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FACTORS INFLUENCING STRENGTH LOSS OF GLASS FIBER COMPOSITE BARS IN THE ALKALINE ENVIRONMENT OF CONCRETE

By

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ABSTRACT

FACTORS INFLUENCING STRENGTH LOSS OF GLASS FIBER COMPOSITE BARS IN THE ALKALINE ENVIRONMENT OF CONCRETE

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Steel corrosion is one of the principal problems present in reinforced concrete construction. Billions of dollars are spent annually for rehabilitation and repair of steel-reinforced concrete infrastructure systems such as bridges and coastal structures due to deterioration caused by corrosion of steel. As a result, materials with better corrosion resistance and similar mechanical properties to steel are on demand. Glass Fiber Reinforced Polymer (GFRP) composite bars are corrosion-proof, provide high strength, are lightweight, and have superior chemical and electromagnetic properties when compared to ordinary steel reinforcement. GFRP bars however, degrade when exposed over long periods of time to the highly alkaline environments of concrete, among other degradation issues. This investigation focuses on the effect of high alkalinity on tensile and bond strength of several types of GFRP bars. Accelerated aging techniques were employed to explore the effects of GFRP characteristics (fiber volume fraction, matrix composition, bar diameter, and presence of protective coating) on their alkali resistance. Test results indicated that alkalinity has less impact on bars with lower fiber volume fractions and on bars treated with protective coating; mixed results were obtained in regard to matrix type and bar diameter comparisons. For the particular bond test specimens investigated in this project, accelerated aging did not change bond strength but altered the failure mechanism associated with bond failure of the specimens.

To my late best friend Guillermo José Pescador.

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CHAPTER 1

INTRODUCTION

1.1 GENERAL

Numerous research studies have concluded that exposure to high alkali environments have a detrimental effect on glass fiber polymer composites. This occurs because of the ability of the basic components in a highly alkaline environment to penetrate and attack the components of glass fiber. Glass fiber, being the main load-bearing component in a composite, degrades by this chemical process and thus, the composite as whole loses its strength and load-bearing capacity. On the other hand, glass fiber composites are unaffected by the effects of corrosion. For this reason, the use of glass fiber reinforced polymer (GFRP) rods is an attractive alternative to regular steel reinforcement in special applications such as structural components or systems that are exposed to highly corrosive environments. GFRP rods are also lightweight, non-magnetic, and have low thermal and electric conductivity.

Hydrated concrete possesses a pH ranging from 13.4-13.6, making this widely used construction material highly alkaline. This alkalinity is a product of the presence of Na^+, K^+, and Ca^{2+} ions in the water trapped in pores within concrete, also known as pore water solution. When GFRP rods are used as concrete reinforcement, the pore water solution penetrates the outer coating or layer of the resin of bars, reaches the fibers and deteriorates their strength capacity over time. The degree of strength loss depends on the time of exposure to alkaline solution, temperature of the solution, porosity of concrete, type of fiber used to manufacture the composite, composition of the matrix in composite, and the coating layer used around the bar (among other less influential factors).

GFRP bars are typically manufactured through a process known as pultrusion in which, continuous fibers are run through a thermoset resin bath. The wet fibers are then passed through a series of dies that apply heat for curing of the matrix and give the bars their final size and shape. Pultrusion enables profiles of constant cross-section to be manufactured continuously. This requires that the constant fiber distribution and cross-sectional shape; no bends or tapers can be introduced. The process is analogous to extrusion of plastics and nonferrous metals. Different means of improving the durability characteristics of GFRP bars in the alkaline environment of concrete have been developed. These include the change from polyester to vinylester resin and introduction of a resin-rich surface layer (with discrete fiber reinforcement). Even though these measures have yielded some gains in alkali resistance of GFRP bars, research has shown that GFRP bars still deteriorate over short periods of accelerated aging in a highly alkaline environment.[1-9]

Fibers constitute critical elements of composites; they are the main load-bearing component of the composites. Fibers generally occupy 30% - 70% of the volume in composites. They can be continuous, chopped, woven, stitched, and/or braided. Fibers are usually treated with sizings such as starch, gelatin, oil or wax to improve bond to binders and also to improve handling attributes.[10] The fibers used to manufacture GFRP bars tested in this research are continuous longitudinal E-glass fibers. Carbon and aramid fibers and other types of glass fibers have also been used to manufacture composite rebar, but their high price makes their use in concrete reinforcement bars very limited.[10]

The primary role of the matrix in composites is to bind the fibers together and protect them from the environment. Two types of resins exist: thermoplastic and thermoset. Thermoplastics melt when heated and solidify when cooled. These long-chain polymers do not chemically cross-link because they do not cure permanently. Thermoset resins are made up by two components, namely a polymeric resin and a hardener. When both are combined at a specific proportion and cured by application of heat, the thermosetting resin will cure permanently by irreversible cross-linking at elevated temperatures. This characteristic favors structural applications of thermoset resin composites. The most common resins used in composites are the unsaturated polyesters, epoxies, and vinyl esters; polyurethanes and phenolics are used less commonly. Thermoset resins exhibit better resistance to environment and desirable mechanical properties.[10] Epoxy resins are also used to manufacture composite bars, but are not very common due to their higher cost. Vinylester has higher physical properties than polyesters, and costs less than epoxies. Bars tested in this study were manufactured using polyester and vinylester resins.

Fillers are added to the resin matrix for controlling material cost and improving its mechanical and chemical properties. Some composites that are rich in resins can be subject to high shrinkage and creep and may also provide low tensile strength.

The three major types of fillers used in the composite industry are calcium carbonate, kaolin, and alumina trihydrate. Other common fillers include mica, feldspar, wollastonite, silica, talc, and glasses. When one or more fillers are added to a properly formulated composite system, gains in performance include improved fire and chemical resistance, high mechanical strength, and reduced shrinkage. Other improvements include increased toughness and fatigue life, and reduced creep. Some fillers cause composites to have lower thermal expansion and exotherm coefficient.[10]

Additives are used in the composites to improve the performance characteristics, aesthetics, and the manufacturing process. They are incorporated into the matrix system during mixing of the components. Additives can be divided into three groups: (1) catalysts, promoters, and inhibitors; (2) coloring dyes; and (3) releasing agents.[10]

In composite bars, a surface layer of distinct attributes may be applied for improved protection against the environment and for enhanced bond characteristics. This layer may have the same base resin as the matrix. Discrete fibers may be included in the resin to improve cracking resistance of this surface layer. A coarse material such as sand may also be used to improve bond between the bar and concrete. Other techniques employed for this purpose are roving of strands of glass fiber around the layer of coating, or press molding to create protrusions or irregular surfaces on the bar.

1.2 SCOPE OF WORK

In this research, we produced comprehensive data on performance of four commercially available GFRP bars (two of which are produced particularly for concrete reinforcement). We also conducted a thorough investigation of the effect of epoxy coating on tensile and bond strength of GFRP bars under accelerated aging conditions. A preliminary assessment was made of the effect of epoxy coating on bond of GFRP bars with surface deformations to concrete. An epoxy coating with 15% silica fume content (by weight) was used; comparisons were made between the aging behavior of uncoated and coated GFRP bars in order to assess the effectiveness of coatings in protecting GFRP bars against attack by the highly alkaline environment of concrete. For the purpose of this study, we focused on the most economical and widely used (E-glass) fiber reinforced composite bars.

1.3 RESEARCH OBJECTIVES

The focus of this study was to investigate the effect of the high alkalinity of concrete environment on tensile and bond strength of Glass Fiber Reinforced Polymer Composite Bars. Also included in the scope of this study was to investigate the effects of fiber volume fraction, bar diameter, matrix type and epoxy coating on alkali resistance of GFRP bars in concrete.

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

Reinforced concrete is the most widely used material for construction of infrastructure systems such as bridges and building structures. It is well known that concrete is strong in compression, but relatively weak in tension; a reinforcing material should thus be used to withstand the tensile stresses in concrete. Steel has been the material of choice for use as concrete reinforcement since the late 1800's. Some properties that have helped this long-lasting tie between concrete and steel are the high tensile strength and low price of steel, and the compatibility in thermal expansion coefficients between both materials.

The use of steel along with concrete in construction has not been free of problems. Steel corrodes in the presence of moisture and air, creating an expansive reaction that causes spalling and breakage of concrete and reduced steel properties. This phenomenon is pronounced in the presence of salt, and is evident in coastal structures such as seawalls and bridges, and also the case of bridge decks and parking structures exposed to de-icing salts. Several methods have been used to prevent steel corrosion from occurring, such as use of stainless steel instead of regular steel, epoxy coating and cathodic protection, but none of them provide a final or practical solution.[1]

The search for a new reinforcement material that provides good tensile strength and corrosion resistance has led to experimentation with Fiber Reinforced Polymer (FRP) materials commonly known as advanced composites. Advanced composites are made up of two main materials, namely a resin (matrix) and fibers. Fibers are the main load-bearing components while the matrix is in charge of binding the fibers together and protecting them from the environment. The origins of these types of materials date back to post-World War II years, where the aerospace and defense applications prompted major development efforts concerning composites.[11] Other uses that followed included sporting goods and medical equipment (prosthetics). It was not until the late 1960's that composite materials were considered for concrete reinforcement.

Composites are resistant to corrosion and provide the necessary strength and stiffness for reinforcement of concrete.[11] FRP rebars have a high strength to weight ratio and desirable fatigue resistance, making this material attractive to construction, however, the durability of composite bars may be affected under specific harsh environments such as the high pH of concrete, and conditions involving temperature variations and exposure to moisture.[10] Vulnerability of FRP bars depends primarily on the constituents and the fabrication method of the composite.

The three most common fiber reinforcement systems used in FRP's are glass, carbon and aramid. Each one possesses different chemical and mechanical properties, and their durability gets affected by exposure to different environments. Carbon and aramid composite FRP bars show higher tensile strengths than glass FRP bars, but their cost is considerably higher. Glass FRP has an adequate tensile strength, is readily available, and its cost is relatively low when compared with other composites.[12]

2.2 FIBER TYPES

2.2.1 Glass Fibers

Glass fibers are the most widely used fibers in polymer composites. These are various types of glass fibers: E-glass is of calcium aluminoborosilicate composition with a maximum alkali content of 2%, it possesses good strength and a moderate elastic modulus, and is a good electrical insulator.[13] C-glass (also called A-glass) is of soda-lime-borosilicate composition and has a better resistance to chemical corrosion than E-glass. S-glass is of magnesium aluminosilicate composition with very high tensile strength and is able to withstand higher temperatures. AR-glass or alkali resistant glass has a higher zirconia (ZrO_2) content, which somewhat improves its behavior under high alkali environments, such as concrete.[14] Because of its low cost, E-glass fibers are used most commonly for the manufacture of polymer matrix composites in construction and other applications, accounting for more than 90% of the total glass fiber production.

Glass fibers are isotropic, meaning that they have the same elastic modulus and tensile strength along the fiber axis and perpendicular to it, due to their three-dimensional network structure. The tensile strength of glass fibers is quite high (3500 MPa [508 ksi]), but the elastic modulus is not very high (around 70 GPa [10.2 Msi]) when compared to carbon or aramid fibers. Consequently, the strength-to-weight ratio is high but the modulus-to-weight ratio is only moderate.[15] This is the reason why the aerospace industry uses other fiber types (the so called advanced fibers) instead of glass. Glass fiber is relatively cheap, and it is mostly used as reinforcement in polyester, epoxy, and phenolic resins within the construction, marine, transportation and other industries. Ordinary steel reinforcement has tensile strength and elastic modulus of around 520 MPa (75 ksi) and 200 MPa (29 Msi) respectively.

Table 2.1. Comparison of Mechanical and Physical Properties of Different Types of Glass Fibers.[13, 14]

Type	Bulk Density g/cm^3 (lb/ft^3)	Tensile Strength GPa (ksi)	Tensile Modulus GPa (Msi)	Failure Strain (%)
E-glass	2.62 (163.5)	3.4 (493.1)	81.3 (11.8)	4.9
S-glass	2.50 (156.1)	4.6 (667.2)	88.9 (12.9)	5.7
C-glass	2.56 (159.8)	3.3 (478.6)	...	4.8
AR-glass	2.78 (173.5)	2.5 (362.6)	70.0 (10.2)	3.6

Glass fiber fabrication starts out by melting the raw materials in a furnace heated to 1 540 °C (2642 °F) (Figure 2.1), feeding into electrically heated bushings, which contain a number of holes at their base.[15] The molten glass flows by gravity through the holes forming fine continuous filaments which are sprayed with water to cool off. These filaments are gathered together to form a single strand, and a "sizing" is applied before winding on a drum. Sizing of fibers is provided to protect them from being damaged in handling and to minimize the introduction of surface defects. For reinforcement purposes, a size based on polyvinyl acetate and containing a resin-coupling agent is used. The resin-coupling agent is compatible with polyester, epoxy and phenolic matrix resins. The coupling agent is used to bond the fibers and the resin matrix together.

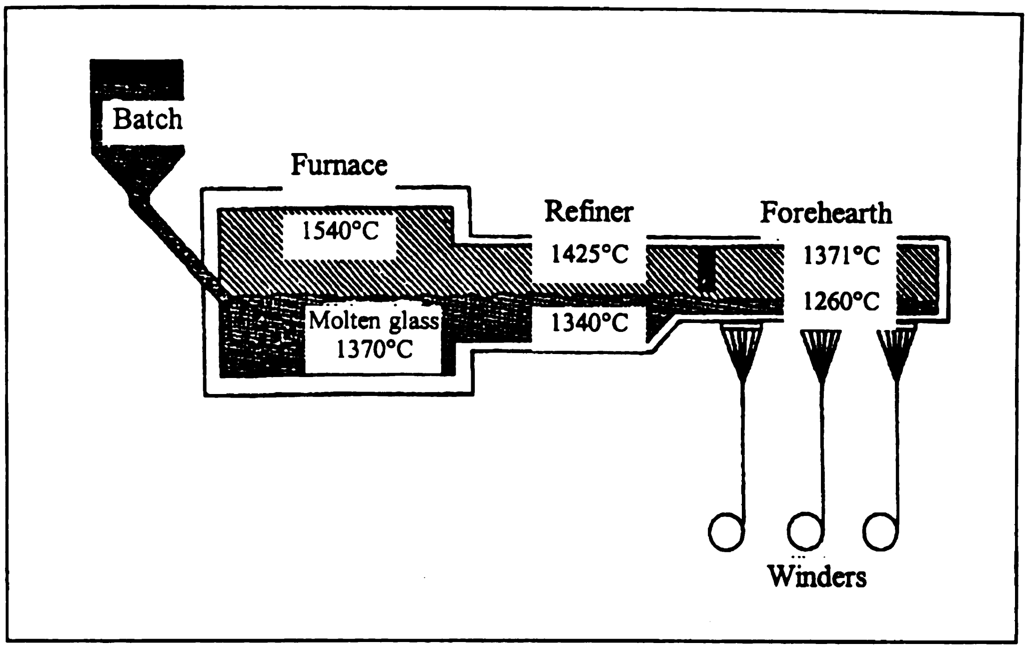
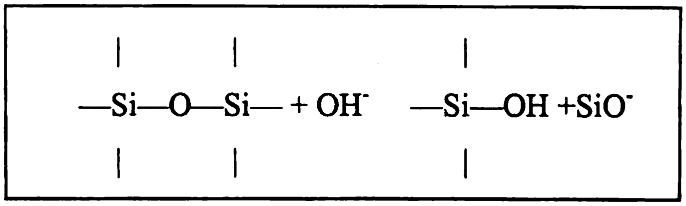


Figure 2.1. Glass Fiber Melting Process.[13]

Fibers can suffer degradation when exposed to different environments; this is caused by the interaction between the fibers and deleterious substances in the surrounding environment. Damage to glass fibers by fluids is initiated by physical or chemical reactions between the two. The extent of damage depends on fluid type, fluid concentration, and the composition of the fibers under attack.[2] Glass fibers are known to degrade in the presence of water, acidic and alkaline solutions.[16] Exposure to highly alkaline environments has been found to have the most severe effect on glass fibers. This is a major concern when utilizing glass fiber reinforced polymers as reinforcement for concrete, since the pore water solution that is present in the micro-voids of concrete has a typical pH of around 13.5. The high alkalinity of concrete is a consequence of the high sodium and potassium solubility in the cement matrix.[17] The hydroxide ions (OH^-) in an alkaline environment attack the primary component of glass (silica or SiO_2) and cause a breakdown in the Si-O-Si bonds in the glass network (Figure 2.2), resulting in fiber degradation and loss of strength and stiffness.[3]



$$—Si—O—Si— + OH^- \quad —Si—OH + SiO^-$$

Figure 2.2. Breakdown of Si-O-Si Bonds in Glass Fibers.

