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**Construction of Fiber Reinforced Polymer (FRP) Jackets for the Protection of Pier
Caps**

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Submitted by

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And

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16. Abstract A fiber-reinforced polymer (FRP) composite jacket was fabricated to protect the deteriorating reinforced concrete pier caps of the Silver Spring Cove Bridge in Rhode Island. The pier caps had undergone severe spalling and cracking and reinforcements were exposed in a number of locations. Vacuum assisted impregnation technique that is used for the fabrication of aerospace structural components, was utilized for the fabrication of a composite jacket to cover the pier caps and stop further deterioration. Commonly referred to as "vacuum bagging" in the aerospace industry, this method is known to result in consistent high quality FRP laminates. This technique, rarely utilized in infrastructure applications, uses atmospheric pressure to remove air voids within the composite during lay-up and develops a strong bond between FRP layers. Excellent performance of fiberglass boats in marine environment for more than four decades provided the primary motivation for constructing fiberglass jackets to protect the pier caps.			
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1. CHAPTER 1

Introduction

There is a worldwide need for major repair and rehabilitation of transportation infrastructures. Insufficient maintenance, overloading, and adverse environmental conditions have led to over 200,000 structurally deficient bridges in the United States. Without proper remediation, such bridges may be load restricted or even may have to be replaced for having inadequate capacity to carry legal traffic loads. To rehabilitate structurally deficient members, a number of repair and strengthening techniques are currently being used. Strengthening of reinforced concrete structures with externally bonded steel plates is one retrofitting technique developed during the 1960's. The attachment of the steel plates can be accomplished using either adhesive bonding or bolting. Unfortunately, large equipment is required to install the heavy steel plates. As a result, the installation costs are significantly higher and traffic is often disrupted (Mufti, 2003; Kurtz, 2001; Barnes, 2001).

Recently, high strength carbon, glass, and Aramid composites are being promoted as a better alternative to steel plates. These systems, called fiber-reinforced polymers (FRP), have some significant advantages including low weight, corrosion resistance, and ease of application. The low weight reduces both the duration and cost of construction since heavy equipment is not needed. The composites can be applied as a thin plate or layer-by-layer. Originally developed for aircrafts, these composites have been used successfully in a variety of structural applications such as aircraft fuselages, ship hulls, cargo containers, high-speed trains, and turbine blades (Feichtinger, 1998; Thomsen et al., 2000; Kim, 1972).

A number of research projects have been carried out to demonstrate the use of FRP composites in the rehabilitation of reinforced concrete structural components (Mufti, 2003;

Taljsten, 2000; Hag-Elsafi, 2003). FRP composites have been applied to a variety of structural members including beams, columns, slabs, and walls. These advanced materials may be applied to the structure to increase any or several of the following properties:

- Axial, flexural, or shear load capacities
- Ductility for improved seismic performance
- Durability against adverse environmental effects
- Remaining fatigue life
- Stiffness for reduced deflections under service and design loads (Buyukozturk, 2003)

In most cases, the FRP composites are applied manually using hand-impregnation technique. Also referred to as hand lay-up, this process involves placing (and working) successive plies of resin-impregnated reinforcement in position by hand. Squeegees and grooved rollers are used to densify the FRP structure and remove much of the entrapped air. Unfortunately, this method lends itself to a host of problems, especially if air voids remain within the composite. These air voids can eventually form cracks that can propagate throughout the composite structure. This will result in a delamination or debonding failure in which the bond between FRP and concrete breaks down, allowing the composite to separate from the concrete. Will this not only lead to a reduction in strength, but will also allow adverse environmental conditions to penetrate and attack the surface of the concrete (Pebly, 1987; May, 1987).

To avoid potential delamination failures from occurring, a denser FRP must be manufactured by removing nearly all air voids within the composite. Two methods that are capable of accomplishing this task are vacuum-assisted impregnation (vacuum bagging) and pressure bag molding (pressure bagging). Vacuum bags apply additional pressure to the

composite and aid in the removal of entrapped air. Pressure bags also invoke the use of pressure but are considerably more complex and expensive to operate. They apply additional pressure to the assembly through an electrometric pressure bag or bladder contained within a clamshell cover, which fits over a mold. However, only mild pressures can be applied with this system (May 1987). Since simplicity is desired in nearly all FRP applications, the more suitable method is therefore vacuum bagging. The most critical element of a vacuum bagging system is that a smooth surface must be provided around the perimeter of the bag to create an airtight seal. For this reason, vacuum bagging is rarely attempted on rough or porous surfaces, such as concrete, masonry, or wood. Vacuum bagging has been performed on smooth concrete surfaces in a controlled laboratory setting (Taljsten et al., 2000). However, it has never been used to rehabilitate a deteriorating reinforced concrete structure. In this case, the texture of the concrete surface is extremely porous and non-uniform, making vacuum bagging more challenging.

1.1 Recent Advances

A number of advances have been made in the area of materials and design procedure. It is recommended that the reader seek the latest report from American Concrete Institute (ACI), Japan Concrete Institute (JCI), ISIS Canada, or CEB for the use of FRP. For example, ACI Committee 440 published a design guidelines document in October 2002 and similar documents are under preparation. JCI also updates documents frequently. ISIS publications can be obtained from University of Manitoba. Since this is an emerging technology, changes are being made frequently to design documents to incorporate recent findings.

In the area of fibers the major development is the reduction in the cost of carbon fibers. Other advances include development of high modulus (up to 690 GPa) carbon fibers and high strength glass fibers. In the case of matrix, the major advance is the development of an inorganic matrix, which is fire and UV resistant. The next few sections present a summary of the developments using this matrix.

1.2 Field Applications

A large number of field applications have been carried out during the last 20 years. The majority of the initial uses were in Japan, followed by applications in Europe and North America. In North America, the popular applications are in rehabilitation of bridges to improve earthquake resistance, repair and rehabilitation of parking structures, strengthening of unreinforced walls and rehabilitation of miscellaneous structures such as tunnels, chimneys and industrial structures such as liquid retaining tanks. Typical examples are shown in Figures 1.1 to 1.3 (ACI Committee 440²¹, 1996).



(a) Bridge pier

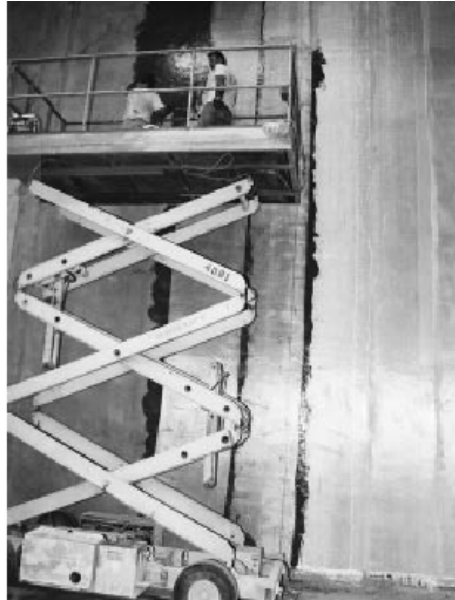


(b) Parking garage

Figure 1.1. Column wrapped with Glass FRP.

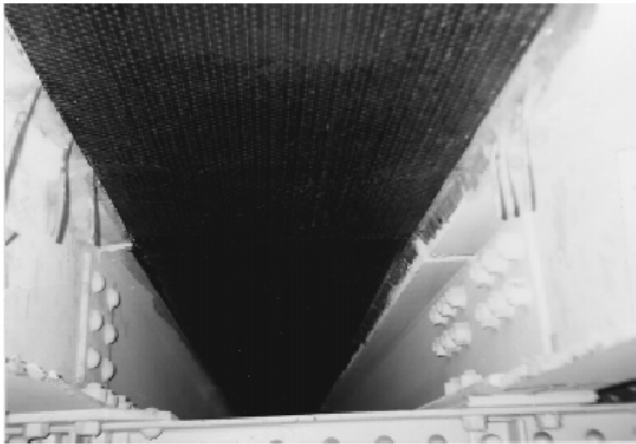


(a) Unreinforced masonry wall



(b) Tilt-up wall

Figure 1.2. Retrofitting for earthquake resistance.



(a) Bridge beam



(b) Tunnel lining

Figure 1.3. Rehabilitation of transportation infrastructure.

Rutgers University in collaboration with University of Rhode Island and the Rhode Island Department of Transportation proposed to use the vacuum bagging technique to fabricate a FRP composite jacket to seal the deteriorating reinforced concrete pier caps of a highway overpass in Rhode Island. The proposal was submitted to Federal Highway Administration under TEA-21 Innovative Bridge Construction Program and was funded in the year 2001. The jackets were fabricated in September 2002 and the construction details are presented in this report. The rehabilitation project utilized both innovative materials and construction techniques.

The details of the bridge and the pier caps are presented in Chapter 2. Chapter 3 deals with the background information. Selection of materials was made using laboratory investigation. This information is presented in Chapter 4. Details of actual fabrication in the field are presented in Chapter 5. Summary of observation are presented in Chapter 6. The sequence of the fabrication process is also presented in Figures 1.4 to 1.7. The monitoring phase is continuing, and is carried out by University of Rhode Island.

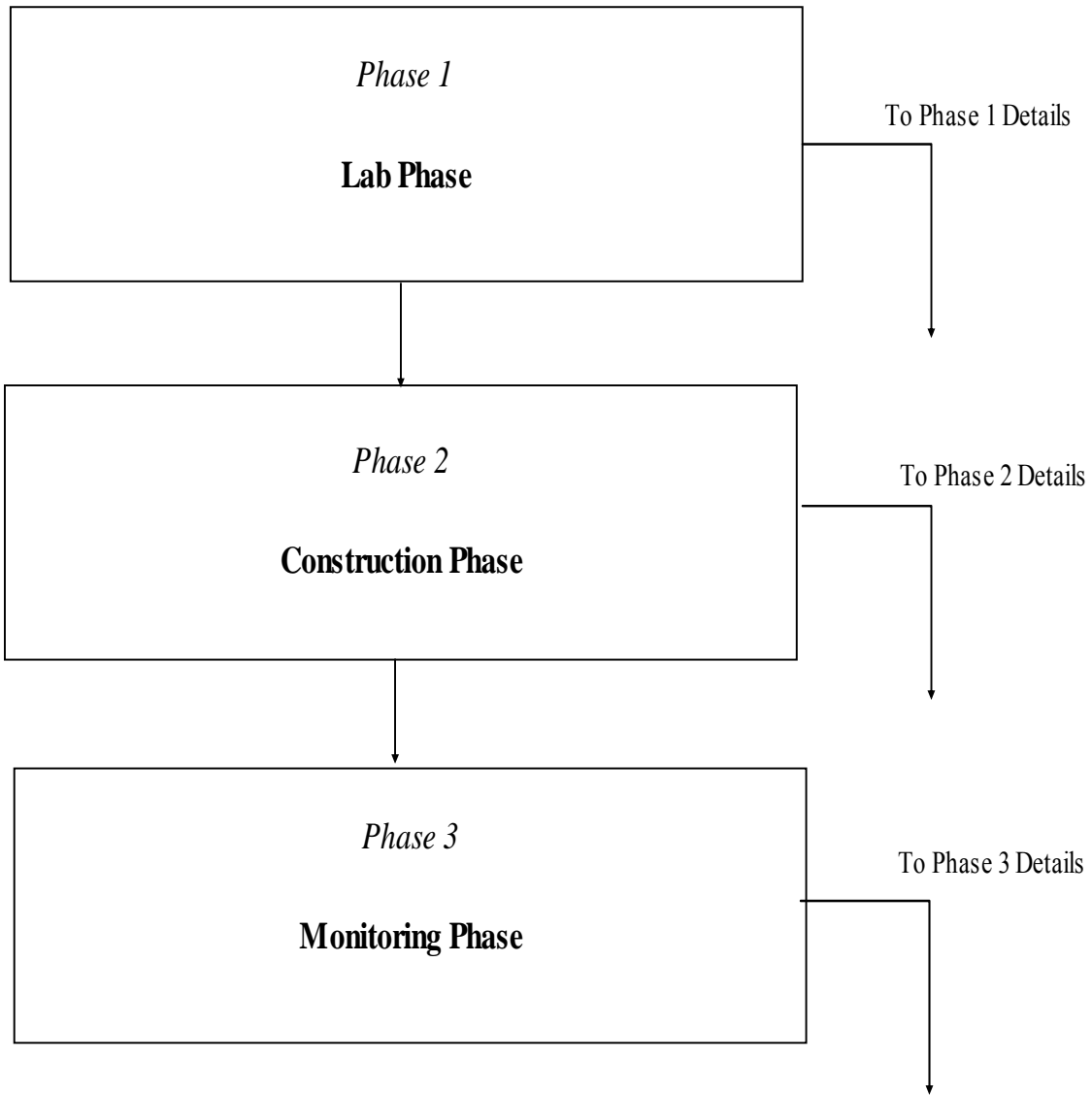
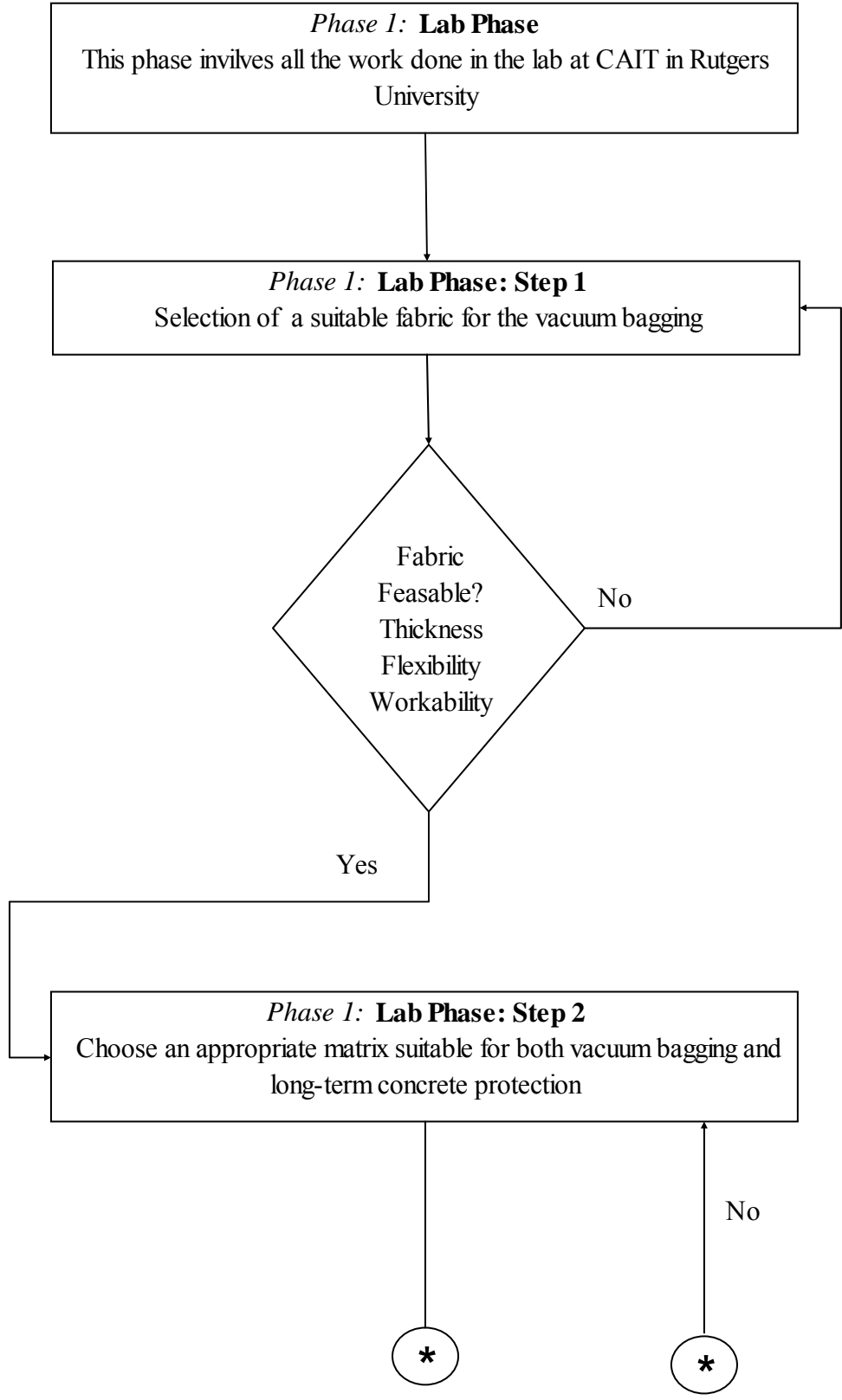
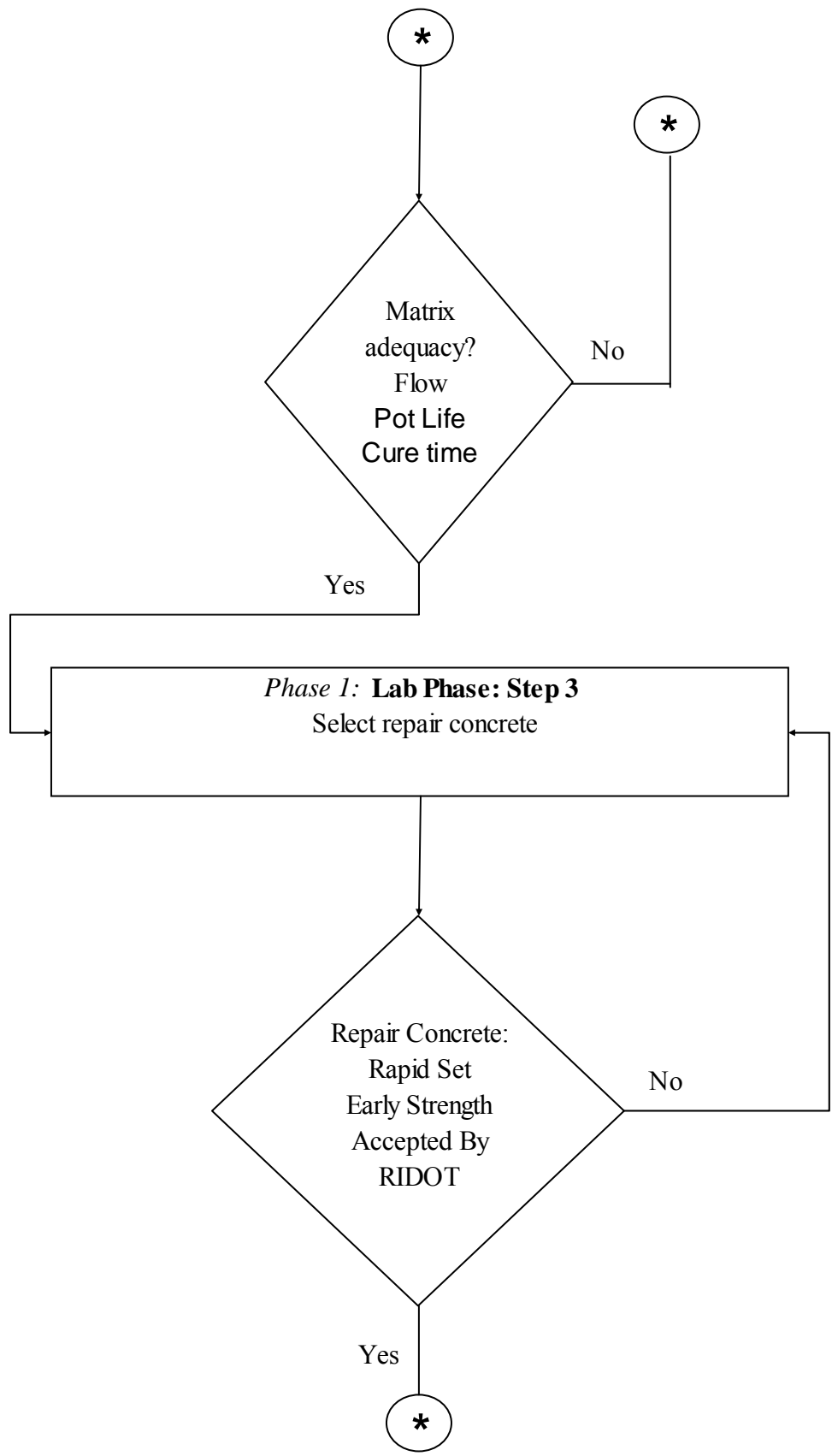


Figure 1.4. The three major phases of the demonstration project.





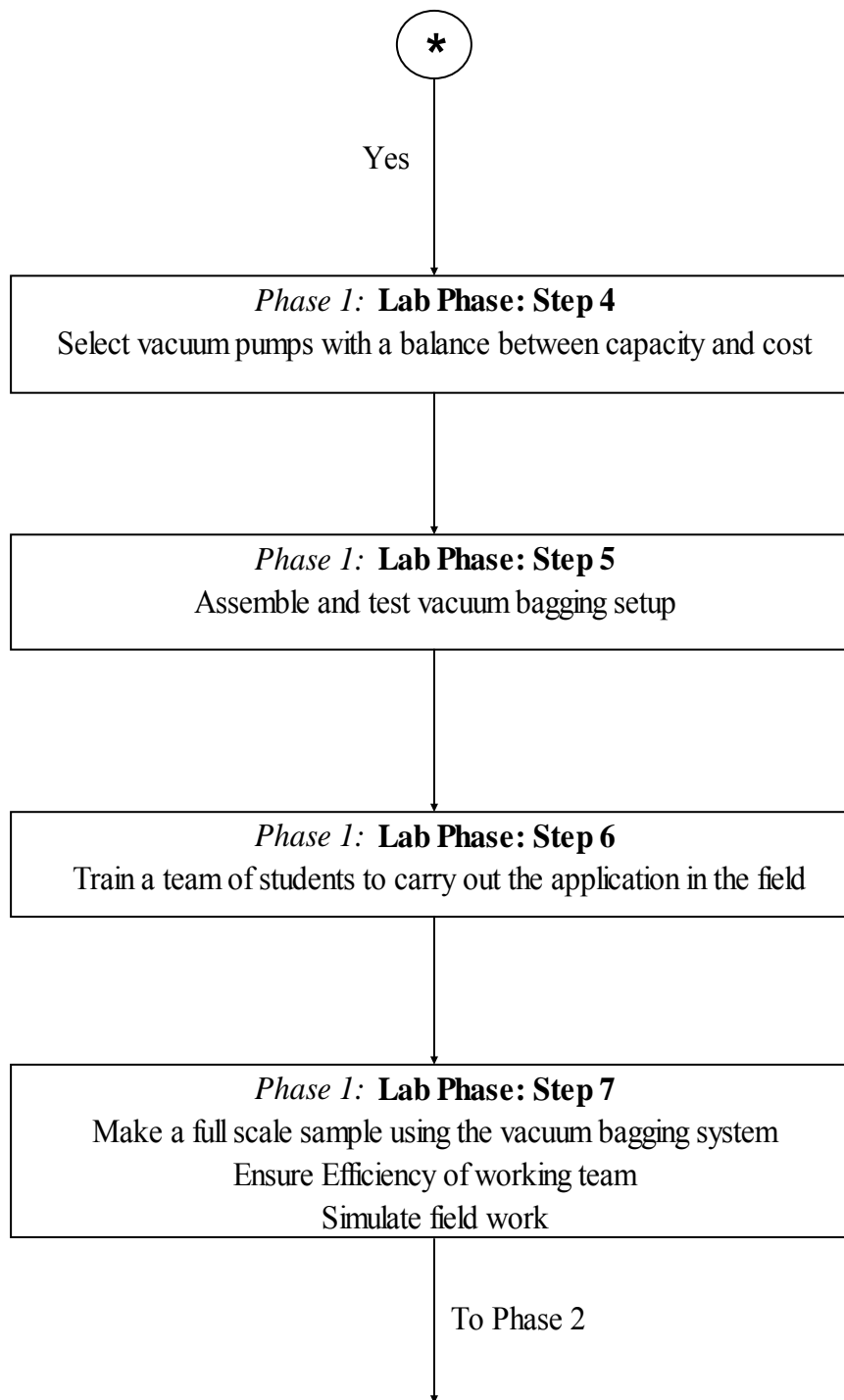


Figure 1.5. Details of laboratory phase of investigation

Phase 2: Construction Phase

Lecture for safety regulations.
The lecture was given by
Rhode Island Department
of Transportation Personnel
Class is mandatory for all people in the work
site

Preparation of Scaffolding and traffic control devices
Chloride samples for monitoring phase
Preparation of heavy equipment to be used at this phase
(This was done by University of Rhode Island team)

Surface Preparation including:
Surface Cleaning
Concrete brushing
Washing with high pressure water gun and concrete soap
Removal of loose concrete parts
Sanding of rust off the exposed steel bars
Repairing of concrete surface using the repair concrete

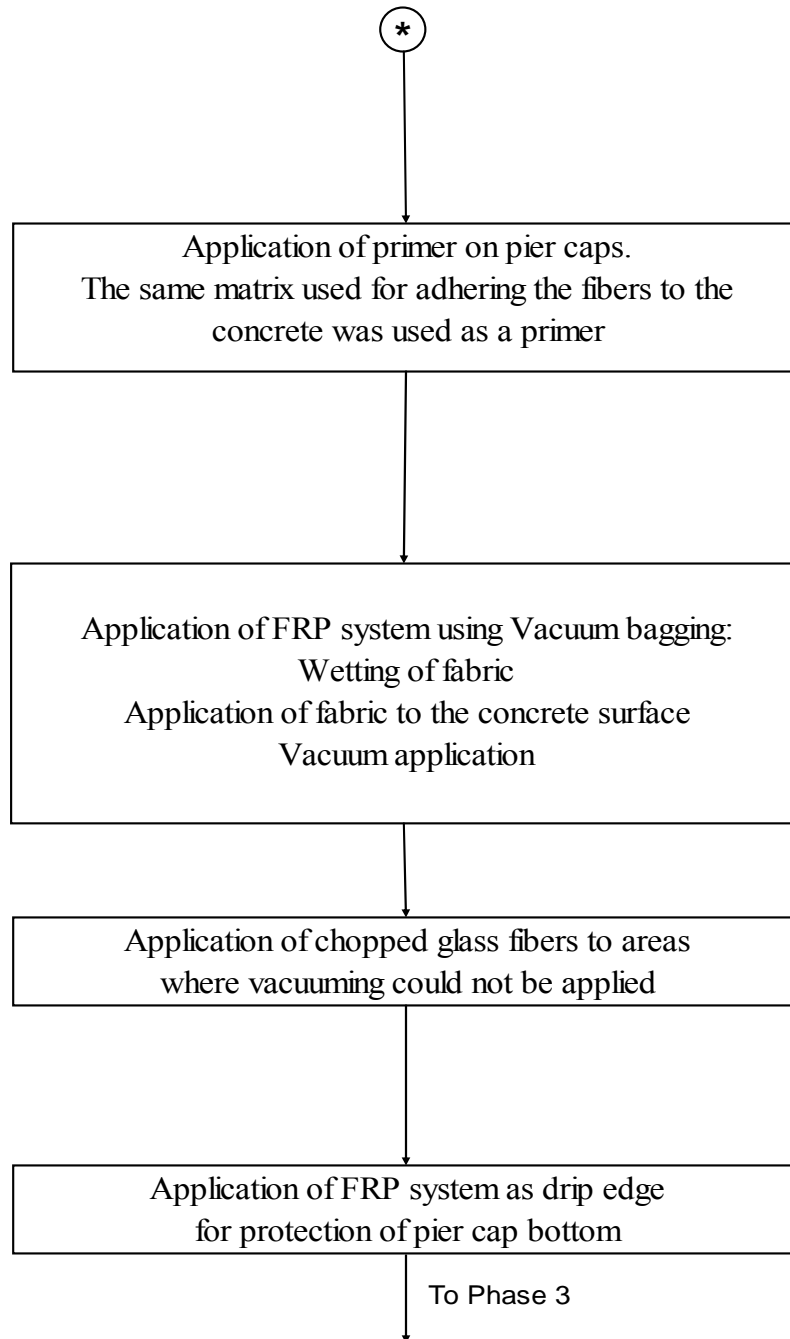


Figure 1.6. Details of jacket fabrication in the field.

