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**INVESTIGATION ON LONG-TERM DURABILITY OF FRP-
CONCRETE BOND INTERFACES UNDER MOISTURE
CONDITIONS**

**湿潤環境下における FRP とコンクリートの付着界面の長期耐久性に関
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Justin Shrestha

September 2015

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By
Justin Shrestha

A thesis submitted in partial fulfillment of the requirements for the
Degree of Doctor of Philosophy in Engineering

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Laboratory of Engineering for Maintenance System
Division of Engineering and Policy for Sustainable Environment
Graduate School of Engineering
Hokkaido University
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ABSTRACT

Strengthening by Fiber Reinforced Polymers (FRPs) is one of the most common solutions to the ageing infrastructures. However, long-term durability of such systems under different environment conditions needs to be understood properly before widely adopting these methods in the field. Among several different environmental issues, moisture is considered as key issues which can deteriorate the bond interface properties between FRP and concrete. Till date the long-term durability issues and its mechanism of deterioration is not well understood. The environmental deterioration factor currently being proposed by some of the guidelines is only limited to the material deterioration without any consideration of the bond interfaces. This is mainly due to lack of proper understanding of the bond deterioration mechanisms and insufficient long-term durability related research data under such various environmental conditions. Therefore, it is necessary to investigate the bond properties to clarify such environmental deterioration mechanisms which can be useful to predict the service life of the structure. This research includes results of extensive experimentation performed to understand the behavior of moisture environmental conditions on material and bond properties between FRP and concrete.

The material properties and its durability characteristics under moisture conditions are determined in 8 epoxy resins and concrete for the maximum period of 18 months at 20°C. The results of immersion in water revealed that the mechanical properties of most of the epoxy resins degraded after exposure indicating some harmful effects of water. The average reduction in the tensile strength of the resins was in the range of 11% to 38% after exposure. These degradations are usually associated with the quantity of the absorbed water by epoxy resins but, no such relationship was found between them in the study. The absorption by the resin specimens varied from 0.71% to 2.65% after 18 months of immersion, in which, the higher water absorption did not necessarily yielded greater deterioration. In fact, highest reduction in the tensile strength occurred in the cases when the water absorption was the least, whereas no changes occurred in some cases despite over 2% of water absorption. This concludes that the quantity of water absorption cannot solely explain the degradation mechanism of the epoxy resins but more depended on the type of epoxy resins. Nonetheless, in contrast to the behavior of the epoxy resins, the concrete compressive strength remained unaffected throughout the exposure durations.

After confirming the material behavior, the effect of water was evaluated by the assessment of the shear and tensile bond interfaces under moisture conditions using 6 commonly used commercial FRP systems in various parts of the world. In laboratory water immersion test for the maximum period of 18 months, two of systems showed 25% and 16% reductions in average shear bond strengths, while the remaining systems showed either improvement or insignificant effect. Two of the most affected systems consistently showed bond failures at the adhesion interface between resin and concrete, while in other cases, the failures were either concrete cohesion or mixed failure of concrete cohesion and resin-concrete interface failure. Observation of the failure modes suggests that, the durability against water related deteriorations are worst in cases when the adhesion bonds between concrete and resin interface are weaker than the cohesive bonds of the adjacent layers. This indicates the importance of strong adhesion bond necessary at the interface that can be achieved by proper surface roughness of substrate concrete and selection of the suitable resins with good adhesion strength with the concrete. Unlike shear bond behavior, failures were governed by the concrete cohesion strength in almost all the cases when the bond interfaces were investigated by the direct pull-off test. Despite the large scatter in the data, average tensile bond strength after exposure was significantly reduced about 19% to 41% depending on the FRP systems. As the properties of the concrete remained unchanged throughout the exposure duration, it can be concluded that loss in tensile bond strength after the immersion is due to adverse effects of water on the bond properties. However, mechanism of deterioration in the tensile bond behavior remains unknown due to limited information generated through the test method itself.

The unique relationship observed between the deterioration in the shear bond strength and the adhesion failure modes due to moisture condition was further confirmed in the high-strength substrate case. With the main purpose of generating both sufficient and insufficient concrete surface roughness profiles,

disk-grinding and sand-blasting methods were adopted while preparing the shear bond specimens. The average arithmetic roughness was determined as 0.11 mm and 0.54 mm respectively in disk-grinded and sand-blasted method. The comparison of the results after water immersion test at 20 °C for 12 months duration confirms that the average bond strength reduction was around 30% for disk-grinded case whereas, the average bond strength reduction was only about 7% in case of sand-blasted specimens. As expected, failure mode changed to adhesion from mixed after exposure in case of insufficient roughness due to disk-grinded case but the mixed failure mode was retained in case of sand-blasted case when the surface roughness was sufficient. The results were further compared in case on normal-strength substrate with concrete surface roughness profile similar to high-strength disk-grinded case. The bond strength reduction was below 7% and the failure modes were mostly mixed modes. Despite the use of same FRP materials, such significant differences in the overall performances show that surface roughness plays a key role in the overall durability of the FRP-concrete bond interfaces. The bond mechanism at the interface between the FRP and concrete is governed by mechanical and chemical bonds. The chemical bonds are the result of interaction between concrete and resin whereas, the mechanical bond is due to the friction and interlocking action due to concrete surface roughness. The water mainly deteriorates the chemical bonds at the interface, but presence of strong mechanical bonds as a result of proper surface preparation could prevent greater loss in bond strength. The study also confirms that the level of sufficient surface roughness requirement varies based on the strength of the concrete.

