DEPARTMENT OF CIVIL AND ENIVORNMENTAL ENGINEERING, UNIVERISTY OF UTAH

The Bond Strength and Impact Resistance of Gigacrete Facing on Expanded Polystyrene for Highway Embankments

Technical Report Prepared by

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Introduction

This report discusses the bonding and impact resistant of Gigacrete™ used as a non-structural permanent facing for Expanded Polystyrene (EPS) geofoam embankments. Gigacrete™ is a mineral-cement based proprietary product manufactured and distributed by GigaCrete Inc. of Scottsdale, Arizona. The intended use of this product is to deploy it as a spray on application (e.g., similar to shotcreting) for the permanent facing and protection of free-standing geofoam embankments.

The exposed sides of a geofoam embankment must be covered to prevent long-term surface degradation of the EPS, mainly from UV degradation and to incidental damage of the geofoam from other environmental factors and from impact. The Boston Central Artery Tunnel (BCAT) Project, known as the "Big Dig" project, deployed an Exterior Insulation and Finishing System (**EIFS**) to cover and protect the EPS geofoam. For this project, approximately 10,000 square feet of EPS blocks were covered using dry mix process shotcrete (http://www.aulson.com/concreterepair.cfm). The EPS was prepared for shotcrete application by etching recessed notches with a heat-welding gun every 12 inches along the permanent face of the EPS structure in preparation for shotcrete adhesion. A wire mesh was fastened to the EPS face with glass-filled nylon fasteners and hook bolts were used to attach the wire mesh to the cast-in-place concrete barrier along the top of the EPS wall. Subsequently, workers applied a two-inch thick layer of dry mix process shotcrete at 400 feet per second along the EPS wall face creating an appearance similar to rubbed concrete.

However, the application explored herein is the direct application of a Gigacrete™ coating to the EPS without recessed notches. Important to this application is the bond strength that develops between the EPS and Gigacrete™. Because EPS wall systems are relatively new in the U.S. and because shotcrete facing is a developing technology, no AASHTO (American Association of State Highway and Transportation Officials) guidelines or specifications exist for this application. An EIFS project specification was developed for the "Big Dig" project (Appendix 1), which can be used a guide for evaluating the design and construction of future systems. However, this specification was developed for a specific project and product. Thus, parts of the "Big Dig" specification may not be applicable to other products and application methods.

This report evaluates the bond strength of Gigacrete™ when applied to EPS geofoam using test performance data performed by the University of Utah Departments of Civil and Environmental Engineering and Geology and Geophysics. Test data were gathered and evaluated for the Gigacrete™ – EPS interface for tension, shear and axial compression. In addition, tests were performed on the axial compression strength of Gigacrete™.

Test Procedures and Results

Expanded Polystyrene

The density, stiffness and strength of the selected EPS are important consideration for roadway and embankment applications. EPS density is that primary factor that determines its weight, strength, compressibility and post-yield behavior. Commonly manufactured EPS densities (kg/m^3) are: EPS12, EPS15, EPS19, EPS22, EPS29, EPS39 and EPS46, where EPS12 represents a density of 12 kg/m^3, etc.). For applications where EPS is placed under roadways, it is recommend that EPS19, or higher, be used to prevent overstressing and damaging of the EPS from wheel loads. For other areas, where trafficking atop the geofoam will not be required, lighter densities of EPS may be used. However, care should be taken not to overstress the geofoam.

The properties of EPS (dry density, compressive strength and flexural strength) are commonly determined by ASTM C578. The acceptance criteria are project specific. For most roadway applications, EPS19 (19 kg/m^3), or higher density, is recommended. For the bonding and impact evaluations discussed in this report, EPS19 was used. The properties of EPS19 were not extensively tested for this report, but they have been previously evaluated in Bartlett et al. (2000).

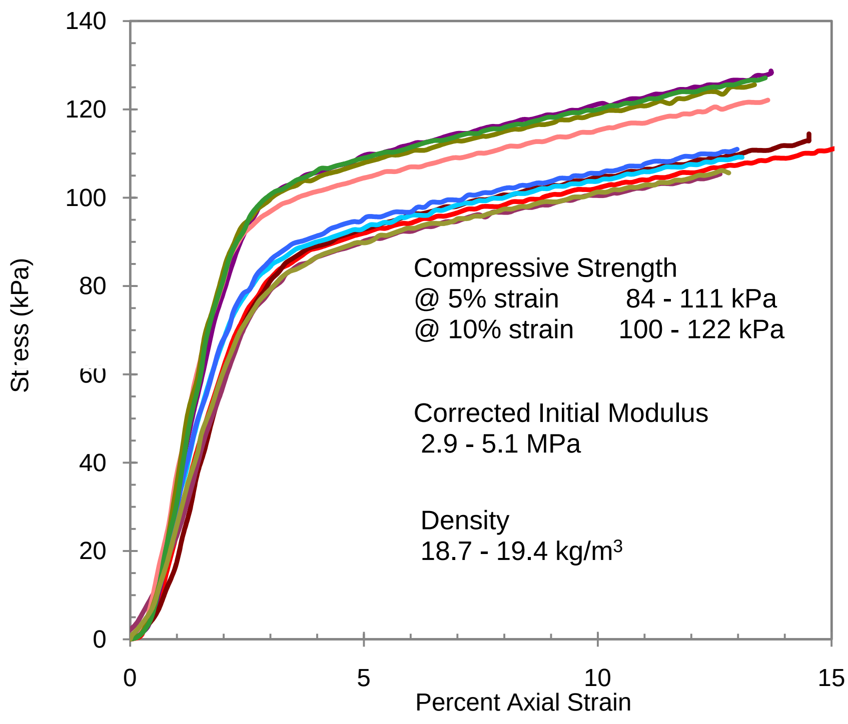

Figure 1. Unconfined Uniaxial Compression Stress-Strain Curves for EPS19 50-mm cubic samples (Bartlett et al. 2000).

The initial strain lag in these curves is due to uneven contact during testing and was adjusted. These data show that EPS19 reaches yield (i.e., plastic behavior) at axial strains of about 2 percent (Figure 2). The corrected initial Young's modulus for the tests shown in Figure 1 ranges from 2.9 to 5.1 MPa. The compressive strength at 5 and 10 percent strain was, on average, 97 and 111 kPa, respectively.

It should be noted that the results shown above should not be used for design of EPS embankments. Young moduli and unconfined compressive strengths calculated from small (i.e., 50-mm) cube samples (Figure 1) are generally too low and do not reflect the properties of large-sized EPS block used in embankment applications. Testing on large block samples performed at Syracuse University (Elragi et al. 2000) show that end and edge effects unduly influence moduli calculated from 50-mm cubes. Elragi et al. (2000) report Young moduli values of about 10 MPa for 2-foot (600 mm) cube samples for EPS20.

Compressive Strength of Gigacrete™

For EIFS, the facing material is not placed in compression, because it is a non-bearing structural facing. Thus the BCAT Project did not specify a performance criterion for compressive strength of the facing material. However, we performed three unconfined compressive strength tests on Gigacrete™ for comparative purposes with other shotcrete and stucco products.

Gigacrete™ samples were prepared in indoor conditions according to the manufacturer's recommendations. The mixture was placed in 4-inch (10-cm) diameter molds that were 8 inches (20 cm) high (Figure 2) and cured for 4, 10, and 12 days at 20 degrees C prior to unconfined compression testing.

Figure 2. Cylinder preparation for unconfined compressive strength tests.