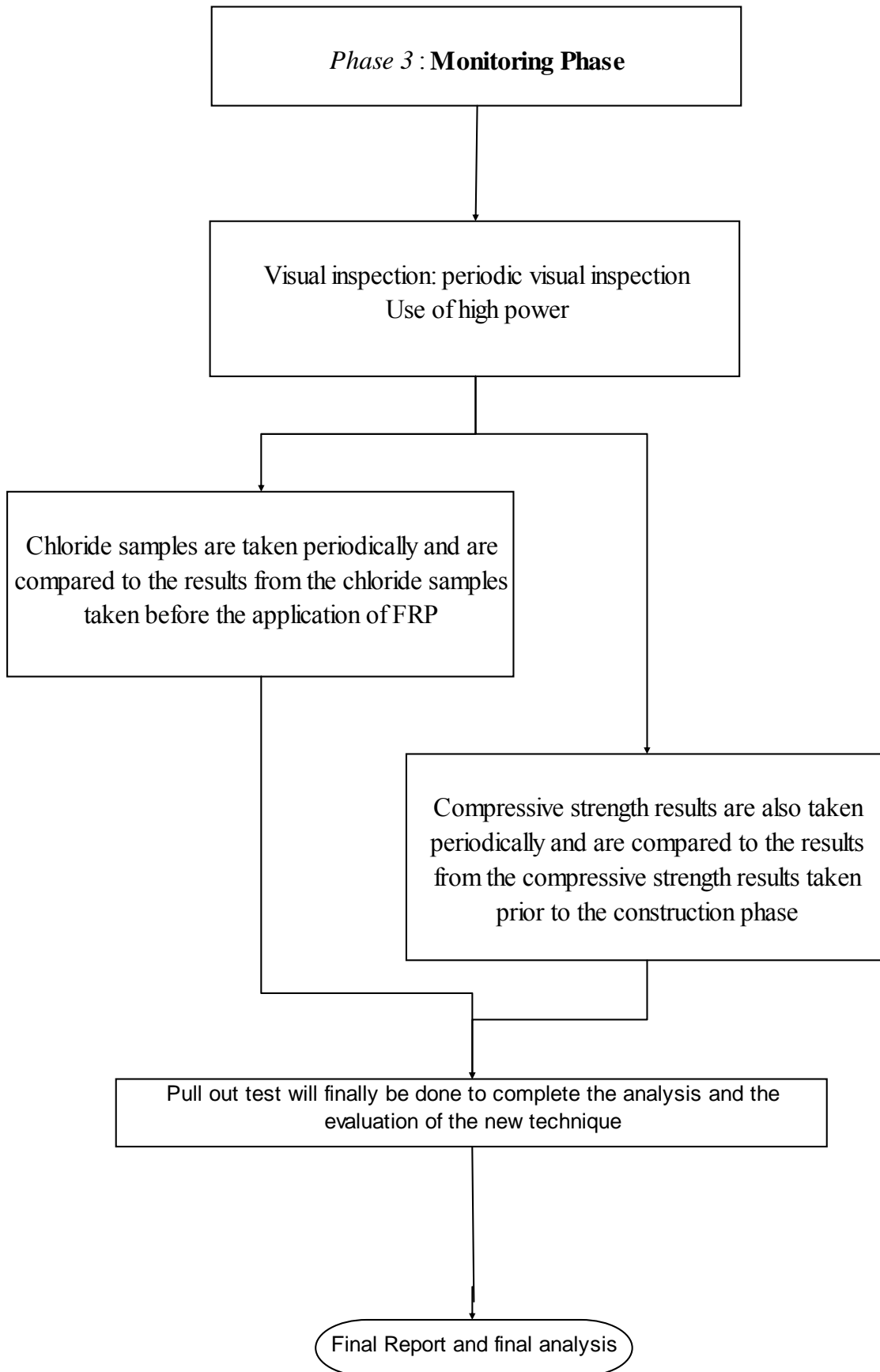


Figure 1.7. Details of monitoring phase

2. CHAPTER 2

Details of the Bridge and Pier Caps

Salt Pond Road Bridge No. 484 is located in South Kingstown, Rhode Island and was constructed in 1960. Nestled next to a recreational boating marina, the bridge carries Post Road (US Route 1) traffic over Salt Pond Road. The bridge consists of two separate roadways, one for northbound traffic, and another for southbound traffic. Each pier cap is approximately 50'-9" long and supports seven prestressed concrete beams. Both pier caps are nearly identical in design and the dimension details are presented in **Error! Reference source not found.**

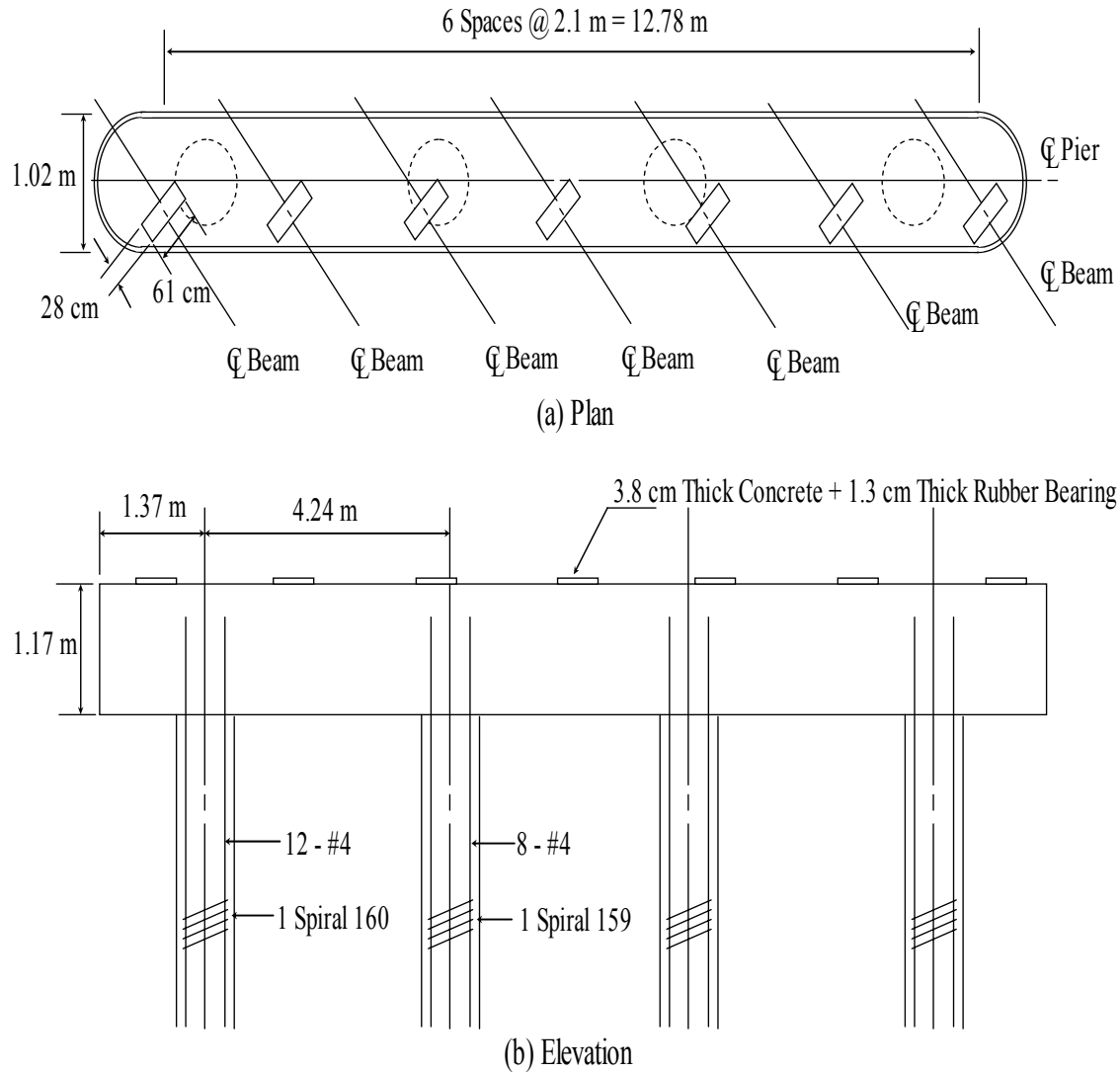


Figure 2.1 : (a) Plan and (b) Elevation Views of Pier Cap and Supporting Columns

The pier cap, which is a reinforced concrete beam, has undergone considerable deterioration, Figure 2. The authors believe that the location near the ocean and the water running through the construction joints played a major role in the deterioration process.



Figure 2.2 : Deteriorated Pier Cap of Salt Pond Road Bridge

Excessive shear and flexural cracking in the concrete was present throughout both pier caps. Contaminated water passing through the expansion joints of the bridge deck flowed over the pier caps, causing unsightly stains and degradation of the concrete surface. More importantly, large sections of concrete had separated from the pier cap structure and fallen off, leaving the reinforcing steel unprotected from the harsh corrosive air from the nearby Atlantic Ocean. Figure 2. (a) and (b) clearly illustrate how much damage was done to the pier cap closest to the marina.

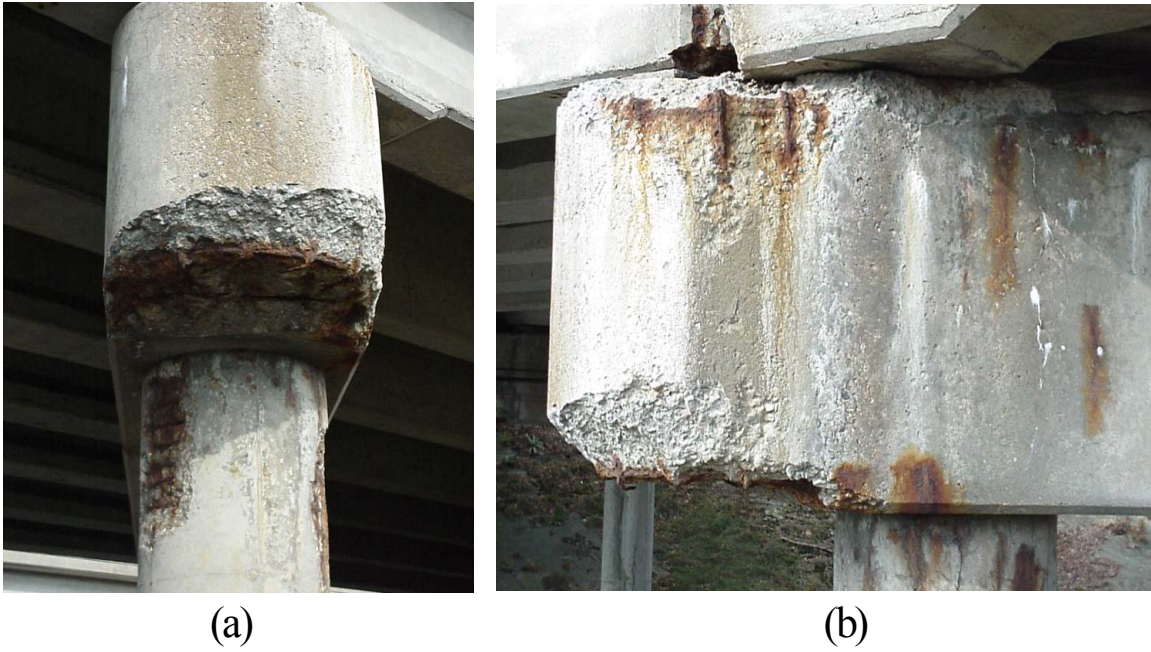


Figure 2.3: (a) Side and (B) Front Views of Deteriorated Pier Cap with Exposed Reinforcement

The piers provided an excellent opportunity to demonstrate the use of FRP caps to reduce further deterioration. The traffic was not too heavy and hence the construction could be carried out without much interference with the daily commuters. Traffic safety measures could also be implemented at minimum cost.

3. CHAPTER 3

Background Information

In this chapter, properties of common types and forms of fiber reinforcement materials and resins are presented. Brief descriptions of the four basic types of hybrids are also discussed. In addition basic information on vacuum assisted impregnation is also presented.

Two major components of a composite are high strength fibers and a matrix that binds these fibers to form a composite-structural component. The fibers provide strength and stiffness and the matrix (resin) provides the transfer of stresses and strains between the fibers. To obtain full composite action the fiber surfaces should be completely coated (wetted) with matrix. Two or more fiber types can be combined to obtain specific composite property that is not possible to obtain using a single fiber type. For example, the modulus, strength, and fatigue performance of glass-reinforced plastics (GRP) can be enhanced by adding carbon fibers. Similarly, the impact energy of carbon fiber reinforced plastics (CFRP) can be increased by the addition of glass or aramid fibers. The optimized performance that hybrid composite materials offer has led to their widespread growth throughout the world (Hancox, 1981; Shan, et al., 2002). In recent years, hybrid composites have found uses in a number of applications such as abrasive resistant coatings, contact lens, sensors, optically active films, membranes, and absorbents (Cornelius, et al., 2002).

3.1 FIBERS

The primary role of the fiber is to resist the major portion of the load acting on the composite system. Depending on the matrix type and fiber configuration, the fiber volume fraction ranges from 30 to 75%. Strength and stiffness properties of commercially available fibers cover a large spectrum and consequently, the properties of the resulting composite have a considerable variation (Mallick, 1993).

3.1.1 Fiber Types

Typical fiber reinforcements used in the composite industry are glass (E-glass and S-glass), carbon, and aramid (Kevlar[®]). The properties and characteristics of these fibers as well as other fiber types such as basalt are presented in the subsequent sections.

3.1.1.1 Glass Fibers

Glass fibers are the most common of all reinforcing fibers used in composites. Major advantages of glass fibers include low cost, high tensile strength, chemical resistance and high temperature resistance. The disadvantages are: low tensile modulus, sensitivity to abrasion while handling, relatively low fatigue resistance and brittleness. Glass fibers are produced by fusing silicates with silica or with potash, lime, or various metallic oxides. The molten mass is passed through micro-fine bushings and rapidly cooled to produce glass fiber filaments ranging in diameter from 5 to 24 μm . These filaments are then drawn together into closely packed strands or loosely packed roving. During this process, the fibers are frequently covered with a coating, known as sizing, to

minimize abrasion-related degradation of the filaments (Miller, D.M., 1987; SP Systems, 2001).

The two most common types of glass fibers used in the fiber-reinforced plastics industry are Electrical glass (also known as E-glass) and Structural glass (commonly referred to as S-glass). Other less common types include Chemical glass (or C-glass) and Alkali-Resistant glass (also known as AR-glass).

Among the glass fibers, the most economical and widely used reinforcement in polymer matrix composites is E-glass. E-glass is a family of glasses with a calcium aluminoborosilicate composition and an alkali content of no more than 2.0% (Miller, D.M., 1987). Because E-glass offers good strength properties at a very low cost, it accounts for more than 90% of all glass fiber reinforcements. As its name implies, it is known for its good electrical resistance. E-glass is especially well suited for applications in which radio-signal transparency is desired, such as in aircraft radomes and antennae. It is also extensively used in computer circuit boards (Composite Basics, 2003).

S-glass has the highest tensile strength among all the glass fibers and was originally developed for missile casings and aircraft components. S-glass has a magnesium aluminosilicate composition and is more difficult to manufacture. Consequently, the cost of S-glass is considerably higher than E-glass (Miller, D.M., 1987; SP Systems, 2001).

Chemical glass (C-glass) has a soda-lime-borosilicate composition that is utilized in corrosive environments where chemical stability is desired. It provides greater corrosion resistance to acids than E-glass. Its primary use is in surface coatings of laminates used in chemical and water pipes and tanks (Miller, D.M., 1987; SP Systems, 2001). Specifically developed for use in concrete, Alkali-Resistant glass (AR-glass) is composed of alkali-zirconium silicates. It is used in applications requiring greater chemical resistance to alkaline chemicals (bases), such as in cement substrates and concrete (Advanced Glass Fiber Yarns, LLC, 2003). Typical properties of E-glass, S-glass, C-glass, and AR-glass are presented in Table 3.1.

Table 3.1 Typical properties for glass fiber types (Advanced Glass Fiber Yarns, LLC., 2003; JPS, 2003; Watson, et al., 1987)

Glass Type	Density	Tensile Strength		Modulus of Elasticity		Dielectric Constant, 1 MHz @ 72°F	Elongation (%)
	(g/cm ³)	(MPa)	(ksi)	(GPa)	(ksi)		
E-glass	2.60	3,445	500	72.4	10,500	6.33	4.8
S-glass	2.49	4,585	665	86.9	12,600	5.34	5.4
C-glass	2.56	3,310	480	68.9	9,993	6.90	4.8
AR-glass	2.70	3,241	470	73.1	10,602	8.10	4.4

3.1.1.2 Carbon Fibers

Carbon fibers offer the highest modulus of all reinforcing fibers. Among the advantages of carbon fibers are their exceptionally high tensile strength-to-weight ratios as well as high tensile modulus-to-weight ratios. In addition, carbon fibers have high fatigue strengths and a very low coefficient of linear thermal expansion and, in some cases, even negative thermal expansion. This feature provides dimensional stability, which allows the composite to achieve near zero expansion to temperatures as high as 300°C in critical structures such as spacecraft antennae. If protected from oxidation, carbon fibers can withstand temperatures as high as 2000°C. Above 2000°C, they will thermally decompose. Carbon fibers are chemically inert and not susceptible to corrosion or oxidation at temperatures below 400°C.

Carbon fibers possess high electrical conductivity, which is quite advantageous to the aircraft designer who must be concerned with the ability of an aircraft to tolerate lightning strikes. However, this characteristic poses a severe challenge to the carbon textile manufacturer since carbon fiber debris generated during weaving may cause “shorting” or electric shocks in unprotected electrical machinery. Other key disadvantages are their low impact resistance and high cost (Amateau, 2003; Mallick, 1993).

Commercial quantities of carbon fibers are derived from three major feedstock or precursor sources: rayon, polyacrylonitrile, and petroleum pitch. Rayon precursors, derived from cellulose materials were one of the earliest sources used to make carbon fibers. Their primary advantage was their widespread availability. The most important drawback was the relatively high weight loss, or low conversion yield to carbon fiber, during carbonization. Carbonization is the process by which the precursor material is chemically changed into carbon fiber by the action of heat. On the average, only 25% of the initial fiber mass remains after carbonization. Therefore, carbon fiber made from rayon precursors is more expensive than carbon fibers made from other materials (Hansen, 1987; Peibly 1987).

Polyacrylonitrile (PAN) precursors constitute the basis for the majority of carbon fibers produced. They provide a carbon fiber conversion yield ranging from 50 to 55%. Carbon fiber based on PAN feedstock generally has a higher tensile strength than any other precursor. This results from a lack of surface defects, which act as stress concentrators and, consequently, reduce tensile strength (Hansen, 1987).

Pitch, a by-product of petroleum refining or coal coking, is a lower cost precursor than PAN. In addition to the relatively low cost, pitches are also known for their high carbon yields during carbonization. Their most significant disadvantage is non-uniformity from batch to batch during production (Hansen, 1987; Mallick, 1993).

Carbon fibers are commercially available with a variety of tensile moduli ranging from 207 GPa on the low end to 1035 GPa on the high end. With stiffer fibers, it requires fewer overall layers to achieve the optimal balance of strength and rigidity. Fiber for fiber, high-modulus and high-strength carbon weigh the same, but since high-modulus is inherently more rigid, less material is required, resulting in a lighter weight composite structure for applications that require stiffer components (Competitive Cyclist, 2003).

Although use of high modulus carbon is not very common, these fibers (> 440 GPa) have been used in a number of structures such as the London Underground subway system, one of the oldest and busiest underground railway networks in the world. High modulus carbon fibers were successfully utilized to strengthen steel beams, cast iron struts, and girders (Moy, 2002). Table 2.2 compares some typical mechanical properties and costs of commercially available carbon fibers categorized by tensile modulus.

Table 3.2 Typical properties of commercially available carbon fibers (Amateau, 2003; Hansen, 1987; SP Systems, 2001)

Grade	Tensile Modulus		Tensile Strength		Country of Manufacture	Manufacturer	Cost Per Pound
	(GPa)	(ksi)	(GPa)	(ksi)			
Standard Modulus (< 265 GPa) (also known as 'High Strength')							
AP38-500	228	33,000	3.4	500	Japan	Graphil	\$16
AP38-600	228	33,000	4.1	600	Japan	Graphil	\$24
AS2	228	33,000	2.8	400	USA	Hercules	
Panex 33	228	33,069	3.6	522	USA / Hungary		
F3C	228	33,069	3.8	551	USA		
T300	230	33,359	3.5	512	USA / France / Japan	Union Carbide / Toray / Amoco	\$26
XAS	234	33,939	3.5	500	USA	Graphil / Hysol	
Celion	234	33,939	3.6	515	USA	Celanese / ToHo	
Celion ST	234	33,939	4.3	629	USA	Celanese / ToHo	
34-700	234	33,939	4.5	653	Japan / USA		
TR30S	234	33,939	4.4	640	Japan		
T500	234	33,939	3.7	529	France / Japan	Union Carbide / Toray	
G30-500	234	34,000	3.8	550	USA	Celion	\$24
G30-600	234	34,000	4.3	630	USA	Celion	\$34
T700	235	34,084	5.3	769	Japan	Toray	
TR50S	235	34,084	4.8	701	Japan		
HTA	238	34,519	4.0	573	Germany		
UTS	240	34,809	4.8	696	Japan		
AS4	241	34,954	4.0	580	USA	Hercules	\$21
T650-35	241	34,954	4.6	660	USA	Amoco	\$28
AS5	244	35,389	3.5	508	USA	Hercules	
AP38-749	262	38,000	5.2	750	Japan	Graphil	
AS6	245	35,534	4.5	653	USA	Hercules	

Table 3.2 (Continued)

Grade	Tensile Modulus		Tensile Strength		Country of Manufacture	Manufacturer	Cost Per Pound
	(GPa)	(ksi)	(GPa)	(ksi)			
Intermediate Modulus (265 - 320 GPa)							
MR40	289	41,916	4.4	638	Japan		
MR50	289	41,916	5.1	740	Japan		
T1000	290	42,000	6.9	1,002	USA	Amoco	\$326
42-7A	290	42,000	5.0	725	USA	Celion	\$59
T650-42	290	42,061	4.8	699	USA	Amoco	\$53
T40	290	42,061	5.7	819	USA	Amoco / Toray	\$55
T800	294	42,641	5.9	862	France / Japan		
M30S	294	42,641	5.5	796	France		
IMS	295	42,786	4.1	598	Japan		
G40-600	296	43,000	4.3	620	USA	Celion	\$45
AP43-600	296	43,000	4.5	650	Japan	Graphil	
G40-700	296	43,000	5.0	720	USA	Celion	\$47
IM6	303	43,946	5.1	740	USA	Hercules	\$48
IM7	303	43,946	5.3	769	USA	Hercules	\$53
IM8	309	44,817	4.3	624	USA		
XIM8	310	45,000	5.2	750	USA	Hercules	
High Modulus (320 - 440 GPa)							
XMS4	331	48000	2.8	400	USA	Hercules	
HMS4	338	49,023	3.1	450	USA	Hercules	
MS40	340	49,313	4.8	696	Japan		
HMS	341	49,458	1.5	220	USA	Graphil / Hysol	
AP50-400	345	50,000	2.8	400	Japan	Graphil	\$55
HMG50	345	50,038	2.1	300	USA	Hitco / OCF	
HMA	358	51,924	3.0	435	Japan		
HMU	359	52,000	2.8	400	USA	Hercules	
G50-300	359	52,069	2.5	360	USA	Celion	\$58
AP53-650	365	53,000	4.5	650	Japan	Graphil	\$100
AP53-750	365	53,000	5.2	750	Japan	Graphil	\$110
M40J	377	54,679	4.4	640	France / Japan		
P55	379	54,969	1.7	251	USA	Union Carbide	
HR40	381	55,259	4.8	696	Japan		
M40	392	56,855	2.7	397	Japan		
PAN50	393	57,000	2.4	350	Japan	Toray	
UMS2526	395	57,290	4.6	661	Japan		

Table 3.2 (Continued)

Grade	Tensile Modulus		Tensile Strength		Country of Manufacture	Manufacturer	Cost Per Pound
	(GPa)	(ksi)	(GPa)	(ksi)			
Ultra High Modulus (~ 440 GPa)							
UMS3536	435	63,091	4.5	653	Japan		
M46J	436	63,236	4.2	611	Japan		
HS40	441	63,962	4.4	638	Japan		
UHMS	441	63,962	3.5	500	USA	Hercules	\$325
GY70	483	70,053	1.5	220	USA	Celion / Celanese	\$750
P75	517	74,985	2.1	300	USA	Union Carbide	
Thornel 75	517	74,985	2.5	365	USA	Union Carbide	
GY80	572	83,000	5.9	850	USA	Celion	\$850
P100	724	105,007	2.2	325	USA	Union Carbide	

3.1.1.3 Aramid Fibers

Aramid fiber is a synthetic organic polymer fiber (an aromatic polyamide) produced by spinning a solid fiber from a liquid chemical blend. Aramid fiber is bright golden yellow and is commonly known as “Kevlar[®],” its DuPont trade name. These fibers have the lowest specific gravity and the highest tensile strength-to-weight ratio among the reinforcing fibers used today. They are 43% lighter than glass and approximately 20% lighter than most carbon fibers. In addition to high strength, the fibers also offer good resistance to abrasion and impact, as well as chemical and thermal degradation. Major drawbacks of these fibers include: low compressive strength, degradation when exposed to ultraviolet light and considerable difficulty in machining and cutting (Mallick, 1993; Smith, 1996; SP Systems, 2001).

