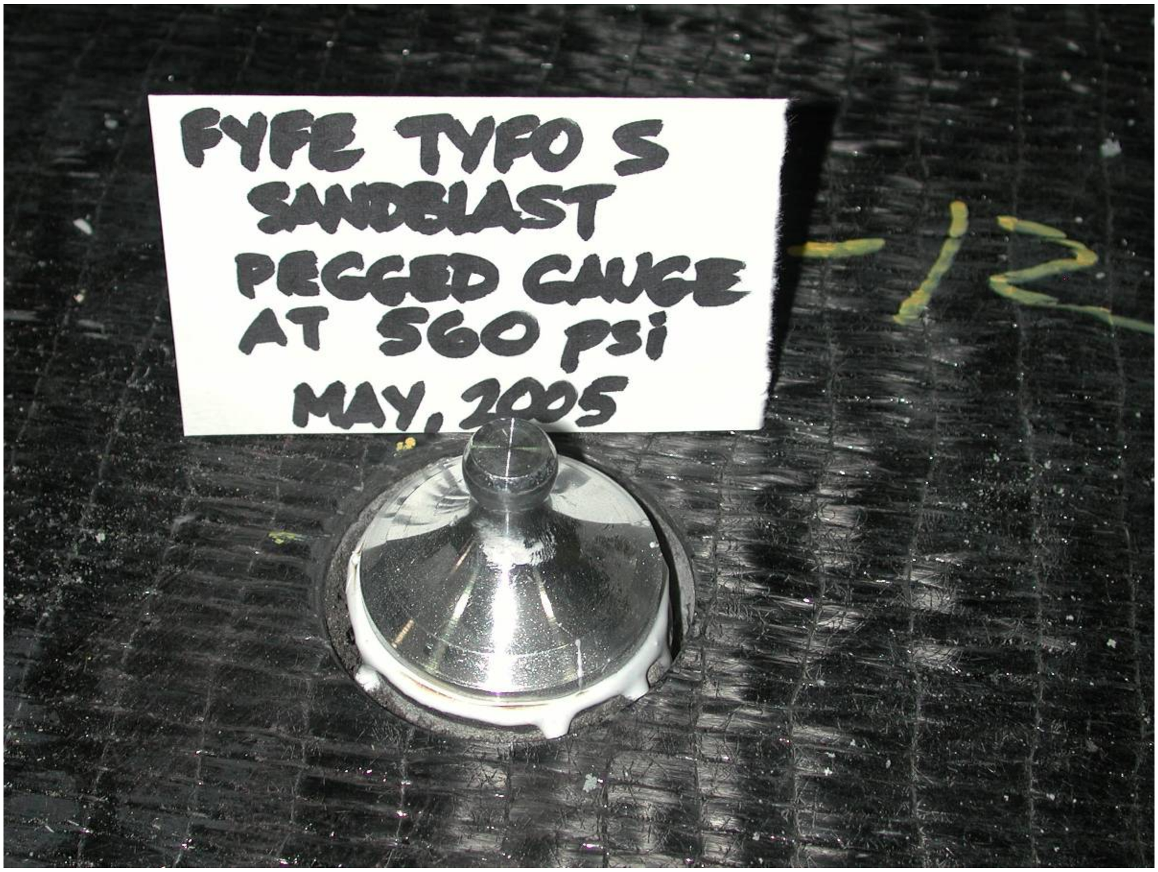


Figure 63: No failure mode.

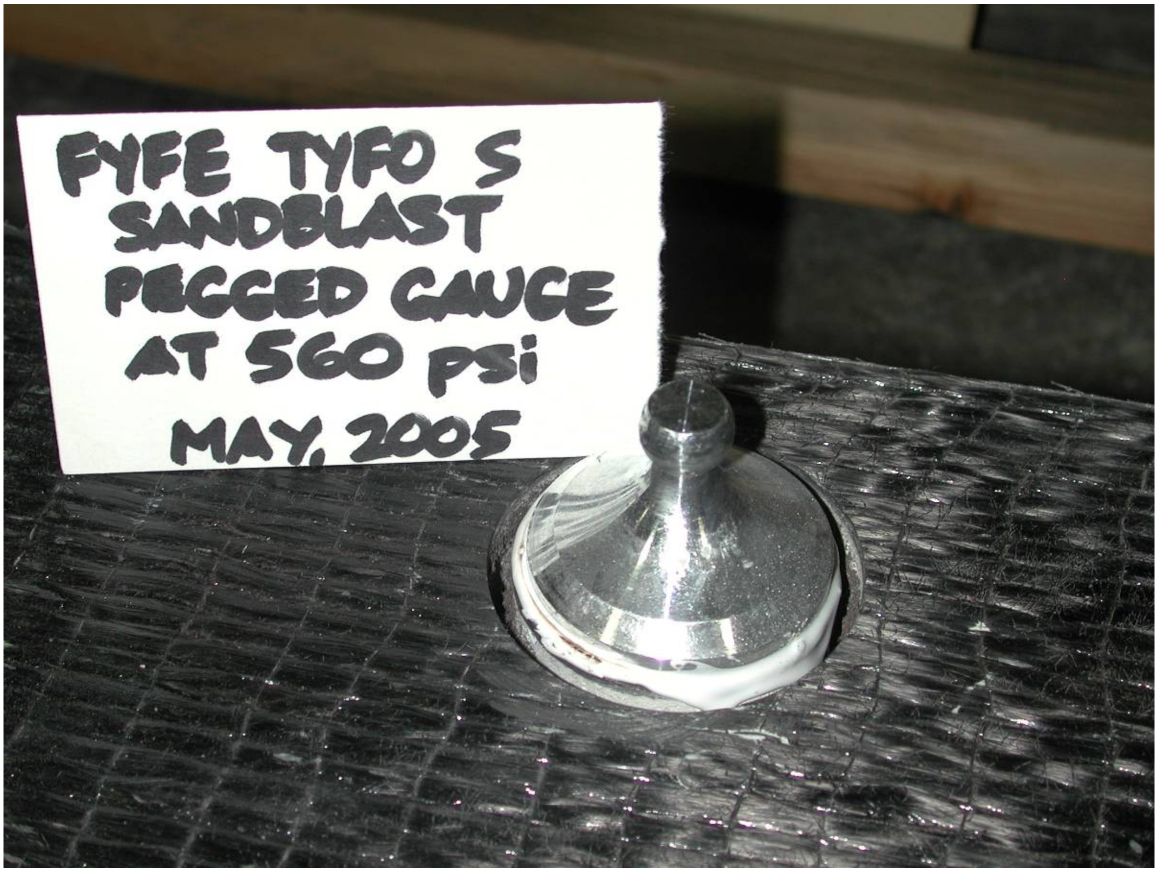


Figure 64: No failure mode.

Figure 65: Dolly to fiber failure mode.

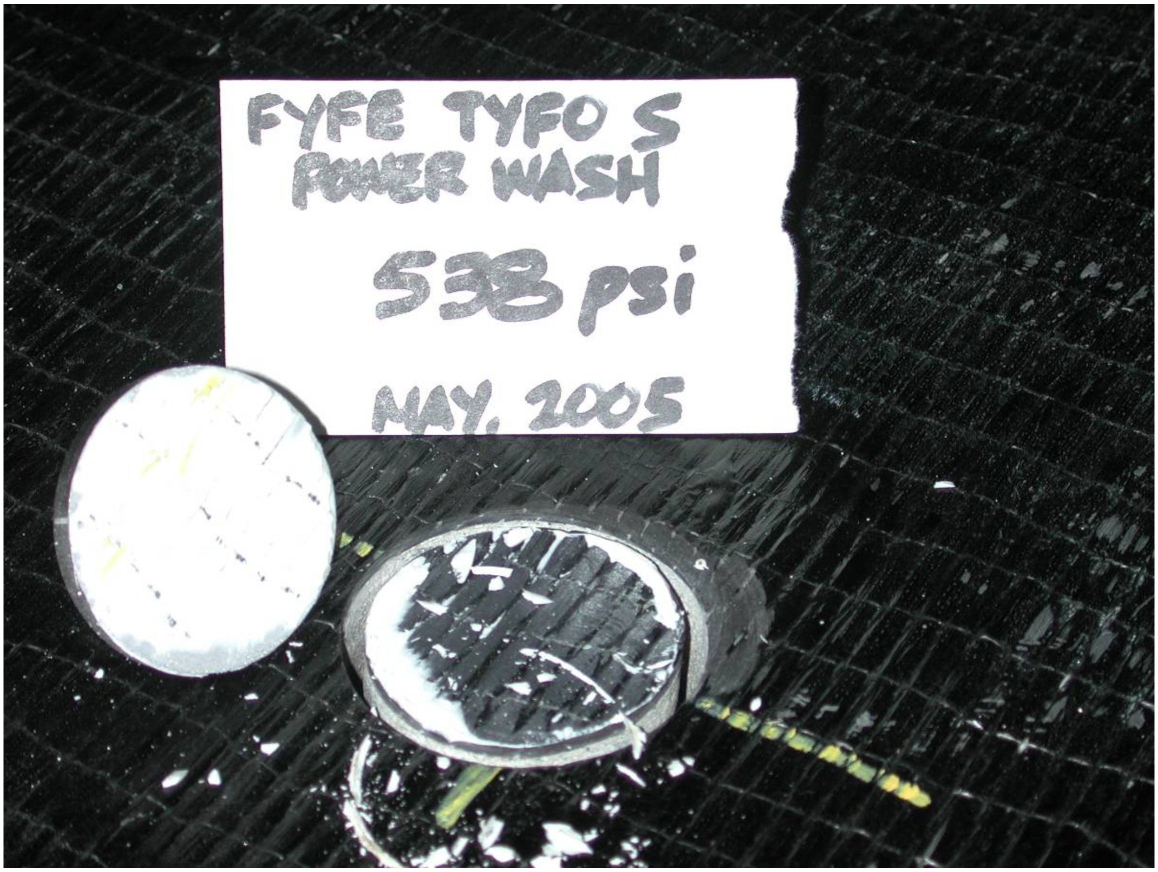


Figure 66: Dolly to fiber failure mode.