The network breakdown leads to surface damage on glass and the reaction products may either dissolve or accumulate on the surface of the glass.[14] E-glass/vinylester rod samples were subjected to a 3% ammonia solution at 80°C (176 °F) for 28 days. The results of Raman spectroscopy studies combined with pH data indicated that elevated pH caused a rapid attack on glass fibers.[4] The same study determined that elevated pH also causes rapid fiber dissolution followed by interface debonding between the fiber and the matrix. Another study used both E-glass/vinylester and E-glass/polyester pultruded rods embedded in concrete to study the effects of the high alkali pore solution of concrete on the bars. After aging in water at 80°C (176 °F) for 14 days it was shown that the reinforcing glass fibers near the surface of the rod, where affected by the alkaline concrete solution, and were proven to be more brittle and susceptible to damage by mechanical stresses than those further away from the surface.[5] Significant weight loss associated with fiber dissolution was observed on a study performed on several fiber/matrix systems utilizing E-glass as the reinforcing fibers after exposure to basic media at different temperatures.[18] Weight loss of the samples increased as the basicity and temperature of the solution increased. In another study, samples made with E-glass fibers and different matrix systems were exposed to a simulated concrete pore solution (pH=13.5) at 60 °C (140 °F) for 9 weeks. The results showed a decrease in mass due to dissolution of the fibers and SEM pictures showed disintegration of the interfacial bonding and erosion of fibers.[6] Another study investigated the durability of vinylester and polyester matrix glass reinforced rods and plates by aging in ammonia solution for up to 224 days at 23 °C (73.4 °F), 50 °C (122 °F), and 80 °C (176 °F).[19] Gravimetric and thermogravimetric analyses showed significant weight losses of all samples associated with fiber dissolution when exposed to the highly basic ammonia solution, with more noticeable effects on the samples exposed to higher temperatures. In contrast, samples exposed to the acetic acid solution for the same period of time showed no weight loss indicating that possible fiber dissolution was not significant.

Most of the research related to the durability of glass fibers has focused on the durability of the composite (fiber/matrix) as a whole. One of those studies utilized 12.7 mm diameter (#4 bars) and 19.05 mm diameter (#6 bars) glass fiber reinforced polymer bars exposed to different types of environments and tested in tension to determine strength losses. The bars showed strength losses of up to 64.3% when exposed to high alkalinity for 203 days, up to 49.1% for a combination of high alkalinity and freeze-thaw cycles, up to 76.5% for a combination of high alkalinity and application of stress, but no significant strength losses were found for the samples subjected to salt attack.[1] A recent study investigated the durability of alkali resistant glass fiber reinforced plastic bars by simulating different exposure conditions at 25 °C (77 °F) and 60 °C (140 °F) for six months and tested for tension.[3] The results showed reductions under 8% in tensile strength for the samples immersed in water at 25 °C (77 °F), losses of up to 20.8% and 28.0% for bars exposed to a high alkali solution (pH=12) at 25 °C (77 °F) and 60 °C (140 °F) respectively, no noticeable strength losses for specimens exposed to an acidic solution (pH=3) at 25 °C (77 °F) and for samples exposed to seawater and deicing salt solutions, and strength losses under 6% for samples subjected to ultraviolet rays. A different study dealt with the durability of GFRP pultruded rods by subjecting samples to two months of immersion in 23 °C (73 °F) distilled water, and to embedment of additional bars in concrete with wetting-drying cycles in water.[7] The test results showed that absorption of water produced small reduction in tensile strength and elastic modulus of the order 1 to 7% and 1 to 10% respectively. The bars embedded in concrete produced losses in tensile strength between 6 to 21%, and in elastic modulus between 3 to 11%.

2.2.2 Other Fibers

Other types of fibers such as carbon and aramid fibers area also used in fiber reinforced polymer (FRP) bars in concrete. Carbon is a very light material and offers the highest modulus and strength of all reinforcing fibers (230 – 320 GPa [33.4 – 46.4 Msi] and 4.5 – 5.5 GPa [653 – 798 ksi], respectively).[20] Two main types of carbon fibers are PAN carbon fibers (made primarily of polyacrylonitrile) and pitch carbon fibers (coal tar pitch is its primary component).[14] Carbon fibers have found a variety of applications in the aerospace and sporting goods industries. Some parts in the U.S. shuttle such as cargo bay doors and booster rocket castings are made of carbon fiber reinforced epoxy composites. Modern commercial aircrafts also use carbon fiber reinforced composites. Various other machinery items are made using carbon fiber reinforcement and also in the field of medicine the applications include equipment as well as implant materials. Carbon fibers do not absorb moisture and are resistant to many chemical solutions, making them particularly suited to environmental exposures.[21]

Aramid fibers consist of planar sheets of molecules linked together by hydrogen bonding. The properties of the fiber, and in particular the modulus of elasticity, depend on the degree of alignment achieved during production, and therefore aramid fibers can be of different qualities. DuPont Company has done extensive research on this type of fiber and has been able to produce high modulus aromatic fibers commercially under the name Kevlar. Kevlar comes in various forms including Kevlar 29, Kevlar 49, and Kevlar 149 differing in morphology between each other due to processing variables. Kevlar 49 has a higher tensile strength and modulus (4.0 GPa [580.2 ksi] and 131 GPa [19 Msi], respectively) than Kevlar 29 (3.2 GPa [464.1 ksi] and 83 GPa [12 Msi], respectively), and thus, it is more widely used for load bearing applications. Kevlar 29 has a higher strain to failure than Kevlar 49 (around 4.0% vs. 2.5% for Kevlar49). Kevlar 149 has an ultra high modulus (186 GPa [27 Msi]).[13] Kevlar fibers are used in a variety of products including reinforcement for rubber products such as radial tires for vehicles, ropes, cables, fabrics such as the ones used for bulletproof vests, as reinforcement in FRP along with different types of resins for use in aerospace, marine, automotive, and sports industries.

2.3 MATRIX PHASE

2.3.1 Overview

The matrix binds the fibers and particles together in a composite, transfers the load to them, and protects them against environmental attack and damage due to handling. There are several types of materials used as matrix in a composite such as ceramic, metal, and polymers, the latter being the material used for the manufacture of composites for the construction industry. Polymers have a low cost, easy processibility, relatively good chemical resistance, and a low specific gravity, but they have a low strength, low elastic modulus, low operating temperatures, and a low resistance to prolonged exposure to ultraviolet rays and some solvents. Because of the predominantly covalent bonding, polymers are generally poor conductors of heat and electricity.

Structurally, polymers are giant chain like molecules with covalently bonded carbon atoms forming the backbone of the chain. Two major classes of polymers can be identified in the production of polymeric matrix composite materials: thermoset and thermoplastic.

2.3.2 Thermoset Matrices

Thermoset polymer matrices are formed from the chemical reactions of low molecular weight monomers, or by homopolimerization of an oligomer. When an epoxide or epoxy monomer is mixed with an amine or curing agent (also known as hardener) along with the application of heat a chemical process known as polymerization occurs.[13] Polymerization is a four-step process (Figure 2.3) that starts out with the melting of the monomer and forming of a low molecular weight prepolymer (A-stage). Afterwards the prepolymer grows and branches (B–stage), the gel point is reached (partial cross linking), and lastly the polymer eventually becomes a fully cured crosslinked glass (C-stage). Upon completion of the curing process an irreversible tri-dimensional network structure is formed. Crosslinking makes sliding of molecules past one another difficult, thus making the polymer strong and rigid. The deformation behavior of thermosets is controlled by the network structure. The thermal stability and elastic modulus increases with crosslink density. The initial viscosity is low for ease of processing and their shelf life is limited due to monomer chemical reactivity.

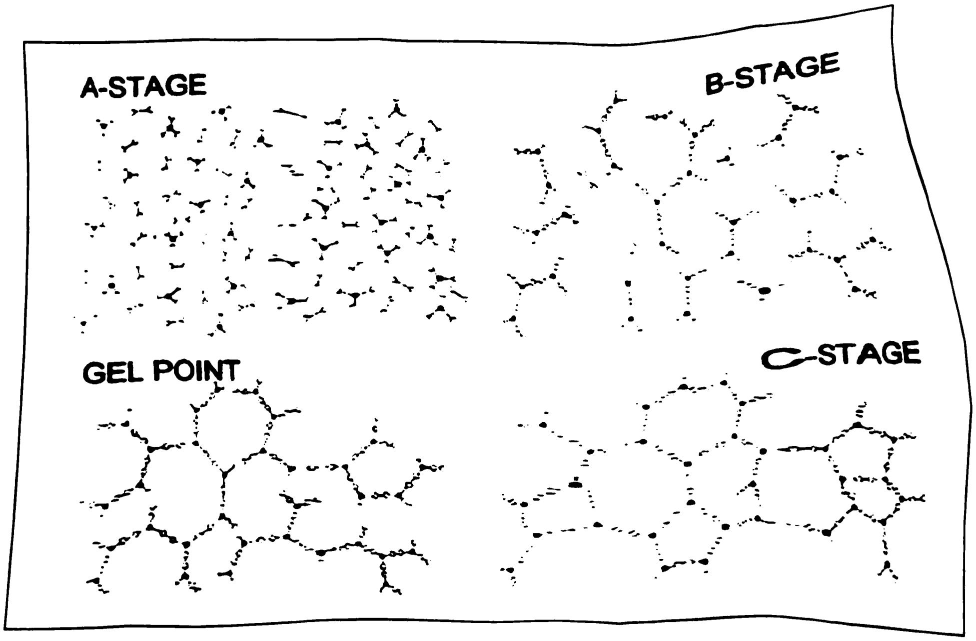


Figure 2.3. Polymerization of Thermoset Resin.[13]

One of the most important properties of thermoset polymers is the glass transition temperature (T_g).[13] The glass transition temperature is defined as the point at which a polymer transforms from a glassy solid to a rubbery material. When a polymer liquid is cooled, it contracts. The contraction occurs because of a decrease in the thermal vibration of molecules and a reduction in the free volume, meaning that the molecules occupy space less loosely. For amorphous polymers, this contraction continues below the melting point of the crystalline polymer T_m to the glass transition temperature T_g where the supercooled liquid polymer becomes extremely rigid owing to extremely high viscosity.[15] Beyond the glass transition temperature the elastic modulus of a polymer is significantly reduced due to changes in its molecular structure. The value of T_g depends on the type of resin but is usually in the range of 65 to 120 °C (149 to 248 °F).

Some of the most common polymer matrices include polyester, epoxy, phenolics, polyimides, and bismaleimides (BMI).[13] A majority of common glass fiber reinforced composites have polyester as the matrix, but polyesters shrink between 4 and 8% on curing and are not very resistant to alkalis and are typically avoided for uses in concrete. Vinylester resins are resistant to a wide range of acids as well as to chloride salts and chlorine making them ideal for marine environments. Polyimides have a relatively high service temperature range (250 - 300 °C [482 - 572 °F]), but like other thermosetting resins, they are brittle.[15] They are mainly used as high temperature polymer matrices in the aerospace industry, and electronics. A major problem with polyimides is the elimination of water of condensation and solvents during processing. BMI polymers can have a service temperature between 180 and 200 °C (356 and 392 °F). They have a good resistance to hygrothermal effects, but being thermosets, they are quite brittle and must be cured at higher temperatures than conventional epoxies. Epoxy resins are more expensive than polyesters but they have a better moisture resistance, lower shrinkage on curing, a higher maximum use temperature, and good adhesion with glass fibers. A very large fraction of high performance polymer matrix composites has thermosetting epoxies as matrices. Some problems with epoxy resins are that they can degrade in the presence of moisture and elevated temperatures. Moisture plasticizes the polymer, leading to swelling, lower strength, lower modulus, and lower glass transition temperature.

2.3.3 Thermoplastic Matrices

The other major class of polymer is the thermoplastic polymer. They are called thermoplastic because they soften or melt upon heating, and can be re-melted and reformed. They are characterized for having a high molecular weight, high viscosity, semi-crystalline or amorphous arrangement, and are soluble in some solvents. Thermoplastic resins are easier to fabricate than thermosetting resins, they also can be recycled and posses unlimited shelf life. Heat and pressure are applied to form and shape them but most often suffer from fabrication strains from cooling gradients and other processing-induced stresses.[13] Some of its advantages are that they can achieve a high toughness, they can be repaired, and a minimum amount of scrap is left out during fabrication. Some commonly used thermoplastics are polycarbonate, PEEK, saturated polyesters, polyamides, nylons, and polypropylenes.

An important problem with polymer matrices is associated with the environmental effects. Polymers can degrade at moderately high temperatures and through moisture absorption. Absorption of moisture from the environment causes swelling in the polymer as well as a reduction in its T_g.[15] In the presence of fibers bonded to the matrix, these hygrothermal effects can lead to severe internal stresses in the composite. The presence of thermal stresses resulting from the thermal mismatch between matrix and fiber is a general problem in all kinds of composite materials. In polymer matrix composites, it is a bigger problem because polymers have high coefficients of thermal expansion.

2.3.4 Fillers

Another important component in the composite matrix additional to the polymer is the filler material. Fillers can be added to thermosetting or thermoplastic polymers to reduce resin cost, control shrinkage, improve mechanical properties, and impart a degree of fire retardancy. In structural applications, fillers are used selectively to improve load transfer and to reduce cracking in unreinforced areas.[22] Clay, calcium carbonate, and glass-milled fibers are frequently used depending upon the requirements of the application. Filler materials are available in a variety of forms and are normally treated with organo-functional silanes to improve performance and reduce resin saturation. Although minor in terms of the composition of the matrix polymer, a range of important additives, including UV inhibitors, initiators (catalysts), wetting agents, pigments and mold release materials are frequently used.

2.4 COMPOSITE FABRICATION

Various techniques are used for making glass fiber polymer matrix composites. Hand lay-up is the simplest of all in which glass fibers are laid onto a mold by hand and the resin is sprayed on or brushed on. Filament winding is another very versatile technique in which continuous tow or roving is passed through a resin impregnation bath and wound over a rotating or stationary mandrel (Figure 2.4).[23,24] A roving consists of thousands of individual filaments. The winding of roving can be polar or helical. In the former the fiber tows do not cross over, while in the latter they do. The fibers are laid on the mandrel in a helical fashion in both polar and helical windings, the helix angle depending on the shape of the object to be made. Successive layers are laid on at a constant or varying angle until the desired thickness is attained. Curing of the thermosetting resin is done at an elevated temperature and the mandrel is removed. Very large cylindrical and spherical vessels are built by filament winding. Glass, carbon, and aramid fibers are routinely used with epoxy, polyester, and vinyl ester resins fo producing filament wound shapes. Filament winding process is a commonly used metho in manufacture of FRP reinforcing bars for construction applications to create irregularities on the surface of the bar that improve bond performance with concrete.

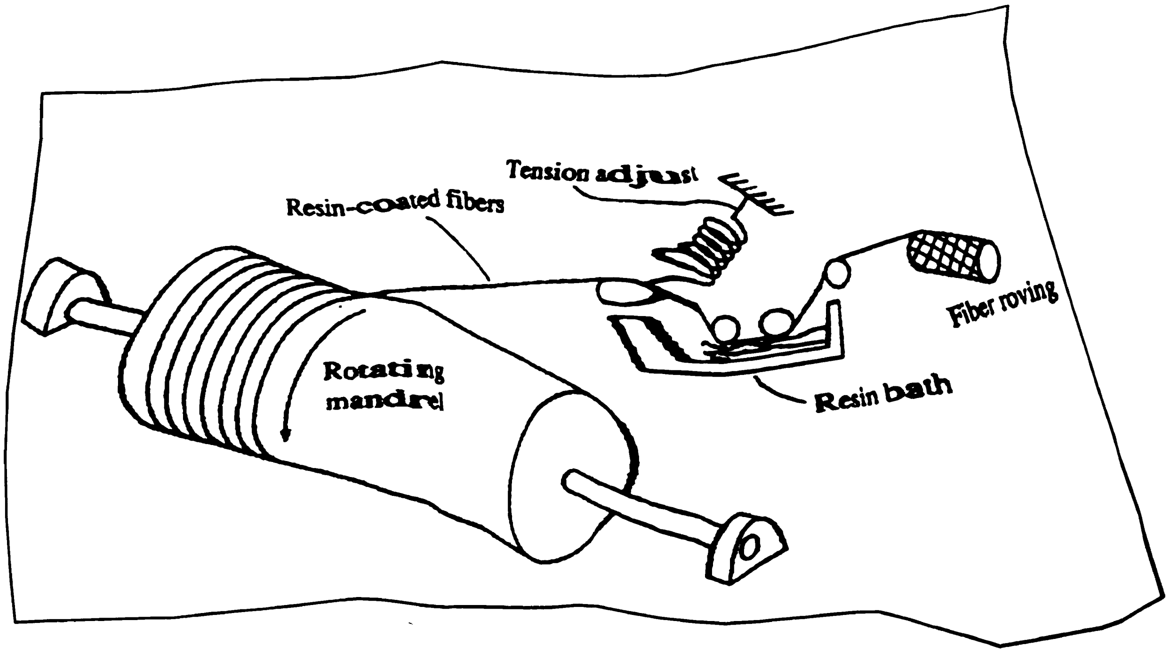


Figure 2.4. Filament Winding Manufacturing Process.[13]

Other manufacturing processes include bag molding (used for maki parts[25]), stacking and subsequent curing of oriented prepregs (thin sheets (less than [0.04 inch]) of partially cured resin containing unidirectionally aligned fibers), inject molding, extrusion, thermoforming[15], and reinforced reaction injection molding (RRIM (widely used in the automotive industry).[26]

Pultrusion is a method that allows the fabrication of continuous, aligned fiber composites in the form of sections such as I or T beams and hollow sections (Figure 2.5).[15] Fibers such as glass, Kevlar, or carbon in desired orientations are impregnated with thermosetting resin and pulled through a heated mold or die. The mold is heated to aid in the curing of the resin. Additional bands of fibers can be wrapped around strands in the production of FRP rebar to create a bonding surface similar to that of st rebar for use in construction purposes. Fiber placement, resin formulation and amo catalyst level, dye temperature, and pulling speed are critical parameters. The commonly used resins in this process are vinylester and polyester resins. Some pr that are produced using this process include reinforcing and prestressing rods, stru elements, gratings, automobile shafts, ground anchors and tiebacks, sheet piling, window frame sections.