Kevlar[®] was commercially introduced in 1972 and is currently available in three different types:

- Kevlar[®]49 has high tensile strength and modulus and is intended for use as reinforcement in composites.
- Kevlar[®]29 has about the same tensile strength, but only about two-thirds the modulus of Kevlar[®]49. This type is primarily used in a variety of industrial applications.
- Kevlar[®] has tensile properties similar to that of Kevlar[®]29 but was initially designed for rubber reinforcement applications.

Table 3.3 shows that Kevlar[®]29 is nearly identical to Kevlar[®]49, with the exception of tensile modulus. The specific modulus in Table 2.3 is simply the modulus of the material divided by the material density, and is a measure of the stiffness of a material per unit weight. Materials with high specific moduli provide the lowest deflection for the lowest weight. Along with its tendency to yield in compression, Kevlar[®] exhibits a higher elongation at failure than glass and carbon fibers, resulting in a tougher and less brittle fiber than other commonly used reinforcing fibers. However, this high toughness is responsible for the significant difficulties in cutting and machining operations. Specially developed ultrasonic tools are needed to cut materials

containing or composed of aramid fibers (Schwartz, 1985).

Table 3.3 Comparative fiber mechanical properties (Albarrie, 2003; Schwartz, 1985)

Property	Kevlar [®]		High Strength Carbon	Glass		Basalt
	29	49		"E"	"S"	
<u>Fiber Density</u>						
(lb/in ³)	0.052	0.052	0.063	0.092	0.090	0.098
(g/cm ³)	1.44	1.44	1.75	2.55	2.49	2.7
<u>Break Elongation</u>						
(%)	4.40	2.90	1.25	4.70	5.60	3.10
<u>Tensile Strength</u>						
(ksi)	525	525	450	500	683	702
(GPa)	3.62	3.62	3.1	3.45	4.71	4.84
<u>Specific Tensile Strength¹</u>						
(10 ⁶ in)	10.1	10.1	7.1	5.4	7.6	7.2
(10 ⁷ cm)	2.5	2.5	1.8	1.4	1.9	1.8
<u>Tensile Modulus</u>						
(ksi x 10 ³)	12	18	32	10	12.4	12.9
(GPa)	83	124	221	69	85	89
<u>Specific Tensile Modulus¹</u>						
(10 ⁸ in)	2.3	3.5	5.1	1.1	1.4	1.3
(10 ⁸ cm)	5.7	9.0	12.6	2.7	3.5	3.3

¹Specific Property = property divided by material density

Kevlar[®] has been extremely successful in a variety of applications including premium tire cords, marine cordage, military body armor, oxygen bottles, high-pressure rocket casings, propeller blades, and in engine cowlings and wheel pants of aircraft, which are subject to damage from flying gravel (Smith, 1993).

3.1.1.4 Basalt Fibers

Basalt fiber is a unique product derived from volcanic material deposits. Basalt is an inert rock, found in abundant quantities, has excellent strength, durability, and thermal properties. The density of basalt rock is between 2800 and 2900 kg/m³. It is also extremely hard – 8 to 9 on the Moh's Hardness Scale (diamond = 10). Consequently, basalt has superior abrasion resistance and is often used as a paving and building material.

While the commercial applications of cast basalt have been well known for a long time, it is less known that basalt can be formed into continuous fibers possessing unique chemical and mechanical properties. The fibers are manufactured from basalt rock in a single-melt process and

are better than glass fibers in terms of thermal stability, heat and sound insulation properties, vibration resistance, as well as durability. Basalt fibers offer an excellent economic alternative to other high temperature resistant fibers and are typically utilized in heat shields, composite reinforcements, and thermal and acoustic barriers (Albarrie, 2003). Table 3.3 compares some typical mechanical properties of basalt fibers with Kevlar[®], high-strength carbon, E-glass, and S-glass. It can easily be seen that the basalt fibers have the highest tensile strength compared to the other fibers.

3.1.2 Comparison of Fiber Properties

Figure 3.1 presents a simple cost comparison for the most common types of fiber reinforcements. The prices are based upon continuous tows (rovings) of each fiber type. It shows that E-glass is the most economical type of fiber available today. In addition, the figure illustrates that higher modulus carbon fibers are the most expensive.

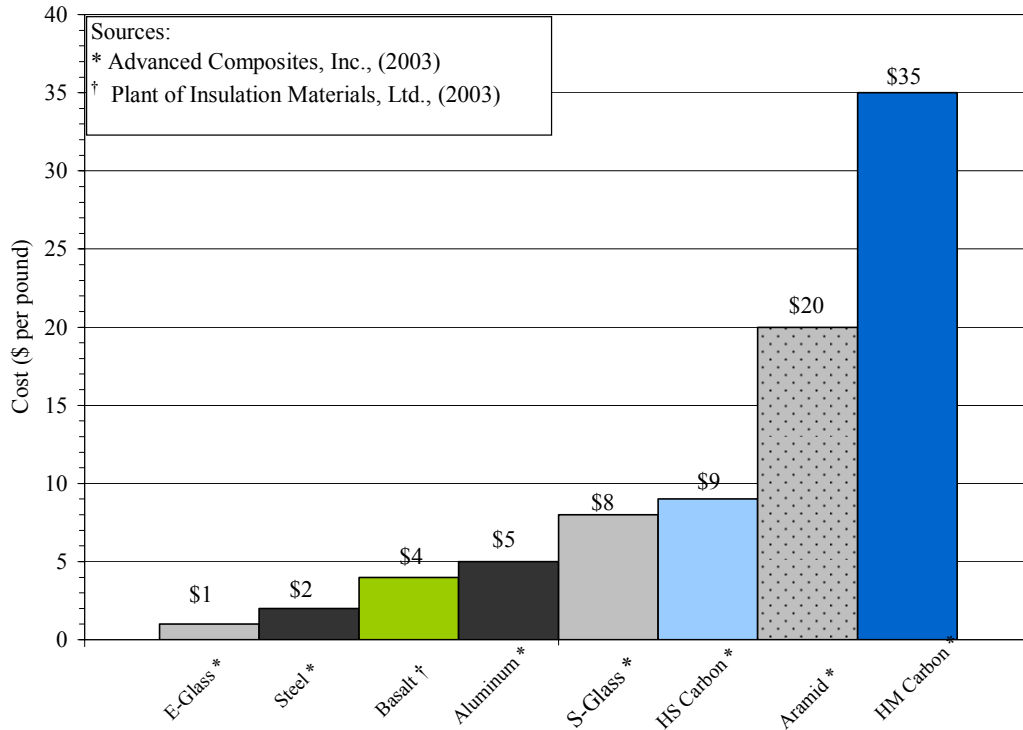


Figure 3.1 Relative ROM (Rough Order of Magnitude) raw material costs

Figure 3.2 compares the tensile modulus (stiffness) of typical fibers with that of traditional metals used in engineering applications. The bar chart shows that ultra high modulus (UHM) carbon fiber has a modulus 3 times that of steel and standard modulus carbon fiber has a modulus twice that of aluminum.

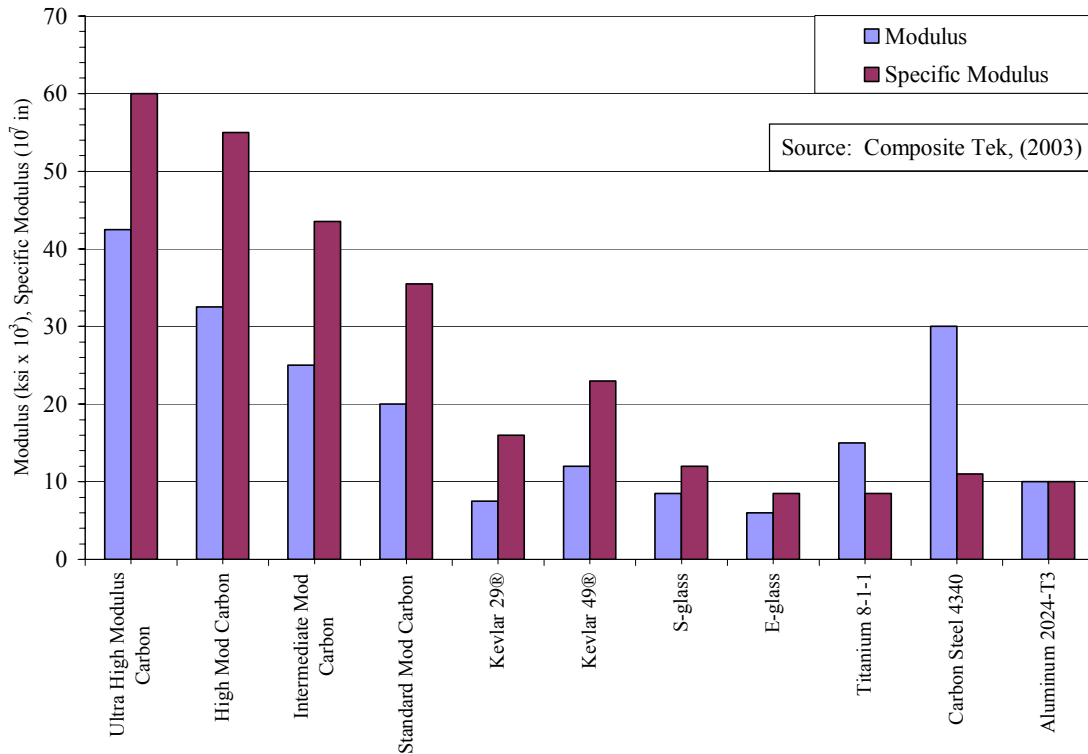


Figure 3.2 **Tensile modulus (stiffness) of typical fibers and metals**

Consider the tensile strength of common fiber reinforcements when compared to that of titanium, steel, and aluminum, Figure 3.3. The tensile strength of the fibers considered here far exceed that of aluminum by as much as 400%. For the most part, carbon, Kevlar®, and fiberglass also exceed the strength of steel by as much as 2 times. The specific strength of all of the fibers surpasses that of the metals by as much as 10 times. Carbon, Kevlar®, and fiberglass fibers offer superior strength at a lower weight when compared to metals.

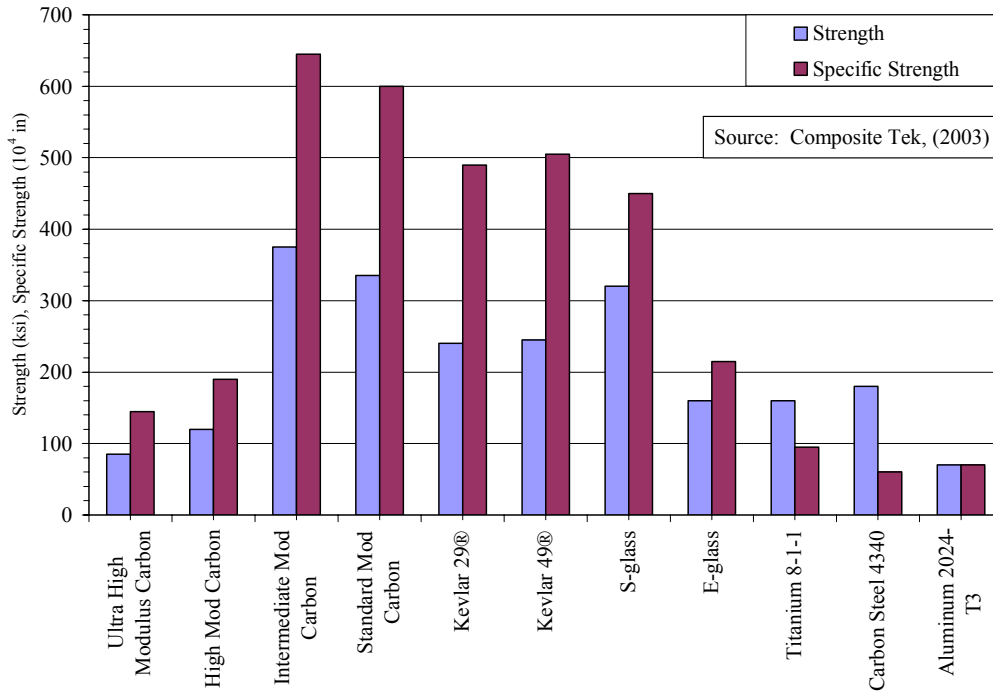


Figure 3.3 Tensile strength of typical fibers and metals

3.1.3 Fiber Sizing

Surface sizings, also known as finishing agents, coupling agents, and size coatings, are an essential factor in fibrous composite technologies. The term “sizing” refers to any surface coating applied to a fiber reinforcement to protect it from damage during processing. The sizing agent also improves the fiber surface wettability with the matrix (resin). This in turn results in a stronger bond between the fiber and the matrix. Good bond between the fiber and the matrix is essential for effective stress transfer from the fiber to the matrix and vice versa. The interfacial bond created by a coupling agent allows a better shear stress transfer between fibers and matrix, which, consequently, improves the tensile strength and the interlaminar shear strength of the composite. Table 3.4 presents the sizing classifications and their typical functions. Many commercially available sizings are formulated to be multifunctional. For instance, a glass fiber sizing may consist of a film-forming polymer to produce a uniform protective coating as well as an organo-functional silane to facilitate adhesion. The degree of bond improvement (or lack thereof) is critically dependent upon the compatibility of the sizing with the matrix (Bascom, 1987; Mallick, 1993).

Table 3.4 Sizing classifications and functions (Bascom, 1987; SP Systems, 2001)

Sizing Type	Purpose	Example	Comments
Film-forming organics and polymers	To protect the reinforcement during processing	Polyvinyl alcohol (PVA), polyvinyl acetate (PVAc)	The polymer is formulated to wet-spread to form a uniform coating that is applied to aid processing but later may be removed by washing or heat cleaning, for example, fugitive sizing.
Adhesion promoters	To improve composite mechanical properties and/or moisture resistance	Silane coupling agents (vinyl, glycidyl, and methacryl silane)	Principally used on inorganic reinforcement, for example, glass fiber
Interlayer	To enhance composite properties by creating an interphase between matrix and reinforcement	Elastomeric coating	Not in commercial use yet
Chemical modifiers	React to form protective coating	Silicon carbide on boron fibers	

Although the main function of the sizing is to improve mechanical properties of fibrous composites, they can present a number of significant disadvantages. Some experts have considered sizing as a “necessary evil” in that they are needed in one stage of processing but can hinder and interfere with subsequent processing. For instance, when carbon fiber is manufactured, sizing must be applied to the fiber tow to prevent the individual filaments from damage when contacting one another or with eyelets or guides during the weaving process. However, this same sizing may actually bond the filaments together, preventing uniform impregnation of the tows by the resin. In addition, sizing treatments may interfere with or adversely affect composite mechanical properties or durability. For example, a sizing that holds the filaments in a bundle so that the strand (tow) can be chopped for discontinuous fiber composites will interfere with later efforts to disperse the fibers during extrusion or injection molding (Bascom, 1987).

3.1.4 Forms of Reinforcement

All the fiber types are available in a variety of forms to serve a wide range of processes and end-product requirements. Fibers supplied as reinforcement include continuous spools of tow (carbon), roving (glass), milled fiber, chopped strands, chopped or thermo-formable mat, and woven fabrics. Reinforcement materials can be tailored with unique fiber architectures and be preformed (shaped) depending on the product requirements and manufacturing process. Table 3.5 provides a simple summary of the various forms of fiber reinforcements. These forms are discussed in the following sections.

Table 3.5 Various forms of fiber reinforcements (“Composite Materials,” 1998)

Reinforcement Form	Description	Principal Processes
Filament	Fibers as initially drawn	Processed further before use
Yarn	Twisted strands (treated with after-finish)	Processed further before use
Tow	Filaments gathered together into one continuous bundle	Hand lay-up; Processed further before use
Roving	Strands bundled together like rope but not twisted	Filament winding; Spray-up; Pultrusion
Chopped Strand	Strands chopped 1/4 to 2 inches long	Injection molding; matched die
Milled Fiber	Continuous strands hammer-milled into short lengths 1/32 to 1/8" in length	Compounding; Casting; Reinforced Reaction Injection Molding (RRIM)
Chopped Strand Mat	Non-woven random mat consisting of chopped strands	Hand lay-up; Resin Transfer Molding (RTM)
Continuous Strand Mat	Non-woven random mat consisting of continuous strands	Resin Transfer Molding (RTM); Cold Press Molding
Surfacing Mat	Random mat of monofilaments	Hand lay-up; Matched die; pultrusion
Woven Fabric	Cloth woven from yarns	Hand lay-up; prepreg
Non-woven Fabric	Felt type mat made from bonded filaments	Hand lay-up; Spray-up; RTM
Woven Roving	Strands woven like fabric but coarser and heavier	Hand lay-up; Spray-up; RTM
Spun Roving	Continuous single strand looped and twisted	Processed further before use

3.1.4.1 Filament

A filament is an individual fiber as drawn during processing (drawing and spinning). It can be considered as the smallest unit of fiber reinforcements. Depending on the material, the filament diameter can range from 1 μm to 25 μm . Table 3.6 presents the standard filament diameter nomenclature as used in the fiberglass industry. It is standard practice to utilize a specific alphabet designation when referring to a specific filament diameter. Very fine fibers, typically used in textile applications, range from AA to G. Conventional composite reinforcements consist of filaments with diameters ranging from G to U. Individual filaments are rarely used as reinforcement; they are typically gathered into strands of fibers (either continuous or chopped) for use in fibrous composites (Watson and Raghupathi, 1987).

Table 3.6 **Standard filament diameter nomenclature (Watson and Raghupathi, 1987)**

Alphabet	Filament Diameter		Alphabet	Filament Diameter	
	(μm)	(10^{-4} in)		(μm)	(10^{-4} in)
AA	0.8 - 1.2	0.3 - 0.5	K	12.7 - 14.0	5.0 - 5.5
A	1.2 - 2.5	0.5 - 1.0	L	14.0 - 15.2	5.5 - 6.0
B	2.5 - 3.8	1.0 - 1.5	M	15.2 - 16.5	6.0 - 6.5
C	3.8 - 5.0	1.5 - 2.0	N	16.5 - 17.8	6.5 - 7.0
D	5.0 - 6.4	2.0 - 2.5	P	17.8 - 19.0	7.0 - 7.5
E	6.4 - 7.6	2.5 - 3.0	Q	19.0 - 20.3	7.5 - 8.0
F	7.6 - 9.0	3.0 - 3.5	R	20.3 - 21.6	8.0 - 8.5
G	9.0 - 10.2	3.5 - 4.0	S	21.6 - 22.9	8.5 - 9.0
H	10.2 - 11.4	4.0 - 4.5	T	22.9 - 24.1	9.0 - 9.5
J	11.4 - 12.7	4.5 - 5.0	U	24.1 - 25.4	9.5 - 10.0

3.1.4.2 Yarn

A yarn is a generic term for a closely associated bundle of twisted filaments, continuous strand of fibers, or strands in a form suitable for knitting, weaving, or otherwise intertwining to form a textile fabric. Yarn occurs in the following forms:

- A spun yarn is a number of fibers twisted together.
- A zero-twist yarn is a number of filaments laid together without twist.
- A twisted yarn is a number of filaments laid together with a degree of twist.
- A monofilament is a single filament with or without twist.
- The last form is simply a narrow strip of material, such as paper, plastic film, or metal foil, with or without twist, intended for use in a textile construction (Celanese Acetate LLC, 2001).

Yarns have varying weights described by their “Tex” (the weight in grams of 1,000 linear meters) or “denier” (the weight in pounds of 10,000 yards or the weight in grams of 9,000 meters). The lower the denier, the finer the yarn. The typical Tex range is usually between 5 and 400. Most yarns, especially glass, follow an internationally recognized terminology as shown in the example of Table 3.7 (Pebly, 1987; SP Systems, 2001).

Table 3.7 **Example of terminology used to identify glass yarn (SP Systems, 2001)**

Glass Type	Yarn Type	Filament Diameter (μm)	Strand Weight (Tex)	Single Strand Twist	No. of Strands	Multi-Strand Twist	No. Turns Per Meter
E	C	9	34	Z	X2	S	150
E = Electrical C = Continuous S = High Strength				Z = Clockwise S = Anti-Clockwise			

3.1.4.3 Tow

A tow is an untwisted bundle of continuous filaments. Also known as a continuous strand, or an “end,” it is commonly used when referring to manufactured fibers, especially carbon. Tow designations are based upon the number of thousands of fibers. For example, a “12k HMC Tow” refers to a high modulus carbon tow consisting of 12,000 fibers. Tows are sold by weight (pounds or kilograms) and are typically wound onto a spool, as shown in Figure 3.4 (Pebly, 1987).



Figure 3.4. Carbon tow wound around spools (Zoltek, 2003)

3.1.4.4 Roving

Unlike yarns, a roving is a *loosely* assembled bundle of untwisted parallel filaments or strands. Each filament diameter in a roving is the same, and is usually between 13-24 μm . Rovings have varying weights and the Tex range is usually between 300 and 4,800. If filaments are gathered together directly after the melting process, the resultant fiber bundle is known as a direct roving. If several strands are assembled together after the glass is manufactured, they are known as an assembled roving. Assembled rovings usually have smaller filament diameters than direct rovings, providing better wet-out and mechanical properties, but they can suffer from catenary problems (unequal strand tension), and are usually more expensive due to more

complex manufacturing processes (SP Systems, 2001).

Rovings are typically used in continuous molding operations, such as filament winding and pultrusion. In addition, rovings can be pre-impregnated with a thin layer of resin to form prepregs (ready-to-mold material that can be stored until time of use). When designating reinforcement weights of rovings, the unit of measure is “yield,” which is defined as the number of linear yards of roving per pound. Thus, “162 yield roving” equals 162 yards per pound (Celanese Acetate LLC, 2001). Figure 3.5 shows glass roving spun onto large spools.

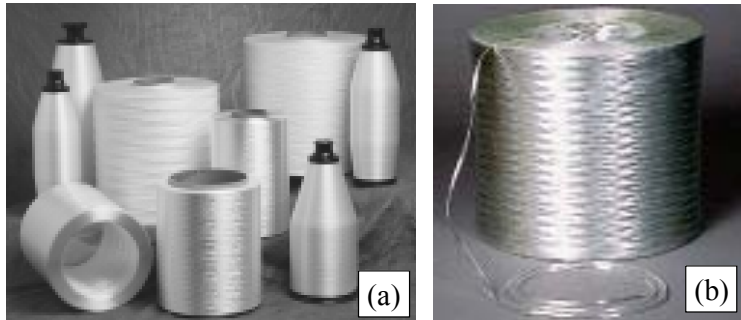


Figure 3.5 **Glass rovings (a) Advanced Glass Fiber Yarns, 2003 (b) Saint Gobain, 2003**

3.1.4.5 Chopped Strands

Chopped strands are produced by cutting continuous strands into short lengths. The ability of the individual filaments to remain together during or after the cutting process depends on the type and amount of sizing applied during manufacturing. Strands of high integrity that remain together are referred to as being “hard” while those that separate more easily are called “soft.” Chopped strands, 3 to 12 mm long, are typically used in injection molding processes. Chopped strand mats are usually made with longer strands, that measure up to 50 mm. Chopped strands of carbon, glass, aramid, and basalt are commercially available and are sold by weight (Mallick, 1993). Pictures of chopped glass and basalt strands are shown in Figure 3.6 (a) and (b), respectively.