Figure 67: Dolly to fiber failure mode.

Figure 68: Dolly to fiber failure mode.

Figure 69: Dolly to fiber failure mode.

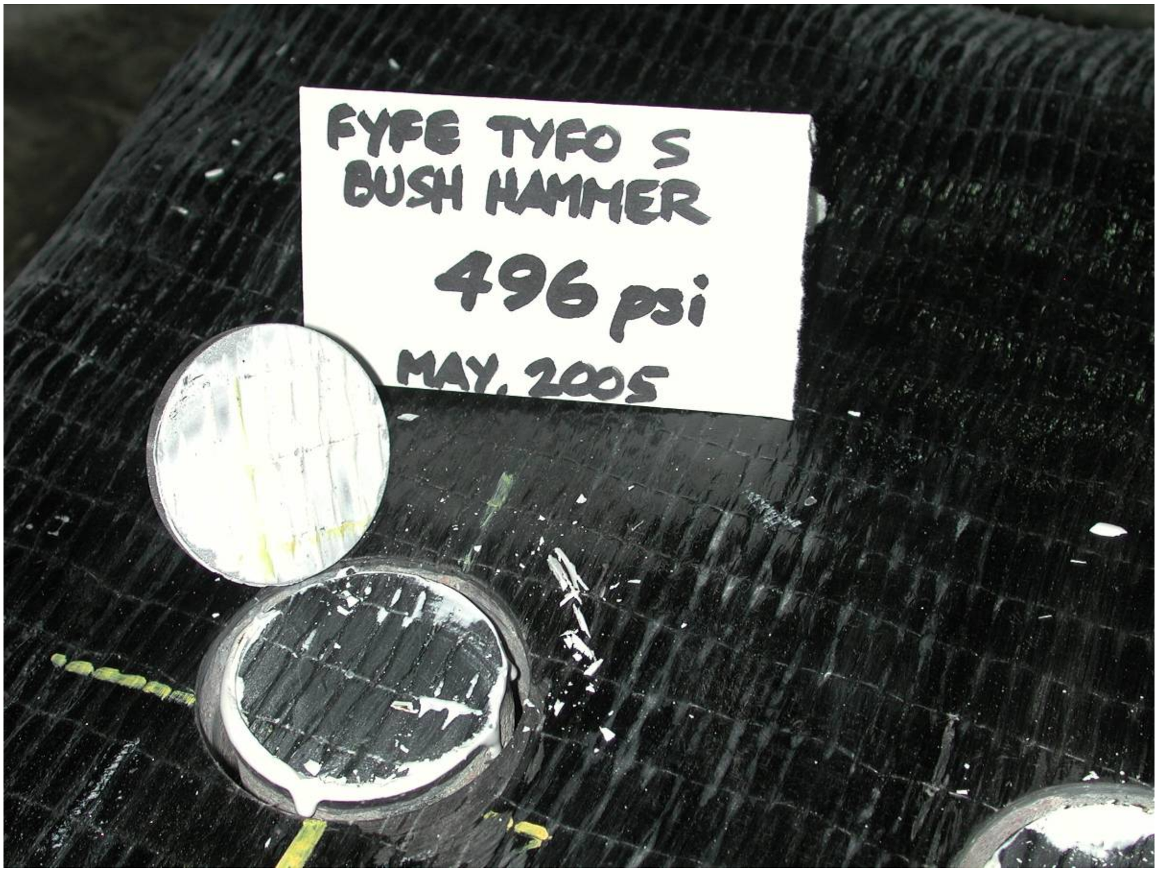


Figure 70: Dolly to fiber failure mode.

Figure 71: Fiber to concrete failure mode.

Figure 72: No failure mode.

Figure 73: No failure mode.

Figure 74: Fiber to concrete failure mode

Figure 75: Concrete substrate failure mode.

Figure 76: Concrete substrate failure mode.

Figure 77: Concrete substrate failure mode.

Figure 78: Fiber to concrete failure mode

Figure 79: Concrete substrate failure mode.

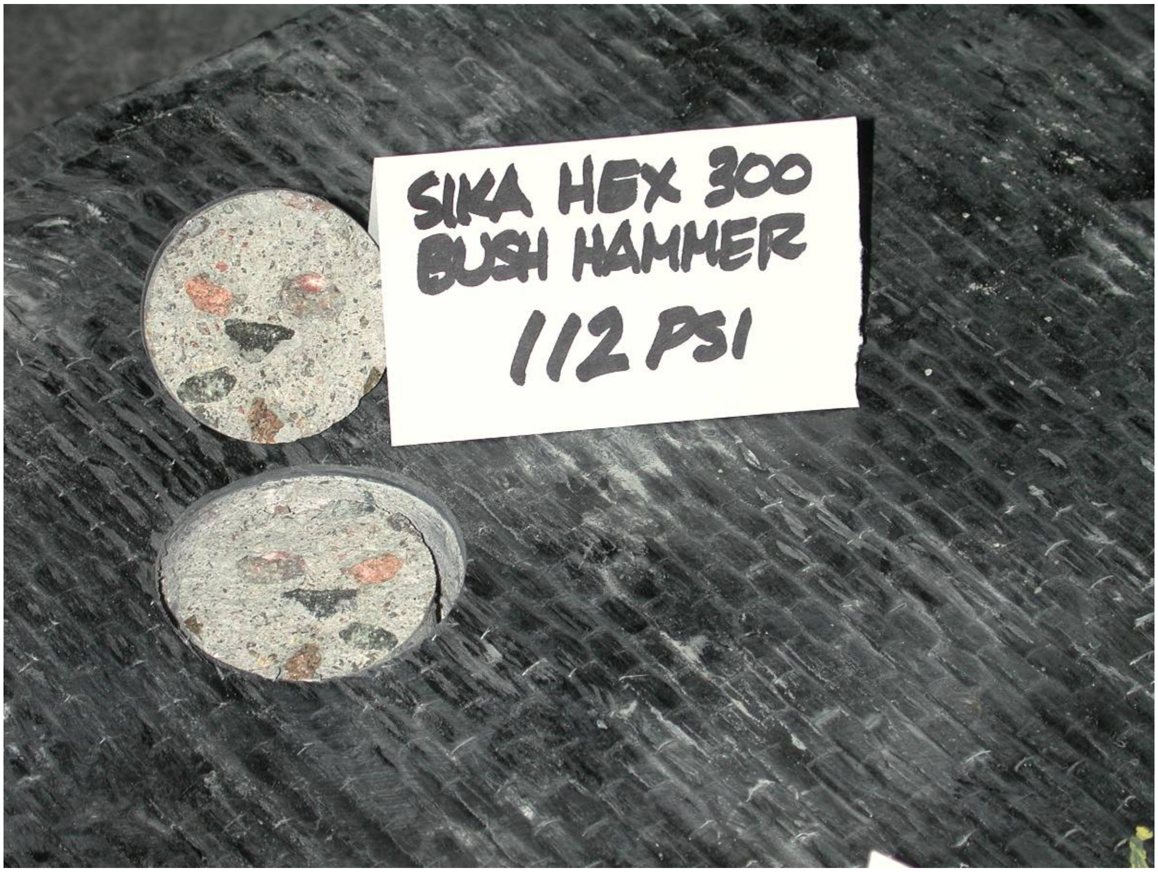


Figure 80: Concrete substrate failure mode.

Figure 81: Concrete substrate failure mode.

Figure 82: Concrete slab without carbon fiber system, prepared to break in three-point load test. Information from this test was used as a reference with the concrete with carbon fiber systems.

Figure 83: Concrete slab without carbon fiber system after testing. Total rupture load was 11,790 lbs.

Figure 84: Slab with DeGussa system (power washed surface) prior to testing.

Figure 85: Degussa power washed slab after testing. Total rupture load was 39,748 lbs.

Figure 86: Slab with DeGussa system (sandblasted surface prep) prior to test.

Figure 87: DeGussa sandblasted slab after testing. Total rupture load was 77,681 lbs.

Figure 88: Slab with DeGussa system (bush hammered surface) before testing. Specimen was offset to account for crack caused during handling of the specimen prior to placing it on the pedestal.

Figure 89: DeGussa bush hammered slab after testing. Total rupture load was 44,800 lbs.