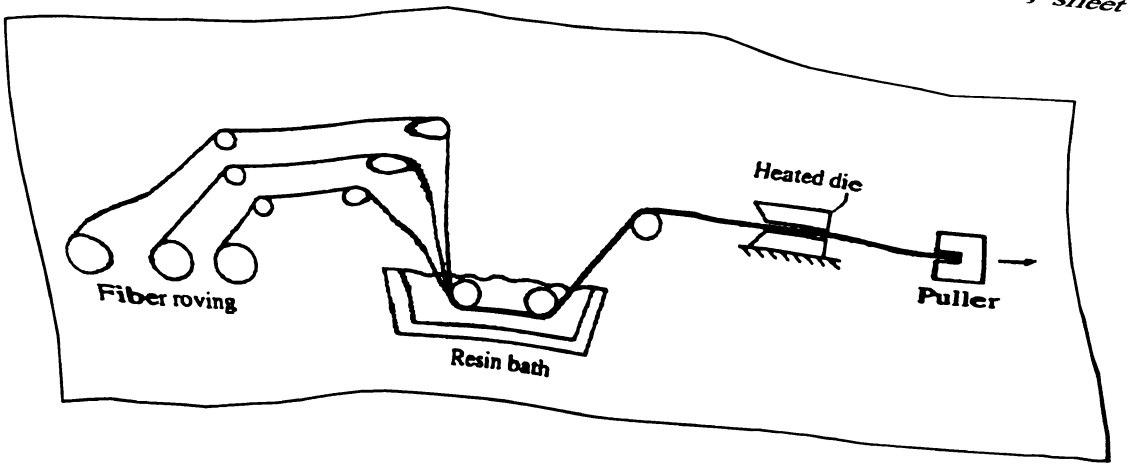


Figure 2.5. Pultrusion Manufacturing Process.[13]

2.5 MECHANICAL AND THERMAL PROPERTIES OF COMPOSITES

2.5.1 Tensile Strength and Elastic Modulus

FRP bars do not exhibit yielding or plastic behavior before failure. Tensi behavior of composite bars is characterized by a linear elastic stress-strain path unt failure (Figure 2.6). Typical tensile strength and elastic modulus values for pultrude glass, carbon and aramid fiber reinforced polymer composite bars with sim

volume fractions are shown in Table 2.2.

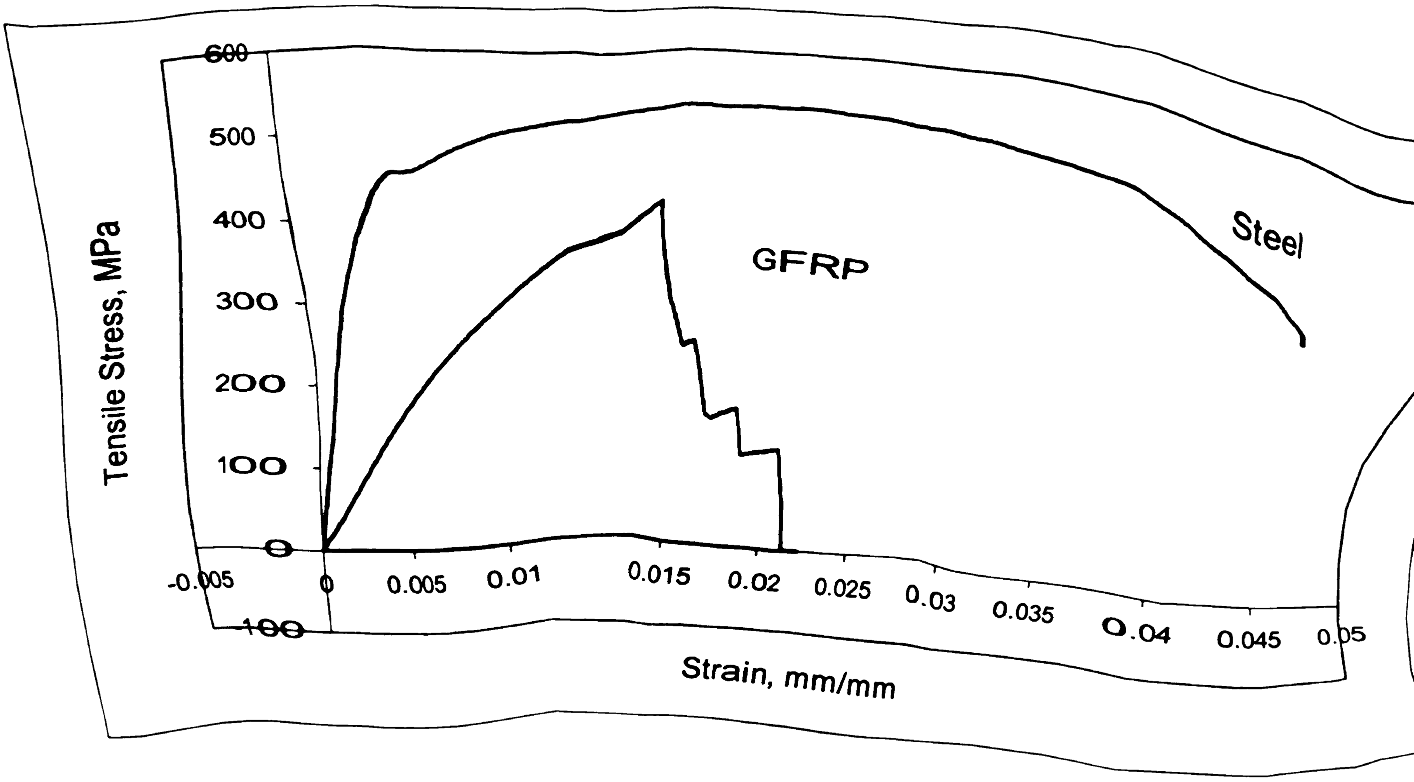


Figure 2.6. Typical Tensile Stress-Strain Relationship of Pultruded GFRP Bars ar
60 Reinforcing Steel.

Table 2.2. Tensile Properties of FRP Composite Bars and Grade 60 Reinforcement.[11]

Bar Type	Tensile Strength MPa (ksi)	Tensile Elastic Modulus GPa (Msi)	Ultimate Strain %
GFRP	483-1600 (70-230)	35-51 (5.1-7.4)	1.2-3.1
CFRP	600-3690 (87-535)	120-580 (15.9-84)	0.5-1.7
AFRP	1720-2540 (250-368)	41-125 (6.0-18.2)	1.9-4.4
Steel (Grade 60)	517-689 (75-100)	200 (29)	6.0-12.0

Tensile characteristics of FRP bars are dependent on several factors such as fi volume fraction, bar diameter, rate of curing, and manufacturing process.[27] The am of fibers present per unit volume will determine the strength and stiffness o composite. Tensile strength reductions of up to 40% have been found for GFRP when due to an increase in diameter from 9.5 to 22.2 mm (0.375 to 0.875 inch).[28] Ten strength properties of FRP bars are, unlike steel bars, not standardized, and should obtained from the manufacturer.

2.5.2 Shear Strength

FRP bars are known to be relatively weak in shear, due to interlaminar lay unreinforced resin between the layers of fibers. Thus, the relatively weak polymer n governs interlaminar shear strength.

Orientation of fibers in an off-axis direction across the layers of fiber will increase the shear resistance; the increase depends upon the degree of offset. This off-axis orientation can be produced by braiding or filament winding of some fibers transverse to the main fibers. Off-axis fibers can also be placed in the pultrusion process by introducing a continuous strand mat in the roving/mat creel. Standard test methods are not yet established to characterize the shear behavior of FRP bars. If the shear properties of a particular FRP bars are needed, they should be obtained from bar manufacturers.[11]

2.5.3 Creep

FRP reinforcing bars subjected to a constant load over time can suddenly fail after a time period called the endurance time. This phenomenon is known as creep rupture (or static fatigue). Creep rupture is not generally an issue with steel bars in reinforced concrete, except in extremely high temperatures such as those encountered in a fire. As the ratio of sustained tensile stress to short-term strength of the FRP bars increases, endurance time decreases. The creep rupture endurance time can also irreversibly decrease under sufficiently adverse environmental conditions, such as high temperature, ultraviolet radiation exposure, high alkalinity, wet and dry cycles, or freezing-thawing cycles. Very limited information is currently available for endurance times beyond 100 hours.[11]

Creep rupture tests conducted on smooth GFRP bars at different load levels indicate that a linear relationship exists between creep rupture strength and the logarithm of time for times up to nearly 100 hours. The ratio of stress level at creep ruptu bars after 500,000 hours (more than 50 years) were linearly extrapolated to be Another investigation of creep rupture has been reported for GFRP rectangular The percentage of initial tensile strength retained followed a linear relation logarithm of time, reaching a value of 55% at an extrapolated 50-yr endurance

2.5.4 Thermal Expansion

The coefficients of thermal expansion of FRP bars vary in longitudina transverse directions depending on the types of fiber and resin, and volume fractio fibers. The longitudinal coefficient of thermal expansion is dominated by the proper of fibers, while the transverse coefficient is dominated by the resin.[31]

Table 2.3. Coefficient of Thermal Expansion of FRP Composite Bars, Ste Concrete.[11]

Bar Type	GFRP	CFRP	AFRP	Steel	Conc
Longitudinal $10^{-6}/°C$ $(10^{-6}/°F)$	6 to10 (3.3 to 5.6)	-2 to 0 (-4 to 0)	-6 to –2 (-3.3 to -1.1)	11.7 (6.5)	7.2 to (4 to
Transverse $10^{-6}/°C$ $(10^{-6}/°F)$	21 to 23 (11.7 to 12.8)	74 to 104 (41 to 58)	60 to 80 (33.3 to 44.4)	11.7 (6.5)	7.2 to (4 to

2.5.5 Bond Strength

Bond performance of an FRP bar is dependent on the design, manufacturing process and mechanical properties of the bar itself, and also on the environmental conditions.[32-36] When anchoring a reinforcing bar in concrete, the bond force can be transferred by the adhesion resistance of interface (chemical bond), frictional resistance of the interface against *slip*, and/or mechanical interlock due to *irregularity* of the interface. In FRP bars, *it is postulated* that the bond force *is transferred through the resin* to the reinforcing fibers, and a bond-shear failure *in the resin is also possible. When* a bonded deformed bar is subjected to increasing tension, the *adhesion between the bar and* the surrounding concrete breaks down, and deformations on the surface of bar cause inclined contact forces between the bar and surrounding concrete. Unlike reinforcing steel, the bond of FRP rebars appears not to be significantly influenced by the concrete compressive strength, provided that adequate concrete cover exists to prevent longitudinal splitting.[37-39]

Environments that degrade the polymer resin or fiber/resin interface *are likely to* degrade the bond strength of composite bars. Direct pullout tests are the most common methods for testing bond of FRP bars to concrete. One study investigated the effect of natural environmental exposure conditions on Glass FRP pullout specimens, and found no significant loss in bond strength over a period of 1 to 2 years.[40, 41] At elevated temperatures, the incompatibility between the transverse coefficient of thermal expansion between composite bars and concrete may influence bond *strength*. Unidirectional FRP bars used in concrete typically have a transverse coeffi*cient of* thermal *expansion 6 to 8* times greater than that of concrete. During temperatures variations, thermal expansion mismatch stresses within the concrete may cause splitting cracks.[42-44] This may result in degradation of bond between concrete and reinforcement, affecting the structural response. Occurrence of splitting cracks under thermal loads depends on several factors such as type of FRP reinforcement, type of concrete, presence of confining action, and geometrical properties of the cross-section. One study revealed that cracking of concrete cover could occur when GFRP pullout specimens were subjected to temperature gradients.[45] In another study, GFRP bars were exposed to wet elevated-temperature environments in concrete (with and without artificially added alkalinity), and found both negative and positive impact on pullout strength over a short period of time.[32, 34, 35, 46]

2.6 MECHANISMS OF GFRP COMPOSITES DEGRADATION

2.6.1 Overview

Even though glass FRP is immune to corrosion attack, it is prone to deterioration in the alkali environment of concrete. There are also concerns with the damaging effects of ultraviolet exposure, elevated temperatures, and moisture on glass FRP.

2.6.2 Alkali Degradation

The environmental condition that has attracted the most interest by investigators concerned with FRP bars is the highly alkaline pore water found in outdoor concrete structures. After concrete has been fully hydrated, its average pH is around 13.6, making it a highly basic (alkaline) medium. Extensive research has been conducted to verify the

effect of this environment on glass FRP rods. Since composite rods are relat
construction material, long-term effects have had to be simulated by accelerat
methods such as immersion in high temperature (60 °C [140 °F]), alkaline
solutions. Based on the results obtained from these investigations it has bee
exposure to high-alkali environments can decrease the tensile strength (
(GFRP) rods by as much as 64.3%[12], although particular results vary tr
according to differences in test methods. Results are also dependent on the man
condition, the resin used to protect and bind the fibers, and the temperature to w
samples have been exposed to during the accelerated aging process.

The high alkalinity of concrete environment is a consequence of the
solubility Sodium and Potassium hydroxides present in hydrated cement matrix
hydroxide ions (OH^-) in an alkaline environment attack the primary component
(silica or SiO_2) and cause a breakdown in the Si-O-Si single bond forming
molecular structure (Figure 2.7). This results in fiber deterioration and loss of stre

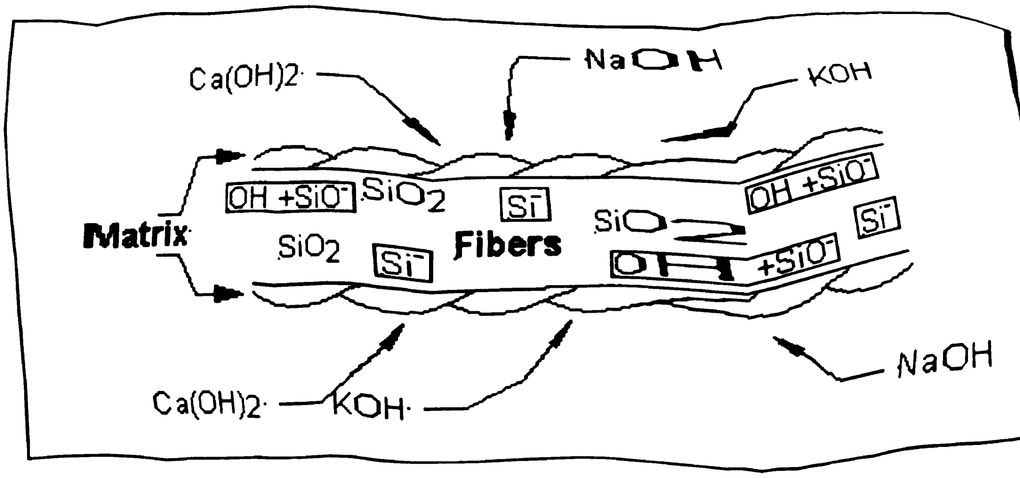


Figure 2.7. Alkali Attack in Pultruded GFRP Bars

One study found that E-glass GFRP rods exposed to basic environments suffer fiber dissolution leading to loss of weight and decrease in strength of the bars.[18] Since the degree and rate of degradation depends strongly on the amount of chemicals that are able to reach and attack the longitudinal fibers, the resin that protects and binds fibers together plays a very important role in this aspect. Different matrix materials are commonly used to protect fibers, including vinylester and polyester-based resins. The Federal Highway Administration sponsored an evaluation of GFRP gratings for use in concrete bridge decks.[8] Tests were conducted in an alkaline environment on two sets of gratings using E-glass fibers, one set with a polyester matrix, another with a vinylester matrix. According to the study, composites with polyester resins are less resistant to alkali attack and showed very rapid deterioration when compared to composites with vinylester resin. Three-point bending tests on grating samples after 160 days of exposure showed strength reductions of up to 80% for polyester resin, and up to 25% for vinylester resin.[8] Another study supported this observation when the outer surface of GFRP samples containing polyester resin matrix showed a higher degree of degradation compared to samples with vinylester resin. This degradation process involved formation of gel-like materials accompanied by swelling, followed by blistering and eventual dissolution of the resin in some cases.[6]

The rod diameter also influences the rate and degree of degradation of glass FRP bars exposed to alkaline environment. One study showed that the larger the diameter of rods, the smaller the percentage weight loss during exposure.[18] In the case of a thicker rod, the average distance of fibers from the surface of the rod increases, the fibers thus become more protected by the matrix and the pH rise in the center of the rod is expected to be more gradual.