Figure 3.6 **(a) Chopped glass strands (b) Chopped basalt strands**

3.1.4.6 Milled Fibers

Milled fibers are produced by grinding continuous strands in a hammer mill into very short lengths. Fiber lengths typically range from particulates to screen opening dimensions ranging from 1 to 3 mm. They are primarily used in the plastics industry as inexpensive filler. Although they provide increased stiffness and dimensional stability to plastics, they do not provide significant reinforcement value. Typical applications include reinforced reaction injection molding (RRIM), phenolics, and potting compounds (Mallick, 1993; Watson, et al., 1987). A picture of milled glass fibers is shown in Figure 3.7. Note the considerable difference in particle size when compared to the chopped fiber strands in Figure 3.6.



Figure 3.7 Milled glass fibers

3.1.4.7 Fiber Mats

A fiber mat, also known as “omni-directional reinforcement” is randomly oriented fibers held together with a small amount of adhesive binder. Fiber mats can be used for hand lay-up as prefabricated mat or for the spray-up process as chopped strand mat. The key points of fiber mats are:

- Cost much less than woven fabrics and are about 50% as strong
- Requires more resin to fill interstices and more vacuum to remove air
- Used for inner layers and helps in filling complex fabrics
- High permeability and easy to handle
- Low stiffness and strength and no orientation control
- Mechanical properties are less than other reinforcements
- Used in non-critical applications

Three typical types of mat reinforcements are:

1. Randomly oriented chopped filaments (chopped strand mat)

2. Swirled filaments loosely held together with a binder (continuous strand mat)
3. Very thin mats of highly filamentized glass (surfacing mat)

A chopped strand mat is a non-woven material composed of chopped fiberglass of various lengths randomly dispersed to provide equal distribution in all directions and held together by a resin soluble binder. Chopped strand mats are commonly used in laminates due to ease of wet-out, good bond provided between layers of woven roving or cloth, and comparatively low cost. Chopped strand mat is categorized by weight per square foot and is sold by the running meter or in bulk by weight in full rolls. Several rolls of a chopped strand mat are shown in Figure 3.8 (SP Systems, 2001; Watson, et al., 1987).



Figure 3.8 **Chopped strand mat (Saint Gobain, 2003)**

A continuous strand mat is similar to a chopped strand mat, except that the fiber is continuous and is made by swirling strands of continuous fiber onto a belt, spraying a binder over them, and then drying the binder. Both hand lay-up and spray-up produce plies with equal physical properties and good interlaminar shear strength. This is a very economical way to build up thickness, especially with complex molds. A roll of a continuous glass strand mat is shown in Figure 3.9. Continuous strand mats are usually designated in gram per square meter (SP Systems, 2001; Watson, et al., 1987).



Figure 3.9 **Continuous strand mat (Fiber Link Inc., 2003)**

A surface mat is a very fine mat made from glass or carbon fiber and is used as a top layer in a composite to provide a more aesthetic surface by hiding the glass fibers of a regular woven fabric. A surface mat is similar in appearance to the chopped strand mat but is much finer (usually 180 to 510 μm), Figure 3.10. It is composed of fine fiberglass strands of various lengths randomly dispersed in all directions and held together by a resin soluble binder. It is characterized by uniform fiber dispersion, a smooth and soft surface, low binder content, fast resin impregnation, and conforms well to molds. This material is used to provide a resin-rich layer in liquid or chemical holding tanks, or as a reinforcement for layers of gelcoat (a quick setting resin applied to the surface of a mold and gelled before lay-up) (SP Systems, 2001; Watson, et al., 1987).



Figure 3.10 **Surfacing mat (Fiber Glass King, 2003)**

3.1.4.8 Fabrics

A fabric is defined as a manufactured assembly of long fibers of carbon, aramid, glass, other fibers, or a combination of these, to produce a flat sheet of one or more layers of fibers. These layers are held together either by mechanical interlocking of the fibers themselves or with a secondary material to bind these fibers together and hold them in place, giving the assembly sufficient integrity for handling. Consequently, fabrics are the preferred choice of reinforcement since the fibers are in a more convenient format for the design engineer and fabricator. Fabric types are categorized by the orientation of the fibers used, and by the various construction methods used to hold the fibers together (Cumming, 1987; SP Systems, 2001). Before each type of fabric architecture is discussed, some relevant terminology is presented.

3.1.4.8.1 Terminology

The weight of a dry fabric is usually represented by its areal density, or weight per unit area (usually just called “weight”). The most common unit of measure is ounces per square yard,

often simply abbreviated as “ounces.” Thus, a fabric with a weight of “5.4 oz” really has an areal density of 5.4 oz/yd².

Each fabric has its own pattern, often called the construction, and is an x, y coordinate system, Figure 3.11. Some of the yarns run in the direction of the roll (y -axis or 0°) and are continuous for the entire length of the roll. These are the warp yarns and are usually called *ends*. The y -axis (90°) is the long axis of the roll and is typically 30 to 150 meters. The short yarns, which run crosswise to the roll direction (x -axis), are called the *fill* or *weft* yarns (also known as picks). Therefore, the x -direction is the roll width and is usually 910 to 3050 mm.

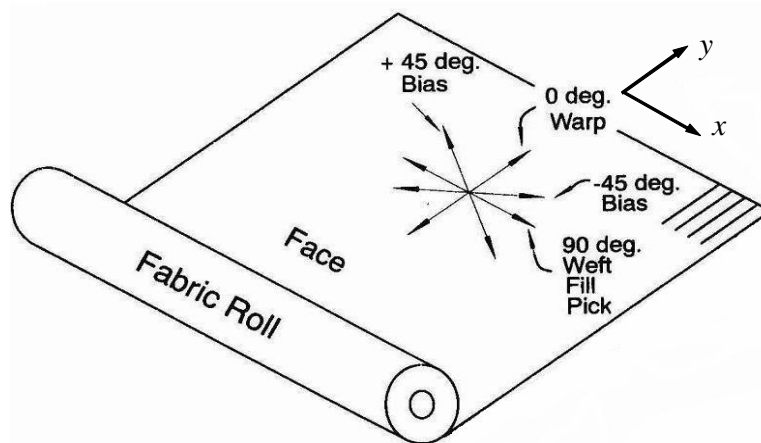


Figure 3.11 Fabric roll orientation (Smith, 1996)

Fabric *count* refers to the number of warp yarns (ends) and fill yarns (picks) per inch. For example, a “24 x 22 fabric” has 24 ends in every inch of fill direction and 22 picks in every inch of warp direction. It is important to note that warp yarns are counted in the fill direction, while fill yarns are counted in the warp direction. Two other important terms are drupe and bias. Drupe refers to the ability of a fabric to conform or fit into a contoured surface and bias represents the angle of the warp and weft threads, usually 90° but can be 45° (Cumming, 1987; SP Systems, 2001).

3.1.4.8.2 Unidirectional Fabrics

A fabric made with a weave pattern designed for strength in only one direction is termed unidirectional. The pick count of a unidirectional fabric is very small and most of the yarns run in the warp direction. Pure unidirectional construction implies no structural reinforcement in the fill direction, although enough warp fibers are included in the weave to ensure ease of handling, Figure 3.12. The small amount of fiberglass fill in the two fabrics of Figure 3.12 can be seen traveling horizontally in the x -direction. Ultra high strength/modulus material, such as carbon fiber, is sometimes used in this form for specific application. Material widths are generally

limited due to the difficulty of handling and wet-out. As a result, unidirectional fabrics are commonly manufactured in tape form or narrow rolls (less than a few inches wide). Typical applications of unidirectionals include highly loaded designed composites, such as aircraft components or race boats. Entire hulls will be fabricated from unidirectional reinforcements if an ultra high performance laminate is desired (Cumming, 1987; Smith, 1996; SP Systems, 2001).

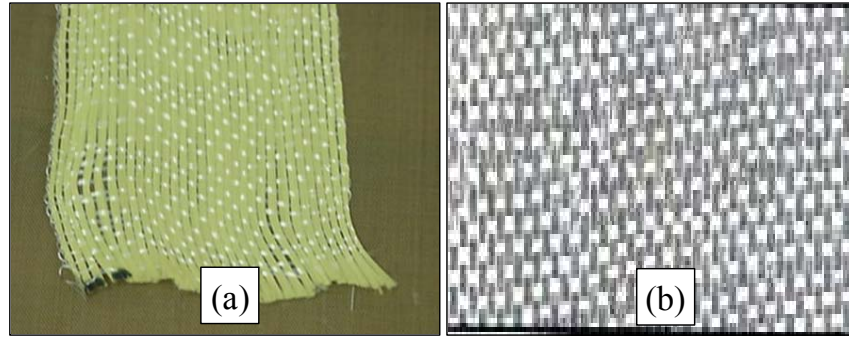


Figure 3.12 (a) Unidirectional Kevlar® tape (b) Unidirectional carbon fabric

3.1.4.8.3 Weave Types

The weave describes how the warp and fill yarns in a fabric are interlaced. Weave determines drapeability and isotropy of strength (some weaves are biased to the warp or fill direction). The most popular weaves are plain, twill, basket weave, harness satin, and crowfoot satin, Figure 3.13.

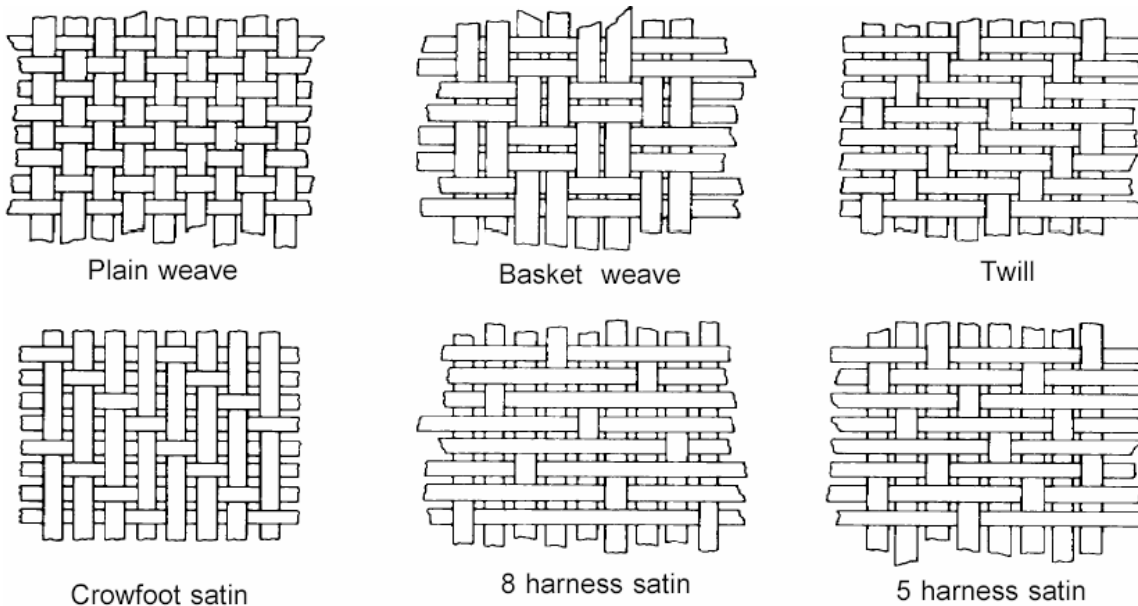


Figure 3.13 Basic weave types (Dominguez, 1987)

The plain weave ($0/90^\circ$) is the most common weave construction used in the composites industry. Shown in Figures 2.13 and 2.14, construction of the plain weave essentially requires only four weaving yarns: two warps and two fill. This basic unit is termed as the *pattern repeat*. The interlacing yarns follow the same simple pattern: one over and one under. For a simple plain-woven fabric, half of the fibers are in the warp (0°) orientation and the other half are in the fill (90°) direction. This weave type is highly interlaced and is, consequently, one of the tighter fabric constructions and very resistant to in-plane shear movement. The fabric is symmetrical, with good stability and reasonable porosity.

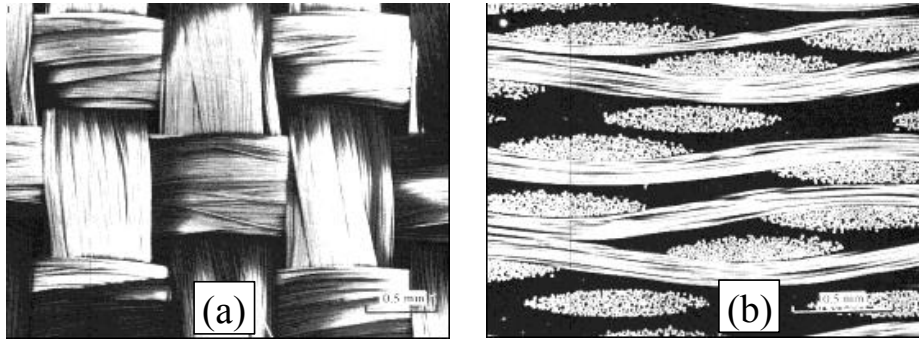


Figure 3.14 Plain weave (a) Plan view (b) Side view (Michigan Tech. University, 2003)

The strength of plain weaves is somewhat compromised due to the severe “pre-buckling” already present in the fabric. Fibers provide their greatest strength when they are perfectly straight. The frequent over-and-under crossing of the threads in a plain weave induces a slight curvature in the fibers, essentially “pre-buckling” the tows even before any load has been applied. This fiber undulation reduces the strength of plain weave types, though they are still adequate for many applications. Plain weaves are the most difficult of the weaves to drape, and the high level of fiber crimp results in relatively low mechanical properties compared with the other weave styles. With large fibers (high Tex), the plain weave gives excessive crimp and therefore not used for very heavy fabrics. Plain weaves are typically used for flat laminates, printed circuit boards, narrow fabrics, molds, and covering wood boats (Cumming, 1987; Hammell, 2000b; SP Systems, 2001).

In a twill weave, one or more warp fibers alternately weave over and under two or more weft fibers in a regular repeated manner. This produces the visual effect of a straight or broken diagonal “rib” to the fabric, Figure 3.15 (a). Twills are characterized by the diagonal pattern that is formed by the weave. This optical illusion often confuses fabricators into laying-up the material 45° off the desired fiber orientation. The twill is formed when the weft passes over warps 1 and 2 and under warps 3 and 4, and in the next pass, the shuttle of the loom passes over warps 2 and 3 and under warps 4 and 5. The advantage of the twill is the fewer number of times the fibers go under and over one another. Better wet out and drape is possible with twill weave over the plain weave with only a small reduction in stability. With reduced crimp, the fabric also has a smoother surface and slightly better mechanical properties. Twills are known for being the

most drapable weave and are often used for complex shapes in both vacuum bagging and wet lay-up applications. Carbon fiber twill material is often chosen for its aesthetic appearance.

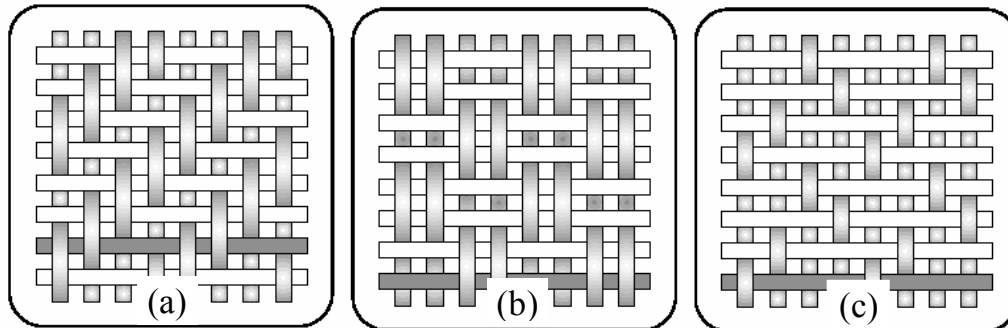


Figure 3.15 (a) Twill weave (b) Basket weave (c) Satin weave (SP Systems, 2001)

The basket weave is fundamentally similar to the plain weave but two yarns are grouped together and woven in an over-two-under-two fashion, Figure 2.15 (b). An arrangement of two warps crossing two wefts is designated as a “ 2×2 basket”, but the arrangement of fiber need not be symmetrical. The weave can be varied where four yarns are woven over-four-under-four, hence, a “ 4×4 basket weave”. Other variations such as 8×2 , 5×4 are possible. A basket weave is flatter, and, through less crimp, stronger and more pliable than a plain weave but less stable. Basket weaves have less pre-buckling because the yarns do not alternate over-and-under as often. It can be used on heavyweight fabrics made with thick (high Tex) fibers without excessive crimping.

The satin weaves represent a family of constructions with a minimum of interlacing. In these fabrics, the weft yarns periodically skip, or “float,” over several warp yarns as shown in Figure 3.15 (c). Satin weaves are fundamentally twill weaves modified to produce fewer intersections of warp and weft. The satin weave repeat is x yarns long and the float length is $(x - 1)$ yarns. Therefore, there is only one interlacing point per pattern repeat per yarn. The floating yarns that are not being woven into the fabric create considerable looseness or suppleness. As a result, the satin weave construction has low resistance to shear distortion and is easily molded (draped) over compound curves. This is one of the key reasons why engineers frequently utilize satin weaves in many aerospace applications.

The “harness” number used in the designation (typically 4, 5, or 8) is the total number of fibers crossed and passed under, before the fiber repeats the pattern. As the number of harnesses increases, so do the float lengths and the degree of looseness, increasing the difficulty during handling operations. For example, consider the 5-Harness satin weave shown in Figure 3.16. In this weave, each yarn goes over 4 and under 1 yarn in both directions.

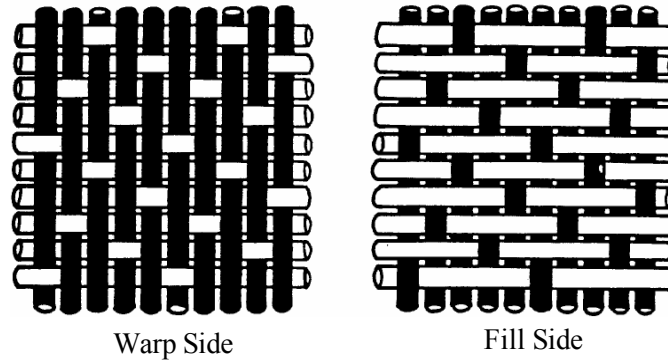


Figure 3.16 **5-Harness satin weave construction (D.O.D., 1996)**

Figure 3.17 shows the 8-Harness satin weave in which each yarn goes over 7 and under 1 yarn in both directions.

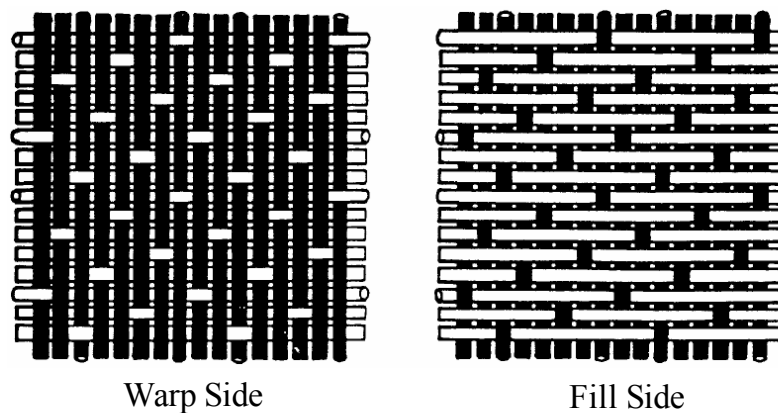


Figure 3.17 **8-Harness satin weave construction (D.O.D., 1996)**

A crowfoot weave is a form of satin weave with a different stagger in the repeat pattern, Figure 3.13.

Satin weaves are known to be very flat, have good wet out properties, low crimp, and a high degree of drape. Satin weaves allow fibers to be woven in the closest proximity and can produce fabrics with a close ‘tight’ weave. Low stability and asymmetry of satin weaves need to be considered. The asymmetry stems from one face of the fabric having fiber running predominantly in the warp direction while the other face has fibers running predominantly in the weft direction. Figures 3.16 and 3.17 illustrate this asymmetry in the 5- and 8-Harness satin weaves, respectively. When assembling multiple layers of these fabrics, care must be taken to ensure that stresses are not built into the component through this asymmetric effect.

Two less common weaves are the leno and mock leno. The leno (also known as locking leno) is a form of plain weave in which two adjacent warp fibers are twisted around each fill yarn to form a spiral pair, essentially “locking” each fill yarn in place, Figure 3.18 (a). The advantages of the leno weave are its high stability in “open” fabrics, which have a low fiber count, and it provides heavy fabrics for rapid build-up of plies. Fabrics in leno weave are usually used in conjunction with other weave styles because if used alone their openness could not produce an effective composite component. Fabrics with leno weaves are frequently used as an inner core for the support of thin coatings for tooling and repairs. The mock leno is a version of the plain weave in which occasional warp fibers, at regular intervals but usually several fibers apart, deviate from the alternate under-over interlacing and instead interlace every two or more fibers. As shown in Figure 2.18 (b), this happens with similar frequency in the fill direction, and the overall effect is a fabric with increased thickness, rougher surface, and additional porosity.

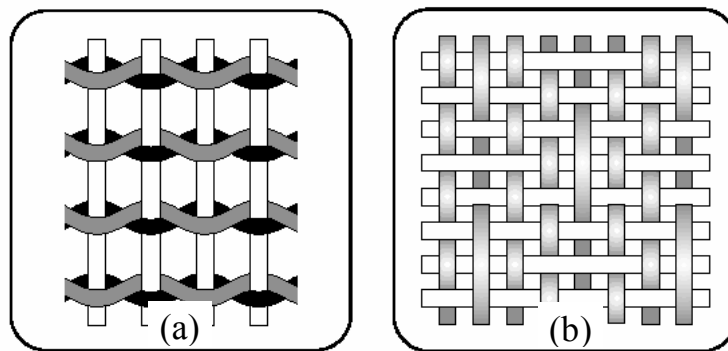


Figure 3.18 (a) Leno and (b) Mock leno weaves (SP Systems, 2001)

Table 3.8 presents a simple comparison of properties for the weaves presented in this section. It can be seen that each fabric has its advantages and disadvantages. For example, consider the satin and leno weaves. While the satin weave has excellent drape and poor stability, the leno weave has excellent stability and very poor drape. The fabric must be inherently stable enough to be handled, cut, and transported to the mold, yet pliable enough to conform to the mold shape and contours. If properly designed, the fabric will allow for quick wet out and will stay in place once the resin is applied (Cumming, 1987; SP Systems, 2001).

Table 3.8 Comparison of properties of common weave styles (SP Systems, 2001)

Property	Plain	Twill	Satin	Basket	Leno	Mock Leno
Good stability	*****	***	**	**	*****	***
Good drape	**	****	*****	***	*	**
Low porosity	***	****	*****	**	*	***
Smoothness	**	***	*****	**	*	**
Balance	****	****	**	****	**	****
Symmetrical	*****	***	*	***	*	****
Low crimp	**	***	*****	**	*****	**
Key:	***** = excellent		*** = acceptable		* = very poor	
	**** = good		** = poor			

3.1.4.8.4 Hybrid Fabrics

The term hybrid refers to a fabric that has more than one type of structural fiber in its construction. In a multi-layer laminate, if the properties of more than one type of fiber are required, then it would be possible to provide this with two fabrics, each ply containing the fiber type needed. However, if low weight or extremely thin laminates are required, a hybrid fabric will allow the two fibers to be incorporated in just one layer of fabric instead of two. It would be possible in a woven hybrid to have one fiber running in the weft direction and the second fiber running in the warp direction, but it is more common to find alternating threads of each fiber in each warp/weft direction. For instance, in an attempt to harness the stiffness and compressive strength of carbon fiber with the impact resistance and tensile strength of aramid fiber, engineers developed a hybrid fabric consisting of carbon and aramid as shown in Figure 3.19.



Figure 3.19 Hybrid fabric (twill weave) of aramid and carbon (Fibre Glast, 2003a)

Although hybrids are most commonly found in 0/90° woven fabrics, the principle is also used in 0/90° stitched, unidirectional, and multi-axial fabrics. The most common hybrid combinations are:

- Carbon / Aramid: The high impact resistance and tensile strength of the aramid fiber combines with the high compressive and tensile strengths of carbon. Both fibers have low density but relatively high cost.
- Aramid / Glass: The low density, high impact resistance, and tensile strength of aramid fiber combines with the good compressive and tensile strength of glass, coupled with its lower cost.
- Carbon / Glass: Carbon fiber contributes high tensile and compressive strengths, high stiffness, and reduces the density, while glass reduces the cost (SP Systems 2001).

3.1.4.8.5 Multi-axial Fabrics

Multi-axial fabrics, also known as non-woven, non-crimped, stitched, or knitted, have optimized strength properties because of the fiber architecture. Stitched fabrics consist of several layers of unidirectional fiber bundles held together by a non-structural stitching thread, usually polyester. The fibers in each layer can be oriented along any combination of axes between 0° and 90°. Multiple orientations of fiber layers provide a quasi-isotropic reinforcement. The entire fabric may be made of a single material, or different materials can be used in each layer. A layer of mat may also be incorporated into the construction. A schematic drawing of a typical knitted biaxial fabric is shown in Figure 3.20 (a).