Finally, for the prediction of service life of the structure strengthened with FRPs in moisture conditions, the interfacial bond-slip models are proposed. Dai's simple method of determining the bond-slip models which is applicable only for the ambient condition was modified to incorporate the moisture conditions. The two key parameters in the model which are interfacial fracture energy (G_f) and ductility index (B) were determined from the experimental results of single lap shear test conducted using six different FRP systems until the maximum exposure period of 18 months. Based on the responses to moisture, the six FRP systems investigated were grouped in to two categories as wet-layup and pre-impregnated systems. Wet-layup systems showed some adverse effects of moisture whereas the pre-impregnated systems showed positive effect. The interfacial fracture energy (G_f) and ductility index (B) were related separately with the exposure duration to incorporate the moisture related effects. The predicted ultimate loads compared with the experimental loads at different exposure duration show fairly good agreement.

Keywords: FRP, moisture, bond, interface, bond-slip relation, fracture energy

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Chapter 1

1. INTRODUCTION

1.1 RESEARCH BACKGROUND

The civil infrastructures around the world are deteriorating faster due to various external environmental exposures over the period of their service lives. In addition, increase in traffic loads, change in design codes and service requirements etc. have felt great necessity to strengthen or rehabilitate these structures to ensure safety and durability. Fiber reinforced polymer (FRP) composites have become a good option to strengthen or rehabilitate such civil infrastructures for past few decades due to various advantages such as high-strength and stiffness, light weight, high durability, ease for construction etc. Further, wide applications of these materials in strengthening of structural members; beams, slabs, bridge deck, column have resulted in extensive studies and thus development of numerous design codes and guidelines/recommendations [1-7]. Despite all of these efforts, environmental degradation has been neglected or not properly addressed in these standards. The environmental deterioration factor currently being proposed by few of the guidelines [2, 8] does not extensively cover deteriorations in bond properties due to various environmental conditions under long-term due to insufficient research in the field. Therefore, the predicted performances of these structures does not match with their behavior in the real scenario. Realizing the importance of durability issues in the FRP composites, recently ACI committee has been developing a guide to accelerated conditioning protocols for durability assessment of internal and external fiber reinforced polymer (FRP) reinforcement for concrete [9]. However, there are still necessities to identify all the severe environmental conditions which can potentially affect the FRP composites and its bond action, determine the deterioration mechanisms, evaluate the long-term durability of the material and bond properties by developing standardized durability testing methods and predict the service life of the structures strengthened or rehabilitated with FRPs.

During the service life of the structures, some of the common severe environments which can affect the durability of the FRP bonded concrete structures are moisture, high temperature, freeze-thaw cycles, wet-dry cycles, UV radiation etc. and their synergies. In order to study the above mentioned durability related issues for the FRP bonded concrete structures, researchers around the world have been using accelerated laboratory ageing method with wide variety of testing methods, materials and exposure durations. Due to lack of guidelines to perform such tests and diversity in availability of materials used, there is no uniformity in the results and the degree of its effect. Therefore, understanding the bond mechanism and effects of all of those factors in the bond performance is essential to enhance the interfacial behavior to ensure safe, economic and durable design of the structures.

In the present study an attempt has been made to address the influence of one of the major durability issues that a structure may face in moist condition such as marine environment.

1.2 CONCEPTUAL FRAMEWORK FOR SERVICE LIFE PREDICTION OF THE STRUCTURE AND KEY CONCERNS

The environmental related durability is one the main concerns which can deteriorate the service life of the structure. In order to meet safety and serviceability requirements, such consideration needs to be incorporated in the initial design phase. But before that, mechanisms of deteriorations due to each individual factor and their combined effects needs to be known in order to predict the service life of the structure. Understanding the mechanism is just one of the challenges but the main concern amongst the researchers is to correlate such results with the outdoor exposures.

Currently there have been many short term studies on numerous environmental actions on the FRP materials and its bond with the concrete conducted in accelerated laboratory conditions. The main objective of such tests is to simulate the real deteriorations of the field conditions in the laboratory accelerated tests. The following are few of the key points which describe the reasons for necessity of laboratory test over the outdoor exposure test.

- The deterioration due to actual environment usually takes longer time which could last for years. Due to the time and cost constraints, researchers opt to choose the accelerated laboratory test over the natural environmental deterioration. In addition to that, the outdoor exposure data is usually scarce.
- The environmental conditions varies according to the geographical location. Studies conducted in certain real environment cannot be applicable for other regions.
- In the actual environmental, there exists more than one variable which causes such deteriorations and it is virtually impossible to pin point any one of them. Lack of understanding such phenomena could cause misinterpretation of the results could lead to incorrect decisions. On the other hand, simulating such real conditions in the laboratory by choosing the correct testing procedures and making a proper evaluation of the results by establishing a good correlation with the outdoor exposure could give the right results. Further, each condition can be investigated separately in the laboratory to determine the mechanisms associated with it.

The FRP is relatively new material which was introduced to civil engineering field just few decades ago. The use of FRP in strengthening and rehabilitating the structures is vastly increasing due to its several advantages over other methods. However, there are no sufficient durability related outdoor exposure data in most of the cases making it extremely difficult for the researchers to relate their laboratory test results. Nevertheless, the researchers need to keep investigating different materials and testing methods under various environmental conditions and determine the ways to make such results applicable to consider the deteriorations in the natural environment.