After curing, the samples were placed in an actuator (Figure 3a) and loaded to until failure occurred (Figure 3b) in a manner similar to that required by ASTM C39. The compressive strength a 4, 10 and 12 day cure times were 5220 psi (36 MPa), 7100 psi (49 MPa) and 8190 psi (57 MPa), respectively. Figure 4 shows how the compressive strength of Gigacrete™ increases as a function of cure time. Obviously, higher strengths than those shown in Figure 4 are possible with longer cure times, but because determination of the compressive strength was not a primary objective of this study, we did not perform additional tests for longer cure times.

Figure 3. (a) Unconfined compression testing of Gigacrete™ cylinder, (b) Failure of Gigacrete sample.

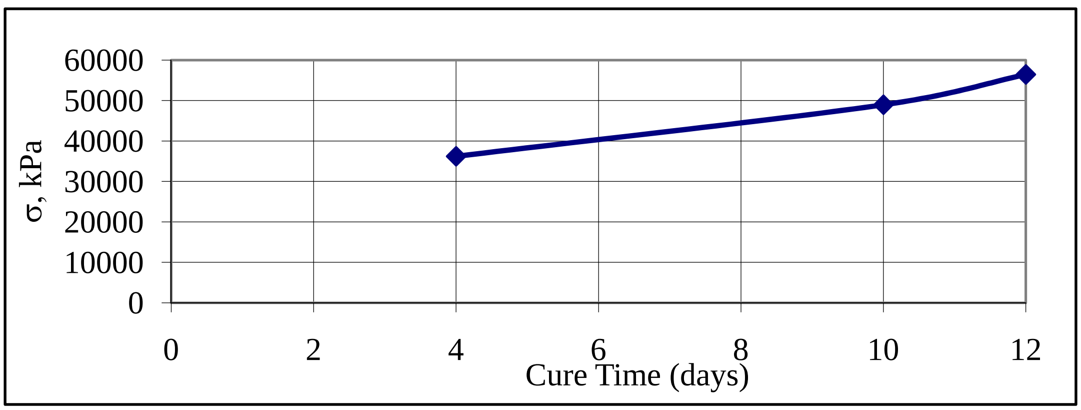

Figure 4. Gigacrete™ compressive strength gain as a function of cure time.

Interface Axial Extension Adhesion Bond Tests

For EIFS applications, the amount of adhesion bond that develops between the facing material and the EPS is an important property for the long-term performance and durability of the permanent facing. The BCAT Project acceptance criterion for EIFS is: "No failure in the adhesive base coat or finish coat. The insulation board shall fail cohesively except that 25 percent adhesive failure is acceptable. For tested values of nineteen (19) psi or greater, adhesive failure up to 100% is acceptable (Appendix 1, p. 8)."

The test method recommended by the BCAT project for determining bond strength is ASTM C297. This test method covers the determination of the core flatwise tension strength, or the bond between core and facings of an assembled sandwich panel. The test consists of subjecting a sandwich construction to a tensile load normal to the plane of the sandwich (Figure 5). The tensile load is transmitted to the sandwich through thick loading blocks bonded to the sandwich facings or directly to the core.

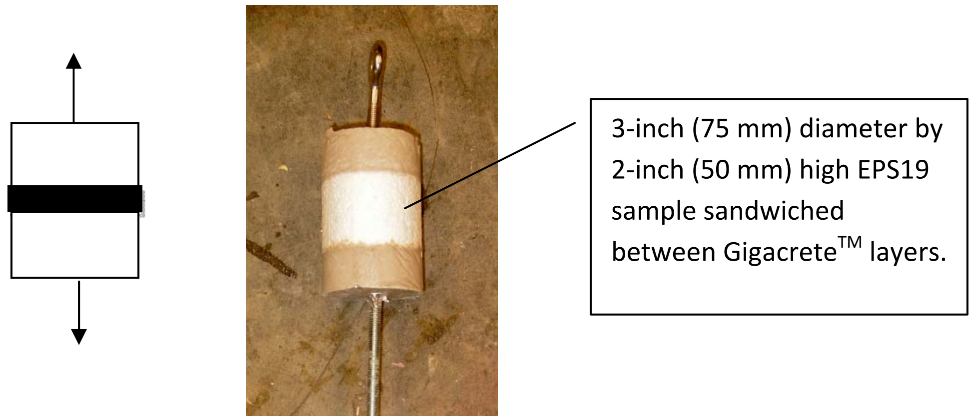

Figure 5. Laminated material subjected to tensile stress normal to the laminate plane to determine adhesion bond strength.

We evaluated the bond strength between EPS and Gigacrete™ in a manner similar to ASTM C297. A 3-inch (75-mm) concrete cylinder was used to mold the laminated sample. An eyebolt was anchored in the top layer of the Gigacrete™ and a threaded rod was anchored in the bottom layer (Figure 5). These were used to attach the weights to apply the normal tensile force.

Two samples were prepared an allowed to curve for 5 and 6 days, respectively. The specimens failed at a tensile stress of 39.6 psi (273 kPa) and 39.5 psi (272 kPa), respectively. Figure 6 shows the failure of specimens, which is a tensile failure of the EPS. In both cases, the bond between the EPS and the Gigacrete™ did not develop an adhesion failure; instead a "cohesive failure" developed with the EPS. Thus, the Gigacrete™-EPS laminate tested meets, or greatly exceeds, the requirements of the BCAT Project performance criterion for bond strength for EIFS (Appendix 1).

Figure 6. Tensile failure of laminated Gigacrete™ - EPS specimens.

In addition to the peak tensile strength, we measure the vertical deformation of the sample as the load was applied. These data are shown in Figure 7. These data suggest that the tensile failure in the EPS occurred at 4 and 20 percent axial strain.

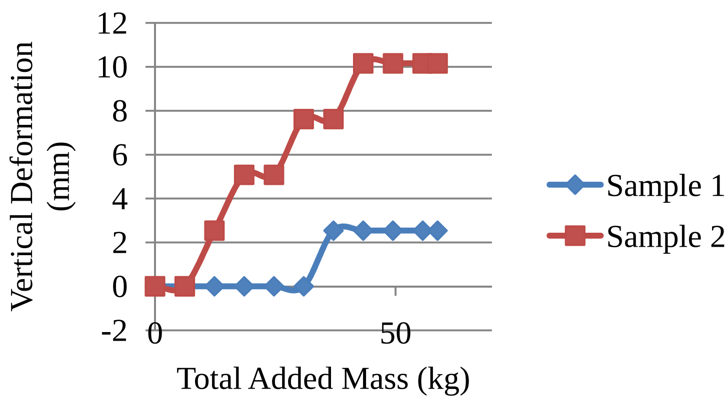

Figure 7. Vertical deformation versus load for laminated samples.

Interface Bond Direct Shear Tests

The shear bond that develops between the facing material and EPS is also important for the long-term durability of the permanent facing. Sufficient bonding in pure shear is required to prevent slippage between the facing material and the EPS when the stress is oriented parallel to the plane of the interface (Figure 8).

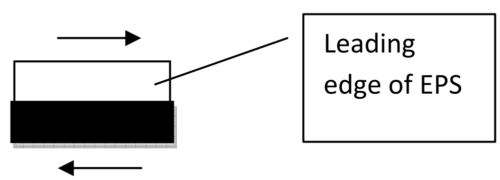

Figure 8. Laminated material subjected to shear stress parallel to laminate plane to determine shear bond strength.

No interface shear performance criterion or tests were required as part of the BCAT project specification (Appendix 1). However, this is a common test done in Geotechnical Engineering to determine the interface shear strength or bond between two dissimilar materials and is commonly performed in a direct shear device (Figure 9). We evaluated the shear bond strength of Gigacrete™ and EPS in a manner similar to ASTM D3080.