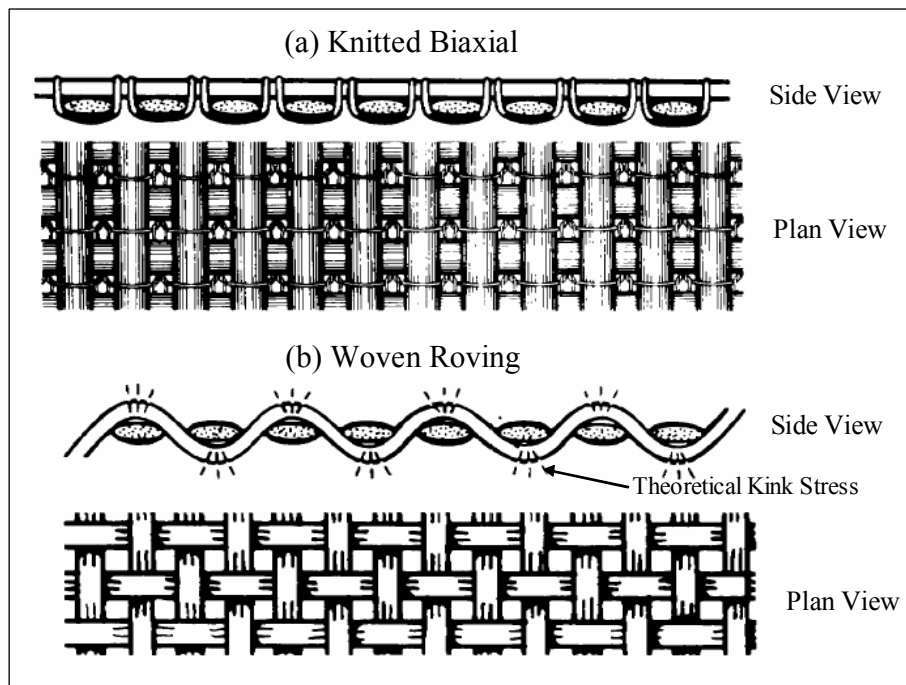


Figure 3.20 (a) Knitted biaxial fabric (b) Woven roving (“Composite Materials,” 1998)

Conventional woven fabrics are made by weaving fibers in two perpendicular directions (warp and fill). However, weaving bends the fibers, reducing the maximum strength and stiffness that can be achieved. In addition, fabrics also tend to fray when cut, making them difficult to handle. Stitched fabrics offer several advantages over conventional woven fabrics. In the simplest case, woven fabrics can be replaced by stitched fabrics, maintaining the same fiber count and orientation. When compared to traditional woven fabrics, stitched fabrics offer mechanical performance increases of up to 20% over woven fabrics primarily from the fact that the fibers are always parallel and non-crimped, and that more orientations of fiber are available from the increased number of layers of fabric. Other noteworthy advantages of stitched fabrics include:

- Stress points located at the intersection of warp and fill fibers in woven fabrics are no longer present in stitched fabrics.
- A higher density of fiber can be packed into a laminate compared with a woven, essentially behaving more like layers of unidirectional.
- Heavy fabrics can be easily produced.
- Increase packing of the fiber can reduce the quantity of resin required (SP Systems, 2001)

Multi-axial fabrics have several disadvantages. First, the polyester fiber used for stitching does not bond very well to some resin systems and so the stitching can serve as a site for failure initiation. The production process can be quite slow and the cost of the machinery high. Consequently, stitched fabrics can be relatively expensive compared to woven fabrics. Extremely heavyweight fabrics can also be difficult to impregnate with resin without some automated process. Finally, the stitching process can bunch together the fibers, particularly in the 0° direction, creating resin-rich areas in the laminate.

For over half a century, these stitched fabrics have been traditionally used in boat hulls. Other applications include wind turbine blades, light poles, trucks, buses, and underground tanks. Currently, these fabrics are used in bridge decks and column repair projects. Woven and knitted textile fabrics are designated in ounces per square yard (oz/yd²) (SP Systems, 2001).

3.1.4.8.6 Woven Roving

Woven roving reinforcement consists of flattened bundles of continuous strands in a plain weave pattern with slightly more material in the warp direction. To form the material, roving is woven into a coarse, square, lattice-type, open weave as shown in Figure 3.20 (b). Woven roving provides great tensile and flexural strengths and a fast laminate buildup at a reasonable cost. Woven roving is more difficult to wet out than chopped strand mat however, and because of the coarse weave, it is not used where surface appearance is important. When more than one layer is required, a layer of chopped strand mat is often used between each layer of roving to fill the coarse weave. Woven roving is categorized by weight per unit area (oz/yd²) and is sold by the running yard or in bulk by the pound or kilogram (Coast Fiber-Tek Products Ltd., 2003).

3.1.4.9 Other Forms

A number of other forms of reinforcement are currently manufactured in the composites industry. Spun roving, for instance, is a heavy low-cost glass or aramid fiber strand consisting of

filaments that are continuous but doubled back on themselves. Braids are fibers that are woven into a tubular shape instead of a flat fabric, as for a carbon fiber reinforced golf club shaft (Pebly, 1987). Some forms of reinforcement discussed earlier as well as other types are illustrated in Figure 3.21.

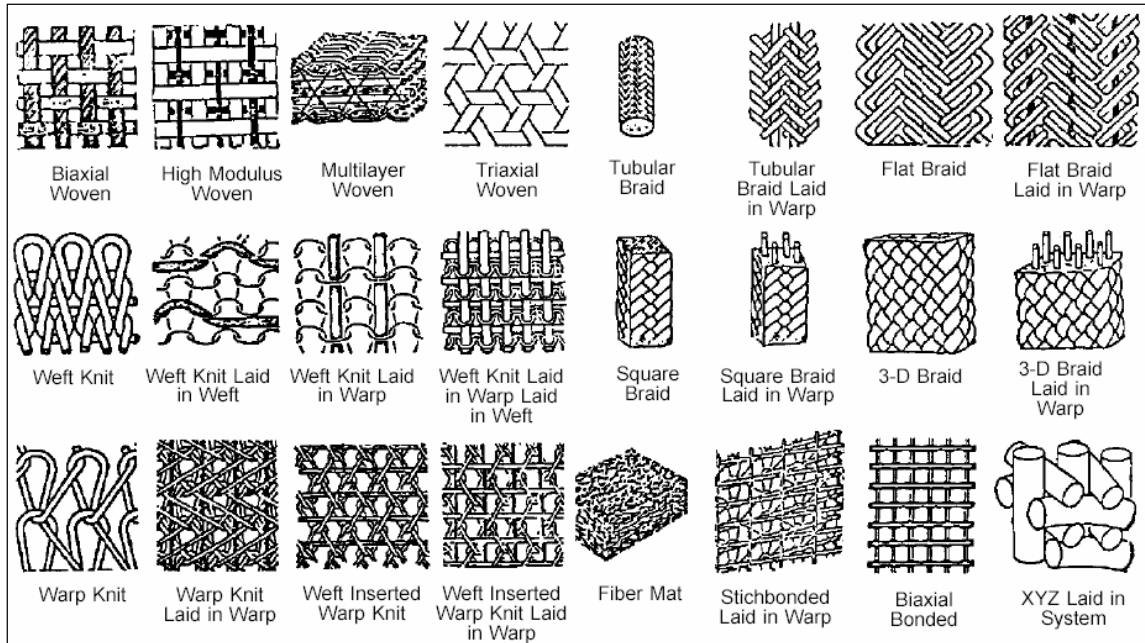


Figure 3.21 Various forms of reinforcement architectures (Ko, 2003)

3.2 MATRIX TYPES

The primary functions of the matrix (or resin) in a composite are:

- To transfer stresses between fibers
- To provide a barrier against the environment
- To protect the surface of the fibers from mechanical abrasion

The matrix plays a major role in a composite and influences the interlaminar shear as well as the in-plane shear properties of the material. The interaction between fibers and matrix is important when designing damage-tolerant structures. Furthermore, the ability to manufacture the composite and defects within it depend strongly on the physical and thermal characteristics such as viscosity, melting point, and curing temperature of the matrix (Mallick, 1993). There are generally two types of matrices, organic and inorganic.

3.2.1 Organic Matrices

Organic matrices, also known as resins or polymers, are the most common and widespread matrices used today. All polymers are composed of long chain-like molecules consisting of many

simple repeating units. Polymers can be classified under two types, thermoplastic and thermosetting, according to the effect of heat on their properties.

Like metals, thermoplastics soften with heating and eventually melt, hardening again with cooling. This process of crossing the softening or melting point can be repeated as often as desired without any noticeable effect on the material properties in either state. Typical thermoplastics include nylon, polypropylene, polycarbonate, and polyether-ether ketone (PEEK) (“Composite Materials,” 1998).

Thermosets are formed from a chemical reaction when the resin and hardener (or catalyst) are mixed and then undergo a nonreversible chemical reaction to form a hard, infusible product. In some thermosets, such as phenolic resins, volatile by-products are often produced. Other thermosetting resins such as polyester and epoxy cure by mechanisms that do not produce any volatile by-products and, thus, are much easier to process. Once cured, thermosets will not become liquid again if heated, although above a certain temperature their mechanical properties will change significantly (Mallick, 1993; SP Systems, 2001).

In general, the three most common of organic resins currently used are polyester, vinyl ester, and epoxy. A brief description of each resin is presented in the following sections.

3.2.1.1 Polyester

Polyester resins are the most economical and widely used resin systems, especially in the marine industry. Nearly one half million tons of this material is used annually in the United States in composite applications. Polyester resins can be formulated to obtain a wide range of properties ranging from soft and ductile to hard and brittle. Their advantages include low viscosity, low cost, and fast cure time. In addition, polyester resins have long been considered the least toxic thermoset resin. The most significant disadvantage of polyesters is their high volumetric shrinkage (Mallick, 1993; SP Systems, 2001).

3.2.1.2 Vinyl Ester

Vinyl ester resins are more flexible and have higher fracture toughness than cured polyester resins. The handling and performance characteristics of vinyl esters are similar to polyesters. Some advantages of the vinyl esters, which may justify their higher cost, include better chemical and corrosion resistance, hydrolytic stability, and better physical properties, such as tensile strength as well as impact and fatigue resistance. It has been shown that a 0.5 to 1.5 mm layer of a vinyl ester resin matrix can provide an excellent permeation barrier to resist blistering in marine laminates (Mallick, 1993).

3.2.1.3 Epoxy

Epoxy resins are a broad family of materials that provide better performance as compared to other organic resins. Aerospace applications use epoxy resins almost exclusively, except when

high temperature performance is a key factor. Epoxies generally out-perform most other resin types in terms of mechanical properties and resistance to environmental degradation. The primary advantages of epoxy resins include:

- Wide range of material properties
- Minimum or no volatile emissions and low shrinkage during cure
- Excellent resistance to chemical degradation
- Very good adhesion to a wide range of fibers and fillers

The high cost of epoxies, long cure time, and handling difficulties are the principal disadvantages (Mallick, 1993).

3.2.1.4 Risks and Hazards of Organic Resins

Although organic resins have gained significant acceptance throughout the composites industry, many health concerns and flammability hazards are worth noting. For example, consider a commercially available general-purpose vinyl ester resin with a MEKP (Methyl Ethyl Ketone Peroxide) hardener. According to the Material Safety & Data Sheet (MSDS), the resin is considered a carcinogen and can cause eye irritation including stinging, tearing, redness, and swelling of the eyes. In addition, the resin can cause various symptoms such as a metallic taste in the mouth, stomach or intestinal upset, irritation, dizziness, drowsiness, weakness, fatigue, nausea, headache, unconsciousness, as well as loss of coordination, confusion, and liver damage. If exposed to an open flame or spark, the resin can ignite explosively and emit toxic fumes (Fibre Glast, 2003b). In addition, the methyl ethyl ketone peroxide hardener is highly flammable and can ignite at temperatures of merely 404°C (759°F). The material is so flammable that water may be ineffective to extinguish a fire (National Fire Protection Association, 1996).

Since most organic polymers soften and ignite at temperatures of 400-600°C, fiber-reinforced composites that utilize organic polymer matrices have very limited uses in applications where fire endurance and fire hazard are important design considerations. This susceptibility to fire currently limits the use of organic polymer composites and becomes a significant design concern. As a result, organic matrices are rarely used in offshore oil platforms, military vehicles, building applications, and public transportation (Lyon, et al., 1996).

3.2.2 Geopolymer

Composites made using inorganic matrices can be utilized when high use temperatures are required. One such resin is Geopolymer, an inorganic matrix that can sustain temperatures up to 1000°C and is currently being evaluated for applications that require fire-resistance, such as the interior of an aircraft. This low-cost, inorganic polymer is derived from naturally occurring geological materials, namely silica and alumina, hence the name Geopolymer (also known as polysialate). The Federal Aviation Administration (FAA) is sponsoring research programs to evaluate the mechanical properties of Geopolymer matrix composites as part of an initiative to research fireproof material for aircraft interiors. Geopolymer matrix composites have excellent potential in many applications where high-use temperatures are anticipated such as engine

exhaust systems, or where fire safety is a critical design parameter such as in aircraft and interior of buildings. Geopolymer is a two-part system consisting of an alumino-silicate liquid and a silica powder and cures at a reasonably low temperature of 150°C. Hardeners can be added to achieve room temperature cure (22°C). It is compatible with carbon, glass, aramid, steel, wood, and a host of inorganic materials such as clay bricks and concrete.

3.2.2.1 Laminate Mechanical Properties

Both carbon and glass fibers have been used to successfully fabricate composite laminate plates. It has been shown that the matrix can withstand more than 1000°C without producing smoke and a carbon composite retained about 63% of its original flexural strength after exposure to 800°C (Foden, 1999; Lyon et al., 1997). In addition, the plates were fabricated using the same procedure and equipment that are utilized for organic composites. Hence, economical, commercially available fabrication equipment and fabrication methods such as vacuum assisted impregnation can be utilized for composites made with polysialates. A considerable amount of testing has been carried out to evaluate polysialate matrix composites for mechanical properties, behavior after high temperature exposure, and durability under various exposure conditions (Foden, 1999; Foden et al., 1996; Hammell, 2000a; Hammell et al., 1998; Lyon, et al., 1997). Some of the common mechanical properties are listed in Table 3.10.

Table 3.10 **Typical properties of Geopolymer composites (Hammell, 2000a)**

Mechanical Property			3k Unidirectional Carbon	3k Woven Carbon
Tension	Strength	(MPa)	623	332
	Modulus	(GPa)	156	76
Compression	Strength	(MPa)	105	54
	Modulus	(GPa)	163	102
Flexure	Strength	(MPa)	511	245
	Modulus	(GPa)	93	45
Interlaminar Shear	Strength	(MPa)	-----	14
	Modulus	(GPa)	-----	-----
In-Plane Shear	Strength	(MPa)	-----	30
	Modulus	(GPa)	-----	4

3.2.2.2 Relative Performance of various inorganic matrix composites

Processing requirements and mechanical properties of various inorganic matrices were compiled by Papakonstantinou et al. to study the relative performance of Geopolymer composites with other high temperature composites. The main conclusion of that study was that Geopolymer composites have mechanical properties that are better than most fire-resistant ceramic composites (2001). Other significant conclusions include the following:

- As expected, the mechanical properties of the high temperature composites are influenced by: (i) the processing method and treatments of the fibers, (ii) the mechanical properties at the fiber-matrix interface, (iii) the constitutive properties of both fiber and matrix, (iv) the volume fractions of resin and fiber, and (v) the orientation of reinforcement.
- Composites made with T300 carbon and polysialate resin have mechanical properties that are comparable to other high temperature carbon-carbon and ceramic matrix composites.
- The high temperature performance of polysialate / carbon composite is also comparable to other carbon/carbon and ceramic matrix composites.
- With curing temperatures below 150°C and an easy fabrication method, composites made with polysialate are much less expensive to produce and, hence, have more potential for widespread applications.

3.2.2.3 Fire Properties of Matrices

Geopolymer composites have shown excellent fire properties when compared to currently available organic matrix composites. Table 3.11 compares the fire properties of polysialate composites with several thermosets, advanced thermosets, phenolics, and engineering thermoplastics. The fire properties presented are weight loss (percentage), time to ignition (seconds), peak heat release rate (HRR, in kW/m²), 300 second average heat release rate (kW/m²), total heat release (MJ/m²), and smoke production (m²/kg).

Table 3.11 **Fire calorimetry data for laminates at 50 kW/m² irradiance (Lyon et al., 1997)**

RESIN	FIBER	Weight Loss	Time to Ignition	300s Peak HRR	Total Average HRR	Heat Release	Smoke
		(%)	(seconds)	(kW/m ²)	(kW/m ²)	(MJ/m ²)	(m ² /kg)
Isophthalic Polyester	Glass	-	77	198	120	-	378
Vinyl Ester	Glass	-	78	222	158	-	861
Vinyl Ester	Glass	26	74	119	78	25	1721
Epoxy	Glass	-	105	178	98	30	580
Epoxy	Glass	19	18	40	2	29	566
Epoxy	Glass	28	49	181	108	39	1753
Epoxy	Glass	22	50	294	135	43	1683
Epoxy	Carbon	24	94	171	93	-	-
THERMOSETS		24	68	175	99	33	1077
Cyanate Ester	Glass	22	58	130	71	49	898
PMR-15 Polyimide	Glass	11	175	40	27	29	170
Bismaleimide	Glass	25	141	176	161	60	546
ADVANCED THERMOSETS		24	124	115	86	43	538
Phenolic	Glass	-	210	47	38	14	176
Phenolic	Glass	12	214	81	40	17	83
Phenolic	Glass	6	238	82	73	15	75
Phenolic	Glass	10	180	190	139	43	71
Phenolic	Glass	3	313	132	22	12	143
Phenolic	Carbon	28	104	177	112	50	253
Phenolic	Carbon	9	187	71	41	14	194
PHENOLICS		11	206	111	66	23	142
Polyphenylenesulfide	Glass	13	244	48	28	39	690
Polyphenylenesulfide	Carbon	16	173	94	70	26	604
Polyarylsulfone	Carbon	3	122	24	8	1	79
Polyethersulfone	Carbon	-	172	11	6	3	145
Polyetheretherketone	Carbon	2	307	14	8	3	69
Polyetherketoneketone	Carbon	6	223	21	10	15	274
ENGINEERING PLASTICS		8	207	35	22	15	310
GEOPOLYMER	Carbon	0		0	0	0	0

According to Lyon, flashover is a phenomenon common to aircraft compartment fires where flammable gases from incomplete combustion accumulate at the ceiling and ignite, resulting in the total involvement of the compartment materials and signaling the end of human survivability. Consequently, the time to flashover is the time available for escape and this is the single most important factor in determining the fire hazard of a material or set of materials in an aircraft compartment fire. Figure 2.22 shows the calculated values for time-to-flashover of organic and Geopolymer composites in a full-scale room test. The bar chart provides a qualitative ranking of the fire hazard of these materials in a burning aircraft compartment. It can be seen that the polysialate composite had an infinite time to flashover. This is expected since there is no flammable material in the inorganic matrix composite. Hence, there can be no flashover in the Geopolymer composite (1997).

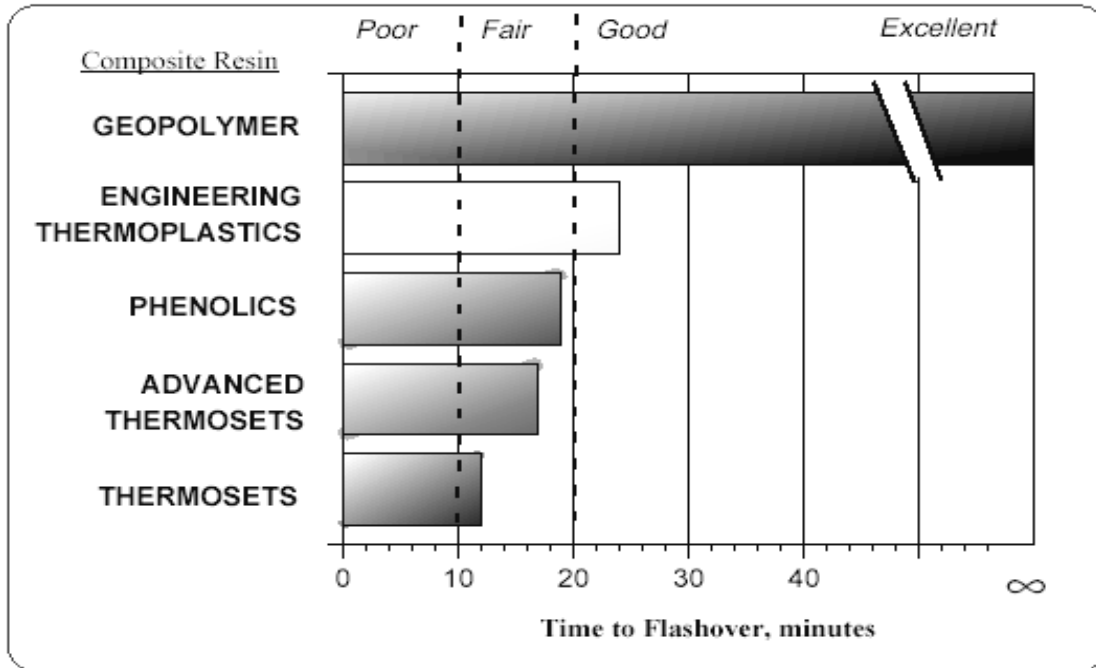


Figure 3.22 Time to flashover in ISO 9705 corner / room fire test for various composites as wall materials (Lyon, et al., 1997)

3.2.2.4 Applications

Geopolymer has been used successfully in a number of noteworthy engineering applications. The matrix has been used to fabricate standard laminate composite plates with carbon, glass, and silicon carbide fibers, sandwich structures using syntactic foam, and strengthening of brick, masonry, and reinforced concrete elements. In addition, composite plates made of wood dust and tissue paper were also developed. Despite the fact that the plates were made out of cellulose fibers, they do not burn. Furthermore, Geopolymer has been used as a protective layer and graffiti-proof coating on a highway median in New Jersey (Balaguru, 2003).

During the Grand Prix season of 1994 and 1995, the Benetton-Renault Formula 1 Sports Car Racing Team designed a unique thermal shield made out of carbon/Geopolymer composite. It assisted Michael Schumacher in winning the world championship twice and led his technical

team to win the World Champion of Car Builders award during these two years. Today, most Formula 1 teams are still using Geopolymer composite materials (Geopolymer Institute, 2003).

3.3 Vacuum-Assisted Impregnation

When utilizing FRP material in a design, it is usually assumed that the materials are joined together as a unified structure. Strength and stiffness predictions rely solely on the assumption that all materials are completely bonded together to form one cohesive element. Therefore, the bond between polymer matrix and the fiber reinforcement is critical in determining the mechanical properties of the resultant composite material. The impregnation process is the most significant way to achieve good adhesion and strong bonding. During impregnation, all surfaces of the reinforcement must be exposed to the resin. Otherwise, gas-filled bubbles, air voids, crevices, and other discontinuities or defects will remain, adversely affecting the mechanical properties of the finished composite. For example, among the individual fiber filaments are microscopic pores and interstices filled with air. This air may prevent the resin from fully impregnating some of these capillary type passages. Sufficient wetting of their surfaces will not occur, resulting in poor bonding. Consequently, these air voids will be primary sites for failure initiation and propagation. Any area of the structure not fully bonded is considered a location for potential failure or at the very least is not performing to its full potential. This is neither an economical use of materials nor an efficient building practice (May, 1997; Diab, 2001)

In addition to structural problems, entrapped air may also lead to cosmetic problems. As the resin cures, gases may be released and will accumulate in voids in the form of a blister. If the composite is exposed to sunlight or ultraviolet rays this process will be aggravated. In addition, voids close to the surface of the composite may absorb moisture or collect dirt or debris, causing unsightly blemishes on the surface of the composite material (Diab, 2001).

To overcome many of these problems, a number of techniques have been developed. The simplest way to develop a strong bond is to apply pressure to the wet composite during lay-up. Early manufacturers of composites stacked lead weights or bricks on top of the composite. Unfortunately, these concentrated loads will produce spotty bonds and will force resin out from underneath the weights, leaving a resin-starved area in the composite. In addition, areas with less weight will tend to pool resin and be much heavier. A more sophisticated and reliable method currently used to develop high quality FRP composites is vacuum-assisted impregnation. Otherwise known as “vacuum bagging” throughout the aerospace industry, this economical and effective method has been used universally for the manufacturing of aerospace structures. Vacuum bagging uses atmospheric pressure to press the wet FRP layers tightly against the surface being covered so that the excess resin is squeezed out and soaked up in a disposable outer wrap. In this process, fiber reinforcement layers are first impregnated with resin, then stacked together and placed inside a sealed bagging system. A vacuum pump is then attached to the bag, removing the air within the bag and allowing external atmospheric pressure to firmly press the FRP composite. The vacuum-bagging system allows for predictable and consistent pressure application, providing control on FRP thickness, reducing void content, improving resin flow, and assisting in bonding (Diab, 2001).

Vacuum bagging provides both vacuum as well as pressure. The vacuum is responsible for drawing out volatiles and trapped air, resulting in a low void content. Pressure compacts the laminate, providing good consolidation and interlaminar bonds. Regardless of whether the part is made up of vertical, horizontal, curved, compound curved surfaces, or a combination of these, the same amount of pressure is applied everywhere. This even distribution of vacuum pressure

results in improved control of the volume fraction of fiber, an important design parameter related to FRP laminate strength (Diab, 2001).