Therefore following conceptual framework is proposed to predict the service life of the structure. Nonetheless, the scope of the dissertation is only limited to the first stage. The particular focus is only given to investigate marine environmental condition where the moisture condition would be highly dominant factor. Different FRP materials and its bond with concrete is tested in continuous water at room temperature to understand the mechanism behind the water related deterioration. Due to lack of outdoor exposure test data, the final target of the study is only limited to proposing a bond durability factor in moisture conditions along with the bond-slip models which can be applicable in moisture environment conditions where the service temperature is way below the glass transition temperature of the epoxy adhesives. The proposed durability factor could be improved by adding more data from the related tests so that the final proposed factor can be used in the design of structures strengthened with FRPs under moisture dominant conditions. Further, the proposed bond-slip model for moisture conditions can be used to predict the member behavior under the specific conditions defined above. With the availability of the outdoor exposure test data in future, the laboratory results could be related to get more rational method to determine the service life of the structure in a precise way.

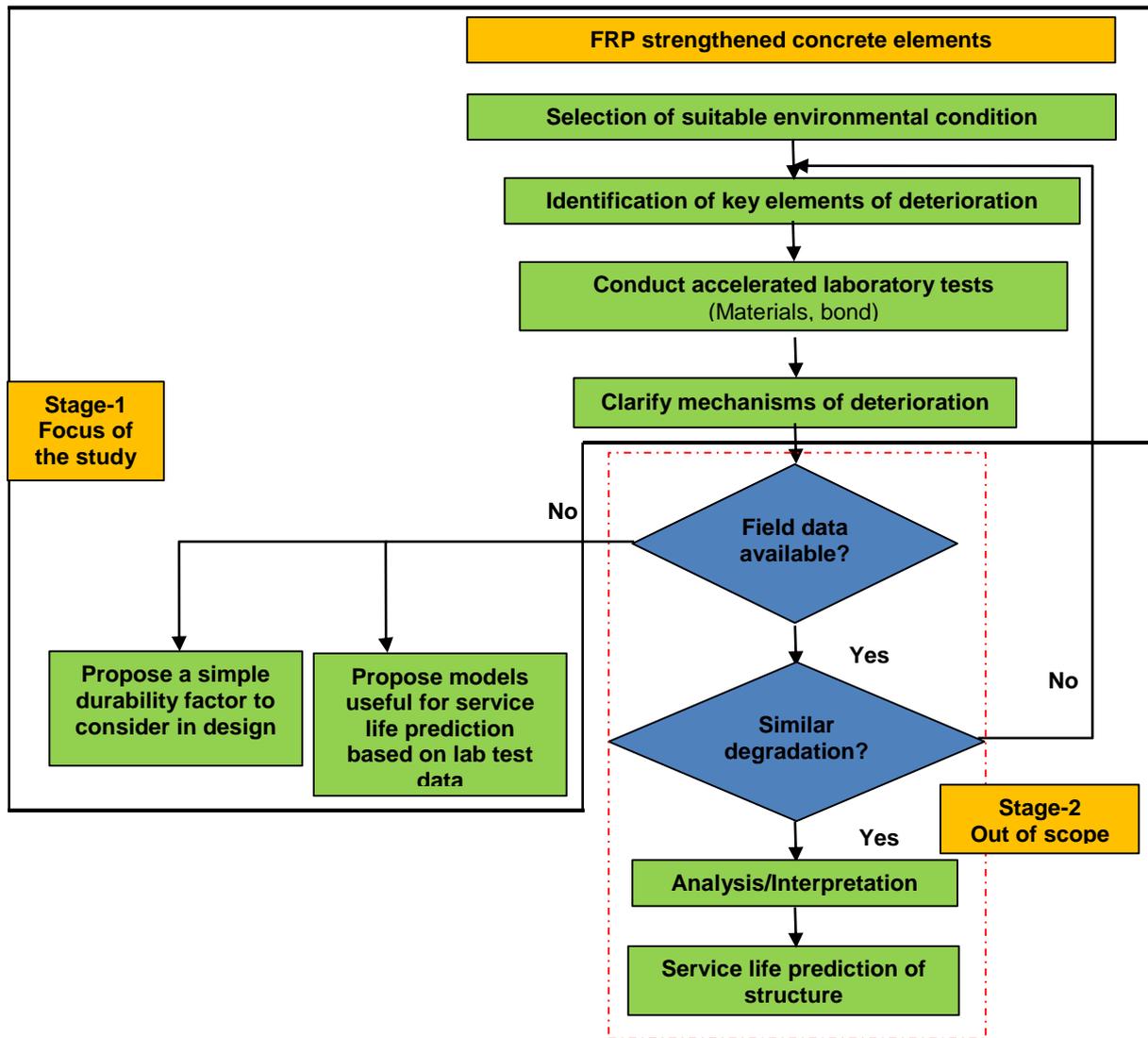


Figure 1-1 Conceptual framework of the service life prediction

1.3 RESEARCH OBJECTIVES

The main objective of the research is to address and clarify one of the key environmental related deterioration mechanisms in the FRP strengthened concrete structures. The more specific objectives are listed as follows:

1. To evaluate the long-term influence of continuous water immersion on the mechanical and thermal properties of the epoxy resins used in FRP composite systems.
2. To clarify the moisture related deterioration mechanism at the FRP-concrete bond interfaces as a result of continuous water immersion.
3. To compare the durability performances of several different commercial FRP systems produced by well-known manufactures around the world to demonstrate the importance of material selection in governing the degree of environmental effects due to moisture.
4. To investigate the influence of several key parameters such as primer, concrete strength, surface roughness, exposure duration, testing conditions etc. in order to clarify their roles on durability of FRP and concrete bonds.