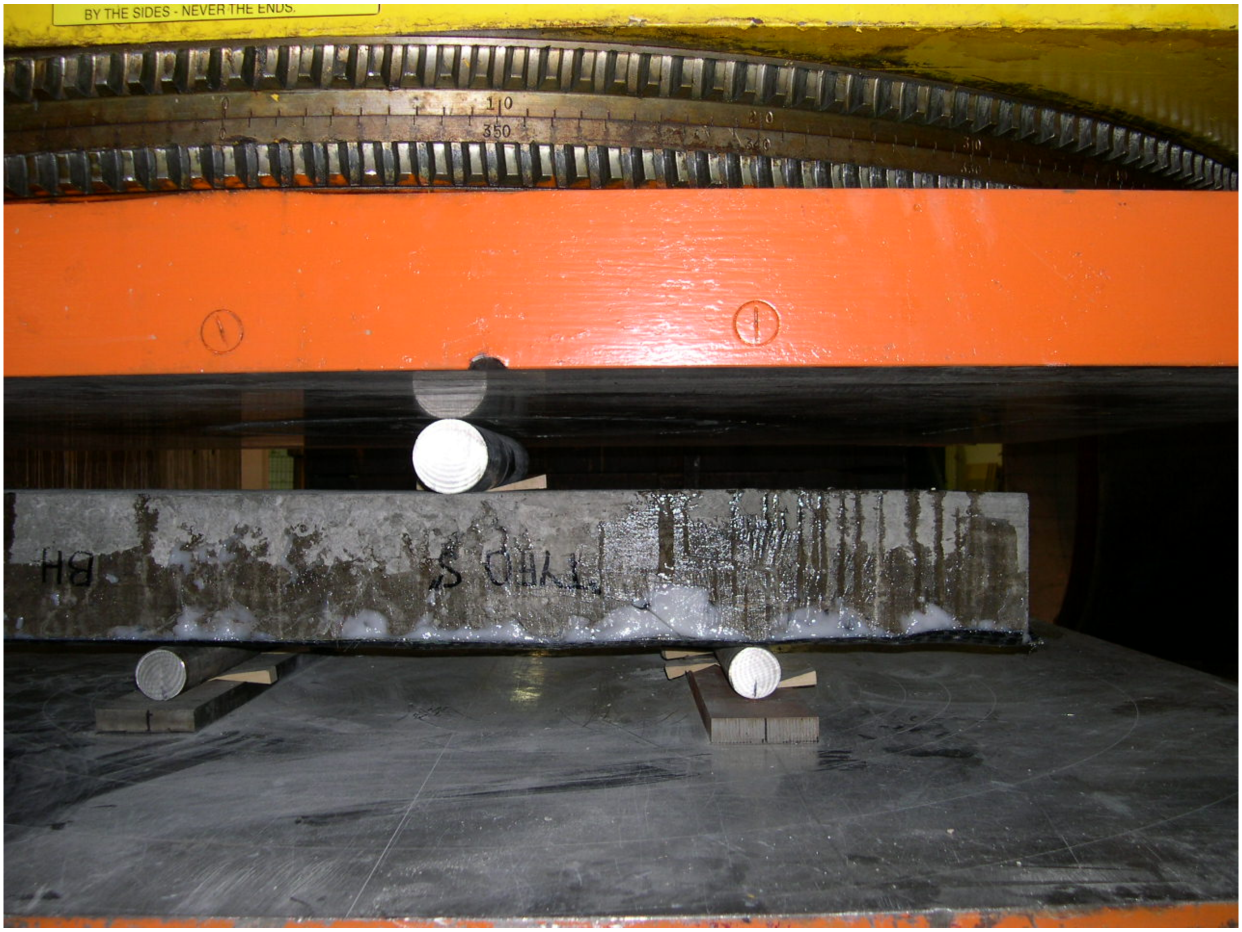


Figure 90: Slab with “TYFO S” (bush hammered surface) before testing.

Figure 91: "TYFO S" bush hammered slab after testing. Total rupture load was 55,042 lbs.

Figure 92: Slab with "TYFO S" (grinder surface) finish slab after testing; no before testing Figure.   Total rupture load was 52,070 lbs.

Figure 93: Slab with “TYFO S” system (sandblasted surface) before testing.

Figure 94: “TYFO S” sandblasted slab after testing. Total rupture load was 59,626 lbs.

Figure 95: Slab with "TYFO S" system (power washed surface) before testing. Black area on slab that is left of the left steel dowel (bottom) is overwrap of the carbon fiber (not bonded to side of slab). This was noted on several other slabs.

Figure 96: "TYFO S" power washed slab after testing. Total rupture load was 45,856 lbs.

Figure 97: Slab with Sika "Hex 300" system (sandblasted slab) before testing.

Figure 98: Sika "Hex 300" sandblasted slab after testing. Total rupture load was 64,000 lbs.

Figure 99: Slab with Sika “Hex 300” system (power washed surface) before testing.

Figure 100: Sika "Hex 300" power washed slab after testing. Total rupture load was 43,054 lbs.

Figure 101: Slab with Sika "Hex 300" system (bush hammered surface) before testing.

Figure 102: Sika "Hex 300" bush hammer slab after testing. Total rupture load was 57,577 lbs.

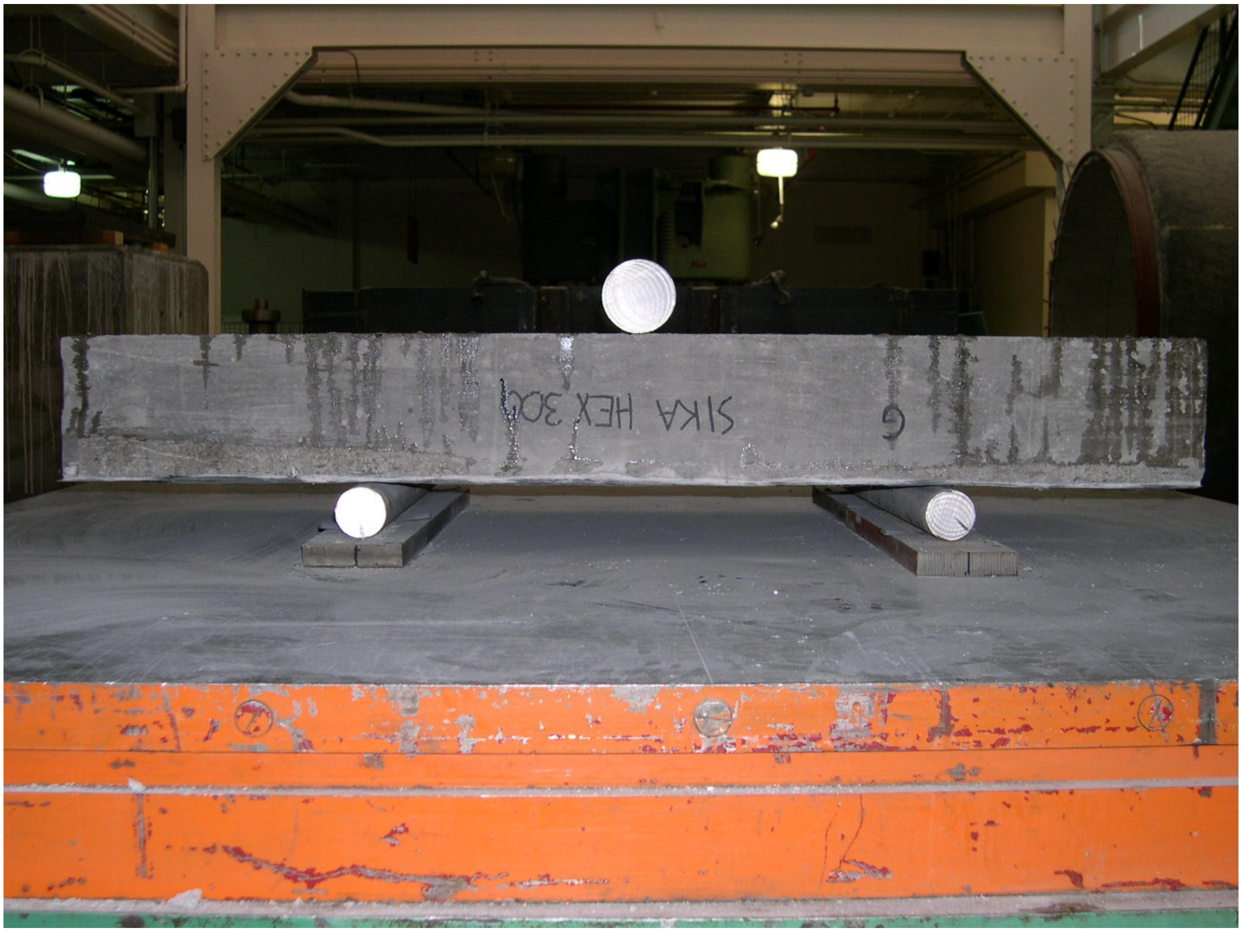


Figure 103: Slab with Sika "Hex 300" system (grinder surface) before testing.

Figure 104: Sika "Hex 300" grinder surface slab after testing. Total rupture load was 50,566 lbs.

Appendix 2

FRP Manufacturers Specification Sheets

FYFE Co. LLC "THE FIBRWRAP® COMPANY"

Tyfo® SCH-41 Composite
using Tyfo® S Epoxy

DESCRIPTION
The Tyfo® SCH-41 Composite is comprised of Tyfo® S Epoxy and Tyfo® SCH-41 reinforcing fabric, which is NSF-Certified. Tyfo® SCH-41 is a custom, uni-directional carbon fabric with glass cross fiber for added strength and fabric stability during installation. The carbon material is orientated in the 0° direction. The Tyfo® S Epoxy is a two-component epoxy matrix material for bonding applications.

USE
Tyfo® SCH-41 Fabric is combined with Tyfo® Epoxy to add strength to bridges, buildings, and other structures.

ADVANTAGES
- ICC ER-5282 listed material
- Component of UL listed, fire-rated assembly
- NSF/ANSI Standard 61 listed product for drinking water systems
- Improved long-term durability
- Good high & low temperature properties
- Long working time
- High tensile modulus and strength
- Ambient cure
- 100% solvent-free
- Rolls can be cut to desired widths prior to shipping

COVERAGE
Approximately 600 sq. ft. surface area with 3 to 4 units of Tyfo® S Epoxy and 1 roll of Tyfo® SCH-41 Fabric when used with the Tyfo® Saturator.

PACKAGING
Order Tyfo® S Epoxy in 55-gallon (208L) drums or pre-measured units in 5-gallon (19L) containers. Tyfo® SCH-41 Fabric typically shipped in 2 rolls of 24" x 300 lineal foot (0.6m x 91.4m) rolls. Typically ships in 12" x 13" x 64" (305mm x 330mm x 1626mm) boxes.

EPOXY MIX RATIO
100.0 component A to 42.0 component B by volume. (100 component A to 34.5 component B by weight.)

SHELF LIFE
Epoxy - two years in original, unopened and properly stored containers.
Fabric - ten years in proper storage conditions.

STORAGE CONDITIONS
Store at 40° to 90° F (4° to 32° C). Avoid freezing. Store rolls at, not on ends, at temperatures below 100° F (38° C). Avoid moisture and water contamination.

CERTIFICATE OF COMPLIANCE
- Will be supplied upon request, complete with state and federal packaging laws with copy of labels used.
- Material safety data sheets will be supplied upon request.
- Possesses 0% V.O.C. level.