Once the wet FRP laminate is constructed, it is immediately placed into the bagging system. All vacuum bagging setups are essentially the same, with some minor variations depending on the specific application. The basic vacuum bagging system consists of several key elements as shown in Figure 3.23.

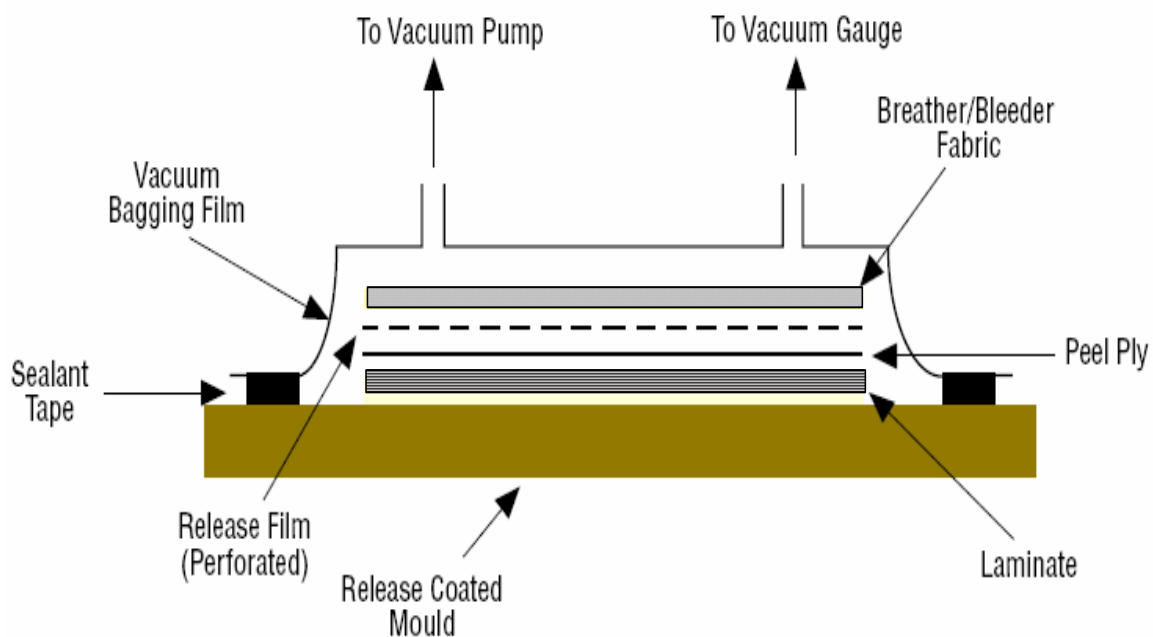


Figure 3.23 **Basic Vacuum Bagging Setup for Laminate Composites (SP Systems, 2001)**

A firm metal tool, or mould, is essentially the foundation of the system. Usually in the form of a metal sheet, the tool is the surface upon which the composite will be pressed. Metal is usually chosen as the base of the system since its surface is non-porous and very smooth. A non-porous surface is essential to ensure a tight bond with the sealant tape. The bag sealant tape is placed around the perimeter of the tool and is used to seal the bagging film to the metal tool. Sealant

tape is a putty-like material, which comes in ½” wide rolls with a release paper on one side. The pliable sealant tape is pressed firmly against the tool, leaving the release paper on until the bag is ready to be sealed. The tape usually goes on after the composite laminate is laid up, especially if it is a wet lay-up. Forming a tight bond between the sealant tape and the metal tool is critical if the bagging system is to perform effectively; even the slightest opening will compromise the entire bagging system. The other components of the system along with a description of each are as follows:

- Release agent – The release agent (film) is the material in direct contact with the metal tool. This agent may be in the form of a liquid coating, a wax, or a solid barrier such as Teflon® fabric. When applying the release agent to the tool, the edges of the tool must remain clear to allow space for the bag sealant tape to stick to the tool.
- Peel ply – Once the laminate is placed on the release agent, a layer of peel ply is then placed on the top surface of the wet FRP laminate plate. A layer of peel ply is optional and serves two primary functions. It is most often used to give the laminate a rough finish, eliminating the need for sanding and grinding prior to secondary bonding operations. Secondly, the peel ply may remain on the wet laminate, keeping it clean until the next stage in construction. Peel plies are a tightly woven fabric such as nylon and impregnated with some type of release agent to allow easy removal from the cured laminate.
- Breather/Bleeder cloth – The breather cloth is a thick material that will compress slightly during vacuuming, yet still allowing air to be drawn through it. If the vacuum bag should wrinkle against the hard laminate, air will become trapped underneath. Since the breather cloth will not compress fully, it prevents this from happening. It is

important that the breather cloth be thick enough to prevent it from become fully saturated with resin. In addition, this cloth also serves as a lightweight blotter to absorb excess resin, which “bleeds” through the peel ply.

- Bagging film – The bagging film is a relatively thick plastic layer that encases all of the material layers and is pressed tightly onto the sealant tape. Bagging film must be flexible, resistant to tearing, highly elastic, and non-porous. Typical materials used as bagging film include nylon, rubber, PVA, polyethylene, and silicone.
- Vacuum gauge – The vacuum gauge is a small gauge attached to the vacuum bagging system and is used to measure the vacuum pressure within the bagging system. It is commonly used as a quality control device to ensure that leaks are not present.
- Vacuum pump – The vacuum pump is one of the most essential parts of the vacuum bagging system and must be able to satisfy two requirements. First, the pump must be capable of pulling a high vacuum of at least 13 psi or higher. Secondly, the pump must be able to quickly evacuate a large volume of air from the bag.

Once the vacuum bagging assembly is properly constructed, the vacuum pump is turned on and begins to pull vacuum. Because the air inside the vacuum bag is removed, the positive external air pressure from the atmosphere outside the bag pushes firmly on all surfaces of the bag, pressing it tightly against the breather cloth. The excess resin is squeezed out of the wet laminate, passes through the release ply, and is then soaked up by the breather. After the laminate has partially cured (typically ~12 hours), the laminate is removed from the bag and the breather cloth and release film are peeled off. At this stage, the breather has soaked up the excess resin and the remainder makes up only about 50% of the bulk, which is ideal. Since the

resin does not bond to the release film, it will separate easily from the laminate and may be reused in another bagging application.

The highlights and key points of vacuum bagging include the following:

- Unlike stacking weights, vacuum bagging provides uniform pressure on all surfaces of the wet composite during curing and, hence, eliminates resin pooling or resin starved areas.
- Vacuum bagging is easier on the base tool since it produces little or no stress on the tool itself. On the contrary, significant bending stresses can be imposed on the tool if heavy weights are stacked on top.
- Removing excess resin from the composite is very simple since the uniform vacuum will draw out unneeded resin and will then be soaked up by the disposable breather cloth.

4. CHAPTER 4

SELECTION OF MATERIALS USING LABORATORY INVESTIGATION

A laboratory investigation was used to select the suitable constituent materials, equipment and the process. This phase of the project was also very useful for training the construction crew which consisted of graduate and undergraduate students. In addition to fiber jacket, materials were also selected for rapid repair of locations where reinforcement was exposed. The primary objectives of this phase can be enumerated as follows.

- Select repair concrete

- Choose an appropriate matrix suitable for both vacuum bagging and long-term concrete protection
- Select a suitable fabric that is flexible
- Select vacuum pumps that can provide the required capacity and reasonable cost
- Assemble and test vacuum bagging setup
- Train a team of students to carry out the application in the field
- Make a full scale sample using the vacuum bagging system

4.1 Fiber Selection

E-glass fiber was selected since it both economical and easy to obtain. The fabric was relatively light, weighing only 2.36 oz/yd². The fiberglass fabric was obtained from the Saint Gobain Company. Some typical properties of the fabric are listed in Table 4..

This particular fabric offered some key advantages including:

- High tensile strength
- Good tear and puncture resistance
- High flexural endurance
- Excellent chemical resistance
- Good weatherability

Table 4.1 : Typical Properties of Fiberglass Fabric (St. Gobain Technical Fabrics, 2001)

Fiber Type:	Eglass
Color:	Semi-translucent
Fiber Orientation:	0°/90° Bi-Directional Weave
Fiber Distribution:	50% Warp Direction (0°)
	50% Fill Direction (90°)
Fabric Weight:	2.36 oz/yd ²
Fiber Tensile Strength:	110 ksi

A picture of the fiberglass fabric is shown in Fig. 4.1.



Figure 4.1: Fiberglass Fabric Used for Composite Jacket

4.2 Matrix Selection

The matrix used for this project had to satisfy a number of requirements. For the vacuum process to operate properly, a low viscosity resin was necessary. The low viscosity allows the resin to flow easily through the fabric reinforcement, fully impregnating the fibers. The working time, or pot life, of the matrix was also a major factor in selecting the appropriate epoxy since additional time was needed to apply vacuum. Since the matrix would cover over 100 m² (1100 ft²), the matrix had to be mixed in large quantities without emitting a large amount of heat or toxic fumes. Resistance to both water and abrasion were other major factors. Considering these factors, three different types of epoxy resins were selected for preliminary analysis. In addition, a concrete surface sealant, methyl methacrylate (MMA), was also selected since its viscosity is extremely low and can impregnate fibers with little effort. A brief description of the different matrices is as follows:

- Tyfo S[®] – Tyfo S[®] is a saturant epoxy that is clear to pale yellow in color and is mixed in a ratio of 100 parts A to 42 parts B. It is part of a wet lay-up composite system used for strengthening structural members.
- Sikadur[®] Hex 300 – Sikadur[®] Hex 300 is a two-component, moisture-tolerant, high-strength, high-modulus epoxy resin. Some typical mechanical properties of the organic resin are listed in Table 4.2. Some of the key advantages of this resin include a long pot life (~ 4 hours), good workability, and a considerable tolerance of moisture before, during, and after cure. In addition, the polymer exhibits excellent adhesion to concrete, masonry, metals, wood, and most structural materials (Sika Corp., 2000).

Table 4.2 : Typical Data and Mechanical Properties of Resin (Sika Corp., 2000)

Polymer Trade Name:	Sikadur [®] Hex 300
Color:	Clear, amber
Viscosity:	550 cps
Setting Time (Pot Life):	4 hours
Service Temperature Range:	-40°F to +140°F
Density of Cured Resin:	1.1 g/cm ³
Tensile Strength (ASTM D638):	10,500 psi
Tensile Modulus (ASTM D638):	459,000 psi
Elongation @ Break (ASTM D638):	4.80%
Flexural Strength (ASTM D790):	17,900 psi
Flexural Modulus (ASTM D790):	452,000 psi

- Sikadur[®] 35, Hi-Mod LV LPL – The resin is a high modulus, low viscosity, high strength, extended pot life, and an epoxy adhesive. It is used to coat low and high-pressure injections of cracks in structural concrete applications. It has been used successfully as an epoxy resin binder for epoxy mortar patching and for sealing reinforced concrete slabs. The resin is mixed in a 2:1 mass ratio of parts A and B, respectively.
- MMA – This amber colored resin is a two-part resin system that has been used as a concrete sealant and has the ability to penetrate concrete cracks as fine as 0.08 mm (0.003 inches). The extremely low viscosity of approximately 5 cps allows MMA to penetrate very dense surfaces. In addition to the low viscosity, other advantages of MMA include excellent adhesion, and the ability to reduce water absorption and chloride ion intrusion in concrete. The resin can be applied easily using a roller, brush, or squeegee. In addition, it is applicable by vacuum processes or vacuum injection. However, MMA has significant disadvantages that are worth noting. Most

importantly, the resin has a distinct pungent acrylic odor and requires ample ventilation and special safety measures to avoid inhalation of the fumes.

To examine the viability of the resins in terms of fabrication and durability, 30 FRP samples were manufactured using the E-glass fabric presented earlier. The samples were laminated onto a number of different concrete surfaces and under varying weather conditions. To evaluate the ability of the resin to adhere to the concrete, the concrete surfaces were oriented both horizontally and vertically while the texture was either rough or smooth. The samples were exposed to both wet and dry weather conditions to examine the durability of the cured composite. Table 4.3 displays a description of the samples and observations made several weeks after lamination. Figures 4.2 to 4.7 present photographs of the cured composites after exposure to varying weather conditions.



Figure 4.2: Tyfo S[®] Composite Delaminating Under Wet Conditions 2 Days after Laminating



Figure 4.3: Sikadur® 35 Composite under Wet Conditions Two Days after Curing



Figure 4.4: Delaminating Tyfo S® Composite under Wet Conditions Three Days after Laminating



Figure 4.5: Sikadur® 35 Composite under Wet Conditions On the Day Three



Figure 4.6: Delamination of Tyfo S® Composite under Wet Conditions on the Day Three



Figure 4.7: Sikadur[®] Hex 300 Composite under Wet Conditions Two Days after Laminating

Table 4.1: Evaluation of Resins on Concrete Elements

Matrix Type	Structural Element	Weather Conditions	Results
MVA	90mm x 540mm rough concrete surface	Dry	Severe delamination
MVA	90mm x 540mm rough concrete surface	Dry	Severe delamination
MVA	90mm x 540mm rough concrete surface	Dry	Loose fibers along the corners
MVA	90mm x 540mm rough concrete surface	Dry	Loose fibers along the corners
MVA	90mm x 540mm rough concrete surface	Dry	Loose fibers along the corners
MVA	90mm x 540mm rough concrete surface	Heated to 60°C	Virtually no separation of the fibers
MVA	90mm x 540mm rough concrete surface	Dry	Severe delamination
Tyfo S	90mm x 540mm rough concrete surface	Dry	Slight separation of the fibers
Tyfo S	1080mm x 1080mm vertical deteriorated Concrete surface	Dry	Slight separation of the fibers
Tyfo S	1080mm x 1080mm horizontal deteriorated Concrete surface	Wet after 24 hours	Separation of fibers
Tyfo S	1080mm x 1080mm horizontal deteriorated Concrete surface	Wet after 24 hours	Slight separation of the fibers
Tyfo S	1080mm x 1080mm horizontal Concrete surface	Wet after 72 hours	Severe delamination
Tyfo S	1080mm x 1080mm horizontal Concrete surface	Wet after 4 hours	Severe delamination
Tyfo S	1080mm x 1080mm vertical Concrete surface	Wet after 72 hours	Severe delamination
S 35	45mm x 540mm smooth concrete surface	Dry	Virtually no separation of the fibers
S 35	45mm x 540mm smooth concrete surface	Dry	Virtually no separation of the fibers
S 35	1080mm x 1080mm horizontal Concrete surface	Wet after 24 hours	Virtually no separation of the fibers
S 35	1080mm x 1080mm horizontal Concrete surface	Wet after 24 hours	Virtually no separation of the fibers
S 35	45mm x 540mm smooth concrete surface	Wet after 24 hours	Virtually no separation of the fibers
S 35	45mm x 540mm smooth concrete surface	Wet after 24 hours	Virtually no separation of the fibers
S 35	45mm x 540mm smooth concrete surface	Wet after 24 hours	Virtually no separation of the fibers
S 35	1080mm x 1080mm horizontal smooth Concrete surface	Wet after 72 hours	Virtually no separation of the fibers
S 35	1080mm x 1080mm horizontal smooth Concrete surface	Wet after 4 hours	Slight separation of the fibers
S 35	1080mm x 1080mm vertical Concrete surface	Wet after 72 hours	Slight separation of the fibers
S 35	1080mm x 1080mm vertical Concrete surface	Wet after 24 hours	Virtually no separation of the fibers
S 300	1080mm x 1080mm horizontal deteriorated Concrete surface	Wet after 24 hours	Virtually no separation of the fibers
S 300	1080mm x 300mm x 2000mm L shape deteriorated concrete surface	Wet after 24 hours	Virtually no separation of the fibers
S 300	1080mm x 300mm x 2000mm L shape deteriorated concrete surface	Wet after 24 hours	Virtually no separation of the fibers
S 300	1080mm x 1080mm horizontal deteriorated Concrete surface	Wet after 4 hours	Virtually no separation of the fibers
S 300	1080mm x 1080mm vertical Concrete surface	Wet after 4 hours	Virtually no separation of the fibers
S 300	1080mm x 1080mm vertical Concrete surface	Wet after 4 hours	Virtually no separation of the fibers
S 300	1080mm x 1080mm horizontal smooth Concrete surface	Wet after 4 hours	Virtually no separation of the fibers
S 300	1080mm x 1080mm horizontal smooth Concrete surface	Wet after 4 hours	Virtually no separation of the fibers

4.3 Selection of Repair Concrete

The repair concrete (mortar) had to satisfy a number of requirements and was selected in accordance with the guidelines set forth by the Rhode Island Department of Transportation (RIDOT). Since a majority of the pier cap consisted of vertical surfaces, the repair concrete had to be capable of being applied to a vertical surface using a trowel. Since vacuum bagging would take place shortly after the concrete patching operation, it was necessary that the concrete could gain high strength and cure in a short period of time. Based upon these requirements, the repair

concrete selected was Five Star Structural Concrete® V/O. The typical mechanical and chemical properties of the repair concrete are displayed in Table 4.4. The repair concrete had the following advantages:

This repair concrete satisfied the previously stated requirements and was also advantageous for a number of other reasons including:

- Very low chloride ion permeability and resistance to sulfate attack
- High three-hour strength gain
- Ability to cure within 8 to 24 hours
- Compatible with cold weather installation

Table 4.2: Common properties of Five Star Structural Concrete® V/O

Compressive Strength, ASTM C 109	
3 hours	2000 psi (13.8 Mpa)
1 Day	3500 psi (24.2 Mpa)
7 Days	4000 psi (27.6 Mpa)
28 Days	5000 psi (34.5 Mpa)
Bond Strength, ASTM C 882	
1 Day	1500 psi (10.4 Mpa)
7 Days	2000 psi (13.8 Mpa)
Linear Length Change, ASTM C 157	
28 Days Wet	0.04%
29 Days Dry	-0.05%
Thermal Coefficient of Expansion, ASTM C 531	
5.0 x 10 ⁻⁶ in/in/°F (9.0 x 10 ⁻⁶ mm/mm/°C)	
Chloride Ion Permeability, ASTM C 1202	
3 Days	Very Low
28 Days	Very Low

4.4 Vacuum Pump Selection

Since the vacuum pump is one of the most critical elements of the vacuum bagging system, considerable attention was given to the selection process. Choosing a vacuum pump with a capacity larger than what is needed would be inefficient while selecting an inferior pump

based solely on cost could compromise the entire vacuum bagging effort. Therefore, a balance between pump cost and capacity had to be achieved.

Based upon on the surface area of each vacuum bagging operation, 3.3 m² (35ft²), and prior experience with the vacuum bagging operation, the authors chose rotary vane high vacuum pumps with a 0.5 horsepower capacity with the ability to achieve 25 microns of vacuum. In addition, the pump ran at a speed of 1725 RPM with a frequency of 60 Hz. Although one pump would be adequate to apply the required vacuum, two pumps would be used per assembly during the construction phase as a factor of safety in the event one vacuum failed.

To connect the vacuum pump to the bagging assembly, a vacuum hose and a series of bushings, tube inserts, nipples, and tee shapes were utilized. In addition, a vacuum gauge was attached to the vacuum pump to measure the amount of vacuum being delivered to the bagging assembly. Figure 4.8 shows the vacuum pump connected to a small-scale vacuum bag.

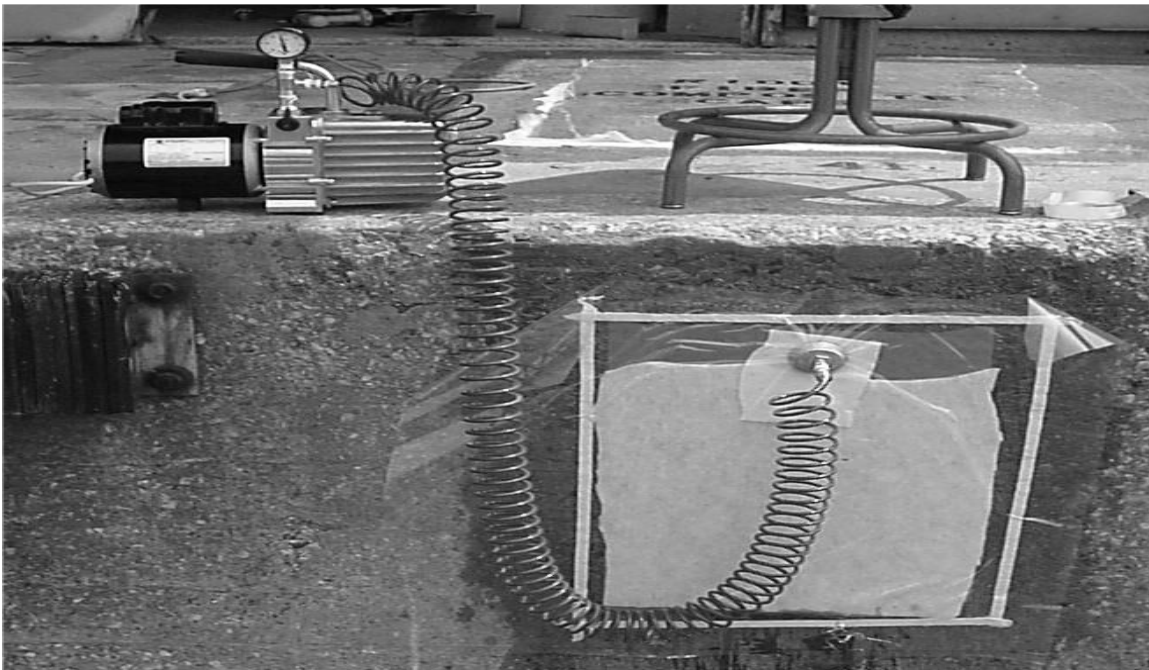


Figure 4.8: Vacuum Pump and Attachments on a Trial Sample

4.5 Selection of Vacuum Bag Materials

The different components needed to create the vacuum were selected from a variety of choices. The first layer of material placed directly on top of the wet FRP composite was a non-porous Teflon[®] release film. This brown colored sheet did not adhere to the wet composite and was very flexible yet durable. Placed atop the Teflon[®] layer was the thick layer of breathing cloth used to distribute the vacuum pressure. A white non-woven polyester breather cloth weighing 0.135 kg/m² (4 oz/yd²) was chosen. The fabric was extremely lightweight and was approximately 3.2 mm (0.125”) thick.

The sealant tape chosen was of industrial strength and was manufactured in 1.27 cm (½”) wide rolls in lengths of 7.62 m (25’) with a release paper on one side to allow for easier handling. The 3.2 mm (0.125”) thick tape was capable of achieving a tight seal with many materials including aluminum, steel, fiberglass, nickel, and graphite tool surfaces yet can be removed easily after the vacuum bagging operation is complete.

To seal the bagging system, a layer of bagging film was needed. The film chosen was a yellow nylon film approximately 0.05 mm (0.002”) thick and 1.5 m (60”) wide. This film is puncture resistant, very strong, and does not stick to the resin in the event of accidental contact with the FRP composite. A small vacuum valve in the shape of a disc is placed just below the bagging film and allows the vacuum hose to be connected to the system. This aluminum valve can be seen in the photograph of Figure 4.8, nestled just below the vacuum hose.

4.6 Training the Fabrication Team

A group of students had to be trained to efficiently carry out the on-site application of the composite jacket. The team consisted of three graduate students majoring in structural engineering and two undergraduate students studying civil engineering. The graduate students had a strong background in the field of composites and vacuum bagging while the undergraduate students had little experience with FRP composites and required more in-depth training.

The training consisted of several stages ranging from small-scale traditional fiber composite applications to a full-scale vacuum-bagged section. Since safety was of paramount concern, all members of the team trained on safety issues related to the materials. Safety protocol, emergency treatment measures, and material safety data sheets were among the focus points of the safety training.

Educating the team members on the fabrication procedures was the next step. To accomplish this, several small-scale trial samples were constructed. Each sample was broken down into a number of tasks that included surface preparation, priming the concrete surface with resin, impregnating the fibers with resin, positioning the wet E-glass fabric onto the concrete surface, and implementing the vacuum bag technology.

The first task was to teach the team the most effective ways to clean and prepare the concrete surface. Steel brushes, a pressure washer, and a commercially available concrete soap were used. Then, the team was trained on using the repair concrete to patch the deteriorated concrete surfaces. Achieving the desired surface texture of the patched areas was a major concern since the vacuum bagging system required a smooth surface to facilitate a tight seal to be formed between the concrete and sealant tape.

The members were then educated on the resin mixing process, pot life, and how to visually inspect and assess the workability of the resin. Over the course of several weeks, the team was

then trained to successfully apply the FRP composite to the concrete surface. This included lessons on the logistics of vacuum bagging, functions of the various layers of bagging materials, and the proper operation of the vacuum pumps. Since the vacuum pumps were critical to the vacuum bagging operation, all members were trained how to assemble, maintain, and check the efficiency of the vacuum pump and its attachments. After each member was well trained on all the different aspects of the project, a full-scale trial section was constructed. The following section provides a detailed description of this stage.

4.7 Full-Scale Trial Application

To ensure the viability of the vacuum bagging technique and to ensure that all five members of the research team were well aware of the process, a full-scale sample was constructed. The sample was constructed on a rough horizontal concrete surface outside a laboratory at Rutgers University in New Jersey. The sample was approximately 0.810 m × 3 m (2.7' × 9.8'). First, the concrete surface was prepared using with a pressure washer to remove loose debris and then washed and scrubbed with the concrete soap. After the surface was cleaned, the repair concrete was used to patch a few small areas where the surface was deteriorated. After the concrete surface was completely dry, a thin layer of the epoxy resin was applied to the surface to serve as a primer and was let to dry for 24 hours. On the second day, the sealant tape was firmly attached to the boundaries of the surface. Next, the E-glass fabric was impregnated with resin on top of a large piece of plywood using grooved plastic rollers. A layer of Teflon[®] placed atop the plywood ensured that the resin would not stick to the wood. Finally, the wet fabric was applied to the concrete surface manually and the different layers of vacuum bagging materials were laid

on top of the glass fabric. Once the wet FRP was sealed in the bagging system, the vacuum pump was then attached to the sample and turned on, Figure 4.9.