Two 2.5-inch (62.5-mm) diameter by 0.5-inch (12.5-mm) Gigacrete™ layers were poured atop an EPS19 sample of identical dimensions. The Gigacrete™ was allowed to cure for 9 days and then tested in direct shear with an applied normal stress of 2.2 psi (15 kPa). (This normal stress was selected because it represents a typical normal stress that develops in the elastic range of the EPS.) The sample was subjected to a horizontal displacement rate in the shear box that corresponds to 0.05 inches (1.25 mm) per minute and tested until a displacement of 0.5 inches (12.5 mm) was realized. Figure 10 shows peak shear bond strengths of 51.3 and 55.2 kPa for samples 1 and 2, respectively.

Figure 9. University of Utah direct shear device manufactured by ELE International.

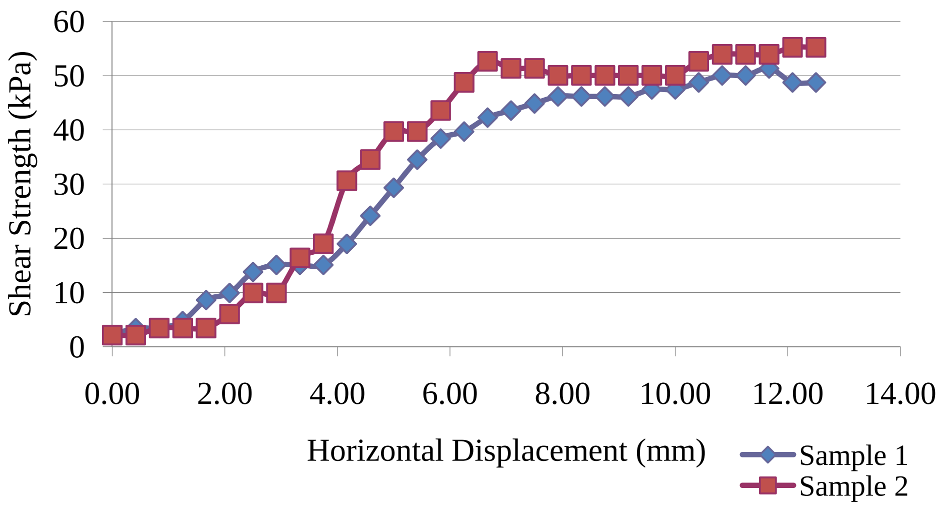

Figure 10. Direct shear test results for Gigacrete™ EPS bond.

After the tests were performed, the samples were visually inspected. There was a significant amount of compression of the EPS, but the interface bond was not broken between the two materials. Figure 11 shows the local deformation and shear that developed along the leading edge of the sample (Figure 8); however, along the trailing edge of the sample, the bond was intact. A careful inspection of the leading edge of the sample showed beads of EPS were still embedded in the Gigacrete™ suggesting that the failure was a localized cohesive failure and not adhesive failure of the interface bond.

Figure 11. Samples of Gigacrete™ – EPS laminate tested in direct shear. EPS sample is located on top and has been compressed during shear. Local shear failure has occurred on the leading edge of the sample.

Interface Shear Strength with Cyclic Unaxial Compression

Shear stresses at Gigacrete™ and EPS interface can develop from cyclic axial loading of the EPS. Such loadings can be a result of differential thermal expansion-contraction of the EPS block relative to the Gigacrete™ facing or can be caused by seismic and traffic loadings (Figure 12).

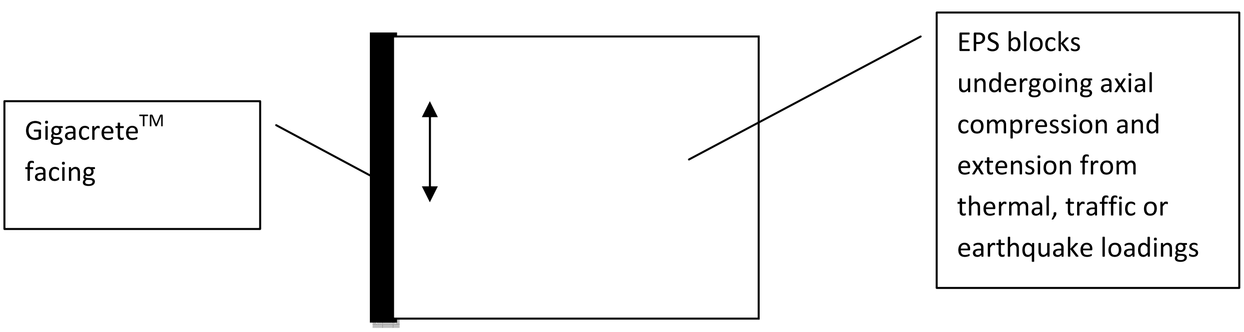

Figure 12. Shear stresses introduced at laminate interface from axial compression and extension.

For example, data gathered from the I-15 Reconstruction Project (Figure 13) shows cyclical axial loading within the EPS due to seasonal thermal expansion and contraction of the EPS wall system (Bartlett et al. 2001). These data suggest a seasonal cycling of about 2 psi (13.8 kPa). (Note that the initial vertical stress of about 5 psi (34.5 kPa) results from the initial placement of the load distribution slab and overlying pavement materials.) It should also be noted that the yield stress (i.e., stress at 2 percent strain) is approximately 80 to 100 kPa (Figure 1); thus the magnitude of the cyclic loadings shown in Figure 13 are within the elastic range of the EPS.

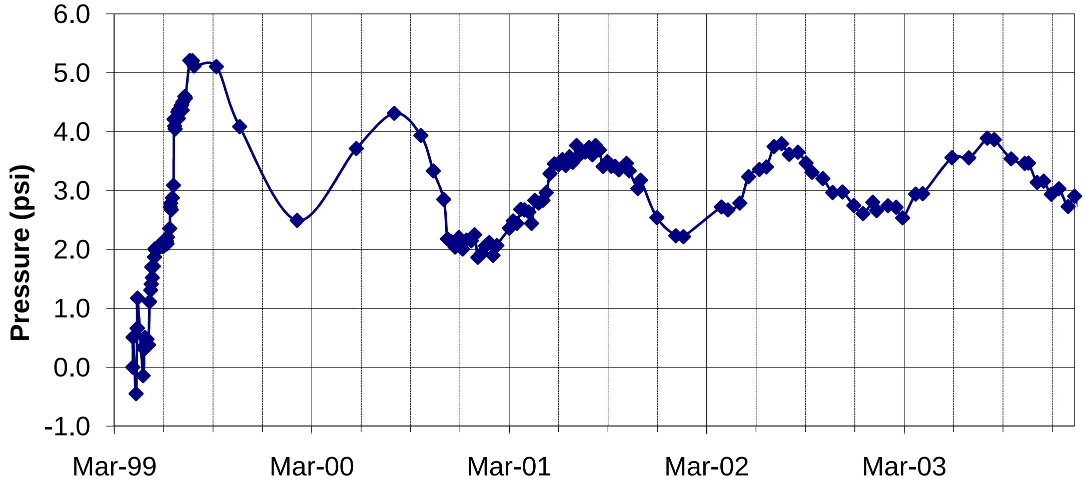

Figure 13. Cyclic loading within the EPS resulting from thermal expansion-contraction of the EPS wall system.