TYPICAL DRY FIBER PROPERTIES	
Tensile Strength	550,000 psi (3.79 GPa)
Tensile Modulus	33.4 x 10^6 psi (230 GPa)
Ultimate Elongation	1.7%
Density	0.063 lbs./in.^{3} (1.74 g/cm^3)
Weight per sq. yd.	19 oz. (644 g/m^2)

COMPOSITE GROSS LAMINATE PROPERTIES

PROPERTY	ASTM METHOD	TYPICAL TEST VALUE	DESIGN VALUE*
Ultimate tensile strength in primary fiber direction, psi	D-3039	143,000 psi (986 MPa) (5.7 kip/in. width)	121,000 psi (834 MPa) (4.8 kip/in. width)
Elongation at break	D-3039	1.0%	0.85%
Tensile Modulus, psi	D-3039	13.9 x 10^6 psi (95.8 GPa)	11.9 x 10^6 psi (82 GPa)
Laminate Thickness		0.04 in. (1.0mm)	0.04 in. (1.0mm)

* Gross laminate design properties based on ACI 440 suggested guidelines will vary slightly. Contact Fyfe Co. LLC engineers to confirm project specification values and design methodology. ICC ER-5282 listed design properties shall be revised.

EPOXY MATERIAL PROPERTIES

Curing Schedule 72 hours post cure at 140° F (60° C).

PROPERTY	ASTM METHOD	TYPICAL TEST VALUE*
Tg 140° F (60° C) Post Cure (24 hours)	ASTM D-4065	180° F (82° C)
Tensile Strength[1], psi	ASTM D-638 Type 1	10,500 psi (72.4 MPa)
Tensile Modulus, psi	ASTM D-638 Type 1	461,000 psi (3.18 GPa)
Elongation Percent	ASTM D-638 Type 1	5.0%
Flexural Strength, psi	ASTM D-790	17,900 psi (123.4 MPa)
Flexural Modulus, psi	ASTM D-790	452,000 psi (3.12 GPa)

[1] Testing temperature: 70° F (21° C) Crosshead speed: 0.5 in. (13mm)/min. Grips Instron 2716-0055 - 30 kips
* Specification values can be provided upon request.

HOW TO USE THE TYFO® S COMPOSITE SYSTEM

DESIGN
The Tyfo® System shall be designed to meet specific design criteria. The criteria for each project is dictated by the engineer of record and any relevant building codes and/or guidelines. The design should be based on the allowable strain for each type of application and the design modulus of the material. The Fyfe Co. LLC engineering staff will provide preliminary design at no obligation.

INSTALLATION
Tyfo® System to be installed by Fyfe Co. LLC trained and certified applicators. Installation shall be in strict compliance with the Fyfe Co. LLC Quality Control Manual.

SURFACE PREPARATION
The required surface preparation is largely dependent on the type of element being strengthened. In general, the surface must be clean, dry and free of protrusions or cavities, which may cause voids behind the Tyfo® composite. Column surfaces that will receive continuous wraps typically require only a broom cleaning. Discontinuous wrapping surfaces (walls, beams, slabs, etc.) typically require a light sandblast, grinding or other approved methods to prepare for bonding. Tyfo® FibrAnchors™ are incorporated in some designs. The Fyfe Co. LLC engineering staff will provide the proper specifications and details based on the project requirements.

MIXING
For pre-measured units in 5-gallon containers, pour the contents of component B into the pail of component A. For drums, premix each component: 100.0 parts of component A to 42.0 parts of component B by volume (100 parts of component A to 34.5 parts of component B by weight). Mix thoroughly for five minutes with a Tyfo® low speed mixer at 400-600 RPM until uniformly blended.

APPLICATION
Feed fabric through the Tyfo® Saturator and apply using the Tyfo® wrapping equipment or approved hand methods (see data sheet on this equipment). Hand saturation is allowable, provided the epoxy is applied uniformly and meets the specifications.

LIMITATIONS
Minimum application temperature of the epoxy is 40° F (4° C). DO NOT THIN, solvents will prevent proper cure.

CAUTION!

COMPONENT A - Irritant:
Prolonged contact to the skin may cause irritation. Avoid eye contact.

COMPONENT B - Irritant:
Contact with skin may cause severe burns. Avoid eye contact. Product is a strong sensitizer. Use of safety goggles and chemical resistant gloves recommended. Remove contaminated clothing. Avoid breathing vapors. Use adequate ventilation. Use of an organic vapor respirator recommended.

SAFETY PRECAUTIONS
Use of an approved particle mask is recommended for possible airborne particles. Gloves are recommended when handling fabrics to avoid skin irritation. Safety glasses are recommended to prevent eye irritation.

FIRST AID
In case of skin contact, wash thoroughly with soap and water. For eye contact, ush immediately with plenty of water; contact physician immediately. For respiratory problems, remove to fresh air. Wash clothing before reuse.

CLEANUP
Collect with absorbent material, ush with water. Dispose of in accordance with local disposal regulations. Uncured material can be removed with approved solvent. Cured materials can only be removed mechanically.

TYFO® S COMPOSITE SAMPLES
Please note that field samples are to be cured for 48-hours at 140° F (60° C) before testing. Testing shall be in accordance with ASTM D-3039 and the Fyfe Co. LLC sample preparation and testing procedures.

SHIPPING LABELS CONTAIN
- State specification number with modifications, if applicable
- Component designation
- Type, if applicable
- Manufacturer's name
- Date of manufacture
- Batch name
- State lot number, if applicable
- Directions for use
- Warnings or precautions required by law

KEEP CONTAINER TIGHTLY CLOSED.
NOT FOR INTERNAL CONSUMPTION.
CONSULT MATERIAL SAFETY DATA SHEET (MSDS) FOR MORE INFORMATION.
KEEP OUT OF REACH OF CHILDREN.
FOR INDUSTRIAL USE ONLY.

Fyfe Co. LLC

"The Fibrwrap® Company"
Nancy Ridge Technology Center
6310 Nancy Ridge Drive, Suite 103, San Diego, CA 92121
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Product Data Sheet
Edition 7.27.2004
Identification no. 332-30
SikaWrap Hex 103C

Construction

SikaWrap® Hex 103C

Carbon fiber fabric for structural strengthening

Description

SikaWrap Hex 103C is a high strength, unidirectional carbon fiber fabric. Material is field laminated using Sikadur 300, Sikadur Hex 300 or Sikadur Hex 306 epoxy to form a carbon fiber reinforced polymer (CFRP) used to strengthen structural elements.

Where to Use

Load increases

- Increased live loads in warehouses
- Increased traffic volumes on bridges
- Installation of heavy machinery in industrial buildings
- Vibrating structures
- Changes of building utilization

Seismic strengthening

- Column wrapping
- Masonry walls

Damage to structural parts

- Aging of construction materials
- Vehicle impact
- Fire
- Blast resistance

Change in structural system

- Removal of walls or columns
- Removal of slab sections for openings

Design or construction defects

- Insufficient reinforcements
- Insufficient structural depth

Advantages

- Approved by ICBO/ICC ER-5558.
- Used for shear, confinement or flexural strengthening.
- Flexible, can be wrapped around complex shapes.
- High strength.
- Light weight.
- Non-corrosive.
- Alkali resistant.
- Low aesthetic impact.

Packaging

Rolls: 25 in. x 50 ft.; 25 in. x 300 ft. **Kits:** Pre-measured kits containing 25 in. x 50 ft. (104 $ft.^2$) roll of fabric and 4 gallons of Sikadur Hex 300/306 epoxy.

How to Use

Surface Preparation

Surface must be clean and sound. It may be dry or damp, but free of standing water and frost. Remove dust, laitance, grease, curing compounds, impregnations, waxes, foreign particles, disintegrated materials and other bond inhibiting materials from the surface. Consult Sikadur 300, Sikadur Hex 300/306 and Sikadur 330 technical data sheets for additional information on surface preparation.
Existing uneven surfaces must be filled with an appropriate repair mortar. The adhesive strength of the concrete must be verified after surface preparation by random pull-off testing (ACI 503R) at the discretion of the engineer. Minimum tensile strength, 200 psi (1.4 MPa) with concrete substrate failure.

Typical Data

Storage Conditions	Store dry at 40°-95°F (4°-35°C)
Color	Black
Primary Fiber Direction	0° (unidirectional)
Weight Per Square Yard	18 oz. (618 g/m^2)

Fiber Properties

Tensile Strength	5.5×10^5 psi (3,793 MPa)
Tensile Modulus	34×10^6 psi (234,500 MPa)
Elongation	1.5%
Density	0.065 $lbs./in.^3$ (1.8 g/cc)

Construction

Cured Laminate Properties with Sikadur Hex 300 Epoxy
Properties after standard cure followed by standard post cure.
[70°-75°F (21°-24°C) - 5 days and 48 hour post cure at 140°F (60°C)]

Property	Average Value[1] US Units psi	Average Value[1] SI Units MPa	Design Value[2] US Units psi	Design Value[2] SI Units MPa	ASTM Test Method
Tensile Strength*	123,200	849	104,000	717	D-3039
Tensile Modulus*	10,239,800	70,552	9,446,600	65,087	D-3039
Tensile % Elongation*	1.12	1.12	0.98	0.98	D-3039
140°F - Tensile Strength	123,000	847	101,400	699	D-3039
140°F - Tensile Modulus	10,136,900	69,843	9,156,500	63,088	D-3039
140°F - % Elongation	1.13	1.13	0.97	0.97	D-3039
Compressive Strength	113,000	779	103,800	715	D-695
Compressive Modulus	9,726,000	67,014	8,930,600	61,532	D-695
90 deg Tensile Strength	3,500	24	2,300	16	D-3039
90 deg Tensile Modulus	705,500	4,861	576,700	3,973	D-3039
90 deg % Tensile Elongation	0.45	0.45	0.33	0.33	D-3039
Shear Strength +/-45 In Plane	7,500	52	6,700	46	D-3518
Shear Modulus +/-45 In Plane	362,500	2,498	347,500	2,394	D-3518
Ply Thickness (inch/mm)	0.04	1.016	---	---	---
Tensile Strength per inch width	4,928 lbs.	21.9 kN	4,160 lbs.	18.5kN	D-3039