2.6.3 Degradation Due to Other Chemicals

Similar to the alkali attack, salt attack will mainly occur due to the presence of OH^- and Cl^- free ions in the solution. Other ions present in the solution could to a lesser degree, react with the fiber and matrix. The Cl^- ions are not as damaging to glass as is the OH^- ions, however Cl^- ions can penetrate the matrix, causing microcracking and fracturing of the matrix which accelerates moisture diffusion as well as debonding of fibers. Debonding of fibers, in turn, will result in the loss of strength of the bar.[3] Tests performed on bars placed for 203 days in a capped PVC pipe filled with salt solution consisting of 97% water and 3% sodium chloride showed no significant loss of tensile strength (some exposed bars even carried a higher load than unconditioned bars).[1] Strength and stiffness losses for the majority of bars were under 10% and 8%, respectively, and gains were within 7.5% and 6% respectively. These minor losses in strength and stiffness show that glass FRP rods are suitable for construction in highly corrosive environments such as in marine structures, and those exposed to deicing chemicals (e.g.: pavements or bridge decks in cold regions).

2.6.4 Moisture Effects

A primary cause of deterioration of GFRP's is the diffusion of moisture and other corrosive solutions into the matrix, which can damage the matrix as well as the fibers. Therefore, moisture absorption and associated changes in material properties must be taken into consideration. Moisture absorption of a composite can be defined in terms of two parameters: maximum moisture content or saturation moisture and mass diffusion coefficient. Maximum moisture content is the moisture level in the composite that is reached asymptotically after a long period of time. It is dependent on material type and temperature and type of the environment.[3] Excessive absorption of water in composites could result in significant loss of strength and stiffness. Water absorption produces changes in resin properties and could cause swelling and warping in composites.[22] There are, however, resins which are formulated to be moisture-resistant and may be used when a structure is expected to be wet at all times. In cold regions, the effect of freeze-thaw cycles must also be considered.

Typically, for glass FRP, losses in tensile and flexural strengths of 10% or more may be expected after a few months of exposure to moisture[7, 47, 48], although some studies indicate that such losses may be negligible.[49] One particular study showed that after 60 days of immersion and wet-dry cycles, for 12, 16 and 20mm (0.47, 0.63 and 0.79 inch) diameter bars, exposure to moisture had a small effect on the ultimate tensile strength, Young modulus and Poisson ratio. The reduction in strength was 1, 7 and 2%, respectively, for the three bar diameters, while the elastic modulus decreased by 6, 9 and 0.5%.[7] The same study concluded that even after 60 days of immersion in water, the GFRP bars had not reached a saturated state, and were continuing to absorb water at a progressively increasing rate. Also, the absorbed water produced small reduction in tensile strength and elastic modulus of the order of 1 to 7% and 1 to 10%, respectively, and the stress-strain curves remained linear after 60 days of immersion in water.

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Tests performed on GFRP bars made with alkali-resistant glass fiber showed that submersion in water resulted in a measured reduction in tensile strength of 7.3% and 5.9% for bars with polyester and vinylester matrices, respectively. Limited changes in the elastic modulus were observed, and these changes were within 5% of the initial values.[3]

2.6.5 Thermal Resistance

Many composites have good to excellent properties at elevated temperatures and do not burn easily. The effect of high temperature is more severe on the resin than on fibers. Resins contain large amounts of carbon and hydrogen, which are flammable. Research is continuing on the development of more fire-resistant resins.[50] Tests conducted in Germany have shown that E-glass FRP bars could sustain 85% of their room-temperature strength, after half an hour of exposure to 300 °C (572 °F) temperature when stressed to 50% of their tensile strength.[51] While this performance is better than that of prestressing steel, the strength loss increases at higher temperatures and approaches that of steel. The problem of fire for a concrete member reinforced with FRP composites is different from that of composite materials subjected to direct fire. In this case, the concrete serves as a barrier to protect the FRP from direct contact with flames. However, as the temperature in the interior of the member increases, the mechanical properties of the FRP may change significantly. It is therefore recommended that the user obtain information on the performance of a particular FRP reinforcement and resin system at elevated temperatures when potential for fire is high.[22]

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The use of FRP reinforcement is not recommended for structures in which fire resistance is essential to maintain structural integrity. Because FRP reinforcement is embedded in concrete, the reinforcement cannot burn due to a lack of oxygen; however, the polymers will soften due to the excessive heat. Beyond the glass-transition temperature T_g, the elastic modulus of a polymer is significantly reduced due to changes in its molecular structure. In a composite material, the fibers (which exhibit better thermal properties than the resin) can continue to support some load in the longitudinal direction. However, the tensile properties of the overall composite are reduced due to a reduction in force transfer between fibers through bond to the resin. Test results have indicated that temperatures of 250 °C (480 °F), much higher than the glass-transition temperature, will reduce the tensile strength of GFRP and bars by more than 20%.[52] Other properties more directly affected by the shear transfer through the resin, such as shear and bending strength, are reduced significantly at temperatures above the T_g.[53]

For FRP reinforced concrete, the properties of the polymer at the surface of the bar are essential in maintaining bond between FRP and concrete. At a temperature close to its glass transition temperature, however, the mechanical properties of the polymer are significantly reduced, and the polymer is not able to transfer stresses from the concrete to the fibers. One study carried out with bars having glass transition temperatures of 60-124 °C (140-255 °F) reports a reduction in pullout (bond) strength of 20 to 40% at a temperature of approximately 100 °C (210 °F), and a reduction of 80 to 90% at a temperature of 200 °C (390 °F).[53] Another study involving FRP reinforced beams reported reinforcement tensile failures when the reinforcement reached temperatures of

250-350 °C (482-662 °F).[54]

2.6.6 Degradation Due to Ultraviolet Rays

The ultraviolet rays present in sunlight can damage composites. These rays cause chemical reactions in a polymer matrix, which can lead to degradation of its properties. Although the problem can be solved with the introduction of appropriate additives to the resin, this type of damage is not of concern when FRP elements are used as internal reinforcement for concrete structures, and therefore not subjected to direct sunlight.[22] Extended exposure of FRP bars to ultraviolet rays and moisture prior to their placement in concrete could adversely affect their tensile strength due to degradation of the polymer constituents and resins. Proper construction practices and resin additives can ameliorate this type of weathering problem significantly.

Resins, in general, will be affected by UV unless adequate protection is provided by additives or coatings. In turn, the composite properties would also be affected, mostly in compression, shear, and transverse tension.[8]

CHAPTER 3

EXPERIMENTAL PROGRAM

3.1 SAMPLE PREPARATION AND CONDITIONING

Tensile tests and pullout (bond) tests were performed on several pultruded GFRP bars provided by four different manufacturers to determine the effects of different properties (fiber volume fraction, matrix composition, bar diameter, coating treatment) on degradation due to alkali exposure. These bars were made out of continuous E-glass fibers with either polyester or vinylester matrices. The experimental plan for tension and bond tests are summarized in Tables 3.1 and 3.2, respectively.

Table 3.1. Tensile Strength Test Program

Manufacturer	Bar Diameter	Matrix	Fiber Volume Fraction by Weight, %	Conditioning of Uncoated Bars	Conditioning of Coated Bars
I	6.35mm (0.25 in.); 9.35mm (0.375 in.)	Vinylester	70	Control; 14, 28, and 42 day Immersion and Wet-dry cycles.	Control; 28 day Immersion and Wet-dry; 42 day Immersion.
II	9.35mm (0.375 in.)	Vinylester	60	Control; 14, 28, and 42 day Immersion and Wet-dry cycles.	Control; 42 day Immersion.
III	8.0mm (0.315 in.)	Polyester	60	Control; 14 and 28 day Immersion and Wet-dry cycles	Control
IV	9.35mm (0.375 in.)	Polyester	50	Control; 28 day Immersion and Wet-dry cycles	28 day Immersion and Wet-dry cycles

Table 3.2. Bond Test Program

Manufacturer	Matrix	Coating		Curing	
		Uncoated	Coated Control	Control	Aged
I	Vinylester	None	Epoxy w. 15% Silica Fume	21 days in 20°C (68°F) lime saturated water	21 days of immersion in 60°C (140°F) water
II	Vinylester	None	Epoxy w. 15% Silica Fume	21 days in 20°C (68°F) lime saturated water	21 days of immersion in 60°C (140°F) water

Bars ranging from 6.35mm to 9.53mm (0.25 in. to 0.375 in.) diameter provided by four different manufacturers were considered in uncoated condition; in addition, some bars received epoxy coating. Bars from manufacturers I and II had deformed surfaces and were produced for concrete reinforcement. Bars from manufacturers III and IV had smooth surfaces and were pultruded for other applications.

Bars were tested in tension either in control (CTR) condition prior to any aging, after two weeks of storage in 50% relative humidity at 20°C (68°F), or after different durations of continuous immersion (CS) or wet-dry cycles (WD) in an alkaline solution. The alkaline solution consisted of 16.6 g/L of Potassium Hydroxide (KOH), 2.36 g/L of Sodium Hydroxide (NaOH), and 2.5 g/L of Calcium Hydroxide ($Ca(OH)_2$) heated to 60 °C (140 °F). This solution was selected to simulate the pore solution of concrete and provided a measured pH value of 13.6 ± 0.1. Figure 3.1 shows the continuous immersion of bars in the solution. In accelerated aging (accelerated test method to predict long-term performance[18, 19]), each wetting-drying cycle involved 16 hours of immersion in a 60°C (140 °F) alkaline solution followed by 8 hours of air-drying. Different samples were subjected to 14, 28, and 42 days of continuous immersion or repeated wetting-drying cycles in 60°C alkaline solution. Close to six replicated tension tests were performed for each distinct condition.

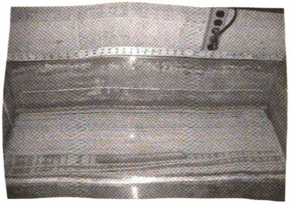


Figure 3.1. Aging Tank with Alkali Solution

Bond tests were executed in order to determine the effects of alkalinity in concrete in bond strength characteristics between GFRP bars and concrete. These tests were performed either in unaged condition after 21 days of moist curing in 20°C (68°F) lime saturated water followed by 7 days of conditioning in 50% relative humidity at 20°C (68°F), or in aged condition after 21 days of moist curing followed by 21 days of immersion in 60°C (140°F) water and then 7 days of conditioning in 50% relative humidity at 20°C (68°F). Four replicated unaged tests and three replicated aged tests were performed for each distinct condition.

3.2 TESTING PROCEDURES

3.2.1 Tension Tests

Tension tests similar to testing procedures previously employed by several researchers[1, 6, 22] were performed on 864mm (34 inch) long bars. Steel pipes 19 mm (¾ inch) diameter and 178 mm (7 inch) long with a thickness of 3 mm (1/8 inch) were placed at the ends of each bar filled with epoxy (AD-932 epoxy resin from Adtech Corp.), and left to cure for 10 days at 22 °C (72 °F) and 50% relative humidity prior to testing (Figure 3.2). A servovalve-controlled hydraulic test system (Figure 3.3) with circular groove jaws was used for tension tests which were performed at controlled deflection rate of 0.01 mm/sec (0.00039 in/sec). Loads and deflections were measured throughout the tension tests.

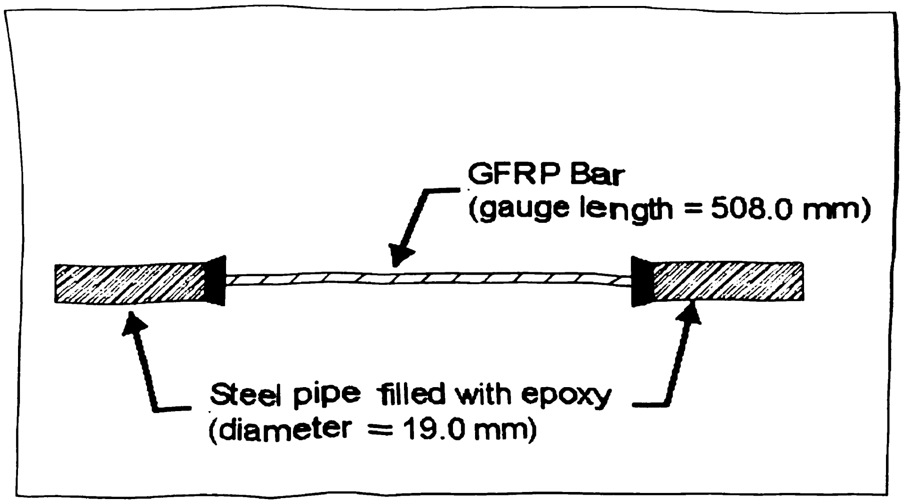


Figure 3.2. GFRP Bar Tension Test Specimen

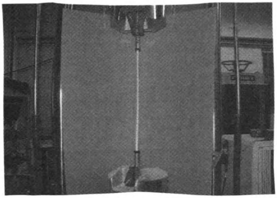


Figure 3.3. Tension Test Set-Up

3.2.2 *Pullout (Bond) Tests*

The bond test set-up is presented in Figure 3.4. 152 mm diameter by 152 mm height (6 inch diameter by 6 inch height) cylindrical plastic molds were used to embed 610 mm (24 in.) long bars in concrete, with an embedment length of 51mm (2 inches) at the center, and debonded 51 mm (2 in.). The bar was located at the center of the concrete cylinder; the bar was debonded from the concrete over a length of 51 mm (2 inches) at both ends of the cylinder (Figure 3.5). A metallic tape covered with grease was used to break the bond between the bar and concrete at two ends (Figure 3.6).

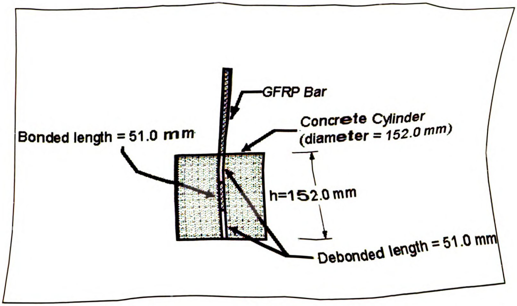


Figure 3.4. Diagram of Bond Test Sample

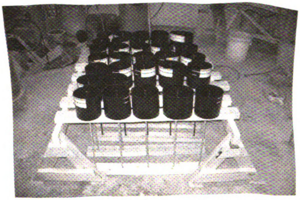


Figure 3.5. Setup of Bond Test Specimens Prior to Pouring of Concrete

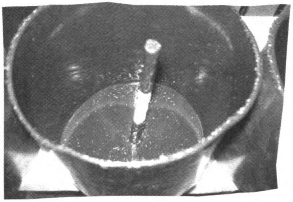


Figure 3.6. Detail of Development Length and Debonded Ends of Bar

Normal strength concrete with an average compressive strength of 11.9 MPa (3500 psi), a slump of 76 mm (3 inches) and 3% air content was used to cast the bond test specimens. An electric concrete vibrator with a rounded head was used to consolidate the concrete inside molds. Bond specimens were cured in 22 °C (72 °F) for 21 days, with only 76 mm (3 in.) of the exposed segment of the bars immersed in water. A steel tube filled with epoxy (similar to that used in tension tests) was attached to the free end of each bar for pullout testing. Two steel frames were placed around the concrete to provide the gripping mechanism to the bond samples during testing. Pullout tests were performed in a servovalve-controlled hydraulic test system (Figure 3.7) at a controlled displacement rate of 0.01 mm/sec (0.00039 in/sec).

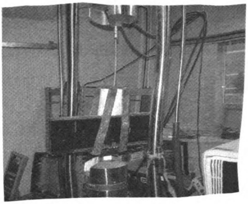


Figure 3.7. Bond Test Setup

Ultimate shear bond strength (T_b) was calculated as follows:

$$T_b = \frac{P_{\max}}{\pi \cdot D \cdot L}$$

where,

$P_{\max}$ = maximum load

D = bar diameter

L = embedment length

CHAPTER 4

EXPERIMENTAL RESULTS AND ANALYSES

4.1 TENSILE STRENGTH OF GFRP BARS

The raw tension test data generated in this investigation are presented in Appendix A. The mean tensile strength values presented in Table 4.1 indicate that accelerated aging through wet-dry or continuous immersion in warm alkaline solution generally causes a drop in tensile strength. The percentage losses of tensile strength after accelerated aging (Tables 4.2(a) and 4.2(b)) are, however, quite variable. While some GFRP bars experience losses as much as 42% in tensile strength, others largely retain their tensile strength after aging.

Table 4.1. Mean Tensile Strength Values (MPa) Prior to and After Aging.

(a) Uncoated GFRP Bars

Manufacturer	Unaged	14 days of aging		28 days of aging		42 days of aging	
	Control	Immersion	Wet-dry	Immersion	Wet-dry	Immersion	Wet-dry
I	747.9	510.8	542.0	473.4	474.4	442.4	450.1
II	653.1	578.1	588.9	524.1	516.8	462.4	486.3
III	585.0	372.4	449.2	381.6	350.0	...	...
IV	384.4	...	...	364.9	375.6	...	...

Table 4.1. (cont'd).