We devised a modified test method to measure the performance of the Gigacrete™ – EPS bond for the case of an EPS embankment with Gigacrete™ placed in cyclic axial compression-extension from environmental loadings (e.g., thermal, seismic, etc). A 4-inch (100-mm) outside diameter cylinder of Gigacrete™ was cast around a 3-inch (75-mm) outside diameter of EPS19 as shown in Figure 14 and cured for 7 days.

Subsequently in a series of stress-controlled cyclic uniaxial tests, the EPS central core was placed in alternating compression-extension using a cyclic triaxial device (Figure 15). The 3-inch (75-mm) end caps for the load frame completely contacted the EPS core, but did not contact the Gigacrete™ outer ring. In this manner only vertical stress was transferred to the EPS (Figure 14).

Figure 14. Cylindrical sample of Gigacrete™ and EPS19 cast to test the bond strength for cyclic unaxial compression.

Initial testing of an EPS19 cylinder without the Gigacrete^{TM} coating showed that creep deformation was initiated in a 3-inch (75-mm) EPS19 sample when a static axial stress of about 30 kPa was applied to the sample. Design of EPS embankment requires that the allowable working stress in the EPS embankment to be approximately 50 percent of the yield stress, so we selected an initial axial compressive stress of 15 kPa for the testing.

Once it was verified that the sample was not undergoing creep under this axial stress, additional cyclic axial stress of 11 kPa was applied to the sample. Thus, the amplitude of the axial stress on the sample varied from +26 kPa to + 4 kPa, where + indicates compression. This is approximately twice the magnitude of the thermal stress cycling occurring in the EPS embankment (Figure 13).

The sample in Figure 14 was subject to 4 sets of 250 cycles each with an initial static axial stress of 15 kPA and an axial cyclic stress of ±11 kPa applied at a frequency of 1 Hz. The results for these tests are shown in Figures 16-19.

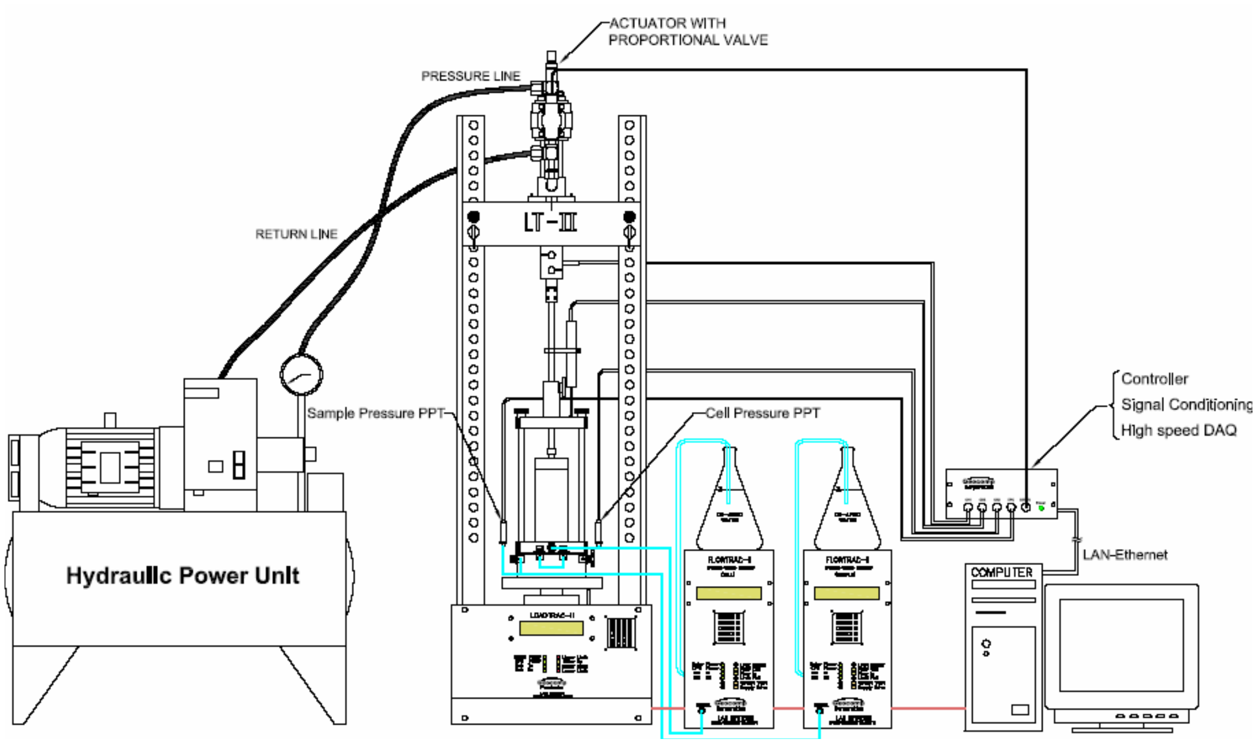

Figure 15. University of Utah cyclic triaxial test apparatus.

(In these plots, the shear stress is plotted instead of the axial stress on the left axis of the figures. The shear stress is the axial stress divided by 2 for the case of uniaxial loading.) Figure 16 shows that slightly less than 0.2 percent inelastic (i.e., plastic) axial strain accumulated in the EPS sample during the first 250 cycle loading set. This suggests that the combination of initial static and cyclic loading had slightly exceeded the elastic limit of the EPS. However, subsequent sets on the same sample showed less inelastic behavior, suggesting the inelastic deformation decreases with the number of cycles.

We note that the sample was completely unloaded after each set of 250 cycles. (This was done so that the system's solenoid could cool down before the next set of 250 cycles was applied.) Because of this, the permanent deformations shown in Figures 16 through 19 cannot be added to get the total permanent axial strain during 1000 cycles.

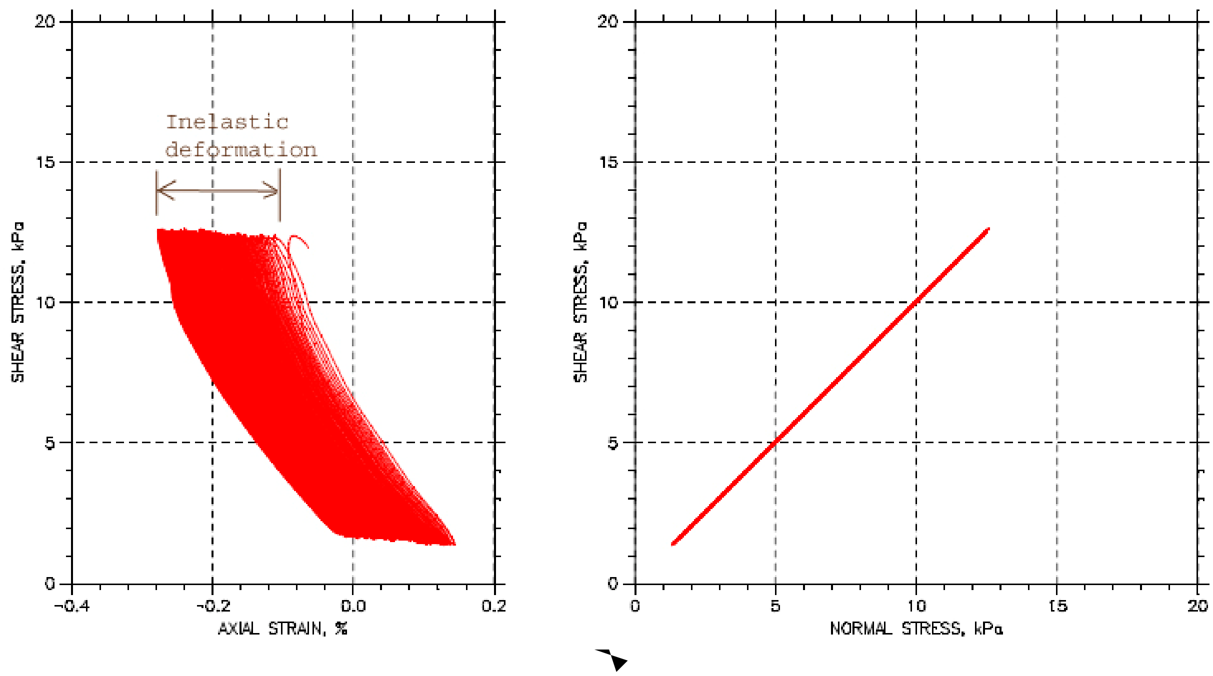

Figure 16. Plots of shear stress versus axial strain for cyclic uniaxial stress tests, cycles 0 – 250.