5. To identify relationship between environmental effects on the mechanical properties of the materials and their bond behavior along with their failure modes to explain the mechanisms of deteriorations at the interfaces.
6. To propose bond deterioration factor applicable in the moisture condition along with the simplified bond-slip models for the FRP-concrete interfaces incorporating the moisture effects.

1.4 ORGANIZATION OF THE DISSERTATION

This dissertation is organized into six chapters described briefly as follows.

Chapter one gives brief idea on the research background, research framework, objectives, and the organization of the dissertation.

Chapter two presents comprehensive literature reviews on the relevant topics of FRP composites and its adhesion mechanisms with concrete. This chapter also focuses on previous studies conducted on environmental related degradations of FRP materials and its bond behavior with concrete.

Chapter three presents comparison of shear and tension bond performances of 6 commercial FRP systems subjected to water immersion for the maximum period of 18 months. This chapter tries to explain the moisture deterioration mechanism based on the comparison of the bond strengths and analysis of the failure modes. The variation of durability outcomes based on the selection of the materials for investigation is also included.

Chapter four tries to explain the necessity of proper surface preparation method and its relationship with the durability of the FRP-concrete bond interfaces under moisture conditions. The chapter mainly focuses on different effect of moisture in high-strength concrete substrate with sufficient and insufficient surface roughness profiles.

Chapter five gives overall formulation of a simple analytical bond stress-slip relationship in moisture conditions based on the strain results obtained from single-lap shear bond tests. The information obtained from the experimental results is used to propose analytical constitutive models taking the effects of moisture conditions.

Chapter six summarizes all the conclusions obtained from my work along with some recommendation for future work.

Appendix includes some of the initial experimentation results on the durability of FRP-concrete bonds under elevated temperature condition.

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Chapter 2

2. LITERATURE REVIEW

2.1 A BRIEF REVIEW ON MATERIALS FOR FRP STRENGTHENING

Fiber reinforced polymer (FRP) is a composite material composed of different materials combined together to form a completely new material. The final properties of the composite widely depend upon the selection of materials and the manufacturing process adopted to form a composite. In order to understand the macro behavior of the composite, detail knowledge of the materials are necessary. In simplest, FRP is a specific type of two-component composite material consisting of high-strength fibers embedded in a polymer matrix (Figure 2-1). Different layers forming a FRP composite is shown in Figure 2-2.

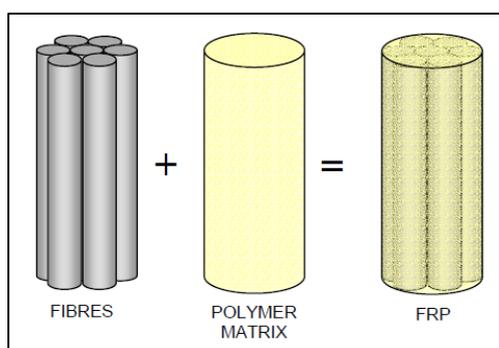


Figure 2-1 Basic material components combined to form FRP composite

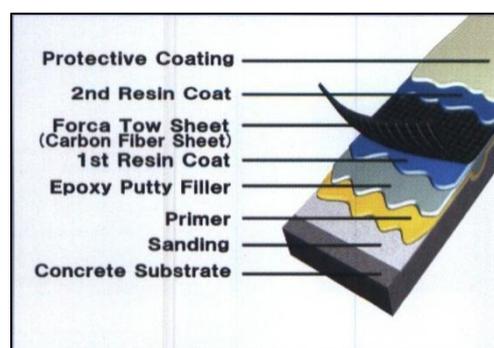


Figure 2-2 Different layers in FRP composite in wet layup

2.1.1 Fiber reinforcement

Fibers are very thin long filaments with diameter ranging from 5-20 μm [1]. Basically, three different types of fibers are popular in the construction industries which are carbon, aramid and glass. Carbon fibers possess higher strength, stiffness and are also highly resistant to the aggressive environmental factors. But the most important disadvantage of carbon fibers is their higher cost. The price is 10-30 times higher than the E-glass [2]. Aramid fibers are organic fibers, made of aromatic polyamides in an extremely oriented form. Their Young modulus of elasticity and tensile strength are intermediate between glass and carbon fibers. There are three different aramid fibers Kevlar, Technora and Twaron produced by major companies. Among these Kevlar has very good tension fatigue resistance, low creep and it can withstand high temperatures however it absorbs some water which causes internal cracks and produce longitudinal splitting [2]. Glass fibers typically have a Young modulus of elasticity lower than carbon or aramid fibers and their abrasion resistance is relatively poor. The glass fibers are cheaper than carbon and aramid fibers but have lower alkali resistance and are more prone to water degradation. The stress strain relations for few of the available fibers are shown in Figure 2-3.

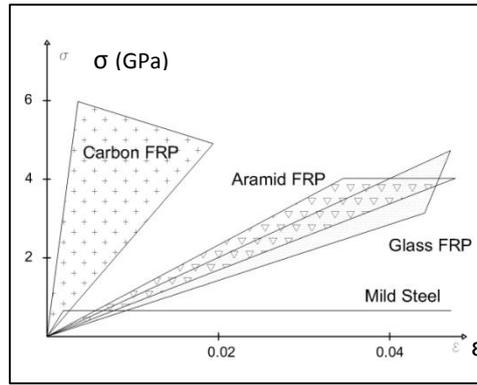


Figure 2-3 Stress-strain diagrams for some available fibers

2.1.2 Resins

A wide range of polymeric resins, including primers, putty fillers, matrices, and adhesives, are used with FRP systems.