(b) Coated GFRP Bars

Manufacturer	Unaged	14 days of aging		28 days of aging		42 days of aging	
	Control	Immersion	Wet-dry	Immersion	Wet-dry	Immersion	Wet-dry
I	740.0	...	...	577.0	633.3	378.2	...
II	677.5	...	...	...	...	514.3	...
III	682.6	...	...	- -.	...	...	...
IV	...	...	...	311.2	...	...	...

Table 4.2. Mean Percentage Drop in Tensile Strength After Aging.

(a) Uncoated GFRP Bars

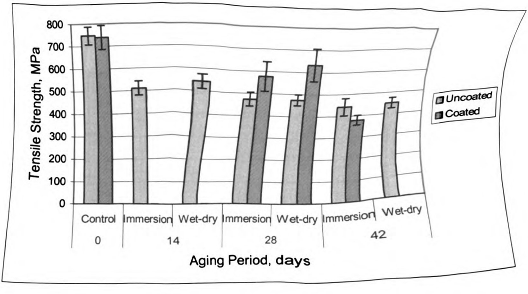
Manufacturer	14 days of aging		28 days of aging		42 days of aging	
	Immersion	Wet-dry	Immersion	Wet-dry	Immersion	Wet-dry
I	29.2	24.9	34.2	33.9	38.2	37.2
II	11.5	9.8	19.7	20.9	29.2	25.5
III	36.3	23.2	34.8	40.2	...	...
IV	...	...	5.1	2.3	...	...

Table 4.2. (cont'd).

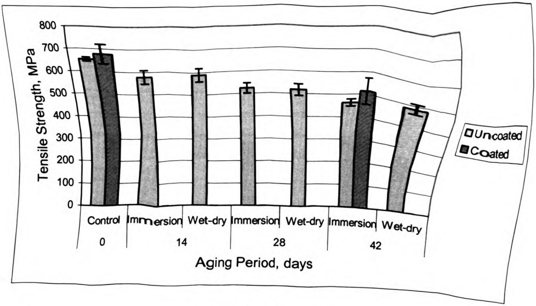
(b) Coated GFRP Bars

Manufacturer	14 days of aging		28 days of aging		42 days of aging	
	Immersion	Wet-dry	Immersion	Wet-dry	Immersion	Wet-dry
I	...	...	27.5	20.3	42.6	...
II	...	...	...	...	14.3	...
III	...	...	...	...	...	...
IV	...	...	19.0	12.3	...	...

GFRP bars from manufacturer I exhibited the highest levels of tensile strength before aging in both uncoated and coated conditions, but suffered major loss of tensile strength upon aging (Figures 4.1(a) and 4.2(a)). Coated and uncoated GFRP bars of manufacturer I lost about 40% of their tensile strength after 42 days of aging. In the case of GFRP bars from manufacturers II and III also major losses of tensile strength occurred after aging (Figures 4.1(b) and (c) and 4.2(b) and (c)). GFRP bars from manufacturers IV, however, largely retained their unaged tensile strength after aging (Figures 4.1(d) and 4.2(d)).

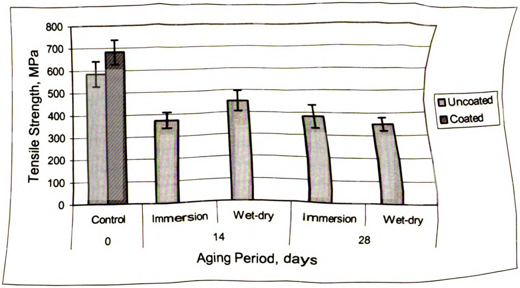


(a) Manufacturer I.

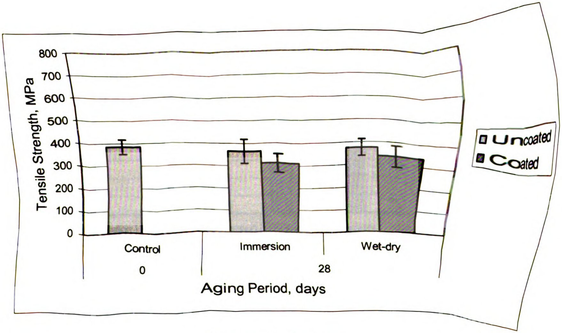


(b) Manufacturer II.

Figure 4.1. Mean Values and Standard Errors of GFRP Bar Tensile Strength Test Results.

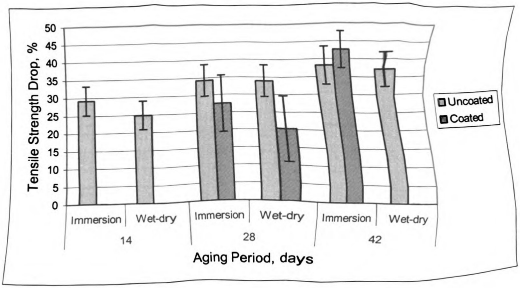


(c) Manufacturer III.

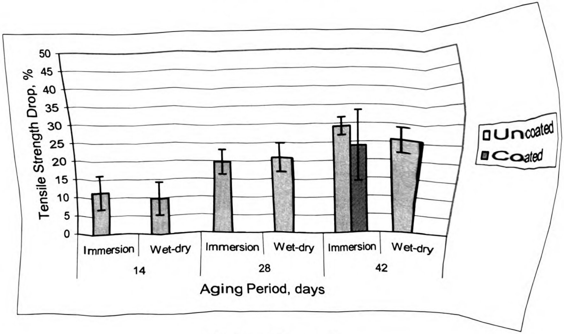


(d) Manufacturer IV.

Figure 4.1. (cont'd).

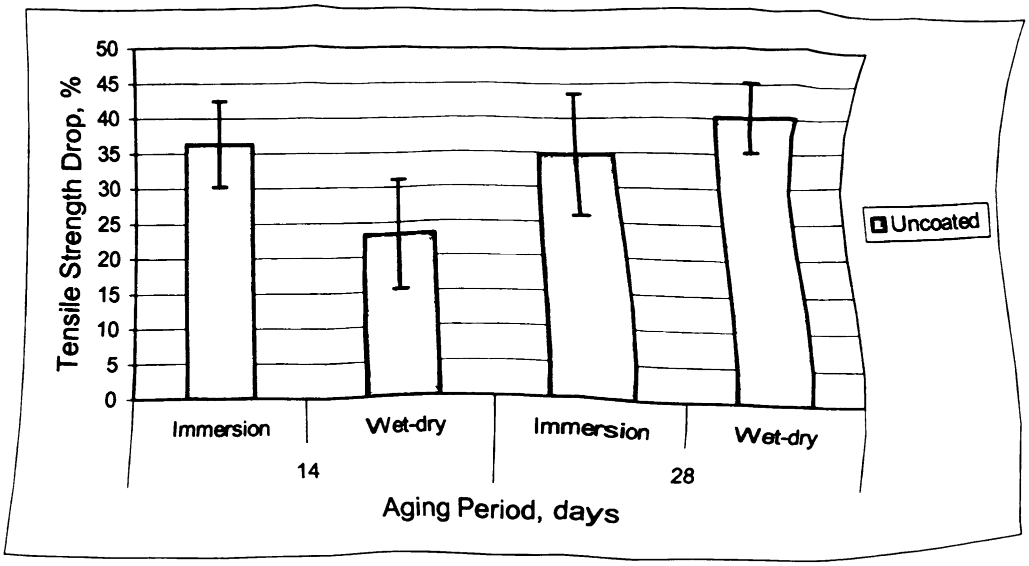


(a) Manufacturer I.

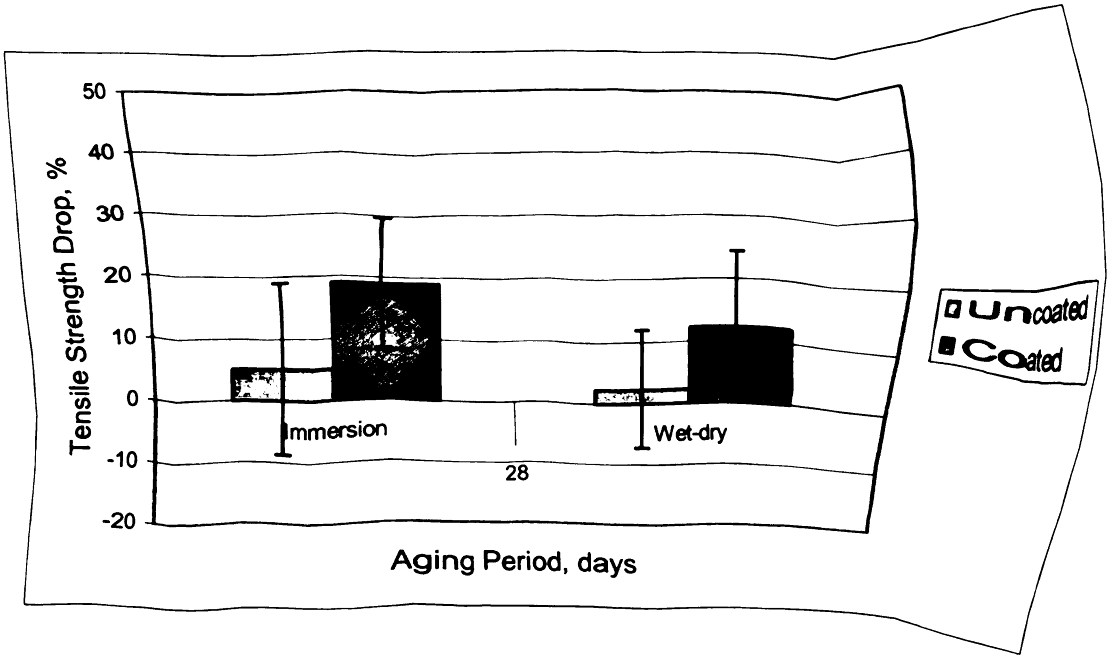


(b) Manufacturer II.

Figure 4.2. Percentage Drop in Tensile Strength (Mean Values and Standard Errors) of GFRP Bars After Aging.



(c) Manufacturer III.



(d) Manufacturer IV.

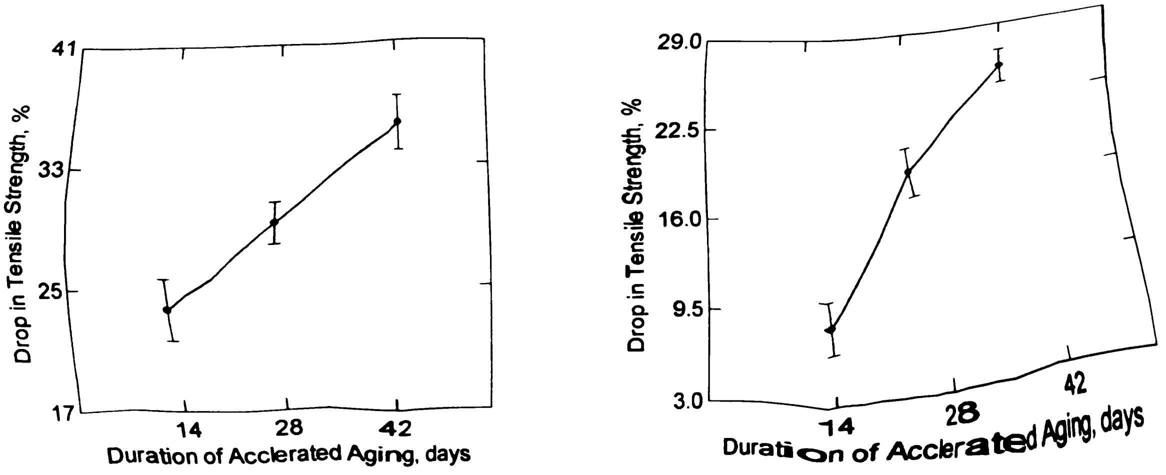
Figure 4.2. (cont'd).

4.2 STATISTICAL ANALYSIS OF TENSILE STRENGTH TEST RESULTS

The Analysis of Variance (ANOVA) technique was used for statistical analysis of results towards assessment of the effects of different variables on resistance of GFRP bars to alkali attack. The first step in analysis of variance of results involved assessment of the effects of aging duration and type (wet-dry vs. continuous immersion) and coating (coated vs. uncoated) on percent loss of tensile strength due to aging of GFRP bars from each manufacturer separately. The results are presented in Table 4.3 in the form of p-values representing the probability of error in the conclusion that there is a statistically significant effect of a particular variable (e.g., aging duration). P-values below 0.05 indicate that the variable has a statistically significant effect at 5% level of significance. The general trends in Table 4.3 indicate that aging duration and coating of GFRP bars have statistically significant effects on their alkali resistance because most of the corresponding p-values fall below 0.05; the effects of aging type (wet-dry vs. continuous immersion), however, are not significant. Pairwise comparison of the results at different aging durations indicated that, in general, aging beyond 28 days did not cause significant additional loss of tensile strength. Figures 4.3 through 4.5 present the trends (in the form of least square means) in effects of different factors on the drop in tensile strength of GFRP bars due to aging.

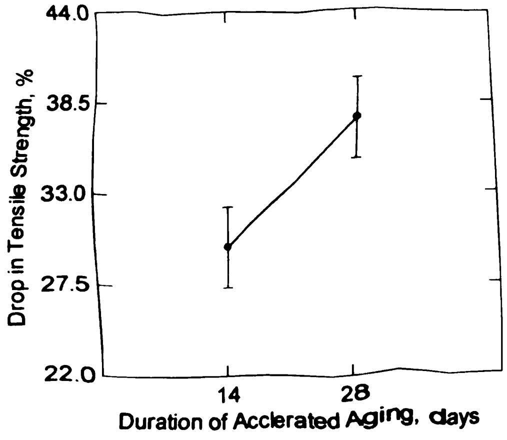
Table 4.3. P-values Associated with Different Factors.

Effect Analyzed	GFRP Bar Manufacturer			
	I	II	III	IV
Aging Duration	0.000	0.000	0.032	...
Type of Aging	0.051	0.288	0.270	0.315
Bar Coating	0.005	0.118	...	0.042



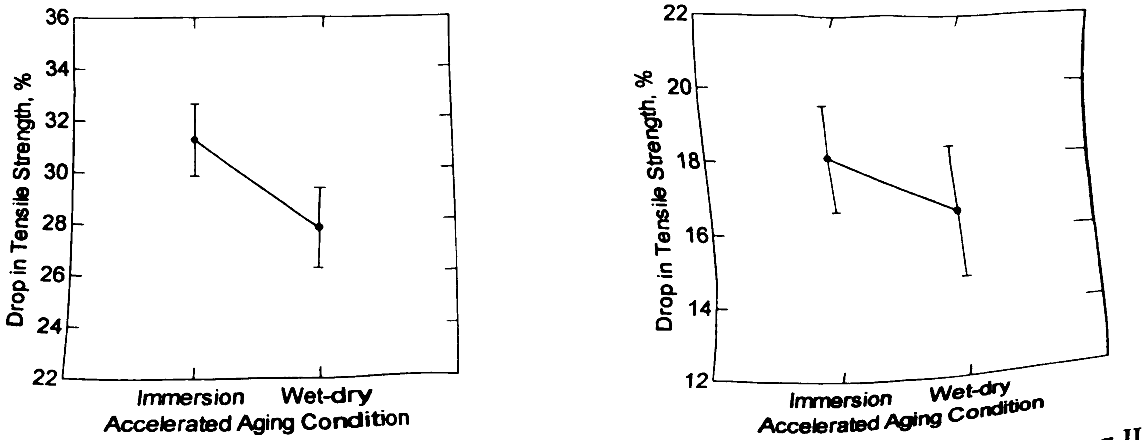
(a) GFRP bars from manufacturer I

(b) GFRP bars from manufacturer II



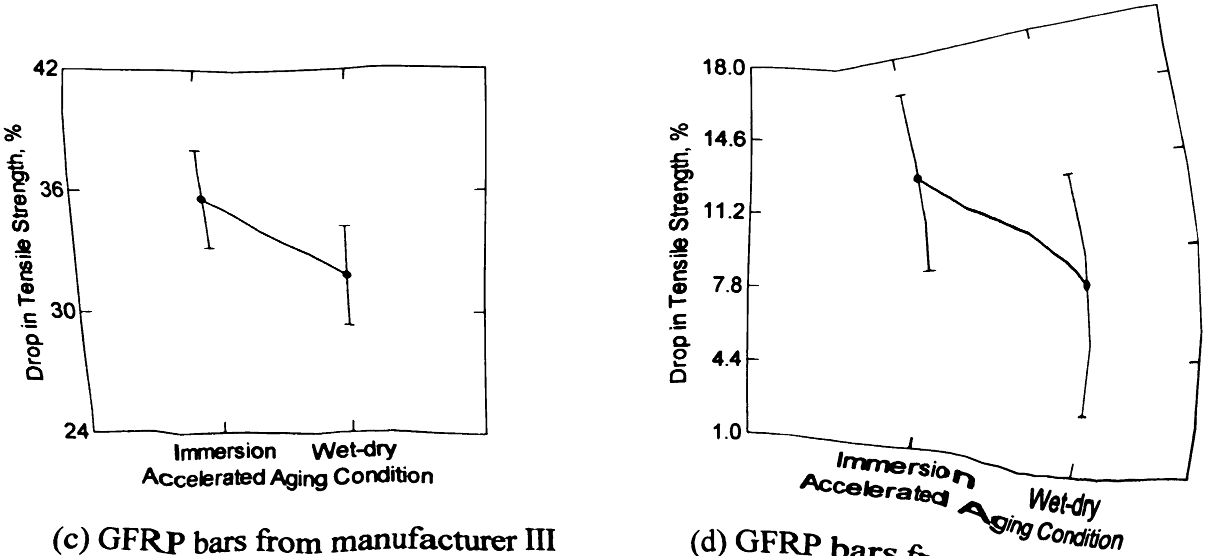
(c) GFRP bars from manufacturer III

Figure 4.3. Least Square Means and Standard Error of % Drop in Tensile Strength vs. Aging Duration.