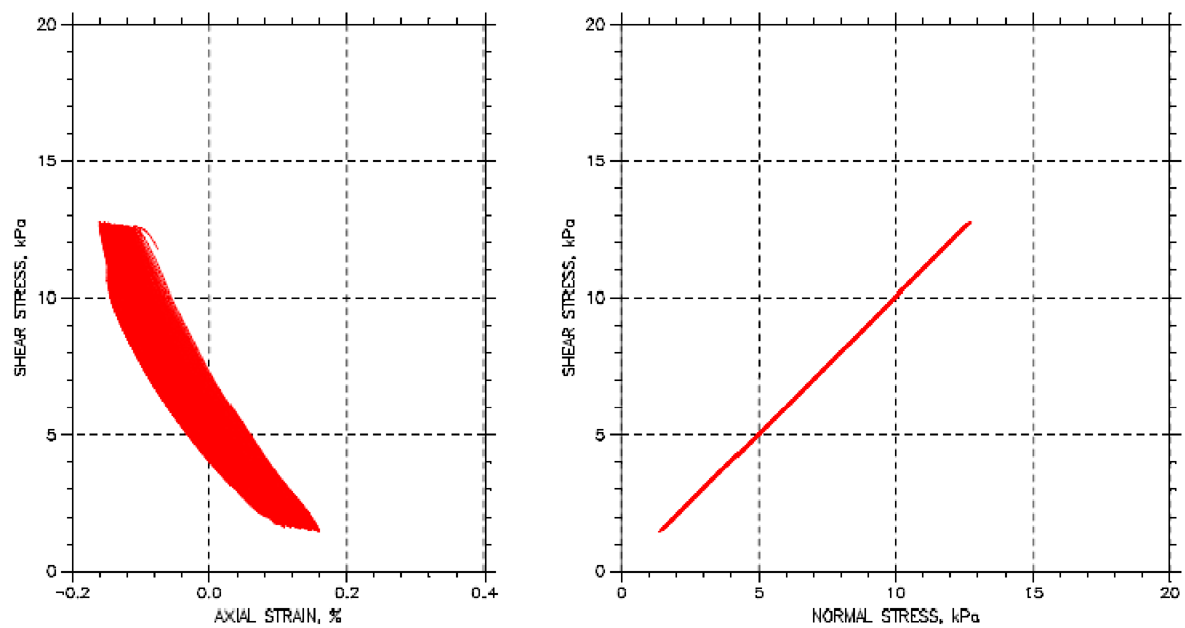

Figure 17. Plots of shear stress versus axial strain for cyclic uniaxial stress tests, cycles 251 – 500.

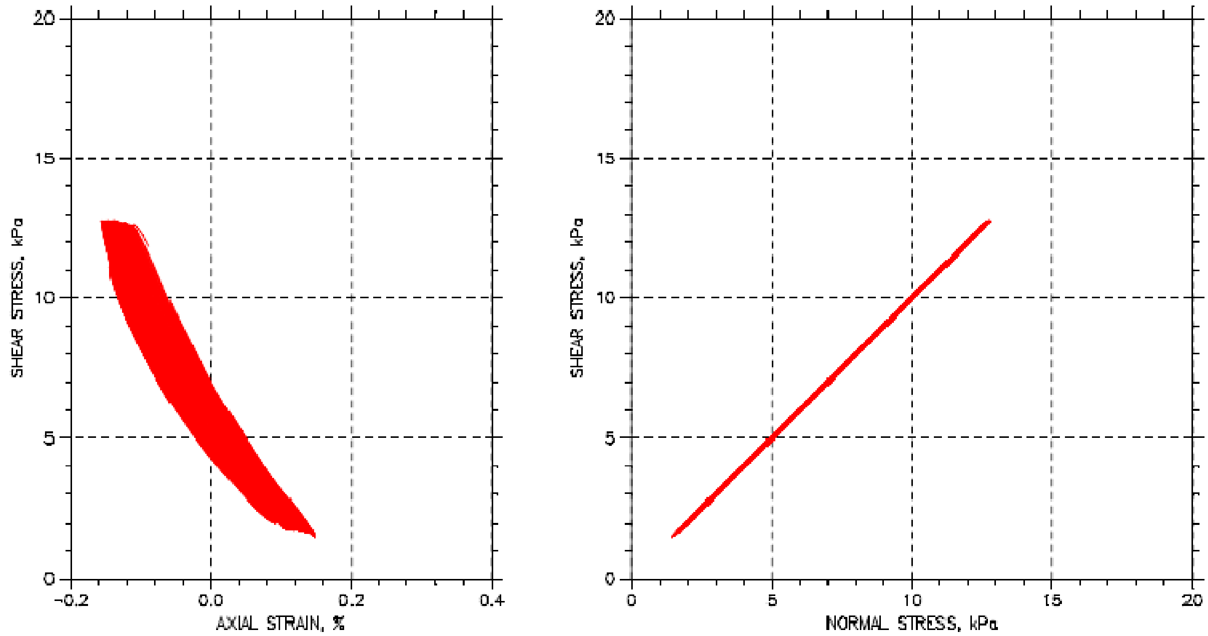

Figure 18. Plots of shear stress versus axial strain for cyclic uniaxial stress tests, cycles 501 – 750.

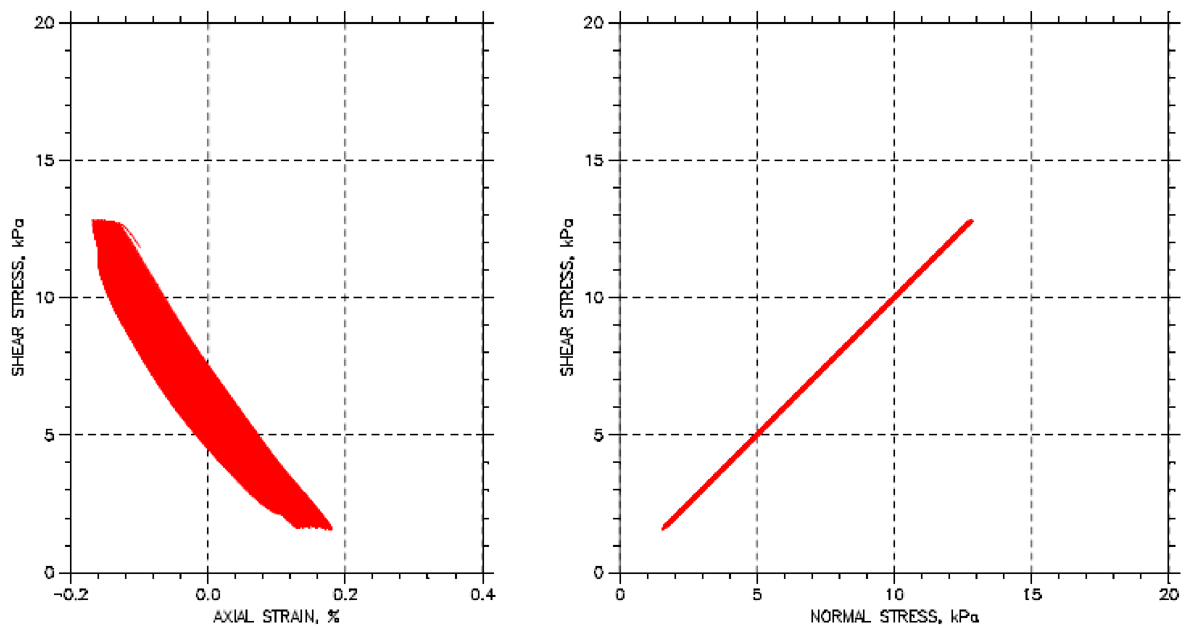

Figure 19. Plots of shear stress versus axial strain for cyclic uniaxial stress tests, cycles 501 – 750.