Basically, resins can be classified into two different categories:

- Thermoplastic resins
- Thermosetting resins

Table 2-1 Compounding Ingredients of Epoxy Resins and Their Roles [3]

Constituents	Ingredients	Roles
Resin content	Epoxy resin	The bisphenol A type is most common. However, there are many other types of epoxy resins having differing properties.
	Curing agents and catalysts	Curing agents and catalysts react with epoxy groups to form a three-dimensional network structure by crosslinking.
Modifying ingredients	Flexibilizers	Elasticity agents flexibilize compounds to improve their peel strength, impact resistance, and elongation.
	Tougheners	Tougheners eliminate brittleness from epoxy resin to prevent cracks and decrease distortion. Unlike flexibilizers, they do not reduce crosslink density.
	Heat-resistant additives	Generally these resins provide increased heat resistance by nature of their multi-functionality and/or aromaticity.
	Fillers	Fillers increase the weight in order to decrease cost and improve various types of properties (application and performance).
	Diluents	Diluents reduce viscosity. Reactive diluents have epoxy groups, and nonreactive diluents have no epoxy groups available for reaction.
	Thixotropic agents	Thixotropic agents impart thixotropy to the adhesive to control flow and increase viscosity.
	Other agents	Pigments, coupling agents, defoaming agents, film formers, etc. are used for specific properties.

Thermoplastic resins may be softened by heating and re-hardened upon cooling without undergoing chemical transformation. Thermoplastic resins can be derivatives of vinyl, polyester, nylon, and cyanoacrylate. Unlike thermoplastics, thermosetting resins do not melt or flow on heating but become ‘rubbery’ and lose strength. The molecular chains present in thermosetting resins may undergo irreversible cross-linking on curing. Common thermosetting resins include Polyester, Vinyl ester, Epoxy, Phenolic and Urethane. Among different types of thermosetting resins, epoxies are the most widely accepted and used due to its high durability and versatility properties which can be blended easily with other modifying components to form a resin with desired properties. The epoxy resins could be either cold cured at room temperature or elevated temperature depending on the requirements but

generally the epoxy resins that cure at elevated temperatures have a higher crosslinking density and glass transition temperature. Commercial epoxy adhesives are primarily composed of an epoxy base and a curing agent. Various additives and modifiers are added to the formulation to improve properties such as strength, flow, heat resistance etc. [4]. Table 2-1 show some of the ingredients of epoxy resins along with their roles.

Epoxies are generally produced by the reaction of epichlorohydrin with bisphenol A. The reaction between bisphenol A and epichlorohydrin can be controlled to produce different molecular weights. Low molecular weight molecules tend to be liquids and higher molecular weight molecules tend to be more viscous liquids or solids. The main reagent is composed of organic fluids with a low molecular weight, containing a number of epoxy groups, rings composed by an oxygen atom and two carbon atoms. A reticulating agent (typically an aliphatic amine) is to be added to this mixture in the exact quantity to obtain the correct structure and properties of the cross-linked resin. The reaction is exothermic and does not produce secondary products. The most commonly used epoxy resin in composite materials for civil applications is the diglycidylether of bisphenol A (DGEBA) (Figure 2-4) [5].

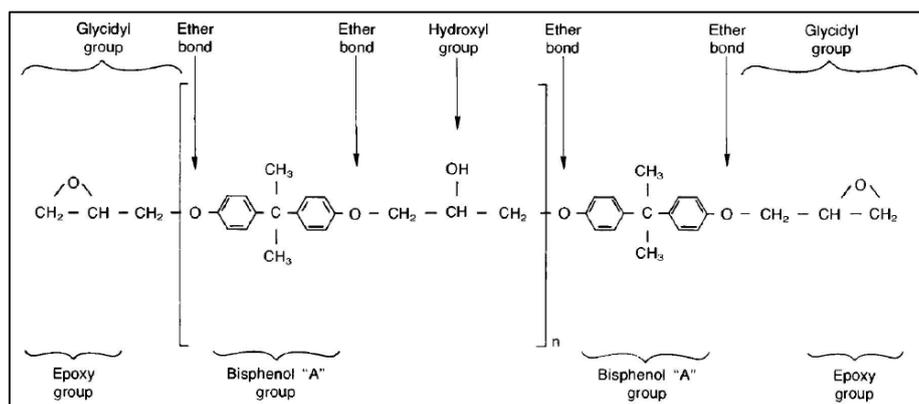
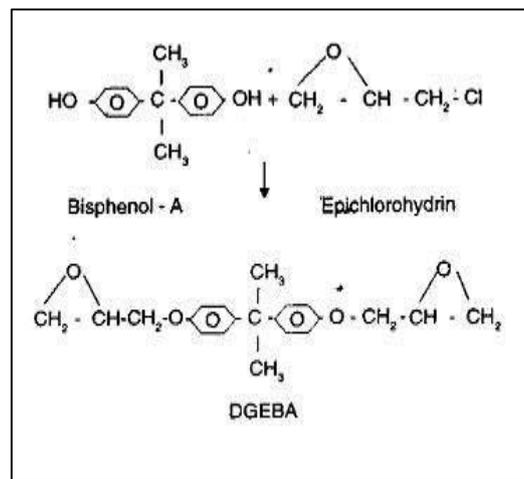