(a) GFRP bars from manufacturer I

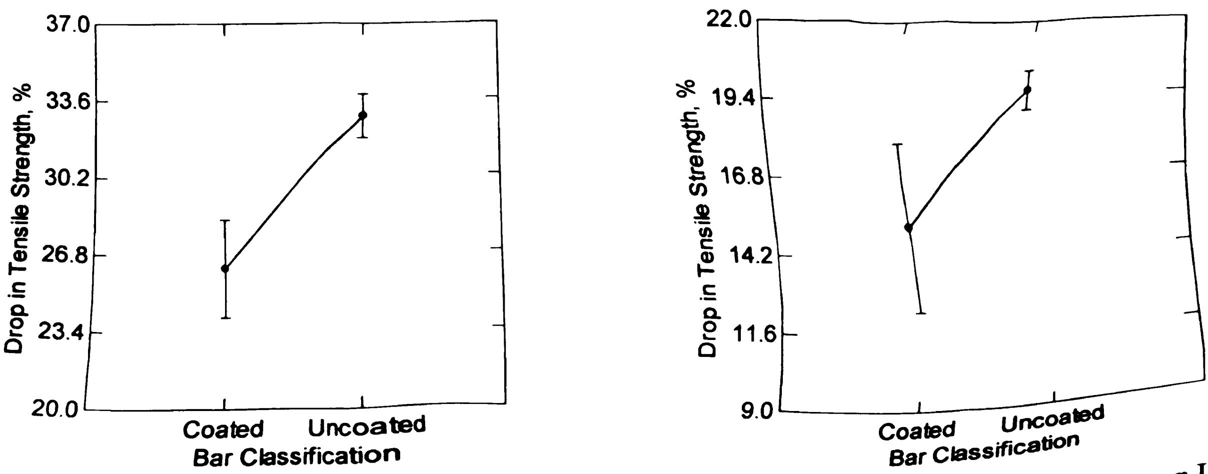
(b) GFRP bars from manufacturer II



(c) GFRP bars from manufacturer III

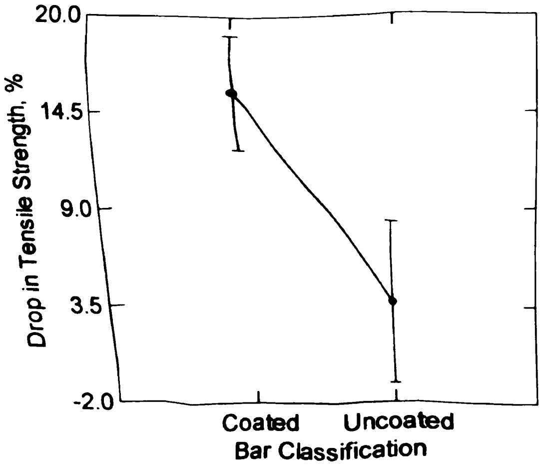
(d) GFRP bars from manufacturer IV

Figure 4.4. Least Square Means and Standard Error of % Drop in Tensile Strength vs. Aging Condition.



(a) *GFRP bars from manufacturer I*

(b) GFRP bars from manufacturer II



(c) GFRP bars from manufacturer IV

Figure 4.5. Least Square Means and Standard Error of % Drop in Tensile Strength vs. Bar Coating Condition.

Given the results presented above concerning the effects of different variables on percentage loss of GFRP tensile strength due to aging, the next step in statistical analysis involved: (1) combination of wet-dry and continuous immersion aging condition irrespective of the aging type; and (2) exclusion of 14 day aging results and combination of 28-day and 42-day aging results irrespective of the aging duration. The combined data on percentage loss in tensile strength of GFRP bars due to aging were then subjected to multiple-variable analysis of variance with fiber volume fraction, bar diameter, matrix type and coating (i.e., coated vs. uncoated) as the key factors. Analysis of variance of the combined data indicated that, at 5% level of significance, fiber volume fraction is the key factor influencing the percent drop in tensile strength of GFRP bars due to aging. The test data was insufficient to draw conclusions regarding the effects of matrix type (polyester vs. vinylester) and bar diameter, and the effect of coating was not statistically significant (at 5% level of significance) in this analysis of combined data. The p-values are presented in Table 4.4; Figures 4.6 through 4.7 show the trends (in the form of least square means) in the effects of different variables on percent loss in strength.

Table 4.4. P-values for Analysis of Combined Data.

Effect Analyzed	P-value
Fiber Volume Fraction	0.000
Bar Diameter	Insufficient data
Coating	0.117
Matrix Type	Insufficient data

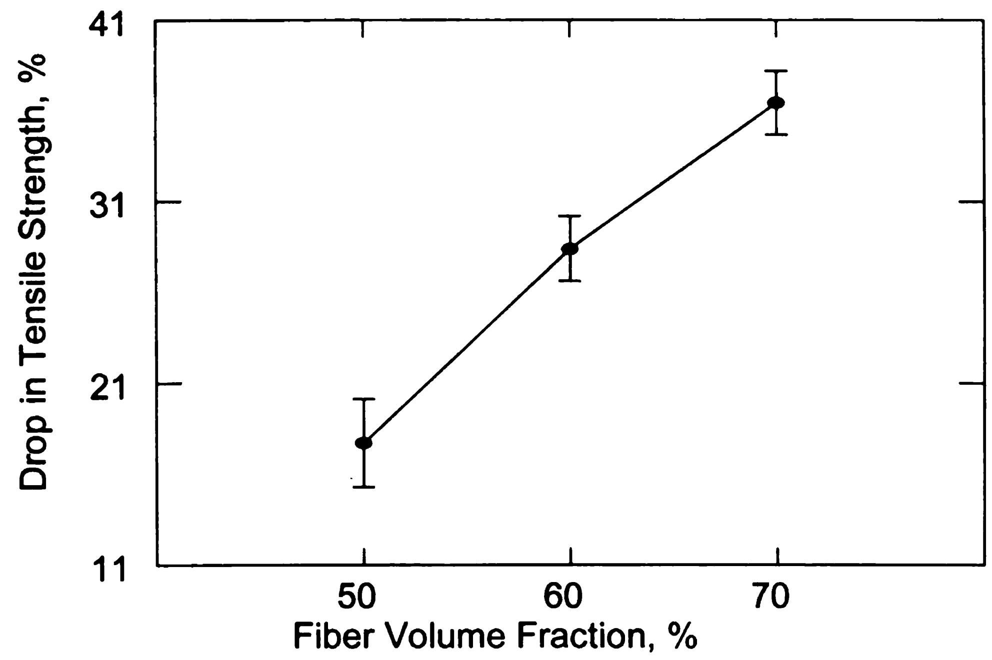


Figure 4.6. Least Square Means of % Drop in Tensile Strength vs. Fiber Volume Fraction for all GFRP Bars Tested After Aging.

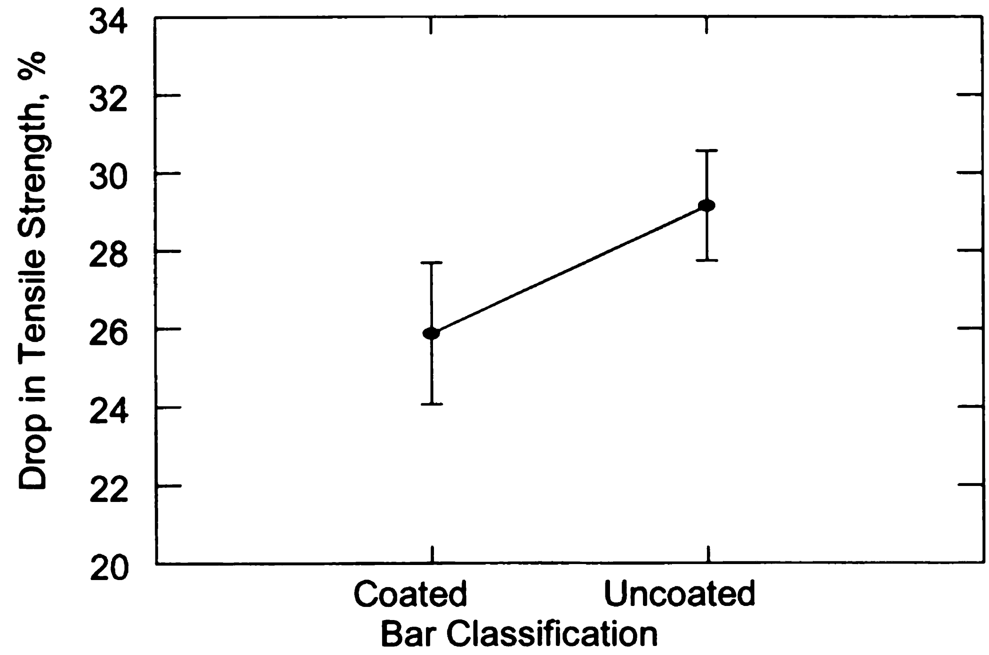
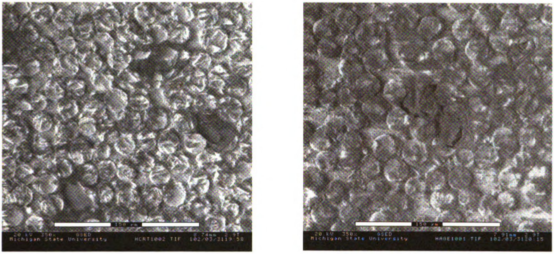


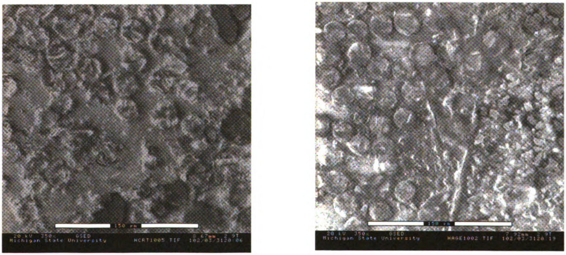
Figure 4.7. Least Square Means of % Drop in Tensile Strength vs. Bar Coating Condition for all GFRP Bars Tested After Aging.

4.3 MICROSCOPIC ANALYSIS OF GFRP BARS

Scanning Electron Microscope (SEM) images were obtained from cross sections of aged and unaged GFRP bar samples to identify damage of fibers. Images demonstrate particular severe fiber degradation near the surface for all bars after exposure to alkaline environment (Figures 4.8-11, (c) and (d)). Damage to fibers near the surface of the bar is more noticeable on bars with polyester matrices (Manufacturers III and IV) than in bars with vinylester matrices (Manufacturers I and II). Images taken from fibers near the center of the bar reveal more extensive damage in aged bars with higher fiber volume fractions (Manufacturers I, II, and III, Figures 4.8-4.10 (a) and (b)), while fibers from Manufacturer IV (fiber volume fraction = 50%) appear to be unaffected by exposure to alkaline solution (Figure (4.11 (a) and (b)).

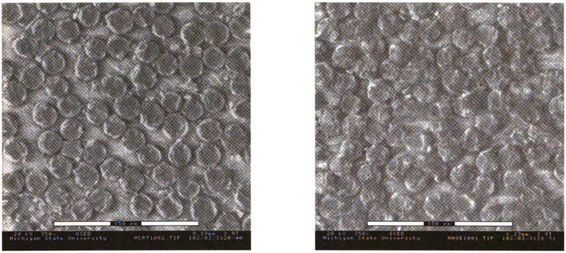


(a) Near Center of Bar, Unaged Condition (b) Near Center of Bar, Aged Condition

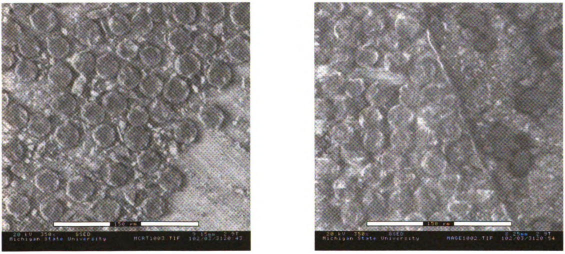


(c) Near Surface of Bar, Unaged Condition (d) Near Surface of Bar, Aged Condition

Figure 4.8. Scanning Electron Microscope (SEM) Images of Glass Fibers in Bars from Manufacturer I (Vinylester Resin, $V_f = 70\%$) at 350X Magnification.

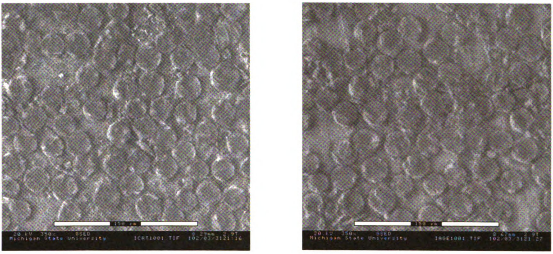


(a) Near Center of Bar, Unaged Condition (b) Near Center of Bar, Aged Condition



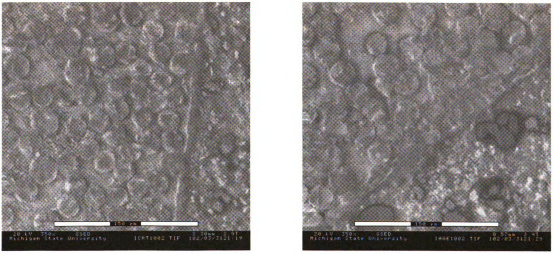
(c) Near Surface of Bar, Unaged Condition (d) Near Surface of Bar, Aged Condition

Figure 4.9. Scanning Electron Microscope (SEM) Images of Glass Fibers in Bars from Manufacturer II (Vinylester Resin, $V_f = 60\%$) at 350X Magnification.



(a) Near Center of Bar, Unaged Condition

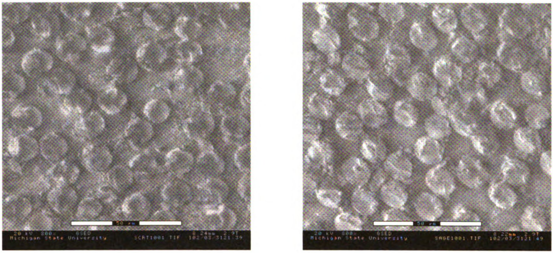
(b) Near Center of Bar, Aged Condition



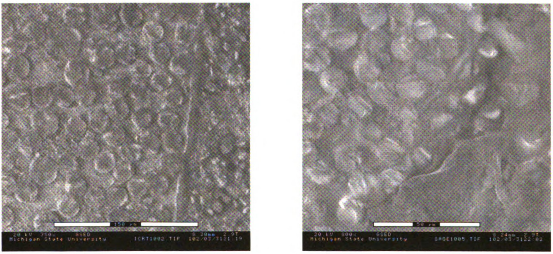
(c) Near Surface of Bar, Unaged Condition

(d) Near Surface of Bar, Aged Condition

Figure 4.10. Scanning Electron Microscope (SEM) Images of Glass Fibers in Bars from Manufacturer III (Polyester Resin, $V_f = 60\%$) at 350X Magnification.



(a) Near Center of Bar, Unaged Condition (b) Near Center of Bar, Aged Condition



(c) Near Surface of Bar, Unaged Condition (d) Near Surface of Bar, Aged Condition

Figure 4.11. Scanning Electron Microscope (SEM) Images of Glass Fibers in Bars from Manufacturer IV (Polyester Resin, $V_f = 50\%$) at 800X Magnification.

4.4 BOND STRENGTH OF GFRP BARS

The raw bond strength test data generated in this investigation are presented in Appendix B. The mean bond strength values (Figure 4.12) indicate that bond strengths of deformed bars from both manufacturers (I and II) immersed for 6 weeks in 70 °C water (aged) were comparable to those of unaged bars (immersed in 20 °C water). Coating also did not strongly impact bond strength. The effects of aging and coating, however, become apparent if one looks at the mechanism of bond failure.