Once 1000 cycles had been applied to the sample, we inspected the Gigacrete™ – EPS interface for any signs of damage due to cycling. No de-bonding or damage was observed at this interface (Figures 20 and 21).

Figure 20. Photographs of the top of the sample before (top) and after (bottom) the application of 1000 loading cycles. No damage was observed at the EPS – Gigacrete^{TM} interface.

Figure 21. Photographs of the bottom of the sample before (top) and after (bottom) the application of 1000 loading cycles. No damage was observed at the EPS – Gigacrete^{TM} interface.

Impact Strength of Gigacrete™

Initially, square samples of EPS19, measuring 1 foot by 1 foot (0.3 m by 0.3 m) and 0.5 ft (0.15 m) thick, were coated with ½ inch (12.5 mm) of unreinforced Gigacrete™ for impact testing. A striker was constructed using a cylindrical shaped weight and a steel ball bearing. This striker was dropped from pre-determined heights and impacted the Gigacrete™ coating applied to the EPS backing. These initial impact tests showed that even at relatively small drop heights, the unreinforced samples on EPS backing will fracture. After discussing the results of the initial impact tests with the manufacturer, it was decided that reinforced samples should be prepared for additional impact testing.

Subsequently, two types of reinforcing meshes were used in the samples: glass-fiber and nylon reinforcing mesh. Twelve EPS19 samples, measuring 0.5 ft by 0.5 ft (0.15 m by 0.15 m) and 2 in (50 mm) thick, were prepared and coated with Gigacrete™ for impact testing. Six of these samples were reinforced with glass-fiber and six were reinforced with a nylon reinforcing mesh. In addition, an identical set of samples were prepared, but using a Gigacrete™ coating thickness of ¾ inch (18.75 mm). This was done to evaluate how the impact performance may improved as the thickness of the Gigacrete™ is increased. It should be noted that a 2-in (50 mm) thickness of EPS19 was chosen for all tests so that the samples prepared with a Gigacrete™ coating could fit underneath the striker.

An addition to the 0.5 ft (0.15 m) square samples, larger-sized square EPS19 samples were also prepared and tested. These samples measured 1 foot by 1 foot (0.3 m by 0.3 m) and 2 in (50 mm) thick. One sample was prepared for each thickness of Gigacrete™ (i.e., 12.5 and 18.75 mm thickness) and for each mesh type for a total of 4 samples.

For all of samples, the reinforcing mesh was placed at mid-depth within the Gigacrete™ coating. However, for the nylon mesh with a 12.5 mm coating of Gigacrete™, the small mesh opening size made preparation of these samples difficult. The Gigacrete™ coating was barely sufficient to fully cover the nylon mesh.

All samples were cured for seven days and then tested using various impact energies. After impacting, each specimen was inspected for cracks, breaks, depth of indentation and to see if the mesh had been penetrated or broken by the impact. A Gardner Striker (ASTM D 5420) apparatus was used for the impact testing (Figure 22). This shape of head produces more concentrated impact than the larger diameter steel balls or weighted bags adapted from other methods and produces a good compromise between puncturing and cracking action. In this test, the sample rests on a base plate over an opening. An impactor sits on top of the test sample and a weight is raised to a predetermined height, then it is released to drop onto the top of the sample. The drop height, drop weight, and the test result are recorded.

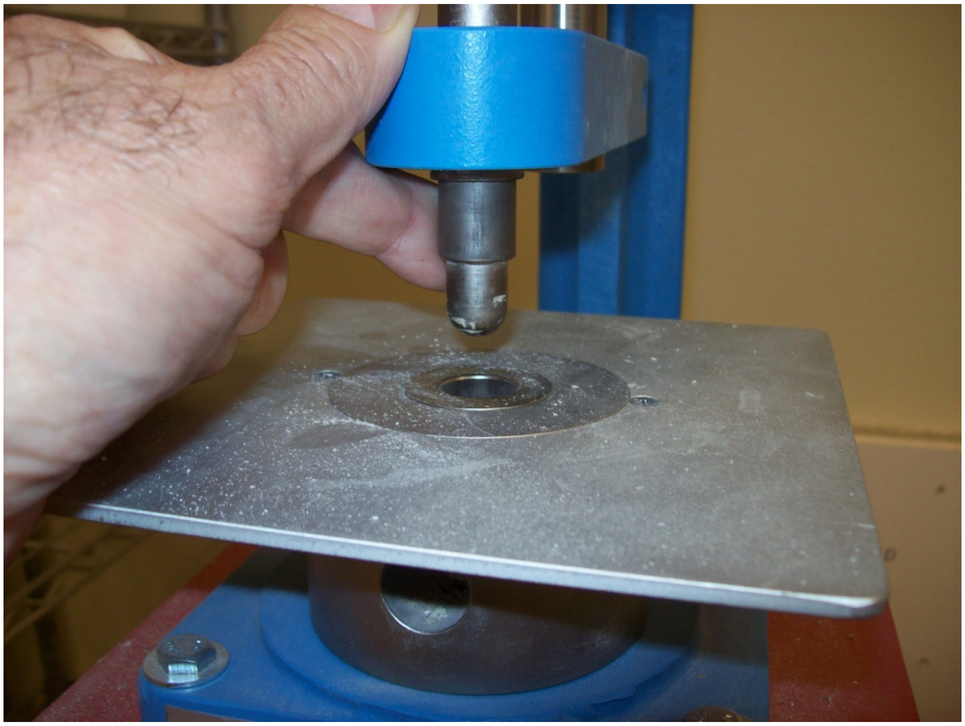

Figure 22. The Gardner Striker Used in Impact Testing.

The 0.5 ft by 0.5 ft (0.15 m by 0.15 m) samples were tested first. Because of their smaller size, it was assumed that cracks would form at lower impact energies; therefore the objective of this part of the testing was to evaluate the approximate impact energy required to penetrate or break the mesh. Subsequently, the 1 foot by 1 foot (0.3 m by 0.3 m) samples were tested to find the impact energy required to crack the coating. The results are shown in Table 2 below.

The test results showed that for the ½" thick fiber-reinforced samples, the impact strength required to crack the samples is estimated to be 280 in-lbs. The impact strength required to penetrate the mesh is consistently higher than the maximum available of 320 in-lbs energy delivered by the Gardner Striker (Figure 23).