Figure 4.9: Full Scale Trial (A) During Vacuuming and (B) Finished Composite Surface

The sample was vacuumed for 4 hours and was then let to dry for another 24 hours. After the additional 24 hours, the vacuum pump was detached and the bagging materials were removed, exposing the finished composite. The composite was then inspected as a measure of quality control and assurance. The smooth and shiny appearance of the finished composite, Figure 4.9, indicated that air voids were successfully removed from the system and a strong bond between the FRP and concrete had been achieved. In addition, the pump was also examined for signs of overheating, possible failure, or other adverse effects. Upon inspection, there appeared to be no indication of any distress caused to the vacuum pump. Since the finished FRP

composite was manufactured successfully and the vacuum pump performed effectively, it was concluded that the resin system and vacuum bagging technique were practical for the actual rehabilitation of the bridge pier caps in Rhode Island.

5 CHAPTER 5

FABRICATION OF THE FRP PIER CAP JACKET

The fabrication of the jacket was completed in six days. Professional staff was responsible for setting up the scaffolding and traffic control. Some of the repair work was also carried out by a professional mason. The rest of the work was carried out by the faculty and students of Rutgers University and the University of Rhode Island. At least one RIDOT engineer was present during the entire working time. Other RIDOT personnel visited the location on various occasions. For the Rutgers team this phase of the project took about 10 days. Major activities during these 10 days are as follows.

- Days 1 and 2: Collection of materials and equipment needed for the fabrication, renting and loading the truck. Materials consisted of: repair mortar, epoxy, glass fabric, release film, breather cloth, adhesion tapes and impermeable top film. The equipment consisted of: generators, mixers, vacuum pumps, drills, hammers and sprayers. A number of consumable supplies such as gloves, overalls, regular adhesion tapes, buckets and clean water were also loaded to the truck. The truck was used for both storage of materials and work space for intricate work.
- Day 3: After verifying the check list of materials and equipment, two graduate students drove the loaded truck to Rhode Island. The remaining crew went in separate cars that were used to obtain a few supplies during the construction. Professional crew set up the Scaffoldings on day 2 and 3.

- Day 4: After making minor modifications to scaffolding, both pier caps were cleaned using pressure washing machines.
- Day 5: Further cleaning and repair of badly damaged areas with rapid repair material was carried out. The repaired areas were covered with wet burlap for curing.
- Days 6 to 9: Fabrication of the actual jacket was carried out on these three days. The major steps were: priming, application of fabric using vacuum bagging, construction of drip edges and covering of areas close to supports of beams. The sequence of application for the two piers is presented in Table 5.1. Areas 1 to 5 are identified in Figures 5.1 to 5.3.

Table 5.1: Series of Tasks to be Accomplished During Construction Phase

Step	Task
1	Surface Preparation (cleaning and patching of concrete surface)
2	Application of primer on both piers
3	Application of FRP system using Vacuum bagging (side of piers - Areas '1')
4	Application of FRP system using Vacuum bagging (side of piers - Areas '2')
5	Application of FRP system using Vacuum bagging (side of piers - Areas '3')
6	Application of chopped glass fibers (top of piers - Areas '4')
7	Application of FRP system as draped edges (bottom of piers - Areas '5')

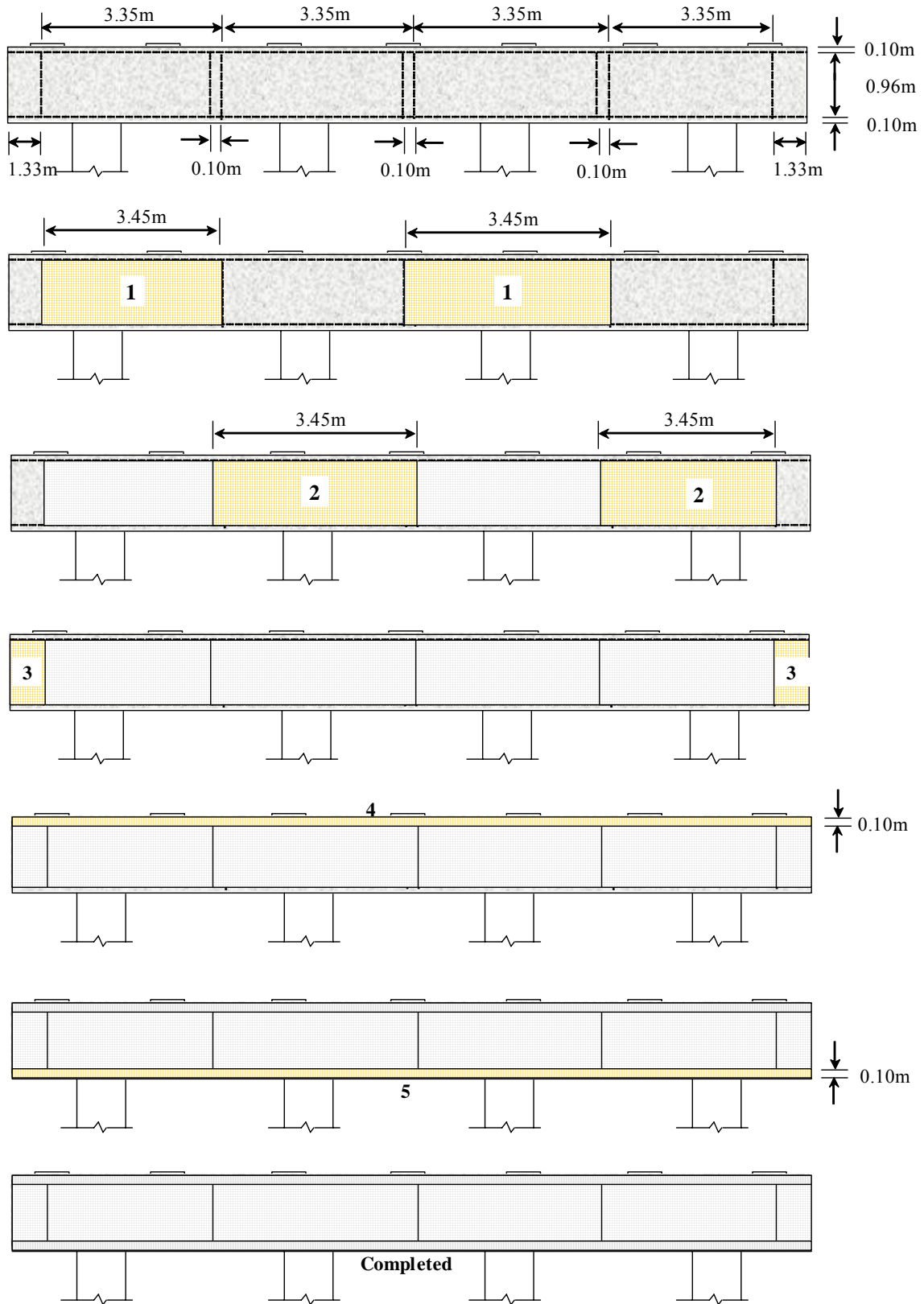


Figure 5.1: (A) Elevation View of Vacuum Bagging Sequence

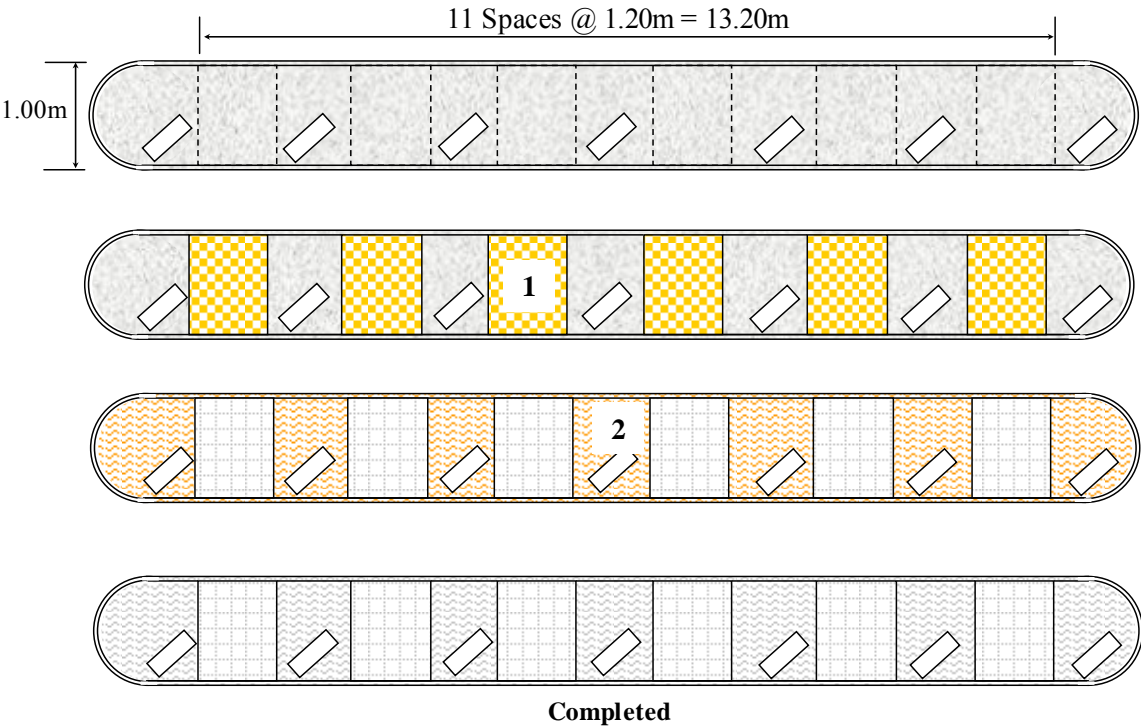


Figure 5.2: (B) Plan View of FRP Application to Top Faces of Piers









	Plain Concrete		Hand lay-up only
	Vacuum Bagged		Cured FRP Composite Jacket
	Chopped Glass + Resin		Cured Chopped Glass + Resin
	Draped Edges		Cured Draped Edges

Figure 5.3: (C) Legend Used To Distinguish Various Materials during FRP Application

- Day 10: Final check of the jacket and return trip to Rutgers University.

The details of the various construction activities are described in the following sections.

5.1 Scaffolding

To provide access to the structure, scaffoldings were erected on both sides of the piers, between the curbs and piers and on the inside upward sloping portion of the bridge. Scaffoldings allowed easy access to the top and sides of the pier caps as shown in Figure 5.4. During the construction, one of the two existing traffic lanes was closed in order to provide adequate working area.





Figure 5.4: Scaffolding and safety measures

Traffic control was set up to provide a safe work site and to facilitate mobile access through the area. Traffic control devices were set-up and removed each day, except for barrels, which were left over night to protect traffic from the scaffolding itself. All necessary materials and equipment were able to fit inside a small box truck. The use of the box truck facilitated easy movement of supplies and equipment to and from the construction site.

5.2. Surface Preparation

The concrete surface of the piers had to be cleaned before the application of the primer. A considerable amount of debris had accumulated over the years on the top surface of both piers. This included organic matter, vegetation, dirt, wood, and other foreign material. The debris was removed manually and the surface was then thoroughly cleaned using a high-pressure washer and concrete soap, Figure 5.5.

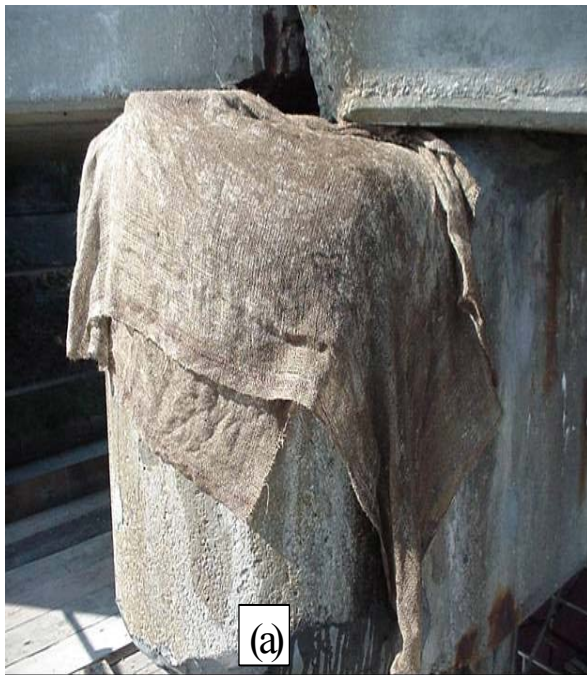


Figure 5.5 : Cleaning and Pressure Washing Of Concrete Surface

5.3 Repair of Spalled Areas

In many locations along the pier caps, cracking in the concrete and, in some cases, even spalling were present. These problems were concentrated mainly on the ends of the pier caps. Therefore, it was necessary to repair the surface before the application of the composite. First, a small chipping hammer was used to remove all weak spalling concrete. The exposed steel was cleaned using a wire brush and a grinder to remove the rust. After the cleaning was completed, the concrete surface was left to dry to a saturated surface dry condition. The primary objective of this surface preparation was to condition the concrete to properly receive the repair material (mortar).

The concrete surfaces requiring remediation were patched using a quick dry concrete mortar. Once the repair material went through final set, wet burlap material was placed over the patches for 24 hours to provide adequate moisture for curing, Figure 5.6.



(a)



(b)

**Figure 5.6 : (A) Wet Burlap Placed Over Freshly Placed Repair Mortar on Pier Cap End
(B) Cured Repair Concrete on Pier Cap End**

In most concrete strengthening applications, the surface of the concrete needs to be smooth. In this case, however, since the vacuum bagging technique was utilized, there was no need for a perfectly smooth surface. Typically, uneven concrete surface irregularities (offsets) must be ground and smoothed to less than 1 mm (0.04"). In addition, voids in the concrete substrate must be filled. Voids greater than 1.27 cm (0.50") in depth may be filled with an appropriate repair mortar (MBrace, 2000).

5.4 Application Of The FRP System

The main stage, applying the FRP composite jacket, started one day after the completion of the concrete surface preparation. Ample time was provided to ensure that the concrete surface was completely dry since the presence of moisture inhibits the adhesion of the epoxy to the substrate. Based on the documentation and specifications of the epoxy manufacturer, a moisture content less than 4% is acceptable. **During this process, control of loose concrete chips, dust, and debris in each area of work was maintained.**

5.4.1. Surface Priming

The first step of the FRP application was the priming of the concrete surface with the Sikadur[®] Hex 300 resin using conventional paint rollers. This was done to ensure that the concrete was fairly smooth and impermeable. In addition, this prevents too much resin used later for FRP impregnation from seeping out of the composite and being absorbed into the concrete surface, leaving behind a resin-starved composite. Cracks too small to be filled with mortar were filled with this epoxy mixed with chopped E-glass fibers. The primer was applied to all areas on

the concrete surface where the FRP composite jacket would be later placed. It should be noted that the top surface around the rubber bearing pads was not primed since an adverse reaction could take place if the resin contacts the rubber bearing pads. The primer was spread uniformly on the prepared surface and was allowed to cure 24 hours before the application of the FRP.



5.4.1.1. Vacuum Bagging Procedure

If the wet epoxy resin contacts the sealant tape, it can severely impair the bond between the tape and the bagging film. This issue was of paramount concern since it could potentially compromise the entire vacuum bagging system. Therefore, to ensure that the sealant tape and vacuum bagging materials remained dry and free from contact with the wet resin, two separate teams were formed; one team handled only the dry materials while the second team worked exclusively with the wet resin. This prevented contamination of the dry bagging materials with the resin during the entire construction phase of the project.

5.4.1.2 Stage One

Schematic diagrams of the FRP application sequence are presented in Figures 5.1 to 5.3.

The FRP jacket on the lateral faces of the pier caps was applied in two stages, Figure 5.1 using pieces of the E-glass fabric with dimensions of 0.96×3.45 m. During the first stage, the FRP was applied in areas denoted as “1” in Figure 5.1. First; the sealant tape was placed on the perimeter of the area, as shown in the photograph of Figure ///. The nylon bagging film was then secured to the sealant tape on the bottom of the pier. It was necessary to seal the lower part of the bagging film since dripping the resin onto the bottom of the pier cap during the hand lay-up method can severely hinder the bonding capability of the sealant tape.



Figure5.7 : Application of Sealant Tape onto Primed Concrete Surface

As the sealant tape was applied to the concrete by the first team, the second team was simultaneously mixing the resin using a high shear mixer according to the specifications set forth by the manufacturer. After the resin was thoroughly mixed, a thin layer was applied on the surface of the concrete and the saturated fabric was applied to the area with uniform and smooth pressure using paint rollers. Plastic squeegees and grooved rollers were used to remove air bubbles and any voids in the wet composite.



During this hand impregnation process, the orientation of the fibers was maintained. A second layer of resin was also applied on top of the composite to ensure that the fabric was impregnated completely. The Teflon[®] release film and the polyester breather cloth were then

placed on top of the wet fabric. Two small vacuum valves in the shape of metal discs were placed on top of the breather. These valves allow the inside of the bagging system to be connected to the exterior pump via the vacuum hose. Finally, the nylon bagging film was rolled up and secured to the sealant tape using a plastic grooved roller. Once sealed, a small opening was cut in the bagging film above each valve to connect the vacuum hose, Figure5.8. Once the two vacuum pumps were turned on, a thorough examination was performed around the perimeter of the area to ensure the seal between the tape and bagging film was airtight. Even the slightest opening would compromise the vacuum bagging system. The pressure gauges on the vacuum pumps were also used to verify whether the correct vacuum pressure (30" of mercury) was applied, Figure1. The pumps were allowed to run for two hours and were regularly inspected to ensure that the proper vacuum pressure was achieved and that the pump was not overheating. After the two hours, the pumps were turned off and the vacuum hoses were disconnected from the vacuum valve but the rest of the system remained intact until the following day. Leaving the system closed prevented any dust or debris from adhering to the tacky FRP composite. A finished vacuum bagging system is shown in Figure5.9.

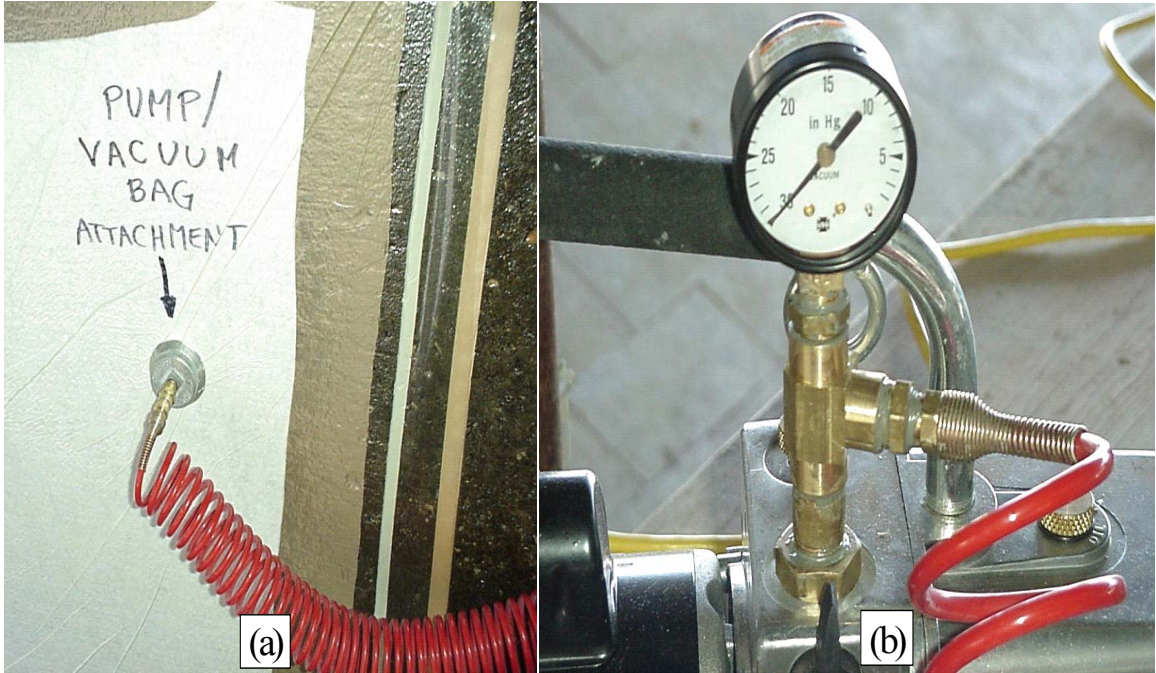


Figure1.8 : (A) Vacuum Hose Attached To Vacuum Valve (B) Vacuum Gauge at 30" Hg





Figure 5.9 : Completed Vacuum Bagging System

5.4.1.3. Stage Two

The second stage of vacuum bagging began 16 hours after the first stage was completed. It began with the removal of the sealant tape, bagging film, and breather cloth. The areas that were vacuumed during this stage are denoted as “2” in Figure 5. Since each bagged area overlapped the adjacent section by about 10 cm on each side, it was important that the adjacent section was tack-free so the sealant tape could be applied. Since the resin gel time indicated by the manufacturer was 15 hours, the sealant tape for the new section was applied approximately 15 to 16 hours after the previous composite was bagged. The overlapping of sections was necessary to ensure that the entire surface of the pier was covered with FRP applied with the vacuum bagging technique. The vacuum bagging procedure in this stage was performed in the same manner as during Stage one.

5.4.1.4. Stage Three

After the lateral surfaces of the pier caps were laminated with the FRP composite, the ends of the piers were also covered with FRP using the same vacuum bagging technique described in the first stage. These areas are denoted as “3” in Figure 5.

This three stage incremental sequence was chosen for a number of reasons including the following:

- Vacuum bagging smaller sections required fewer laborers and allowed leaks in the system to be easily detected.
- It was proven from laboratory experiments that handling and impregnating large pieces of fabric was problematic and inefficient.
- Sealant tape must be applied on a dry, smooth, tack-free surface to achieve a tight seal between the tape and concrete surface. In addition, the removal of the sealant tape after vacuum bagging can be extremely difficult if bonded to the wet resin below the tape.



5.4.1.5. Drip Edges

After the majority of the pier sides were covered, FRP composite was laminated onto the top edge of the pier cap since a 10 cm (4") gap remained where the sealant tape was placed. This area is denoted as "4" in Figure 5. and was covered using 15 cm wide, 2 m (6.5') long strips of E-glass fabric impregnated with resin. In addition, a similar task was performed on the lower portion of the pier caps to form "drip edges." These edges are shown in Figure 5. as area "5." The edges were intended to shed water off the face of the concrete pier cap onto the ground, preventing the water from attacking the underneath surface of the pier cap. The fabric was approximately 15 cm wide, while 10 cm were bonded onto the concrete edge. The remaining 5 cm was allowed to extend below the edge of the concrete. The E-glass fabric was impregnated with the Sikadur[®] resin before being applied to the concrete surface. Then plastic grooved rollers were used to remove all possible air bubbles between the fabric and the concrete substrate.



5.4.1.6. Top Face

After all sides of the piers were laminated with the FRP composite jacket, the top surface of the pier cap was laminated with the composite. However, the concrete surface was too jagged and irregular for vacuum bagging. Therefore, sections of E-glass fabric measuring 1.2 m (4') wide and 1 m (3.3') long were impregnated with resin and placed upon the surface. These areas are designated as "1" in Figure 5. and were laminated using a hand lay-up technique. The remaining areas around the beam seats (labeled "2" in Fig. 17(b)) were covered with a mixture of resin and chopped fibers. The Sikadur[®] resin was mixed with 12 mm long (0.5") chopped E-glass fibers in a mass ratio of 100:2. The mixing was performed in a 5-gallon bucket using a high shear mixer to ensure thorough impregnation. Fearing an adverse reaction between the rubber bearing pads and the epoxy resin, the rubber bearing pads were covered using a special polyethylene tape to prevent contact with the epoxy. The fiber-reinforced epoxy was then applied on the surface using plastic squeegees.

5.4.2 Observations

In all stages of the placement of the composite jacket, the following observations were made:

- The preparation of the resin system was performed in accordance with the specifications provided by the manufacturer.
- The reinforcing E-glass fabric was laminated onto the concrete surfaces with sufficient resin to achieve full saturation of the fibers.
- The reinforcement was pressed onto the concrete surface using grooved rollers and squeegees to achieve intimate contact. Entrapped air between layers was released or rolled out before the resin sets.
- Field supervisors observed all aspects of onsite preparation and material application including surface preparation, resin component mixing, application of primer, and application of resin and fiber sheet, vacuum bagging, and curing of composite.
- After allowing at least 24 hours for initial resin cure to occur, a visual and acoustic tap test inspection of the layered surface was performed.

5.5. Monitoring Phase

The monitoring stage consists of a series of tests and visual inspections. This stage will be used for the evaluation of the efficiency and durability of the used technique. Two types of tests took place. The first test was a test to measure the chloride levels and the second test type

was to measure the compressive strengths of the pier caps and the repair concrete used.

5.5.1. Chloride Level Test

To measure the chloride for both the piers and the repair concrete, samples of both were taken before the application of the fibers. These samples were then used after the completion of the project as control samples. Eight samples were taken per pier. Two samples were also taken of the Five Star V/O patching material. Samples were taken where water from the road drips in order to maximize chloride exposure levels. The samples were taken by an engineer from the RIDOT. **Error! Reference source not found.** shows the chloride content sample.