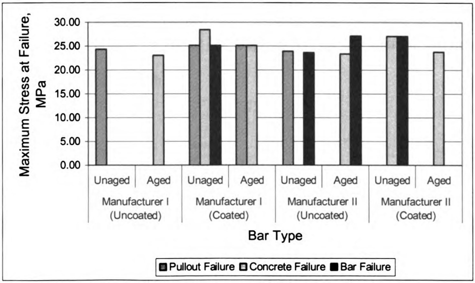
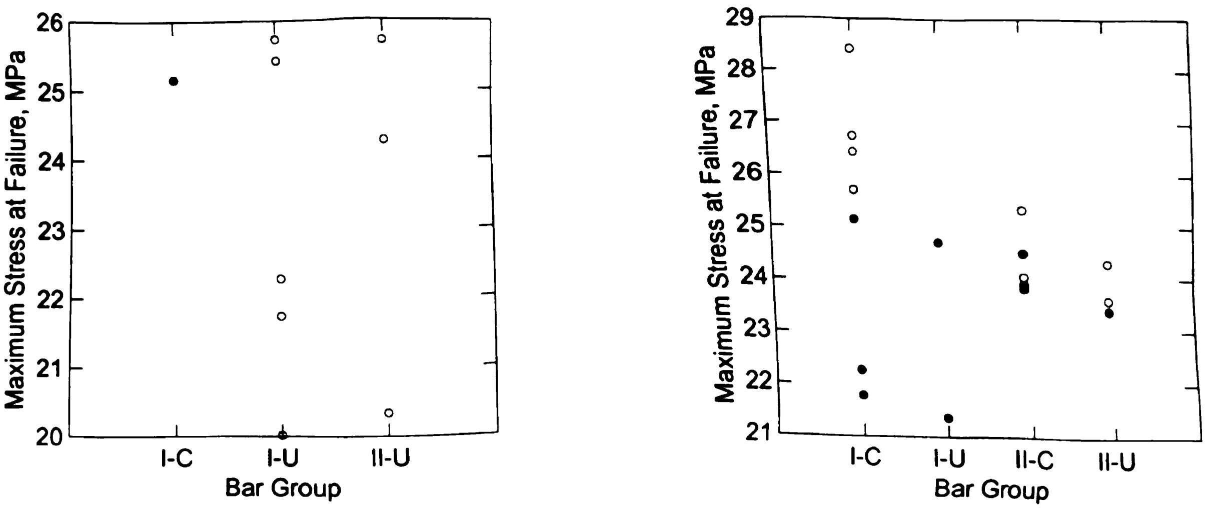


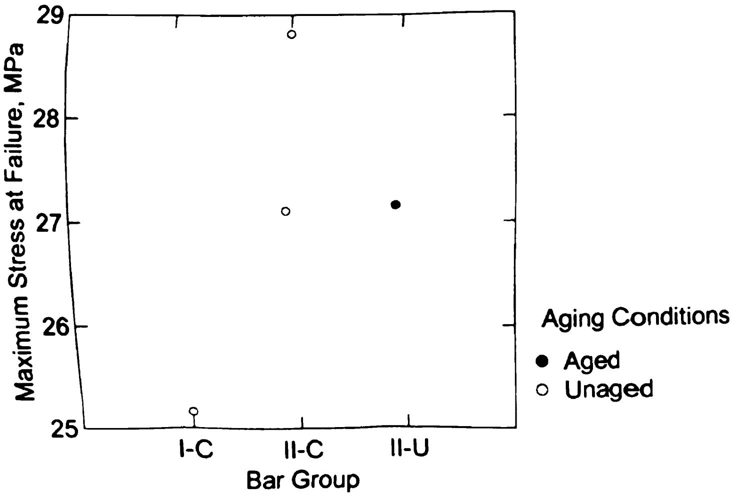
Figure 4.12. Bond Strength Test Results for Uncoated and Coated GFRP Bars in Unaged and Aged Condition.

Pullout of GFRP bars from concrete was the predominant failure mechanism for unaged specimens. Splitting of concrete occurred in most aged specimens in both uncoated and coated conditions (Figure 4.13). Unaged and aged concrete specimens developed similar compressive strengths of 26.7 and 25.6 MPa (3,876 psi and 3,709 psi), respectively. This suggests that aging changed the bond failure mode because it produced some interaction between GFRP rebars and concrete. Our hypothesis is that, due to the thermal expansion mismatch of GFRP bars (in radial direction) and concrete, tensile stresses develop in concrete at the elevated temperature of aging (70 °C [158 °F]). These tensile stresses essentially produce microcracks in concrete, which lower the tensile strength of concrete and thus promote the split-cracking mode of bond failure (in concrete) in lieu of bar pullout. The observations reported in the literature support this hypothesis.[43-45] The details of pullout specimen would determine if concrete microcracking could lower pullout strength of GFRP bars. One should not neglect the potential for adverse effects of GFRP bar degradation on the alkaline environment of concrete on their pullout strength.



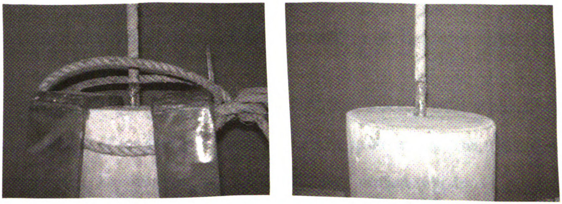
(a) Pullout Failure

(b) Concrete Failure

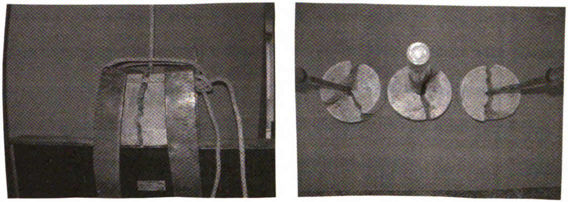


(c) Bar Failure

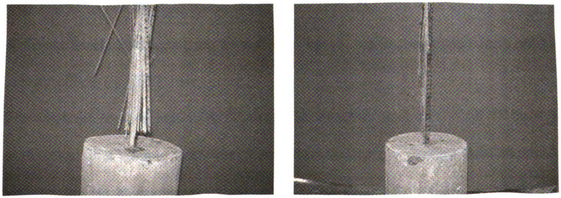
Figure 4.13. Bond Strength Values for Different Failure Mechanisms. (C = Coated; U = Uncoated).



(a) Pullout Failure



(b) Concrete Failure



(c) Bar Failure

Figure 4.14. Bond Strength Failure Mechanisms.

CHAPTER 5

CONCLUSIONS

GFRP bars were subjected to accelerated alkali attack in order to simulate the long-term effects of concrete pore solution on GFRP reinforcement. The effect of fiber volume fraction, bar diameter, epoxy coating, aging method (wet-dry vs. continuous immersion), aging period, and matrix composition were investigated. Tensile strength tests were performed in order to assess the percent loss in tensile strength associated with alkali attack. The effect of accelerated aging on bond strength of GFRP bars to concrete was also investigated. Uncoated and coated bars embedded in concrete were placed in a heated water tank for six weeks. Bond tests were conducted to determine the effects of concrete alkaline environment on bond strength of coated and uncoated GFRP bars. The following conclusions were drawn from the experimental results:

1. Alkali attack caused significant loss of tensile strength in glass fiber composite bars. The loss in tensile strength under alkali attack increased with time up to a certain age; different accelerated aging processes (wet-dry vs. continuous immersion) produced similar effects on GFRP bars.
2. Fiber volume fraction had a significant effect on alkali resistance of GFRP bars; bars with lower fiber volume fractions ($V_f = 50\%$) suffered less damage from exposure to highly alkaline environments than bars with higher fiber volume fractions ($V_f \geq 60\%$). This is due to the higher amount of matrix material surrounding fibers, providing additional protection against the alkaline environment. Even though lower fiber volume fractions in GFRP bars entail lower initial tensile strengths, their higher

alkali resistance allows for the preservation of tensile strength over time, thus yielding economic benefits. Further investigations for verification of this conclusion are needed.

3. Although analysis of the effect of bar diameter on alkali resistance was inconclusive, it is believed that GFRP bars with larger diameters could provide better protection against alkali attack. Increased radial distance of a greater fraction of fibers from the surface of larger bars should make it more difficult for detrimental ions from concrete pore solution to attack the bulk of fibers in larger diameter bars.
4. Epoxy coating of GFRP bars generally improved their alkali resistance. The trends were, however, inconsistent; more investigations are needed to further clarify the coating effects on alkali resistance of GFRP bars.
5. The results concerning matrix type effects on alkali resistance of GFRP bars were inconclusive. The effects of fiber volume fraction could have potentially overshadowed any adverse effects of lower-cost matrix systems. This requires further investigation.
6. For the specific geometry of bond test specimens considered in this investigation, accelerated aging did not significantly alter the peak bond strength, but altered the failure mechanism of the bond samples. The predominance of concrete splitting failure after aging pointed at damage to concrete caused by aging effects, which could be explained by the thermal expansion mismatch of GFRP bars and concrete.

APPENDICES

APPENDIX A

RAW TENSION TEST DATA

Table A.1. Tensile Strength Results of GFRP Bars from Manufacturer I.

(a) Uncoated GFRP Bars

Sample I.D.	Duration of Aging (days)	Aging Method	Bar Diameter (inches)	Tensile Strength (MPa)
ACTR-01	0	Control	0.25	729.46
ACTR-02	0	Control	0.25	809.08
ACTR-03	0	Control	0.25	725.06
ACTR-04	0	Control	0.25	817.64
ACTR-05	0	Control	0.25	813.49
ACTR-06	0	Control	0.25	823.35
ACTR-07	0	Control	0.25	819.98
ACTR-08	0	Control	0.25	820.49
ACTR-09	0	Control	0.25	718.05
ACTR-10	0	Control	0.25	724.54
ACS14-01	14	Immersion	0.25	645.96
ACS14-02	14	Immersion	0.25	608.61
ACS14-03	14	Immersion	0.25	588.12
ACS14-04	14	Immersion	0.25	507.21
ACS14-05	14	Immersion	0.25	456.64
ACS14-06	14	Immersion	0.25	597.98
ACS14-07	14	Immersion	0.25	409.95
ACS14-08	14	Immersion	0.25	589.68
ACS14-09	14	Immersion	0.25	394.39
ACS14-10	14	Immersion	0.25	492.17
AWD14-01	14	Wet-dry	0.25	507.21
AWD14-02	14	Wet-dry	0.25	468.05
AWD14-03	14	Wet-dry	0.25	541.96
AWD14-04	14	Wet-dry	0.25	472.46
AWD14-05	14	Wet-dry	0.25	629.36
AWD14-06	14	Wet-dry	0.25	635.84
AWD14-07	14	Wet-dry	0.25	616.13
AWD14-08	14	Wet-dry	0.25	440.56
AWD14-09	14	Wet-dry	0.25	676.56
AWD14-10	14	Wet-dry	0.25	675.00

Table A.1(a) (cont'd).

Sample I.D.	Duration of Aging (days)	Aging Method	Bar Diameter (inches)	Tensile Strength (MPa)
ACS28-01	28	Immersion	0.25	378.83
ACS28-02	28	Immersion	0.25	357.31
ACS28-03	28	Immersion	0.25	553.37
ACS28-04	28	Immersion	0.25	374.42
ACS28-05	28	Immersion	0.25	576.45
ACS28-06	28	Immersion	0.25	452.49
ACS28-07	28	Immersion	0.25	575.16
ACS28-08	28	Immersion	0.25	521.21
ACS28-09	28	Immersion	0.25	583.20
ACS28-10	28	Immersion	0.25	424.48
AWD28-01	28	Wet-dry	0.25	516.54
AWD28-02	28	Wet-dry	0.25	412.55
AWD28-03	28	Wet-dry	0.25	381.95
AWD28-04	28	Wet-dry	0.25	436.41
AWD28-05	28	Wet-dry	0.25	522.51
AWD28-06	28	Wet-dry	0.25	564.52
AWD28-07	28	Wet-dry	0.25	370.02
AWD28-08	28	Wet-dry	0.25	515.25
AWD28-09	28	Wet-dry	0.25	426.03
AWD28-10	28	Wet-dry	0.25	471.68
ACS42-01	42	Immersion	0.25	511.88
ACS42-02	42	Immersion	0.25	353.68
ACS42-03	42	Immersion	0.25	276.65
ACS42-04	42	Immersion	0.25	592.01
ACS42-05	42	Immersion	0.25	538.07
ACS42-06	42	Immersion	0.25	596.94
ACS42-07	42	Immersion	0.25	317.63
ACS42-08	42	Immersion	0.25	507.99
ACS42-09	42	Immersion	0.25	320.74
ACS42-10	42	Immersion	0.25	568.41
AWD42-01	42	Wet-dry	0.25	480.50
AWD42-02	42	Wet-dry	0.25	481.01
AWD42-03	42	Wet-dry	0.25	534.96
AWD42-04	42	Wet-dry	0.25	343.56
AWD42-05	42	Wet-dry	0.25	390.76
AWD42-06	42	Wet-dry	0.25	449.63
AWD42-07	42	Wet-dry	0.25	412.29
AWD42-08	42	Wet-dry	0.25	447.04
AWD42-09	42	Wet-dry	0.25	349.53
AWD42-10	42	Wet-dry	0.25	372.61

Table A.1(a) (cont'd).

Sample I.D.	Duration of Aging (days)	Aging Method	Bar Diameter (inches)	Tensile Strength (MPa)
KCTR-01	0	Control	0.375	705.19
KCTR-02	0	Control	0.375	638.86
KCTR-03	0	Control	0.375	688.12
KCTR-04	0	Control	0.375	636.71
KCS14-01	14	Immersion	0.375	479.22
KCS14-02	14	Immersion	0.375	465.21
KCS14-03	14	Immersion	0.375	490.05
KCS14-04	14	Immersion	0.375	503.95
KCS14-05	14	Immersion	0.375	503.23
KCS14-06	14	Immersion	0.375	540.03
KCS14-07	14	Immersion	0.375	492.50
KCS14-08	14	Immersion	0.375	465.93
KCS14-09	14	Immersion	0.375	504.97
KCS14-10	14	Immersion	0.375	479.73
KWD14-01	14	Wet-dry	0.375	520.71
KWD14-02	14	Wet-dry	0.375	488.21
KWD14-03	14	Wet-dry	0.375	520.81
KWD14-04	14	Wet-dry	0.375	520.30
KWD14-05	14	Wet-dry	0.375	547.59
KWD14-06	14	Wet-dry	0.375	521.12
KWD14-07	14	Wet-dry	0.375	514.88
KWD14-08	14	Wet-dry	0.375	516.83
KWD14-09	14	Wet-dry	0.375	526.33
KWD14-10	14	Wet-dry	0.375	500.37
KCS28-01	28	Immersion	0.375	468.89
KCS28-02	28	Immersion	0.375	499.45
KCS28-03	28	Immersion	0.375	424.13
KCS28-04	28	Immersion	0.375	439.05
KCS28-05	28	Immersion	0.375	471.35
KCS28-06	28	Immersion	0.375	437.41
KCS28-07	28	Immersion	0.375	484.22
KCS28-08	28	Immersion	0.375	477.58
KCS28-09	28	Immersion	0.375	493.83
KCS28-10	28	Immersion	0.375	475.74
KWD28-01	28	Wet-dry	0.375	462.45
KWD28-02	28	Wet-dry	0.375	545.55
KWD28-03	28	Wet-dry	0.375	498.33
KWD28-04	28	Wet-dry	0.375	428.01
KWD28-05	28	Wet-dry	0.375	453.77
KWD28-06	28	Wet-dry	0.375	511.41
KWD28-07	28	Wet-dry	0.375	488.52
KWD28-08	28	Wet-dry	0.375	504.56
KWD28-09	28	Wet-dry	0.375	477.27

Table A.1(a) (cont'd).

Sample I.D.	Duration of Aging (days)	Aging Method	Bar Diameter (inches)	Tensile Strength (MPa)
KWD28-10	28	Wet-dry	0.375	500.17
KCS42-01	42	Immersion	0.375	428.93
KCS42-02	42	Immersion	0.375	442.42
KCS42-03	42	Immersion	0.375	423.41
KCS42-04	42	Immersion	0.375	451.72
KCS42-05	42	Immersion	0.375	433.94
KCS42-06	42	Immersion	0.375	471.14
KCS42-07	42	Immersion	0.375	454.79
KCS42-08	42	Immersion	0.375	430.46
KCS42-09	42	Immersion	0.375	431.28
KCS42-10	42	Immersion	0.375	483.41
KCS42-11	42	Immersion	0.375	319.67
KCS42-12	42	Immersion	0.375	376.91
KWD42-01	42	Wet-dry	0.375	495.16
KWD42-02	42	Wet-dry	0.375	458.88
KWD42-03	42	Wet-dry	0.375	457.34
KWD42-04	42	Wet-dry	0.375	464.50
KWD42-05	42	Wet-dry	0.375	433.22
KWD42-06	42	Wet-dry	0.375	485.76
KWD42-07	42	Wet-dry	0.375	488.92
KWD42-08	42	Wet-dry	0.375	458.47
KWD42-09	42	Wet-dry	0.375	483.61
KWD42-10	42	Wet-dry	0.375	515.19

(b) Coated GFRP Bars

Sample I.D.	Duration of Aging (days)	Aging Method	Bar Diameter (inches)	Tensile Strength (MPa)
GCTR-01	0	Control	0.25	797.67
GCTR-02	0	Control	0.25	804.93
GCS28-01	28	Immersion	0.25	539.89
GCS28-02	28	Immersion	0.25	718.83
GCS28-03	28	Immersion	0.25	456.12
GCS28-04	28	Immersion	0.25	764.22
GCS28-05	28	Immersion	0.25	711.05
GCS28-06	28	Immersion	0.25	539.63
GWD28-01	28	Wet-dry	0.25	787.04
GWD28-02	28	Wet-dry	0.25	619.24
GWD28-03	28	Wet-dry	0.25	539.11
GWD28-04	28	Wet-dry	0.25	658.66
GWD28-05	28	Wet-dry	0.25	398.54
GWD28-06	28	Wet-dry	0.25	684.86

Table A.1(b) (cont'd).