* 24 sample coupons per test series; all other values based on 6 coupon test series
[1] Average value of test series
[2] Average value minus 2 standard deviations

Cured Laminate Properties with Sikadur Hex 306 Epoxy
Properties after standard cure followed by standard post cure.
[70°-75°F(21°-24°C) - 5 days and 48 hour post cure at 140°F(60°C)]

Property	Average Value[1] US Units psi	Average Value[1] SI Units MPa	Design Value[2] US Units psi	Design Value[2] SI Units MPa	ASTM Test Method
Tensile Strength*	116,200	801	97,000	668	D-3039
Tensile Modulus*	9,754,500	67,209	8,421,100	58,021	D-3039
Tensile % Elongation*	1.13	1.13	0.99	0.99	D-3039
140°F - Tensile Strength	117,700	811	102,700	708	D-3039
140°F - Tensile Modulus	10,107,800	69,641	9,478,200	65,305	D-3039
140°F - % Elongation	1.10	1.10	0.94	0.94	D-3039
Compressive Strength	93,300	643	55,900	385	D-695
Compressive Modulus	9,755,100	67,213	8,678,700	59,796	D-695
90 deg Tensile Strength	4,100	28	3,300	23	D-3039
90 deg Tensile Modulus	651,700	4,490	586,700	4,042	D-3039
90 deg % Tensile Elongation	0.64	0.64	0.52	0.52	D-3039
Shear Strength +/-45 In Plane	7,100	49	6,100	42	D-3518
Shear Modulus +/-45 In Plane	344,300	2,372	326,500	2,250	D-3518
Ply Thickness (inch/mm)	0.04	1.016			
Tensile Strength per inch width	4,648 lbs.	20.6 kN	3,880 lbs.	17.2kN	D-3039

Preparation Work: Concrete - Blast clean, shotblast or use other approved mechanical means to provide an open roughened texture.
In certain applications and at the engineer's discretion, the intimate contact between the substrate and the fabric may be determined to be non-critical. In these cases, a thorough cleaning of the substrate using low pressure sand or water blasting is sufficient.

Mixing
Consult Sikadur 300 or Sikadur Hex 300/306 data sheets for information on epoxy resins.

Application
Prior to placing the fabric, the concrete surface is primed and sealed using Sikadur 300 or Sikadur Hex 300 epoxy. Material may be applied by spray, brush or roller. SikaWrap Hex 103C can be impregnated using either the Sikadur Hex 300 or Sikadur Hex 306 epoxy. For best results on larger projects, the impregnation process should be accomplished using a mechanically driven fabric saturator or similar device. In special cases where the size of the project does not justify the use of a saturator, the fabric may saturate by hand using a roller prior to placement. In either case, installation of this system should be performed only by a specially trained, approved contractor.
For overhead or vertical applications, prime concrete with Sikadur 30 or Sikadur 330 to improve tack. Saturate fabric with Sikadur 300, Sikadur Hex 300 or Sikadur Hex 306. Coat the exposed surface of final fabric layer using Sikagard 670W or Sikagard 62.

Cutting SikaWrap
Fabric can be cut to appropriate length by using a commercial quality heavy duty scissor. Since dull or worn cutting implements can damage, weaken or fray the fiber their use should be avoided. Consult MSDS for proper handling procedures.

Limitations
- Design calculations must be made and certified by an independent licensed professional engineer.
- System is a vapor barrier. Concrete should not be encapsulated in areas of freeze/thaw.

Caution
SikaWrap fabric is non-reactive. However, caution must be used when handling since a fine "carbon dust" may be present on the surface. Gloves must therefore be worn to protect against skin irritation.
Caution must also be used when cutting SikaWrap fabric to protect against airborne carbon dust generated by the cutting procedure. Use of an appropriate, properly fitted NIOSH approved respirator is recommended.

KEEP CONTAINER TIGHTLY CLOSED — KEEP OUT OF REACH OF CHILDREN
NOT FOR INTERNAL CONSUMPTION — FOR INDUSTRIAL USE ONLY
CONSULT MATERIAL SAFETY DATA SHEET FOR MORE INFORMATION

Visit our website at www.sikausa.com — **1-800-933-SIKA NATIONWIDE**

Regional Information and Sales Centers. For the location of your nearest Sika sales office, contact your regional center.

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Sika Mexicana S.A. de C.V.
Carretera Libre Celaya Km. 8.5
Corregidora, Queretaro
C.P. 76920 A.P. 136
Phone: 52 42 25 0122
Fax: 52 42 25 0537

QUALITY ISO 9001 9002 ACHIEVEMENT

Quality Certification Numbers: Lyndhurst: FM 69711 (ISO 9000), FM 70421 (QS 9000), Marion: FM 69715, Kansas City: FM 69107, Santa Fe Springs: FM 69408

Wabo®MBrace CF 530

Unidirectional High Modulus Carbon Fiber Fabric

for the Wabo®MBrace Composite Strengthening System

DESCRIPTION:

Wabo®MBrace Carbon Fiber Fabrics are dry fabrics constructed of very high strength, aerospace grade carbon fibers. These fabrics are applied onto the surface of existing structural members in buildings, bridges, and other structures using the Wabo®MBrace family of performance polymers. The result is an externally bonded FRP (fiber reinforced polymer) reinforcement system that is engineered to increase the strength and structural performance of these members. Once installed, the Wabo®MBrace System delivers externally bonded reinforcement with outstanding long-term physical and mechanical properties.

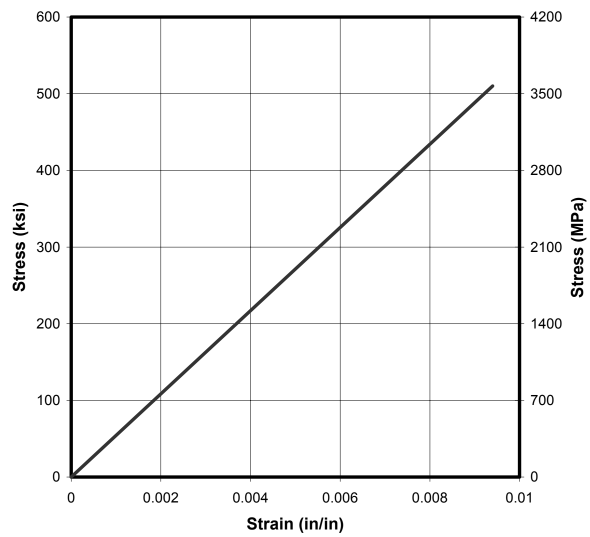
RECOMMENDED FOR:

Wabo®MBrace CF 530 is one of a variety of fiber reinforcements used in the Wabo®MBrace System. Fiber reinforcements are the backbone of the Wabo®MBrace system and provide the system's strength. Wabo®MBrace CF 530 Fiber Reinforcement is typically used in the following applications:

- Upgrade load bearing capacities of concrete and masonry structures
- Increase bending strength and stiffness of concrete beams, slabs, and walls
- Increase shear strength of concrete beams and walls
- Enhance fatigue endurance of concrete members
- Improve the capacity of concrete silos, pipes, tanks, and tunnels
- Seismic Retrofit
- Improve strength and ductility of concrete columns
- Provide additional confinement and strength to concrete connections
- Prevent shear failure of concrete beams and walls
- Strengthening of steel members

FEATURES / BENEFITS:

- High strength, very high stiffness
- Lightweight
- Highly durable, non-corrosive
- Low installation time
- Easy to conceal, minimal change to existing member dimensions
- Forms around complex surface shapes



PACKAGING:

Available in the following units:

Unit	Width	Length
540 ft^2(50 m^2)	24 in (610 mm)	270 ft (82 m)
200 ft^2 (18.6 m^2)	24 in (610 mm)	100 ft (30.5 m)

COLOR:

Black

STORAGE AND HANDLING:

degussa.
Construction Chemicals

Store in a cool, dry area [50 to 90 °F (10 to 32 °C)] away from direct sunlight, flame, or other hazards.

Wabo®MBrace Fiber Reinforcements contain carbon, glass, and/or aramid fibers. While handling Wabo®MBrace Fiber Reinforcements, wear appropriate work clothing to minimize contact.

Product Material Safety Data Sheets (MSDS) are available and should be consulted and on hand whenever handling these products.

These products are for professional and industrial use only and are only installed by trained and qualified applicators. Trained applicators must follow installation instructions.

MAINTENANCE:

Periodically inspect the applied material and repair localized areas as needed. Consult a Wabo®MBrace representative for additional information.

Visit us on the web for the most current product information and news:

www.wbacorp.com

Wabo®MBrace CF 530 *High Modulus Unidirectional Carbon Fiber Fabric*	
Physical Properties:	
Fiber Material:	High Modulus Carbon
Areal Weight:	0.062 lb/ft^2 [300 g/m^2]
Fabric Width:	24 in [610 mm]
Nominal Thickness, t_f (1)	0.0065 in/ply [0.165 mm/ply]
Functional Properties:	
CTE:	-0.46·10^{-6}/°F (-0.83·10^{-6}/°C)
Thermal Conductivity:	476-Btu·in/hr·ft^2·°F (68.7-W/m·K)
Electrical Resistivity:	1.0·10^{-3} Ω·cm
0° Tensile Properties (2,3)**:**	
Ultimate Tensile Strength, f^*_{fu}	510 ksi [3500 MPa]
Tensile Modulus, E_f	54000 ksi [373 GPa]
Ultimate Tensile Strength per Unit Width, $f^*_{fu}\,t_f$	3.31 kips/in/ply [0.577 kN/mm/ply]
Tensile Modulus per Unit Width, $E_f\,t_f$	351 kips/in/ply [62 kN/mm/ply]
Ultimate Rupture Strain, ε^*_{fu}	0.94 %
90° Tensile Properties (2,4)**:**	
Ultimate Tensile Strength:	0
Tensile Modulus:	0
Ultimate Rupture Strain:	n/a

NOTES:

(1) The nominal fabric thickness is based on the total area of fibers (only) in a unit width. From experience, the actual cured thickness of a single ply laminate (fibers plus saturating resins) is 0.020 to 0.040 in (0.6 to 1.0 mm).