The samples were taken in accordance with the AASHTO T-260 procedure. Samples for chloride testing are taken periodically for comparison with the control chloride samples mentioned above. The samples will be taken every year for 4 years. The analysis of the data obtained will be mentioned in a proceeding section.

It was estimated by the RIDOT technician Ian Frament, that the pier caps have a Mohs hardness of approximately 6-7. The Mohs hardness test is a scratch test, which rates hardness on a scale from 1 (softest) to 10 (hardest). Hardness is a measure of a mineral's resistance to abrasion and reflects the atomic structure of a mineral. What follows is the Mohs Hardness Scale:

1. Talc
2. Gypsum
3. Calcite
4. Fluorite
5. Apatite

6. Orthoclase
7. Quartz
8. Topaz
9. Corundum
10. Diamond

A mineral of a given hardness will scratch a mineral of a lower number. It was also determined that the concrete was of standard weight (>125 lbs/cu ft); therefore silver color PRS-01 probes were used.

5.5.2 Compressive Strength Test

Windsor Probe testing was used to achieve the data for testing the compressive strength of the concrete of the pier caps. A total of 64 probe tests were taken. Sixteen tests were performed on each side of both pier caps. Sixteen samples on each side of the pier cap are enough to ensure the accuracy of such test. The results from this test and the chloride levels will be used as control for comparison purposes during the monitoring period. A RIDOT technician Ian Frament, Kyung Won Park, and Craig Boyer from the University of Rhode Island performed Windsor probe testing. Figure shows the components of the testing equipment.

Figure shows the performance of the Windsor Probe test. The Windsor probe testing was carried out in accordance with ASTM test C 803. The analysis of the Windsor probe test will be presented in a proceeding section.

5.5.3 Chloride Test Data Analysis

Chloride levels were established for samples obtained on March 28, 2003. Table shows

the summary of test results along with baseline values established on September 16, 2002. Initially, values were expressed in percent chloride by weight of concrete. A value of 3915 lb/ft³ was used for the conversion, this value was provided by Aeries Support Services. This value was assumed based on normal weight concrete with an average weight of 145.0lb/ft³.

Figure 5.1 shows the graphical representation of baseline chloride levels taken on 9/16/02. Chloride concentration and comparative analysis will be reported on a yearly basis.

Figure 5. and Figure 5.2 show the percentage increase in chloride levels after the first cycle of testing. The samples were taken as mentioned on the 28th of March 2003. Further cycles are needed to determine the rate of increase of chloride levels in the concrete.

5.5.4. Compressive Strength Test Data Analysis

Correlated compressive strengths of the pier caps were generated from Windsor probe data collected by Ian Frament, Mike Sock, and Steve Quintin of RIDOT on September 16th, 2002. This data was provided to URI by RIDOT in tabular form. The beam seat numbers mentioned are referenced from the south end of the caps. The reading was taken at 14in. and 28in. from the bottom of the caps. Mohs' value was assumed to be 7 for correlation of compressive strength.

Figure 5., Figure 5., Figure 5.and Figure 5. show the baseline correlated strengths. Careful analysis of all the readings leads to the following observations:

- Almost all of the readings indicate that the compressive strengths are higher than 3,000 psi. It appears that the compressive strengths are higher than the design compressive strength.
- As expected, there is a large variation in the estimated compressive strength values. This is most likely due to the surface degradation, actual variation in strength, the presence of

large aggregate at test locations, and intrinsic experimental variation as in the case of the chloride analysis.

- This data will be used as baseline data for further evaluation at yearly intervals.

5.6. Discussion

The monitoring phase will go on for several years. Periodic visual inspections along with more Chloride samples will be taken. In addition, a pull out test will be performed. Further discussion and analysis will be performed once the data becomes available.

Table 5.2 : Chloride Content Data

Levels for Chloride Ion Content (3-28-03):		
Sample	lb/yd ³	
	9/16/2002	3/38/2003
1) NW pier, North face under beam 2 (from east) midpoint vertical, 2" depth	3.015	13.076
1) NW pier, North face under beam 2 (from east) midpoint vertical, 1" depth	7.556	9.357
2) NW pier, North face under beam 3 (from east) midpoint vertical, 2" depth	2.623	6.107
2) NW pier, North face under beam 3 (from east) midpoint vertical, 1" depth	5.873	5.598
3) NW pier, North face under beam 4 (from east) midpoint vertical, 2" depth	5.207	6.577
3) NW pier, North face under beam 4 (from east) midpoint vertical, 1" depth	3.837	8.848
4) NW pier, North face under beam 5 (from east) midpoint vertical, 2" depth	4.894	5.324
4) NW pier, North face under beam 5 (from east) midpoint vertical, 1" depth	3.680	2.780
5) NE pier, North face under beam 3 (from east) midpoint vertical, 2" depth	2.310	8.496
5) NE pier, North face under beam 3 (from east) midpoint vertical, 1" depth	3.289	2.545
6) NE pier, North face under beam 4 (from east) midpoint vertical, 2" depth	3.602	4.581
6) NE pier, North face under beam 4 (from east) midpoint vertical, 1" depth	5.520	11.236
7) NE pier, North face under beam 5 (from east) midpoint vertical, 2" depth	2.466	3.563
7) NE pier, North face under beam 5 (from east) midpoint vertical, 1" depth	4.228	10.766
8) NE pier, North face under beam 6 (from east) midpoint vertical, 2" depth	2.858	4.620
8) NE pier, North face under beam 6 (from east) midpoint vertical, 1" depth	0.979	4.737

Note (1): Levels for chloride ion content were calculated by
Aries Support Services Inc. in accordance with the AASHTO T -260 test.

Note (2): NW Pier represents Pier #2
NE Pier represents Pier #4
This notation was adopted by RIDOT engineers during baseline chloride testing.



Figure 5.10 : shows the components of the testing equipment.



Figure 5.11: Windsor Probe Test

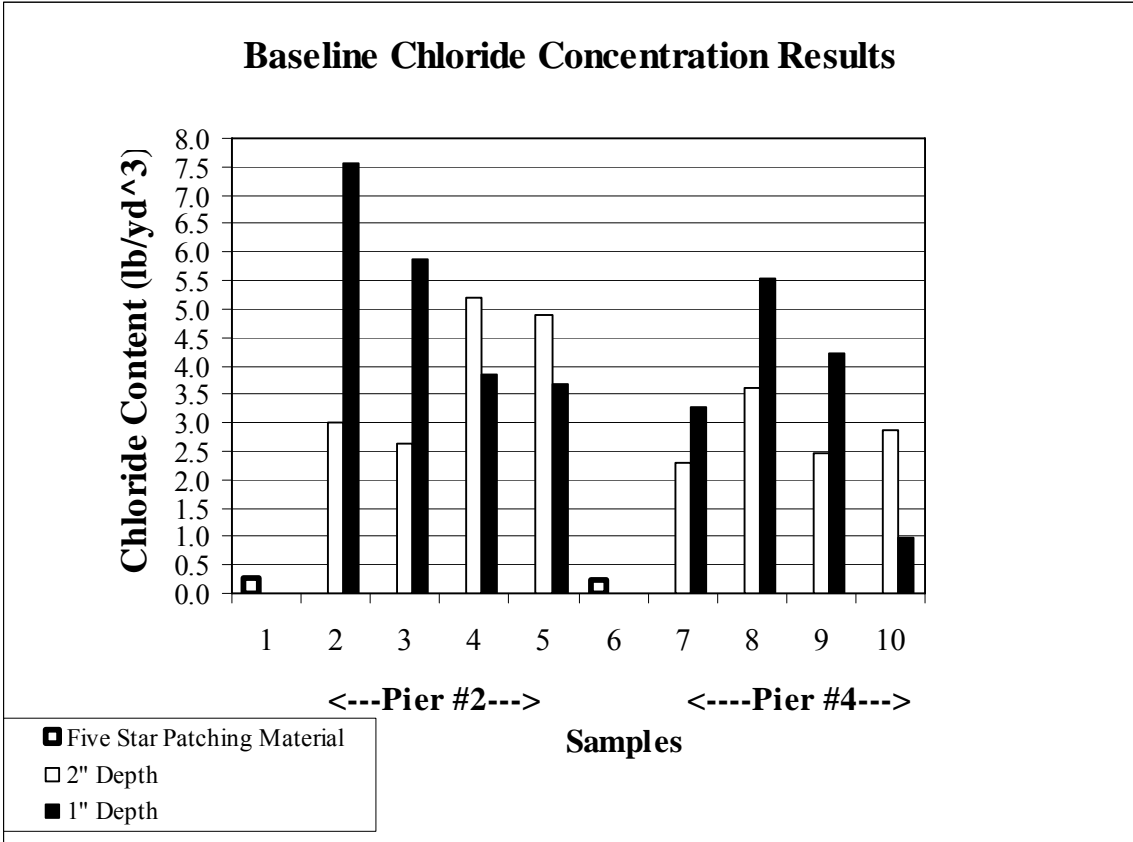


Figure 5.12: Baseline Chloride Concentration for 9/16/02 Inspection

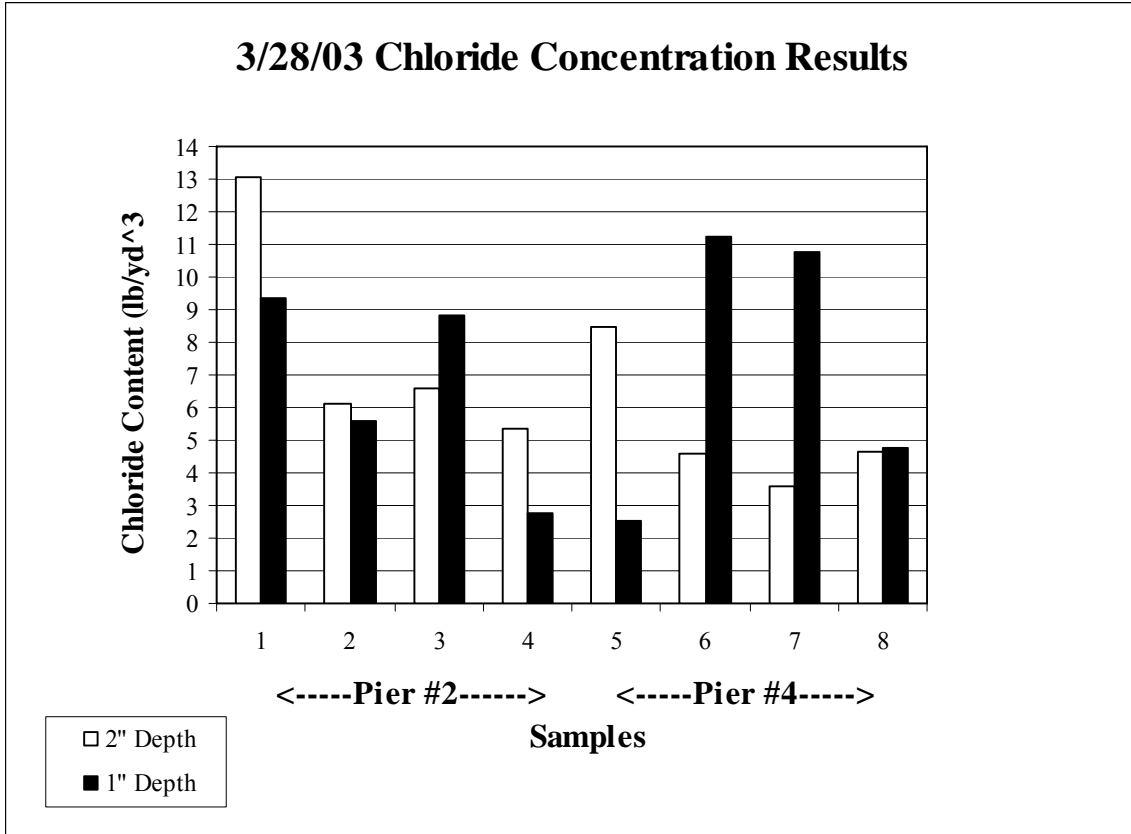


Figure 5.13 : Baseline Chloride Concentration Results for 3/28/03 Inspection

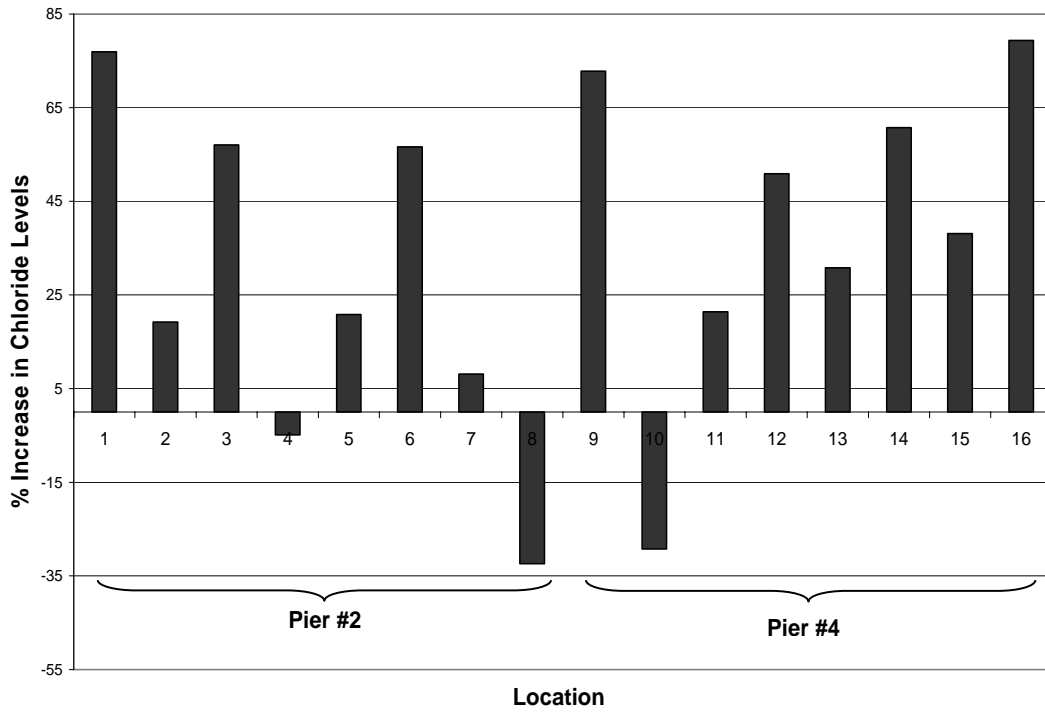
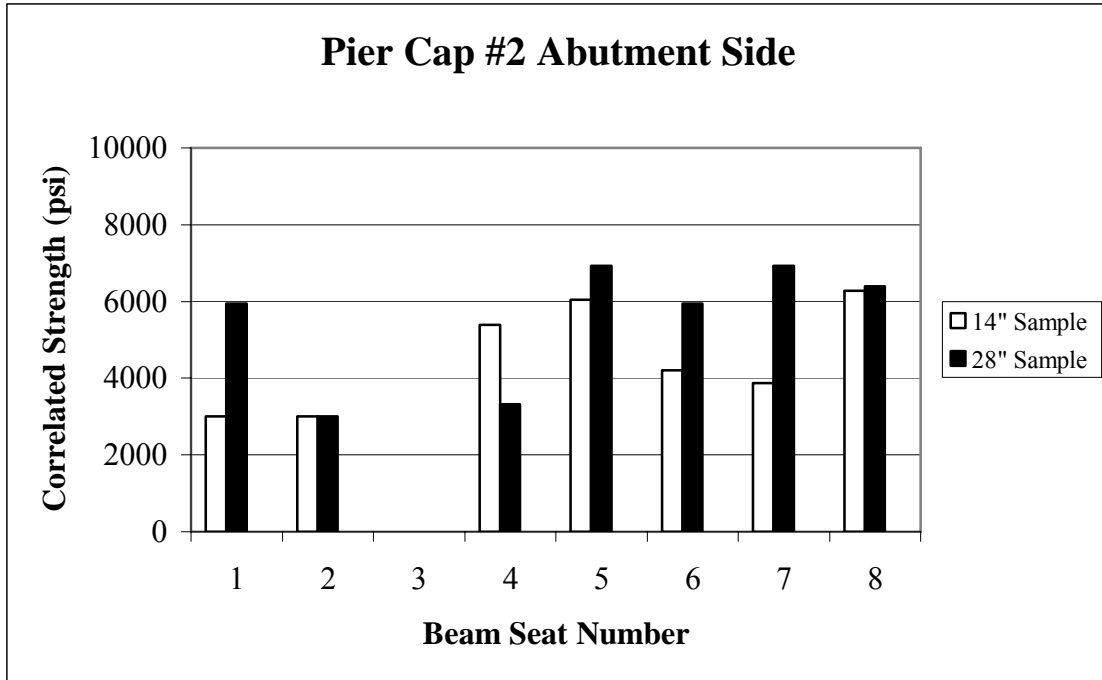
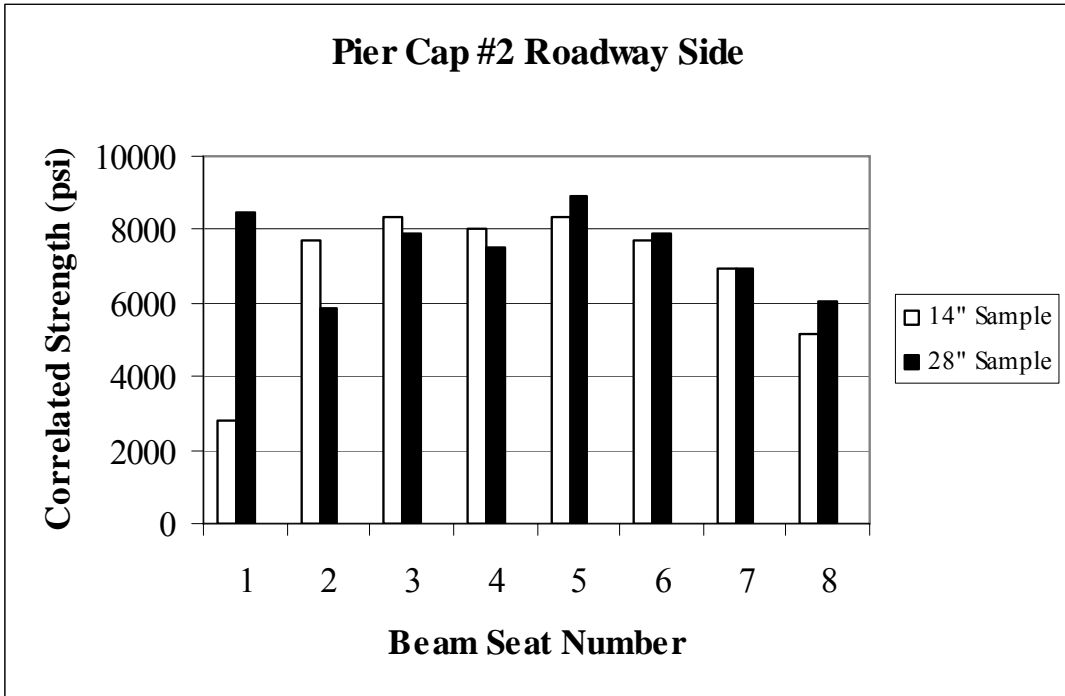


Figure5.24: Percentage of Change in Chloride Levels



Note: Beam seat #8 data represents west end/east end values.
 Both tests for beam seat 3 resulted in spalling.
 Average correlated strength for 14" sample = 4200psi
 Average correlated strength for 28" sample = 5300psi

Figure 5.16: Baseline Correlated Strength – Pier Cap #2 Abutment Side (North Face)

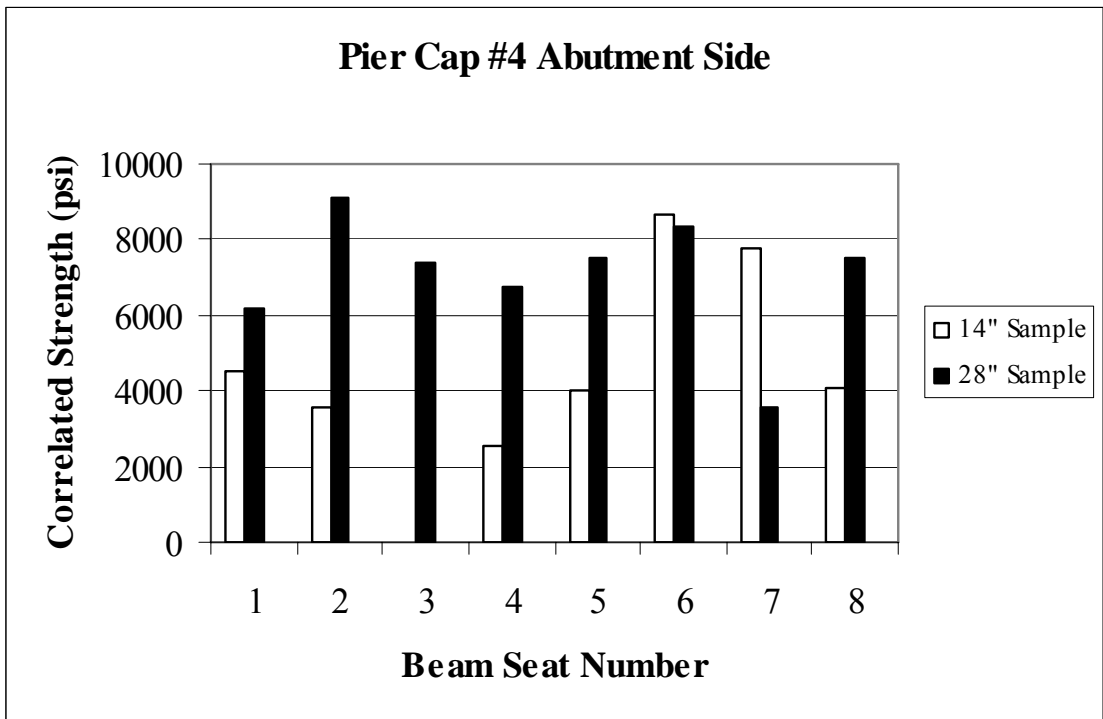


Note: Beam seat #8 data represents west end/east end values.

Average correlated strength for 14" sample = 7000psi

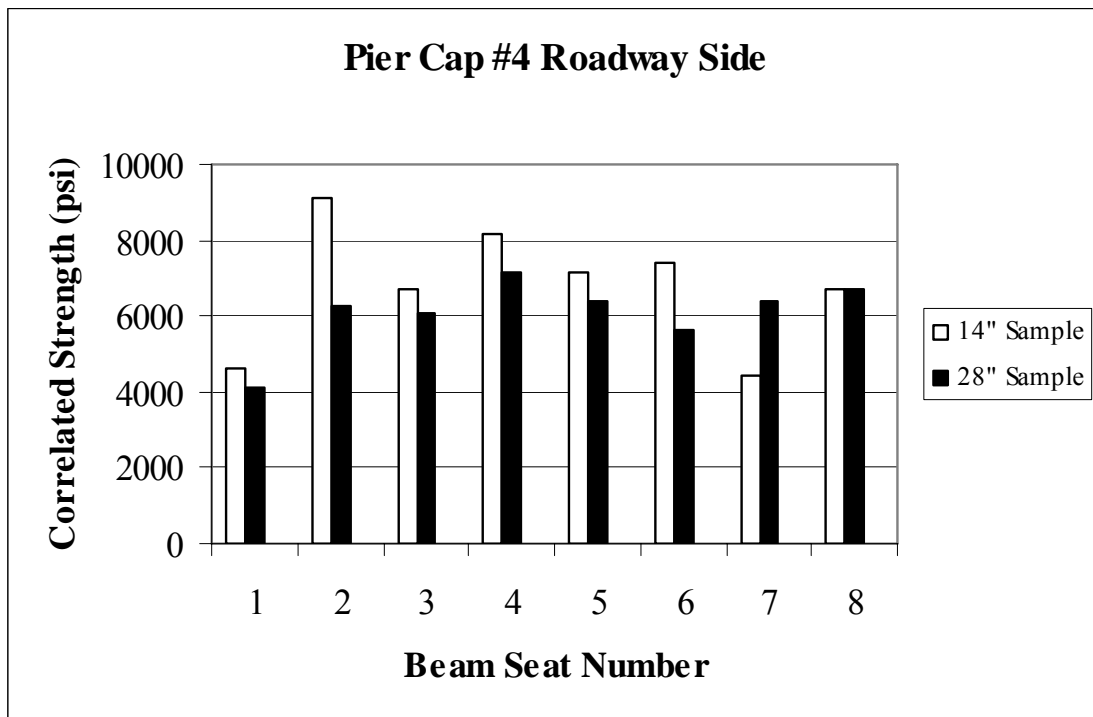
Average correlated strength for 28" sample = 7600psi

Figure 5.17 : Baseline Correlated Strength – Pier Cap #2 Roadway Side (South Face)



Note: Beam seat #8 data represents west end/east end values.
 Tests for beam seat 3, 14" resulted in spalling.
 Average correlated strength for 14" sample = 5100psi
 Average correlated strength for 28" sample = 6900psi

Figure 5.18: Baseline Correlated Strength – Pier Cap #4 Abutment Side (North Face)



Note: Beam seat #8 data represents west end/east end values.
 Average correlated strength for 14" sample = 6700psi
 Average correlated strength for 28" sample = 6000psi

Figure 5.19: Baseline Correlated Strength – Pier Cap #4 Roadway Side (South Face)

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