Sample I.D.	Duration of Aging (days)	Aging Method	Bar Diameter (inches)	Tensile Strength (MPa)
HCTR-01	0	Control	0.25	786.26
HCTR-02	0	Control	0.25	804.93
HCTR-03	0	Control	0.25	834.24
HCTR-04	0	Control	0.25	729.21
HCS28-01	28	Immersion	0.25	466.23
HCS28-02	28	Immersion	0.25	606.02
HCS28-03	28	Immersion	0.25	587.09
HCS28-04	28	Immersion	0.25	549.74
HCS28-05	28	Immersion	0.25	507.99
HCS28-06	28	Immersion	0.25	476.61
HWD28-01	28	Wet-dry	0.25	629.88
HWD28-02	28	Wet-dry	0.25	702.23
HWD28-03	28	Wet-dry	0.25	769.40
HWD28-04	28	Wet-dry	0.25	736.47
HWD28-05	28	Wet-dry	0.25	498.65
HWD28-06	28	Wet-dry	0.25	575.67
UCTR-01	0	Control	0.375	682.91
UCTR-02	0	Control	0.375	679.74
UCS42-01	42	Immersion	0.375	343.08
UCS42-02	42	Immersion	0.375	381.81
UCS42-03	42	Immersion	0.375	364.13
VCTR-01	0	Control	0.375	629.25
VCTR-02	0	Control	0.375	650.61
VCS42-01	42	Immersion	0.375	400.82
VCS42-02	42	Immersion	0.375	389.99
VCS42-03	42	Immersion	0.375	389.48

Table A.2. Tensile Strength Results of GFRP Bars from Manufacturer II.

(a) Uncoated GFRP Bars

Sample I.D.	Duration of Aging (days)	Aging Method	Bar Diameter (inches)	Tensile Strength (MPa)
BCTR-01	0	Control	0.375	661.00
BCTR-02	0	Control	0.375	655.42
BCTR-03	0	Control	0.375	642.55
BCTR-04	0	Control	0.375	629.44
BCTR-05	0	Control	0.375	648.02
BCTR-06	0	Control	0.375	677.88
BCTR-07	0	Control	0.375	649.71
BCTR-08	0	Control	0.375	649.84

Table A.2(a) (cont'd).

Sample I.D.	Duration of Aging (days)	Aging Method	Bar Diameter (inches)	*Tensile Strength (MPa)*
BCTR-09	0	Control	0.375	659.18
BCTR-10	0	Control	0.375	658.09
BCS14-01	14	Immersion	0.375	518.50
BCS14-02	14	Immersion	0.375	568.27
BCS14-03	14	Immersion	0.375	610.02
BCS14-04	14	Immersion	0.375	605.90
BCS14-05	14	Immersion	0.375	605.78
BCS14-06	14	Immersion	0.375	602.86
BCS14-07	14	Immersion	0.375	602.13
BCS14-08	14	Immersion	0.375	601.16
BCS14-09	14	Immersion	0.375	489.01
BCS14-10	14	Immersion	0.375	577.25
BCS28-01	28	Immersion	0.375	518.99
BWD14-01	14	Wet-dry	0.375	609.05
BWD14-02	14	Wet-dry	0.375	621.92
BWD14-03	14	Wet-dry	0.375	589.63
BWD14-04	14	Wet-dry	0.375	526.39
BWD14-05	14	Wet-dry	0.375	596.91
BWD14-06	14	Wet-dry	0.375	506.97
BWD14-07	14	Wet-dry	0.375	609.78
BWD14-08	14	Wet-dry	0.375	627.02
BWD14-09	14	Wet-dry	0.375	619.13
BWD14-10	14	Wet-dry	0.375	581.74
BCS28-02	28	Immersion	0.375	549.33
BCS28-03	28	Immersion	0.375	533.43
BCS28-04	28	Immersion	0.375	517.65
BCS28-05	28	Immersion	0.375	513.28
BCS28-06	28	Immersion	0.375	536.59
BCS28-07	28	Immersion	0.375	505.15
BCS28-08	28	Immersion	0.375	556.50
BCS28-09	28	Immersion	0.375	453.32
BCS28-10	28	Immersion	0.375	557.10
BWD28-01	28	Wet-dry	0.375	491.31
BWD28-02	28	Wet-dry	0.375	485.25
BWD28-03	28	Wet-dry	0.375	478.08
BWD28-04	28	Wet-dry	0.375	560.14
BWD28-05	28	Wet-dry	0.375	565.11
BWD28-06	28	Wet-dry	0.375	497.14
BWD28-07	28	Wet-dry	0.375	544.96
BWD28-08	28	Wet-dry	0.375	474.08
BWD28-09	28	Wet-dry	0.375	522.63
BWD28-10	28	Wet-dry	0.375	548.97

Table A.2(a) (cont'd).

Sample I.D.	Duration of Aging (days)	Aging Method	Bar Diameter (inches)	Tensile Strength (MPa)
BCS42-01	42	Immersion	0.375	479.90
BCS42-02	42	Immersion	0.375	482.21
BCS42-03	42	Immersion	0.375	491.19
BCS42-04	42	Immersion	0.375	471.04
BCS42-05	42	Immersion	0.375	471.53
BCS42-06	42	Immersion	0.375	474.81
BCS42-07	42	Immersion	0.375	445.68
BCS42-08	42	Immersion	0.375	472.50
BCS42-09	42	Immersion	0.375	454.90
BCS42-10	42	Immersion	0.375	489.25
BCS42-11	42	Immersion	0.375	411.69
BCS42-12	42	Immersion	0.375	452.11
BCS42-13	42	Immersion	0.375	414.48
BWD42-01	42	Wet-dry	0.375	472.62
BWD42-02	42	Wet-dry	0.375	495.68
BWD42-03	42	Wet-dry	0.375	528.94
BWD42-04	42	Wet-dry	0.375	473.23
BWD42-05	42	Wet-dry	0.375	485.49
BWD42-06	42	Wet-dry	0.375	485.73
BWD42-07	42	Wet-dry	0.375	499.69
BWD42-08	42	Wet-dry	0.375	516.68
BWD42-09	42	Wet-dry	0.375	411.45
BWD42-10	42	Wet-dry	0.375	493.01

(b) Coated GFRP Bars

Sample I.D.	Duration of Aging (days)	Aging Method	Bar Diameter (inches)	Tensile Strength (MPa)
SCTR-01	0	Control	0.375	664.64
SCS42-01	42	Immersion	0.375	575.07
SCS42-02	42	Immersion	0.375	521.17
TCTR-01	0	Control	0.375	697.17
TCTR-02	0	Control	0.375	670.71
TCS42-01	42	Immersion	0.375	461.70
TCS42-02	42	Immersion	0.375	475.66
TCS42-03	42	Immersion	0.375	537.92

Table A.3. Tensile Strength Results of GFRP Bars from Manufacturer III.

(a) Uncoated GFRP Bars

Sample I.D.	Duration of Aging (days)	Aging Method	Bar Diameter (inches)	Tensile Strength (MPa)
CCTR-01	0	Control	0.315	622.95
CCTR-02	0	Control	0.315	528.66
CCTR-03	0	Control	0.315	621.92
CCTR-04	0	Control	0.315	422.37
CCTR-05	0	Control	0.315	585.92
CCTR-06	0	Control	0.315	474.66
CCTR-07	0	Control	0.315	444.65
CCTR-08	0	Control	0.315	517.17
CCTR-09	0	Control	0.315	594.49
CCTR-10	0	Control	0.315	445.68
CCTR-11	0	Control	0.315	668.89
CCTR-12	0	Control	0.315	773.29
CCTR-13	0	Control	0.315	655.52
CCTR-14	0	Control	0.315	727.86
CCTR-15	0	Control	0.315	584.72
CCTR-16	0	Control	0.315	691.18
CCS14-01	14	Immersion	0.315	432.65
CCS14-02	14	Immersion	0.315	281.28
CCS14-03	14	Immersion	0.315	367.85
CCS14-04	14	Immersion	0.315	349.85
CCS14-05	14	Immersion	0.315	362.54
CCS14-06	14	Immersion	0.315	346.59
CCS14-07	14	Immersion	0.315	456.14
CCS14-08	14	Immersion	0.315	386.88
CCS14-09	14	Immersion	0.315	400.94
CCS14-10	14	Immersion	0.315	339.74
CWD14-01	14	Wet-dry	0.315	447.23
CWD14-02	14	Wet-dry	0.315	347.45
CWD14-03	14	Wet-dry	0.315	505.34
CWD14-04	14	Wet-dry	0.315	484.94
CWD14-05	14	Wet-dry	0.315	370.08
CWD14-06	14	Wet-dry	0.315	538.43
CWD14-07	14	Wet-dry	0.315	397.17
CWD14-08	14	Wet-dry	0.315	507.23
CWD14-09	14	Wet-dry	0.315	481.68
CWD14-10	14	Wet-dry	0.315	412.43
CCS28-01	28	Immersion	0.315	469.34
CCS28-02	28	Immersion	0.315	398.71
CCS28-03	28	Immersion	0.315	448.94
CCS28-04	28	Immersion	0.315	458.20
CCS28-05	28	Immersion	0.315	294.31

Table A.3(a) (cont'd).

Sample I.D.	Duration of Aging (days)	Aging Method	Bar Diameter (inches)	*Tensile Strength (MPa)*
CCS28-06	28	Immersion	0.315	311.79
CCS28-07	28	Immersion	0.315	453.40
CCS28-08	28	Immersion	0.315	332.19
CCS28-09	28	Immersion	0.315	299.96
CCS28-10	28	Immersion	0.315	349.17
CWD28-01	28	Wet-dry	0.315	320.02
CWD28-02	28	Wet-dry	0.315	296.88
CWD28-03	28	Wet-dry	0.315	365.97
CWD28-04	28	Wet-dry	0.315	362.02
CWD28-05	28	Wet-dry	0.315	391.68
CWD28-06	28	Wet-dry	0.315	287.96
CWD28-07	28	Wet-dry	0.315	357.22
CWD28-08	28	Wet-dry	0.315	329.11
CWD28-09	28	Wet-dry	0.315	414.48
CWD28-10	28	Wet-dry	0.315	374.54

(b) Coated GFRP Bars

ICTR-01	0	Control	0.315	597.92
ICTR-02	0	Control	0.315	763.69
ICTR-03	0	Control	0.315	692.38
ICTR-04	0	Control	0.315	513.91
ICTR-05	0	Control	0.315	635.63
ICTR-06	0	Control	0.315	774.15

Table A.4. Tensile Strength Results of GFRP Bars from Manufacturer IV.

(a) Uncoated GFRP Bars

Sample I.D.	Duration of Aging (days)	Aging Method	Bar Diameter (inches)	Tensile Strength (MPa)
NCTR-01	0	Control	0.375	304.25
NCTR-02	0	Control	0.375	302.92
NCTR-03	0	Control	0.375	358.67
NCTR-04	0	Control	0.375	379.11
NCTR-05	0	Control	0.375	318.27
NCTR-06	0	Control	0.375	385.64
NCTR-07	0	Control	0.375	380.19
NCTR-08	0	Control	0.375	363.99
NCTR-09	0	Control	0.375	343.91

Table A.4(a) (cont'd).

Sample I.D.	Duration of Aging (days)	Aging Method	Bar Diameter (inches)	Tensile Strength (MPa)
NCTR-10	0	Control	0.375	385.76
NCTR-11	0	Control	0.375	437.88
NCTR-12	0	Control	0.375	394.83
NCTR-13	0	Control	0.375	503.07
NCTR-14	0	Control	0.375	353.23
NCTR-15	0	Control	0.375	425.67
NCTR-16	0	Control	0.375	513.47
NCS28-01	28	Immersion	0.375	321.90
NCS28-02	28	Immersion	0.375	397.25
NCS28-03	28	Immersion	0.375	363.51
NCS28-04	28	Immersion	0.375	424.34
NCS28-05	28	Immersion	0.375	289.25
NCS28-06	28	Immersion	0.375	393.13
NWD28-01	28	Wet-dry	0.375	379.23
NWD28-02	28	Wet-dry	0.375	443.69
NWD28-03	28	Wet-dry	0.375	366.29
NWD28-04	28	Wet-dry	0.375	349.96
NWD28-05	28	Wet-dry	0.375	349.23
NWD28-06	28	Wet-dry	0.375	365.08

(b) Coated GFRP Bars

Sample I.D.	Duration of Aging (days)	Aging Method	Bar Diameter (inches)	Tensile Strength (MPa)
LCS28-01	28	Immersion	0.375	331.34
LCS28-02	28	Immersion	0.375	230.23
LCS28-03	28	Immersion	0.375	254.42
LCS28-04	28	Immersion	0.375	230.96
LCS28-05	28	Immersion	0.375	267.97
LCS28-06	28	Immersion	0.375	226.36
LWD28-01	28	Wet-dry	0.375	319.73
LWD28-02	28	Wet-dry	0.375	282.96
LWD28-03	28	Wet-dry	0.375	439.70
LWD28-04	28	Wet-dry	0.375	276.67
LWD28-05	28	Wet-dry	0.375	229.39
LWD28-06	28	Wet-dry	0.375	252.85
MCS28-01	28	Immersion	0.375	338.59
MCS28-02	28	Immersion	0.375	340.41
MCS28-03	28	Immersion	0.375	377.17
MCS28-04	28	Immersion	0.375	376.81
MCS28-05	28	Immersion	0.375	373.06
MCS28-06	28	Immersion	0.375	387.57

Table A.4(b) (cont'd).

Sample I.D.	Duration of Aging (days)	Aging Method	Bar Diameter (inches)	Tensile Strength (MPa)
MWD28-01	28	Wet-dry	0.375	356.13
MWD28-02	28	Wet-dry	0.375	355.52
MWD28-03	28	Wet-dry	0.375	356.37
MWD28-04	28	Wet-dry	0.375	456.99
MWD28-05	28	Wet-dry	0.375	302.43
MWD28-06	28	Wet-dry	0.375	418.29

APPENDIX B

RAW BOND TEST DATA

Table B.1. Bond Strength Results of GFRP Bars from Manufacturer I.

Sample I.D.	Coating	Aging Condition	Stress at Failure (MPa)	Mode of Failure
KCTR-01	Uncoated	Unaged	26.88	Bar Pullout
KCTR-02	Uncoated	Unaged	20.02	Bar Pullout
KCTR-03	Uncoated	Unaged	25.42	Bar Pullout
KCTR-04	Uncoated	Unaged	21.75	Bar Pullout
KCTR-05	Uncoated	Unaged	27.55	Bar Pullout
KCS-01	Uncoated	Aged	22.01	Concrete Splitting
KCS-02	Uncoated	Aged	24.70	Concrete Splitting
UCTR-01	Coated	Unaged	25.16	Bar Failure
UCTR-02	Coated	Unaged	28.42	Concrete Splitting
UCTR-03	Coated	Unaged	29.32	Bar Pullout
UCS-01	Coated	Aged	25.16	Concrete Splitting
UCS-02	Coated	Aged	25.16	Bar Pullout
VCTR-01	Coated	Unaged	26.75	Concrete Splitting
VCTR-02	Coated	Unaged	25.72	Concrete Splitting
VCTR-03	Coated	Unaged	26.45	Concrete Splitting
UCS-01	Coated	Aged	22.26	Concrete Splitting
UCS-02	Coated	Aged	21.78	Concrete Splitting

Table B.2. Bond Strength Results of GFRP Bars from Manufacturer II.

Manufacturer	Sample I.D.	Coating	Aging Condition	Stress at Failure (MPa)	Mode of Failure
II	BCTR-01	Uncoated	Unaged	36.83	Concrete Splitting
II	BCTR-02	Uncoated	Unaged	35.75	Concrete Splitting
II	BCTR-03	Uncoated	Unaged	36.80	Bar Pullout
II	BCTR-04	Uncoated	Unaged	30.83	Bar Pullout
II	BCTR-05	Uncoated	Unaged	38.97	Bar Pullout
II	BCS-01	Uncoated	Aged	35.46	Concrete Splitting
II	BCS-02	Uncoated	Aged	41.16	Bar Failure
II	SCTR-01	Coated	Unaged	41.10	Bar Failure
II	SCS-01	Coated	Aged	36.10	Concrete Splitting
II	TCTR-01	Coated	Unaged	38.40	Concrete Splitting
II	TCTR-02	Coated	Unaged	36.43	Concrete Splitting
II	TCTR-03	Coated	Unaged	43.68	Bar Failure
II	TCS-01	Coated	Aged	37.14	Concrete Splitting
II	TCS-02	Coated	Aged	36.23	Concrete Splitting

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