Figure 2-4 Chemical structure of DGEBA

Epoxy resins have several advantages over other polymers as adhesive agent for civil engineering use, namely: [6, 7]

- a. high surface activity and good wetting properties for a variety of substrates
- b. possibly formulated to have a long open time (the time between application and closing of the joint)
- c. high cured cohesive strength; joint failure may be dictated by adherend strength (particularly with concrete substrates)
- d. possibly toughened by the inclusion of a dispersed rubbery phase
- e. lack of by-products from curing reaction minimizes shrinkage and allows the bonding of large areas with only contact pressure (in stark contrast to the phenolic commonly used in the aerospace industry)
- f. low shrinkage compared with polyesters, acrylics and vinyl types; hence, residual bond-line strain in cured joints is reduced
- g. low creep and superior strength retention under sustained load
- h. possibly made thixotropic for application to vertical surfaces
- i. able to accommodate irregular or thick bond-lines (e.g. concrete adherends)
- j. possibly modified by (a) selection of base resin and hardener (b) addition of other polymers (c) addition of surfactants, fillers and other modifiers.

A major disadvantage of epoxides is that these various modifications and the materials concerned make them relatively expensive when compared with other adhesives. The resins can be further sub-divided into different categories based on their function as described below.

2.1.2.1 Adhesive

The main purpose of the adhesive is to provide a shear bond path between the concrete surface and the composite material, so that full composite action may develop [8]. Adhesives are also used to bond together multiple layers of precured FRP laminates.

2.1.2.2 Matrix

The purpose of the matrix/impregnating resin is to bind the fibers together and distribute the load. In addition to this, it also protects the fibers against abrasion or environmental corrosion [8]. The matrix also serves as the adhesive for wet layup systems, providing a shear load path between the previously primed concrete substrate and the FRP system [9]. Mostly same resin is used as matrix and adhesive.

2.1.2.3 Primer

The primer is applied to the concrete surface to ensure a good bond between concrete surface and the FRP sheet. It also prevents air bubbles from developing between the FRP sheet and the surface of concrete during construction or curing. The primer penetrates the surface of concrete and strengthens the surface layer creating the required bond strength between the continuous fiber sheets and the surface of the concrete [10]. The requirement of the primer layer is usually dependent on the manufacturer providing the FRP composite.

2.1.2.4 Putty

Putty is used to fill small surface voids or defects on the surface of the substrate and provides a smooth surface to which the FRP system can be bonded. Filled surface voids also prevent bubbles from forming

during curing of the saturating resin [9]. However, this is an optional layer which can be applied depending on the surface condition.

2.2 FRP STRENGTHENING SYSTEMS

There are major three bonding systems named as pre-cured systems, wet layup systems and prepreg systems for the FRP strengthening [5]. The first two systems are most often used.

i. Pre-cured system

In pre-cured system, the composites are manufactured in various shapes by pultrusion or lamination which is bonded onto the concrete surface with the use of appropriate adhesive. In this case the quality of the composite will be very high and easy to apply in the field. Figure 2-5 shows the application of CFRP plated for flexure strengthening of bridge decks.



Figure 2-5 Application of CFRP for flexural strengthening of bridge decks

ii. Wet layup system

In wet layup, FRP sheets or fabrics are manufactured but the process of impregnating the resin matrix is carried out in-situ which makes it easy to incorporate any dimensional changes in the site whereas on the other hand the final quality of the system is highly dependent in the workmanship. This method is a slow and highly labor intensive process therefore special attention should be paid in order to achieve the consistent quality. Figure 2-6 and Figure 2-7 show the application of wet layup in shear and axial strengthening of bridge girder and pier respectively.



Figure 2-6 Shear strengthening of bridge girder



Figure 2-7 Axial strengthening of bridge piers

iii. Prepreg system

Finally in prepreg system, the composites are manufactured with unidirectional or multidirectional fiber sheets or fabrics pre-impregnated at the manufacturing plant with partially polymerized resin. They may be bonded to the member to be strengthened with (or without) the use of additional resins.

2.3 MECHANISM OF ADHESION

The efficiency of adhesion depends on many factors, such as surface treatment, chemical composition and viscosity of the adhesive, application technique, and hardening or cross-linking process of the adhesive itself. Adhesion mechanisms primary consist of interlocking of the adhesive with the surface of the support with formation of chemical bonds between polymer and support. As a result, adhesive strength is enhanced by surface treatments that improve interfacial properties of the support by increasing the roughness of the surface to be strengthened [5]. Generally four main mechanisms of adhesion have been proposed which are namely [11]:

- i. Mechanical interlocking
- ii. Adsorption theory
- iii. Diffusion theory
- iv. Electrostatic theory

i. Mechanical interlock theory:

This theory essentially proposes that mechanical keying, or interlocking, of the adhesive into the irregularities of the substrate surface is the major source of intrinsic adhesion [11]. The bond exploits the mutual creep resistance between locally permeated surfaces; therefore, it is important to have irregular surfaces to allow spreading of the adhesive, filling of the support pores, and cracks before solidification takes place [5]. A rough surface will have a larger potential bonding area than a smooth one. In general, any improvement in joint strength from greater adherend rugosity may be ascribed to other factors such as the increased surface area, improved wetting, or enhanced energy dissipation of the adhesive during joint fracture [7].