In comparison, the ½" thick nylon-reinforced samples of 1' x 1' dimensions cracked at 200 in-lbs. Also at 304 in-lbs, the striker penetrated through the mesh and into the EPS (Figure 24).   In addition, at impact energy of 200 in-lbs, or more, the damage to the 6" x 6" samples was severe, including cracks that propagated into the EPS. Also, the bond between the EPS and Gigacrete™ failed at the corners and edges (Figure 24). However, the nylon mesh was not penetrated until impacts of over 300 in-lbs were used.

When the ¾" thick 1' x 1' samples with glass-fiber reinforcement was struck with 200 in-lbs, small cracks formed; but at the highest energy of 320 in-lbs, the mesh was not ruptured (Figure 25).   Also, it is interesting to note that for sample 1 of the 6" x 6" samples did not crack at 200 in-lbs of impact energy

(Table 2). Furthermore, none of the 6” x 6” glass-fiber samples were penetrated at the maximum impact energy of 320 in-lbs (Table 2).

In comparison, the ¾” nylon-reinforced 1’ x 1’ sample had small cracks at 240 in-lbs but the mesh was not penetrated when struck again at 320 in-lbs (see Figure 26). The 6” x 6” samples also cracked at lower energies, but the mesh remained un-penetrated at maximum impact or 320 in-lbs.

Table 2. Impact Testing Results for Gigacrete™ coating ,

Gigacrete™ thickness: 1/2" Sample Size: 6" x 6" x 2” EPS

Reinforcement: Glass Fiber

Sample Number	Drop Energy (in-lbs)	Indentation Depth (in)	Penetrated Mesh? (Y/N)	Observations:
1	152	--	N	No cracks
	200	0.162	N	Cracked to edges, small chips
2	200	0.015	N	No cracks, no chips
	224	0.078	N	Cracked to edges, small chips
3	224	0.171	N	Cracks to edges
4	280	0.177	N	Cracks to edges
5	304	0.080	N	Cracks to edges
6	320*	0.037	N	Cracks to edges

Gigacrete™ thickness: 1/2" Sample Size: 1' x 1' x 2” EPS

Reinforcement: Glass Fiber

Sample Number	Drop Energy (in-lbs)	Indentation Depth (in)	Penetrated Mesh? (Y/N)	Observations:
1	280	0.184	N	1 small crack
	304	0.386	N	Cracked to edges
	320*	0.201	N	Cracked to edges

Gigacrete™ thickness: 3/4" Sample Size: 6" x 6" x 2” EPS

Reinforcement: Glass Fiber

Sample Number	Drop Energy (in-lbs)	Indentation Depth (in)	Penetrated Mesh? (Y/N)	Observations:
1	200	--	N	No cracks
	248	--	N	Cracked to edges, small chips
2	320*	0.013	N	Cracks to edges
3	320*	0.013	N	Cracks to edges
4	320*	0.010	N	Cracks to edges
5	320*	0.038	N	Cracks to edges
6	320*	0.022	N	Cracks to edges

Gigacrete™ thickness: 3/4" Sample Size: 1' x 1' x 2” EPS

Reinforcement: Glass Fiber

Sample Number	Drop Energy (in-lbs)	Indentation Depth (in)	Penetrated Mesh? (Y/N)	Observations:
1	320*	0.076	N	Cracks to edges
2	200	0.026	N	Cracks to edges

Gigacrete™ thickness: 1/2" Sample Size: 6" x 6" x 2” EPS

Reinforcement: Nylon

Sample Number	Drop Energy (in-lbs)	Indentation Depth (in)	Penetrated Mesh? (Y/N)	Observations:
1	248	0.024	N	Large Cracks to edges and into EPS
2	200	0.045	N	Large Cracks to edges and into EPS
3	152	0.008	N	Cracks to edges
4	120	0.012	N	Cracks to edges
5	96	0.005	N	Cracks to edges
	280	--	N	Large Cracks to edges and into EPS
6	320*	--	Y	Large Cracks to edges and into EPS

Gigacrete™ thickness: 1/2" Sample Size: 1' x 1' x 2” EPS

Reinforcement: Nylon

Sample Number	Drop Energy (in-lbs)	Indentation Depth (in)	Penetrated Mesh? (Y/N)	Observations:
1	104	0.019	N	No Cracks
	200	0.182	N	Cracks to edges
	304	--	Y	Penetrated into EPS

Gigacrete™ thickness: 3/4" Sample Size: 6" x 6" x 2” EPS

Reinforcement: Nylon

Sample Number	Drop Energy (in-lbs)	Indentation Depth (in)	Penetrated Mesh? (Y/N)	Observations:
1	200	--	N	Cracks to edges
	248	--	N	Cracks to edges, small chips
2	320*	0.013	N	Cracks to edges
3	320*	0.013	N	Cracks to edges
4	320*	0.010	N	Cracks to edges
5	320*	0.038	N	Cracks to edges
6	320*	0.022	N	Cracks to edges

Gigacrete™ thickness: 3/4" Sample Size: 1' x 1' x 2” EPS

Reinforcement: Nylon

Sample Number	Drop Energy (in-lbs)	Indentation Depth (in)	Penetrated Mesh? (Y/N)	Observations:
1	240	0.016	N	Cracks to edges
	304	--	N	Cracks to edges, small chips

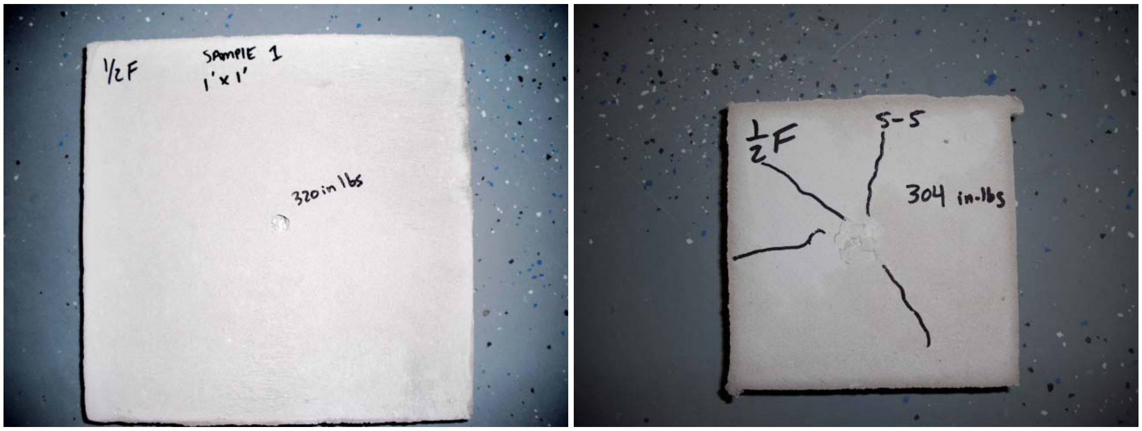

Figure 23. Photographs of ½" thick glass fiber reinforced 1' x 1' and 6" x 6" samples.