(2) The tensile properties given are those to be used for design. These values are derived by testing cured laminates (per ASTM D3039) and dividing the resulting strength and modulus per unit width by the nominal fabric thickness.

(3) The 0° direction denotes the direction along the length of the fabric.

(4) The 90° direction denotes the direction along the width of the fabric.

LIMITED WARRANTY:

Watson Bowman Acme Corp. warrants that this product conforms to its current applicable specifications. WATSON BOWMAN ACME CORP. MAKES NO OTHER WARRANTY, EXPRESS OR IMPLIED, INCLUDING ANY WARRANTY OF MERCHANTABILITY OR WARRANTY OF FITNESS FOR A PARTICULAR PURPOSE. The sole and exclusive remedy of Purchaser for any claim concerning this product, including, but not limited to, claims alleging breach of warranty, negligence, strict liability or otherwise, is the replacement of product or refund of the purchase price, at the sole option of Watson Bowman Acme Corp. Any claims concerning this product shall be submitted in writing within one year of the delivery date of this product to Purchaser and any claims not presented within that period are waived by Purchaser. IN NO EVENT SHALL WATSON BOWMAN ACME CORP. BE LIABLE FOR ANY SPECIAL, INCIDENTAL, CONSEQUENTIAL (INCLUDES LOSS OF PROFITS) OR PUNITIVE DAMAGES.
Other warranties may be available when the product is installed by a Wabo-certified installer. Contact your local Wabo representative for details.
The data expressed herein is true and accurate to the best of our knowledge at the time published; it is, however, subject to change without notice.

Contact
Watson Bowman Acme Corp. 95 Pineview Drive, Amherst, NY 14228
phone:716-691-7566 / fax: 716-691-9239 / email: info@wbacorp.com / web site: http://www.wbacorp.com

Appendix 3

Bond Strength Testing Equipment Information Sheets

elcometer

Elcometer 106 Pull off Adhesion Tester

Elcometer 106 Pull off Adhesion Tester

At a glance

- *Simple, low coat range of adhesion gauges for measuring coating adhesion.*
- *Dependant on model, the adhesive from "0"-22 MPa /"0"-3200 PSI can be measured quickly & reliably.*

Can be used in accordance with:	
ANSI N5.12	ASTM D 4541
BS EN 24624	ISO 4624
NF T 30-062	

Elcometer 106 Pull off Adhesion Tester

The Elcometer 106 Adhesion Tester - easy to operate and fully portable, provides a numerical value for adhesion. Applications include: paint or plasma spray on bridge decking, coatings on steel, aluminium or concrete, etc.

- Comes in a carrying case – ideal for site tests
- Hand operated so you don't have to worry about a power supply!

Test Method

A test dolly is bonded to the coating using an adhesive. The 106 houses a spring arrangement which applies a lift force to the dolly.

When the dolly is pulled off the surface, an indicator on the scale shows the numerical value of adhesion expressed in terms of the force required to remove the dolly.

Test from low adhesion values of 5-30 PSI (0.05 - 0.2 N/mm²) up to 500 - 3200 PSI (5 - 22 N/mm²)

For an approximate value in kg/cm² multiply N/mm² by 10.

Adhesion

From the largest man-made structures to the smallest household appliances, most manufactured products have a protective or cosmetic coating. Premature failure of this coating can, at the very least, result in costly penalties or rework.

Adhesion testing during the coating process will quantify the strength of the bond between substrate and coating, or between different coating layers or the cohesive strength of some substrates. Routine testing is also used as part of inspection and maintenance procedures to help detect potential coating failures.

Elcometer offer a highly comprehensive range of Adhesion Gauges designed specifically to meet your requirements. These gauges can be split into three categories:

Cross Hatch / Cross Cut Method

The coating is cut into small squares, thereby reducing lateral bonding, and the adhesion assessed against ISO, ASTM or Corporate Standards

Pull Off Adhesion Method

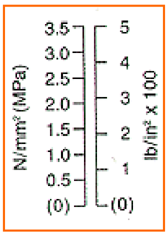
Tensile Dollies (or stubs) are glued to the coating and, once the adhesive has cured, the force required to pull the dolly off the surface is measured.

Push Off Adhesion Method

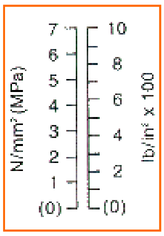
Similar to the Pull Off Adhesion Test, a dolly is glued to the coating, once the adhesive has cured, however, the dolly is pushed off the surface by the adhesion gauge.

The Elcometer 106 Adhesion Tester is available in 5 scale ranges, please take note of the appropriate adhesion value of the equipment before ordering.

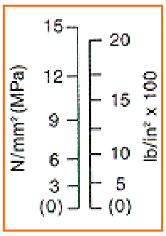
Scale 1



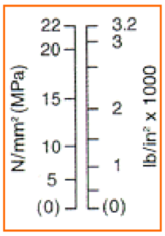
Scale 2



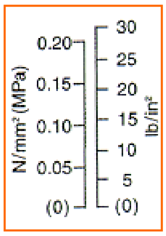
Scale 3



Scale 4



Scale 5



Instrument Dimensions	*Height*: 152mm (6.0")	*Diameter*: 76mm (3.0")	
Dolly Size	*Diameter*: 20mm (0.76")	*Area*: 314mm² (0.5sq inch)	
Gross Weight of Kit in Case	*Scales 1, 2 & 5*: 2.1kg (4.7lb)	*Scale 3*: 3.4kg (7.5lb)	*Scale 4*: 3.6kg (8.0lb)

Model	**Description**	**Range**		**Part Number**
		N/mm² (Mpa)	**PSI**	
Elcometer 106/5	Elcometer 106 Adhesion Tester – Scale 5	(0) – 0.2	(0) – 30	F106----5
Elcometer 106/1	Elcometer 106 Adhesion Tester – Scale 1	(0) – 3.5	(0) – 500	F106----1
Elcometer 106/2	Elcometer 106 Adhesion Tester – Scale 2	(0) – 7	(0) – 1000	F106----2
Elcometer 106/3	Elcometer 106 Adhesion Tester – Scale 3	(0) – 15	(0) – 2000	F106----3
Elcometer 106/4	Elcometer 106 Adhesion Tester – Scale 4	(0) – 22	(0) – 3200	F106----4
Accessories	Spare Dollies (Pack of 100)			T1062895-
	Large Dollies 40mm Diameter (Pack of 5)			T1062914-
	Large Base Ring			T1062915-
	Araldite Epoxy Adhesive			T99912906

HOW TO SELECT THE CORRECT ADHESION GAUGE

Cross Hatch Cutters

Advantages:
A fast, low cost, comparison method – *see table below*

Possible Limitations:
A subjective test for flat surfaces for a limited thickness range.

Applications:
Paint and powder coating adhesion up to a thickness of 125µm (5 mils).

Pull Off Adhesion Testers

Advantages:
Simple to use, quantitative range – giving you a definitive adhesion value

Possible Limitations:
Time required for adhesive to cure

Applications:
Ideal gauge for the laboratory or field – flat or curved substrate applications

Push Off Adhesion Testers

Advantages:
Fast cure time adhesives can be used, ideal for curved surfaces

Possible Limitations:
High forces exerted by gauge may cause thin substrates to deform

Applications:
Pipelines and metal spray coatings.

Related products

Elcometer 108

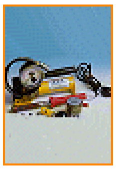
An extremely versatile hydraulic adhesion tester which will cope with many adhesion test requirements. Test can be made on flat or curved (concave and convex) surfaces. A reusable dolly is adhered to the coating's surface and the force required to push the dolly from the surface is applied using the handle. The value of the force applied is displayed either on a digital display or on an analogue dial.

Elcometer 110

The Elcometer 110 Patti® is a portable pneumatic adhesion tester which uses compressed gas from either a canister or the compressed air feed. Due to the controlled force being applied, the resultant adhesion value is highly repeatable. This, together with the gauge's suitability on thin substrates provides the User with an ideal testing instrument in the laboratory or the field.

Elcometer 1910

This lightweight, portable, hydraulic adhesion tester has built in hydraulic safety devices for smooth and drift proof accuracy. The special test head allows adhesion tests on both internal and external curved surfaces, making this an ideal gauge for pipelines and protective coatings applications.



Elcometer 1940

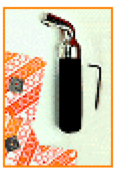
The most popular in the Elcometer PAT tester range, a manual hydraulic tensile adhesion tester for measuring the bond strength of all types of paints, thermal sprayed coatings, thin films, concrete coatings, ceramics, etc. A portable, precision gauge with both MPa and PSI readings which gives accurate and comparable test results both in the laboratory and on site.

Elcometer 1941

A 20 or 40kN manual hydraulic tensile adhesion tester for testing of coatings (including thermal sprayed coatings), on test panels, sprayed components. Designed for testing with 50mm (2") diameter test elements and with the square 50 x 50mm (2 x 2") test element for adhesion testing of tile adhesives and other cementitious materials.

Elcometer 1970

For use with the Elcometer PAT, Elcometer 106, and Elcometer 108 Adhesion Testers, this Portable Field Calibration Verification Unit is ideal for confirming your adhesion gauge calibration. Connect the appropriate pull stub to the unit, pull your adhesion tester and compare the adhesion tester reading to the reading on the Portable Calibration Unit's Display.