ii. Adsorption theory

This theory proposes that with sufficiently intimate contact, the adhesive macro-molecules are physically adsorbed on to the substrate surface because of the forces acting between the atoms in the two surfaces. In effect, the polar nature of the adhesive molecules acts like a weak magnet and they are attracted towards polar adherend surfaces. The most common interfacial forces are van der Waals' forces, referred to as secondary bonds, although hydrogen bonding and primary chemical bonding (ionic or covalent) are involved in some cases [7, 11].

iii. Diffusion theory

This theory proposes that adhesive macromolecules diffuse into the substrate, thereby eliminating the interface, and so can only apply to compatible polymeric substrates. It requires that the chain segments of the polymers possess sufficient mobility and are mutually soluble. The joining of plastic service pipes for carrying gas and water makes use of the diffusion mechanism [7].

iv. Electrostatic theory

It is postulated that adhesion is due to the balance of electrostatic forces arising from the transfer of electrons between adhesive and substrate, resulting in the formation of a double layer of electrical charge at the interface [11].

In case of FRP and concrete, the governing adhesion mechanisms are mechanical interlocking and chemical bonding.

2.4 DURABILITY OF FRP AND ITS CONTITUENT MATERIALS

All engineering materials are subject to mechanical and physical deterioration with time, load, and exposure to various harmful environments. When FRPs are used for reinforcement or strengthening of reinforced concrete structures, they can be expected to be exposed to a variety of potentially harmful physical and chemical environments [12]. The durability of the FRP is a key concern for its wide application. Even though the FRPs are considered as highly durable material with outstanding longevity in civil infrastructure application, lack of widely accepted test procedures and uncertainty of the correlation between accelerated conditioning and natural long-term conditioning in the field complicate the practical interpretation of the results.

FRPs' individual characteristics also influence their durability performance, including the matrix and fiber types, the relative proportions of the constituents, the manufacturing process, the installation procedures, and the short-term and long-term loading and exposure conditions (both physical and chemical). Clearly, the constituent materials used in the fabrication of any FRP component must be chosen based on both structural performance and long-term durability requirements. Based on available research, when FRP materials are used as reinforcement and strengthening materials for concrete structures, the factors shown in Figure 2-8 should be considered significant in terms of long-term durability. The degree to which each of these factors could be a concern depends on the application, the timing and geographic location of the project, the age of the structure, the specific formulation of the FRP reinforcement, and the quality of the installation and construction [12].

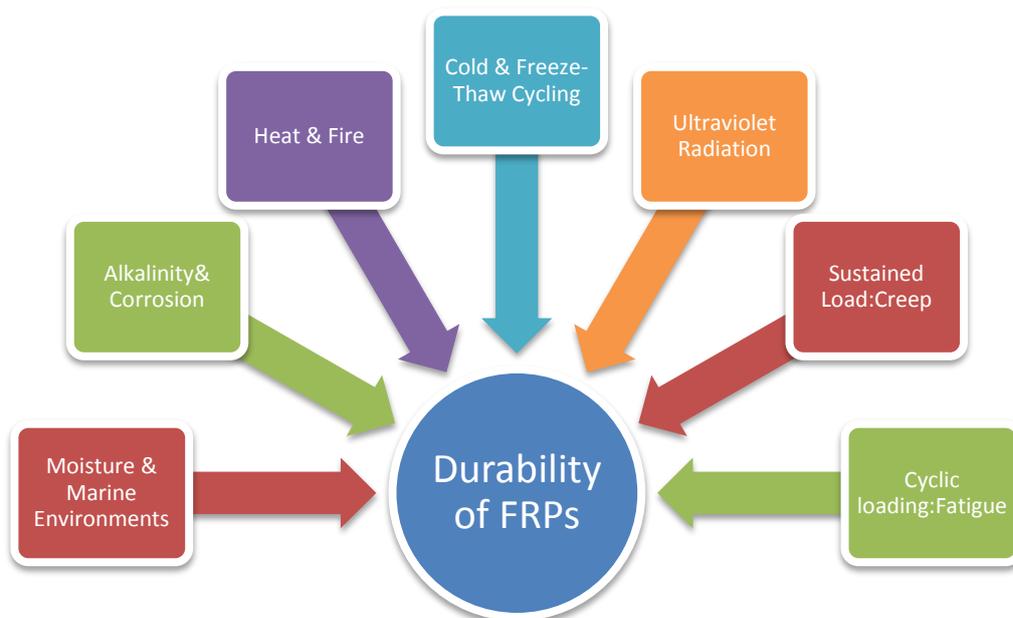


Figure 2-8 Factors affecting durability of the FRPs [12]

Structures may experience various hostile environments which could accelerate the bond deterioration process thus reducing the overall performance of the structures. One of such issues in marine environment could be the moisture which could adversely affect the resin properties and the interface. But the moisture related damage mechanism of the FRP composites is complex phenomenon and the previous studies on the long term durability of these materials in civil applications are limited. Therefore, understanding the mechanism of moisture degradation is essential to enhance the interfacial bond performance thus ensuring safe, economic and durable design of the structures. The moisture may gain access into the composite through capillary action along the longitudinal axis of the fiber or at the resin-fiber interface, transfer through cracks and voids in the structure, diffusion through the resin matrix etc. [8].