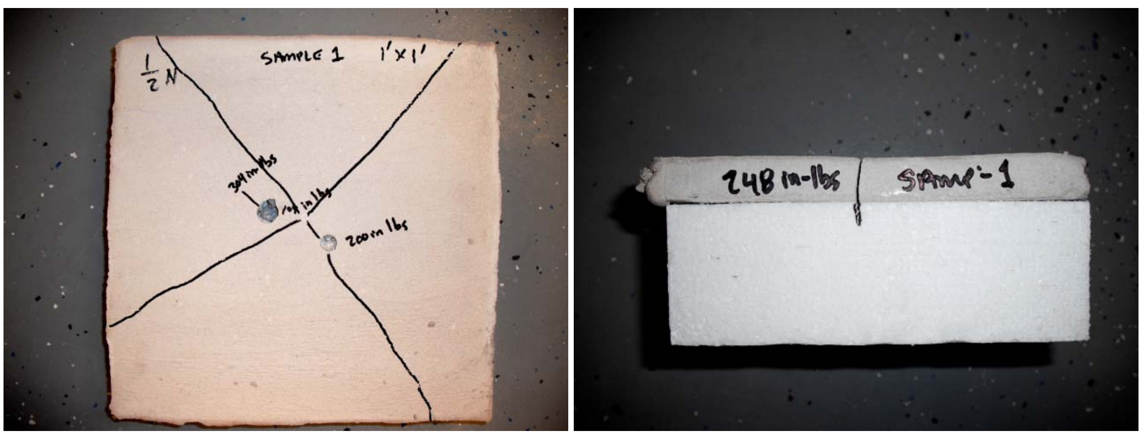

Figure 24. Photographs of ½" nylon reinforced 1' x 1' and 6" x 6" samples.

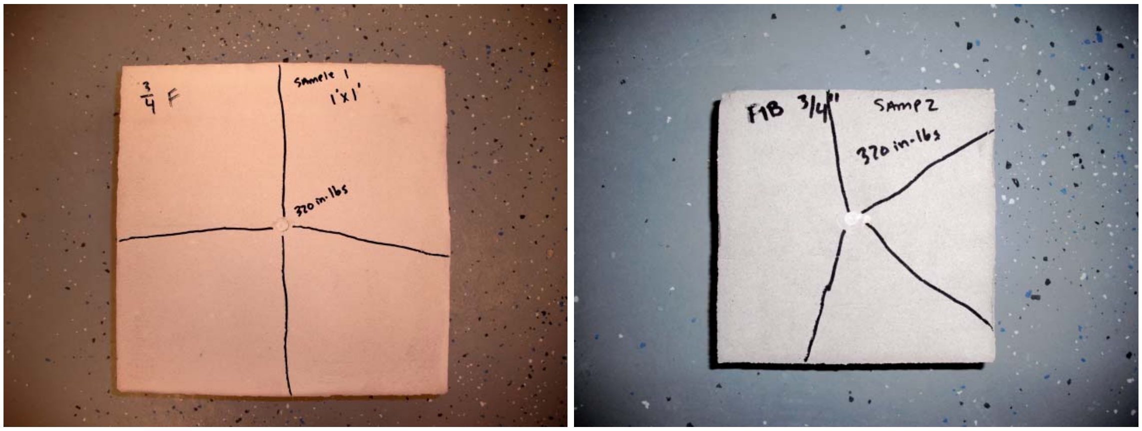

Figure 25. Photographs of ¾" glass fiber reinforced 1' x 1' and 6" x 6" samples.

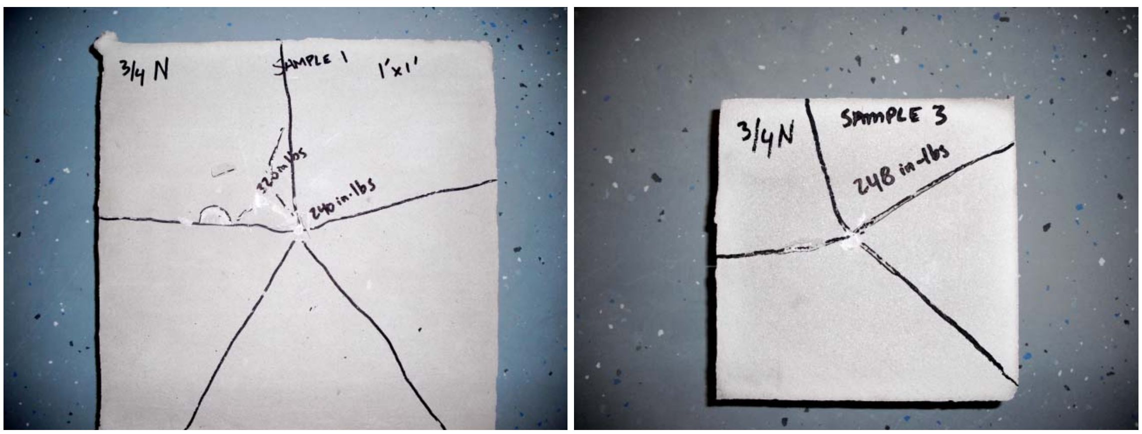

Figure 26. Photographs of ¾" nylon reinforced 1' x 1' and 6" x 6" samples.

Summary and Conclusions

The impact testing results are summarized in Table 3. Because of the small number of samples tested for each case (i.e., maximum of six samples), the results below are not statistically robust, but do suggest the relative performance for each case.

Table 3. Summary of Impact Testing

Gigacrete™ Thickness:	Reinforcement	Impact to Crack (in-lbs)*	Impact to Penetrate Mesh (in-lbs)
1/2"	Glass-Fiber	>280	>320
1/2"	Nylon	200	<304
3/4"	Glass-Fiber	>200	>320
3/4"	Nylon	<240	>320

In summary, samples reinforced with either type of mesh (glass fiber or nylon) have impact performance that is significantly higher than the highest EIFS Industry Members Association (EIMA) classification, which is Level 4 (Table 4).

Table 4. EIMA Classification for Impact Resistance

EIMA Classification	Impact Range J (in-lb.s)	Minimum Value Required J (in-lbs)
Level 1	2.83 – 5.54 (25 – 49)	3 (30)
Level 2	5,65 – 10.1 (50 – 89)	6 (56)
Level 3	10.2 – 17 (90 – 150)	12 (108)
Level 4	>17 (>150)	20 (175)

It should noted that samples with glass-fiber reinforcement generally performed better than those reinforced with nylon. In addition, for the glass fiber mesh, increasing the thickness of the Gigacrete™ coating from ½" to ¾" did not significantly improve the resistance to cracking (Table 3). However, it is recommended that a coating thickness of ½", or greater, be applied to sufficiently cover the mesh.

The test results for the compressive strength and bond strengths are summarized in Table 5.

Table 5. Summary of compressive and bond strength tests.

Test	Result (kPa)	Notes	Miscellaneous
Compressive strength	3620	Gigacrete sample	4-day cure
Compressive strength	49000	Gigacrete sample	10-day cure
Compressive strength	56500	Gigacrete sample	12-day cure
Tensile bond strength	272	Bond did not fail; failed in EPS	6-day cure
Tensile bond strength	273	Bond did not fail; failed in EPS	5-day cure
Direct Shear bond strength	51	Bond did not fail; failed in EPS	9-day cure
Direct Shear bond strength	55	Bond did not fail; failed in EPS	9-day cure
Cyclic loading bond strength	15 static + 11 cyclic	Bond did not fail; no damage to EPS	7-day cure

These tests results show that the tensile bond that develops between Gigacrete™ and EPS19 meets or exceeds the performance requirements adopted by the BCAT project for Exterior Insulation and Finishing Systems (EIFS). In addition, the bond strength was tested in direct shear and cyclic uniaxial compression-extension. The direct shear test results show that a "cohesive" shear failure developes within the EPS, but the interface bond with the Gigacrete™ is not broken. The cyclic loading tests show that the interface bond is not broken or even apparently damaged after 1000 cycles of axial loading. This bond remains intact even though some inelastic deformation accumulated in the EPS. Thus, for cyclic loading, it appears that the interface bond will not be damaged as long as the cyclic loading amplitude is maintained within the elastic range of the EPS.

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Appendix 1

Section 909.300

Exterior Insulation and Finish Systems (EIFS)

Boston's Central Artery Tunnel Project