Elcometer 107

The coating may be continuous and look good, but how well is it connected to the substrate? The Elcometer 107 cross hatch cutter provides an instant assessment of the quality of the bond to the substrate. Due to its rugged construction this gauge is ideal for thin, thick or tough coatings on flat or curved surfaces. An ideal field or laboratory test.

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Specifications

Dolly Size	20 mm
Resolution	± 1 psi (0.01 MPa)
Accuracy	± 1% Full Scale
Adhesion Strength	0 – 3000 psi (0 – 20 MPa)

Each Kit includes:

- Adhesion tester with digital display
- 20 mm aluminum test dollies (20)
- Abrasive pad
- Cutting tool
- Adhesive with mixing sticks and palettes
- Cotton swabs
- AAA batteries (2)
- Instruction booklet
- Certificate of Calibration traceable to NIST
- Instructional video
- One-year warranty
- Sturdy, lightweight carrying case

Kit Weight (with case): 12 lbs / 5.5 kg

Carrying Case Dimensions: L – 17 in / 43 cm
W – 13 in / 33 cm
H – 6 in / 15 cm

Options

- **50 mm Accessory Kit**
  - Ideal for lower bond strength finishes such as coatings on wood, concrete and plastic
  - Larger surface area of dolly provides improved low range precision and repeatability
  - Range 0 – 500 psi (0 – 3.5 MPa)
  - Includes 50 mm stand-off, 50 mm hole saw and 50 mm aluminum test dollies (12)
- **Drilling Template for 50 mm Dollies –** Drilling template and drill bits to isolate test area, ideal for thicker coatings on concrete
- **PosiSoft® for Windows® analysis software –** see details on previous page
- **Adhesive Kit –** Additional adhesive, mixing sticks, palettes and cotton swabs
- **Dollies**
  - Additional supplies of standard 20 mm and 50 mm dollies
  - Custom 10 mm and 14 mm dollies

50 mm Accessory Kit

DeFelsko®
The Measure of Quality

DeFelsko Corporation
802 Proctor Ave., P.O. Box 676 • Ogdensburg, New York 13669 USA
Phone: 315-393-4450 • Fax: 315-393-8471 • Email: techsale@defelsko.com
Toll Free: 1-800-448-3835 • Web: www.defelsko.com

MADE IN THE USA

NEW

PosiTest® *Pull-Off Adhesion Tester*

Now Digital... ***Measures adhesion of coatings to metal, wood, concrete and other substrates – revolutionary self-alignment feature and pull rate indicator***

DeFelsko®
The Measure of Quality

PosiTest® *Pull-Off Adhesion Tester*

Measures the force required to pull a specified test diameter of coating away from its substrate using hydraulic pressure. The pressure is displayed in psi or MPa on a precision digital indicator.

Simple

- Portable, hand-operated instrument requires no external power source – ideal for lab and field use
- NEW Large, easy-to-read LCD
- NEW Pull Rate Indicator – allows operator to easily monitor and adjust the rate of pull in accordance with international test methods
- NEW Easily select dolly sizes, change measurement units or store readings, with the touch of a button
- NEW Conversion charts not required – tester automatically calculates pressure based on dolly size
- Inexpensive, single-use dollies eliminate cleaning for re-use and can be kept as a permanent record
- Each kit comes with everything needed for testing

Durable

- Weatherproof, dustproof and shockproof
- Quality hydraulic pump can be used in any position
- Rugged carrying case
- One year warranty

Accurate

- Every PosiTest Adhesion Tester pressure system is calibrated and certified to ± 1% accuracy using an NIST traceable load cell
- Self-aligning dolly enables accurate measurements on smooth or uneven surfaces
- Hi-grade, industrial pressure sensor ensures continued accuracy
- Conforms with ASTM D4541, ISO 4624 and others

Versatile

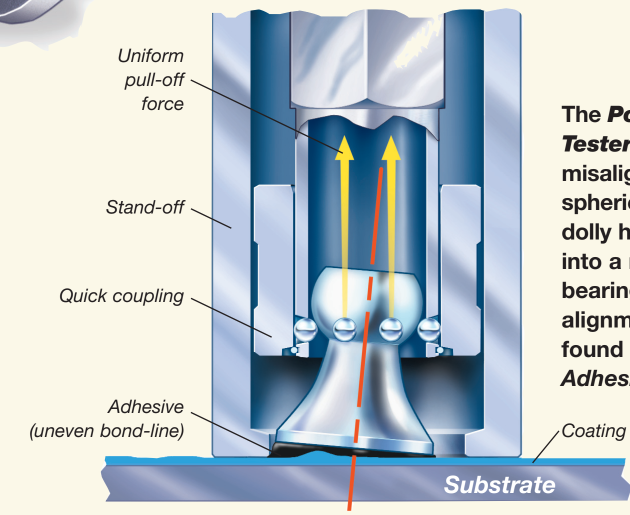
- NEW Internal Memory stores maximum pull-off pressure, rate of pull, test duration and dolly size for up to 200 pulls
- NEW Optional PosiSoft® software available for downloading to a computer
- 10, 14, 20 or 50 mm dollies maximize capability and accuracy across a wide range of bond strengths
- LCD displays pressure value in psi or MPa

__Test Dollies:__ The PosiTest Adhesion Tester uses inexpensive single-use aluminum dollies designed according to internationally accepted standards and practices. Available with full 10, 14, 20 or 50 mm surface diameters for different shapes and bond strengths.

Self-Alignment Feature

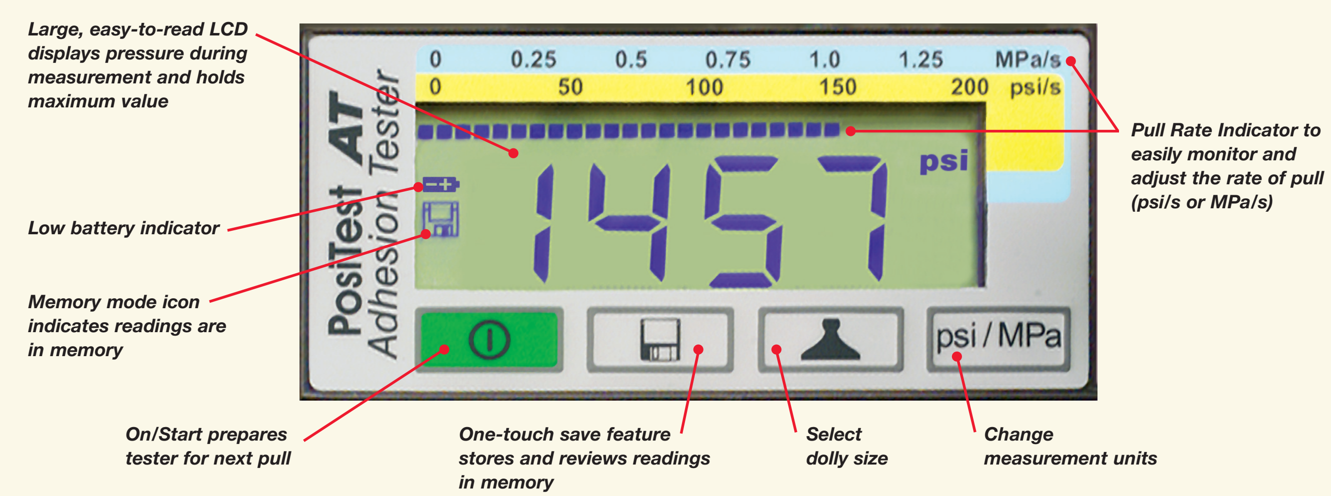
Unequal pulling force during testing caused by uneven adhesive bond lines and coating surfaces can result in random, unexplainable readings. To obtain more repeatable and meaningful adhesion measurements, it is imperative that the pulling force applied to the test dolly is uniformly distributed over the surface being tested.

The Self-Aligning Dolly enables uniform distribution of the pulling force over the surface being tested, preventing a one-sided pull-off.



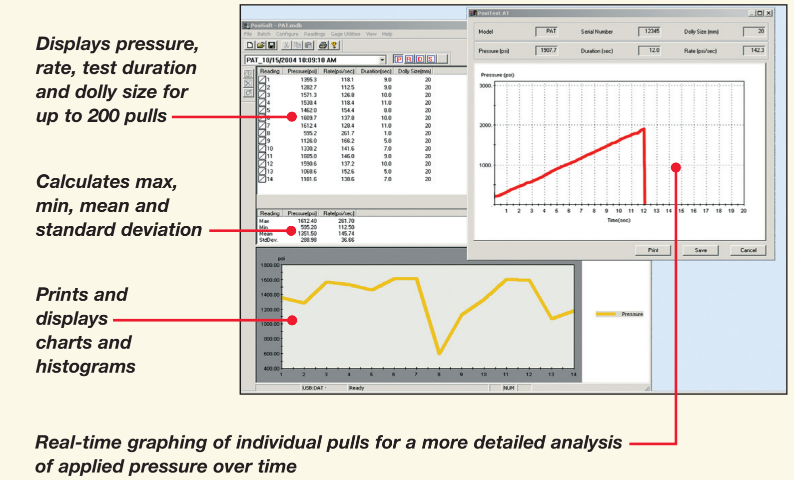
The *PosiTest Adhesion Tester* compensates for misalignment. The uniquely spherical articulating dolly head is engaged into a ring of small ball bearings, ensuring correct alignment. This feature is found only on the *PosiTest Adhesion Tester.*

New Digital LCD *(shown actual size)*



PosiSoft® Software for Windows® *(optional)*

- Ideal solution for those who wish to download to a PC for printing or archiving
- Allows entry of notes and annotations
- Multi-language support including English, German, Italian, Spanish and French
- Exports to a document or spreadsheet
- Includes USB cable for computer hook-up



Appendix 4
ASTM C 293-02

Designation: C 293 – 02

Standard Test Method for Flexural Strength of Concrete (Using Simple Beam With Center-Point Loading)[1]

This standard is issued under the fixed designation C 293; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

This standard has been approved for use by agencies of the Department of Defense.

1. Scope

1.1 This test method covers determination of the flexural strength of concrete specimens by the use of a simple beam with center-point loading. It is not an alternative to Test Method C 78.

1.2 The values stated in inch-pound units are to be regarded as standard. The SI equivalent of inch-pound units has been rounded where necessary for practical application.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

C 31 Practice for Making and Curing Concrete Test Specimens in the Field[2]

C 78 Test Method for Flexural Strength of Concrete (Using Simple Beam with Third Point Loading)[2]

C 192 Practice for Making and Curing Concrete Test Specimens in the Laboratory[2]

C 617 Practice for Capping Cylindrical Concrete Specimens[2]

C 1077 Practice for Laboratories Testing Concrete and Concrete Aggregates for Use in Construction and Criteria for Laboratory Evaluation[2]

E 4 Practices for Force Verification of Testing Machines[3]

3. Significance and Use

3.1 This test method is used to determine the modulus of rupture of specimens prepared and cured in accordance with Practices C 31 or C 192. The strength determined will vary where there are differences in specimen size, preparation, moisture condition, or curing.

3.2 The results of this test method may be used to determine compliance with specifications or as a basis for proportioning, mixing and placement operations. This test method produces values of flexural strength significantly higher than Test Method C 78 (Note 1).

NOTE 1—The testing laboratory performing this test method may be evaluated in accordance with Practice C 1077.

4. Apparatus

4.1 The testing machine shall conform to the requirements of the sections on Basis of Verification, Corrections, and Time Interval Between Verifications of Practices E 4. Hand operated testing machines having pumps that do not provide a continuous loading to failure in one stroke are not permitted. Motorized pumps or hand operated positive displacement pumps having sufficient volume in one continuous stroke to complete a test without requiring replenishment are permitted and shall be capable of applying loads at a uniform rate without shock or interruption.

4.2 *Loading Apparatus*—The mechanism by which forces are applied to the specimen shall employ a load-applying block and two specimen support blocks. It shall ensure that all forces are applied perpendicular to the face of the specimen without eccentricity. A diagram of an apparatus that accomplishes this purpose is shown in Fig. 1.

4.2.1 All apparatus for making center-point loading flexure tests shall be similar to Fig. 1 and maintain the span length and central position of the load-applying block with respect to the support blocks constant within ±0.05 in. (±1.3 mm).

4.2.2 Reactions shall be parallel to the direction of the applied load at all times during the test, and the ratio of the horizontal distance between the point of load application and nearest reaction to the depth of the beam shall be 1.5 ± 2 %.

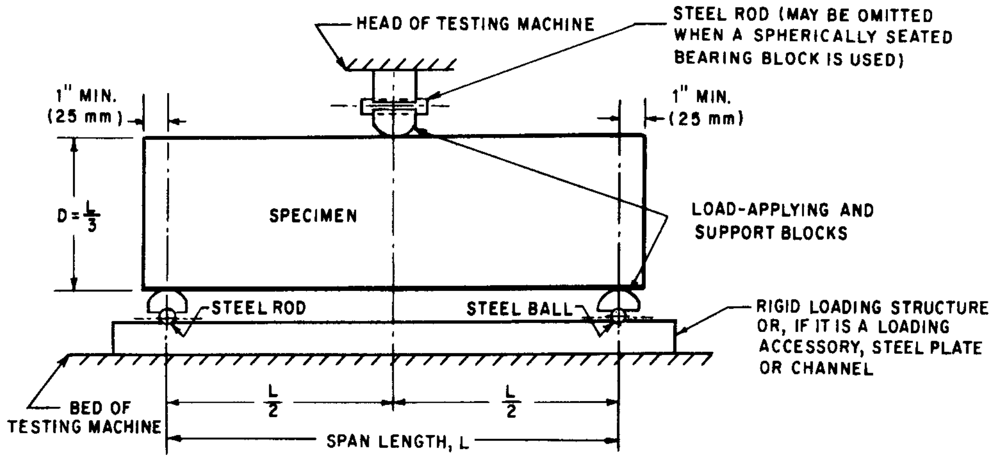
4.2.3 The load-applying and support blocks shall not be more than 2½ in. (64 mm) high, measured from the center or the axis of pivot, and shall extend at least across the full width of the specimen. Each hardened bearing surface in contact with the specimen shall not depart from a plane by more than 0.002 in. (0.05 mm) and shall be a portion of a cylinder, the axis of which is coincidental with either the axis of the rod or center of the ball, whichever the block is pivoted upon. The angle subtended by the curved surface of each block shall be at least

[1] This test method is under the jurisdiction of ASTM Committee C09 on Concrete and Concrete Aggregatesand is the direct responsibility of Subcommittee C09.61 on Testing for Strength.

Current edition approved Feb. 10, 2002. Published April 2002. Originally published as C 293 – 52 T. Last previous edition C 293 – 00.

[2] *Annual Book of ASTM Standards*, Vol 04.02.

[3] *Annual Book of ASTM Standards*, Vol 03.01.



NOTE 1—Apparatus may be used inverted.

FIG. 1 Diagrammatic View of a Suitable Apparatus for Flexure Test of Concrete by Center-Point Loading Method.

45° (0.79 rad). The load-applying and support blocks shall be maintained in a vertical position and in contact with the rod or ball by means of spring-loaded screws that hold them in contact with the pivot rod or ball. The rod in the center load-applying block in Fig. 1 may be omitted when a spherically seated bearing block is used.

5. Test Specimen

5.1 The test specimen shall conform to all requirements of Practice C 31 or C 192 applicable to beam and prism specimens and shall have a test span within 2 % of being three times its depth as tested. The sides of the specimen shall be at right angles with the top and bottom. All surfaces shall be smooth and free of scars, indentations, holes, or inscribed identification marks.

6. Procedure

6.1 Flexural tests of moist-cured specimens shall be made as soon as practical after removal from moist storage. Surface drying of the specimen results in a reduction in the measured modulus of rupture.

6.2 Turn the test specimen on its side with respect to its position as molded and center it on the support blocks. Center the loading system in relation to the applied force. Bring the load-applying block in contact with the surface of the specimen at the center and apply a load of between 3 and 6 % of the estimated ultimate load. Using 0.004 in. (0.10 mm) and 0.015 in. (0.38 mm) leaf-type feeler gages, determine whether any gap between the specimen and the load-applying or support blocks is greater or less than each of the gages over a length of 1 in. (25 mm) or more. Grind, cap, or use leather shims on the specimen contact surface to eliminate any gap in excess of 0.004 in. (0.10 mm). Leather shims shall be of uniform ¼ in. (6.4 mm) thickness, 1 to 2 in. (25 to 50 mm) in width, and shall extend across the full width of the specimen. Gaps in excess of 0.015 in. (0.38 mm) shall be eliminated only by capping or grinding. Grinding of lateral surfaces shall be minimized inasmuch as grinding may change the physical characteristics of the specimens. Capping shall be in accordance with Practice C 617.

6.3 Load the specimen continuously and without shock. The load shall be applied at a constant rate to the breaking point. Apply the load so that the extreme fiber stress increases at a rate betweeen 125 and 175 psi/min (0.9 and 1.2 MPa/min). The loading rate is computed using:

$$r = 2Sbd^2/3L \quad (1)$$

where:
r = loading rate, lb/min (MN/min),
s = rate of increase in extreme fiber stress, psi/min (MPa/min),
b = average width of the specimen, in. (mm),
d = average depth of the specimen, in. (mm), and
L = span length, in. (mm).

7. Measurement of Specimens After Test

7.1 To determine the dimensions of the specimen section for use in calculating modulus of rupture, take measurements across one of the fractured faces after testing. For each dimension, take one measurement at each edge and one at the center of the cross section. Use the three measurements for each direction to determine the average width and the average depth. Take all measurements to the nearest 0.05 in. (1 mm). If the fracture occurs at a capped section, include the cap thickness in the measurement.

8. Calculation

8.1 Calculate the modulus of rupture as follows:

$$R = 3\,PL/2bd^2 \quad (2)$$

where:
R = modulus of rupture, psi, or MPa,
P = maximum applied load indicated by the testing machine, lbf, or N,
L = span length, in., or mm,
b = average width of specimen, at the fracture, in., or mm, and
d = average depth of specimen, at the fracture, in., or mm.

NOTE 2—The weight of the beam is not included in the above calculation.

9. Report

9.1 Report the following information:

9.1.1 Identification number,

9.1.2 Average width to the nearest 0.05 in. (1 mm), at the fracture,

9.1.3 Average depth to the nearest 0.05 in. (1 mm), at the fracture,

9.1.4 Span length in inches (or millimetres),

9.1.5 Maximum applied load in pounds-force (or newtons),

9.1.6 Modulus of rupture calculated to the nearest 5 psi (0.05 MPa),

9.1.7 Record of curing and apparent moisture condition of the specimens at the time of test,

9.1.8 If specimens were capped, ground, or if leather shims were used,

9.1.9 Defects in specimens, and

9.1.10 Age of specimens.

10. Precision and Bias

10.1 *Precision*—The coefficient of variation of test results has been observed to be dependent on the strength level of the beams.[4] The single operator coefficient of variation has been found to be 4.4 %. Therefore, results of two properly conducted tests by the same operator on beams made from the same batch sample should not differ from each other by more than 12 %. The multilaboratory coefficient of variation has been found to be 5.3 %. Therefore, results of two different laboratories on beams made from the same batch sample should not differ from each other by more than 15 %.

10.2 *Bias*—Since there is no accepted standard for determining bias in this test method, no statement on bias is made.

11. Keywords

11.1 beams; concrete; flexural strength testing; modulus of rupture

[4] See "Improved Concrete Quality Control Procedures Using Third Point Loading" by P. M. Carrasquillo and R. L. Carrasquillo, Research Report 119-1F, Project 3-9-87-1119, Center For Transportation Research, The University of Texas at Austin, November 1987, for information as to the relationship of strength and variability under center point loading.