2.5 DURABILITY OF EPOXY RESINS IN MOISTURE CONDITIONS

Water is one of the most common and damaging environmental agents which can affect the durability of epoxy resins. But the effect of the water is very complex phenomenon as it depends on several different factors but it is already known that it starts after absorption of moisture. The amount of moisture absorbed may cause reversible or irreversible physical, mechanical and/or chemical changes. There are great variations within the types of epoxy resins because of differences in chemical linkages, formulation parameters, cross-linking density, etc. [13]. The major effects of water on epoxy resins mainly includes three phenomenon which are

- i. Plasticization
- ii. Hydrolysis
- iii. Cracking and crazing

i. Plasticization

The moisture absorption typically results in plasticization (or softening) of the matrix caused by interruption of weak (Van der Waals) bonding between polymer chains. This can result in reductions in the polymer's strength, modulus, strain at failure, and toughness, and can subsequently cause reductions in matrix-dominated (off-axis) properties such as bond, shear, and flexural strength and stiffness. In some cases this may also affect the longitudinal tensile strength and stiffness of an FRP [12]. Moisture absorption also tends to cause a mild reduction in the glass transition temperature (T_g) of polymer matrices. The T_g value is the temperature at which the mechanical properties of a polymer change from a rigid and brittle solid to a viscous plastic fluid, and polymer matrices are generally considered structurally ineffective at temperatures significantly greater than T_g . Water permeation generally lowers the glass transition temperature of the polymer by reducing the attractive forces between molecules [13].

ii. Hydrolysis

Another very important type of water-related degradation is hydrolysis, which may influence the adhesive, the adherend (e.g. polyesters) or the adherend/adhesive interface and cause irreversible effects. Certain chemical linkages (e.g. ester groups) are prone to hydrolytic attack and, if present in an adhesive or at the interfacial regions, are potential targets for reaction with water which has penetrated into the bulk of the adhesive or into the joint. Hydrolysis requires the presence of water and generally also needs the presence of a strong acid, or a strong base, and can be activated by elevated temperatures and stress on the joint. The hydrolytic attack on an ester linkage, in the presence of water at high pH, is an important example of this mode of attack. It may cause chain shortening or main chain scission in the polymeric adhesives or adherends, and hence can lead to loss of cohesive strength within the adhesive or adherend and to failure of the joint [14].

iii. Cracking and crazing

Moisture-induced swelling of the polymer matrix can cause irreversible damage through matrix cracking and fiber-matrix debonding.

Some of the results showing reduction in mechanical and thermal properties due to environmental epoxies on the structural epoxy resins are shown in Table 2-2.

Table 2-2 Summary of the existing results on environmental degradation on mechanical and thermal properties

Authors	Resin information	Exposure condition/ duration	Property Changes		
			Reduction in mechanical properties (%)		T_g
			Tensile	Modulus	
Au [15]	Bisphenolic epoxy resin and amine hardener	23°C in deionized water/ 4 weeks	13	19	Reduction by 6 °C
		50°C in deionized water/ 4 weeks	28	37	Reduction by 3 °C
	Two-component epoxy resin and amine hardener	23°C in deionized water/ 8 weeks	22	15	Reduction by 7 °C
		50°C in deionized water/ 8 weeks	10	10	Reduction by 3 °C
Frigione et al. [16]	Bisphenolic epoxy resin (MW<700)	23±1 °C in water/ 19 weeks	9	17	Reduction by 3 °C
	Bisphenolic epoxy resin 66% inorganic filler	23±1 °C in water/ 38 weeks	12	36	Increase by 3 °C
	Bisphenolic epoxy resin 49% of inorganic filler	23±1 °C in water/ 38 weeks	18	21	Increase by 2 °C
Yang et al. [17]	Bisphenolic epoxy resin and aliphatic amine	23°C in deionized water/ 24 months	47	34	Reduction by 5%
		37.8°C in deionized water/ 24 months	44	40	Insignificant
		60°C in deionized water/ 24 months	69	68	Insignificant
		23°C in salt solution/ 24 months	36	30	Reduction by 4%
		23°C in alkali solution/ 24 months	53	50	Reduction by 5%
Sciolti et al. [18]	Two-component commercial epoxy primer	23 °C in water/ 27 weeks	64	67	Reduction by 20 °C
	Two-component commercial adhesive	23 °C in water/ 29 weeks	46	59	Reduction by 3 °C
	Two-component commercial putty	23 °C in water/ 31 weeks	66	83	Reduction by 18 °C
Benzarti et al. [19]	Bisphenolic epoxy resin and Polyamide hardener	40°C and 95% RH/ 265 days	73	73	Reduction by 6-30 °C
	Bisphenolic epoxy resin and amine hardener	40°C and 95% RH/ 206 days	47	31	Increase by 20°C

2.6 DURABILITY OF FRP-CONCRETE BOND INTERFACES UNDER MOISTURE CONDITIONS

Many moisture related FRPs' durability have been studied in past decade. The discussions below highlight those factors that are seen as most significant based on available research on long-term investigation on durability of FRP-concrete bond under moisture.

Karbhari and Ghosh [20] conducted experimental study to determine the effects of environmental exposure on durability of bond strength between different commercially available FRP strengthening systems and concrete using direct pull-off test. When 10 different FRP systems were exposed for 2 years, the maximum deterioration was noted for the case of exposure to a sub-zero environment compared to immersion in salt water and deionized water. The authors also suggested that the deterioration of the bond between FRP and the concrete substrate should be considered in the design of rehabilitation measures. Dai et al. [21] also investigated on the influence of moisture on the tensile and shear bond behavior of FRP to concrete interfaces subjected to accelerated wet-dry cycles (4 days wet at 60°C and 3 days dry) for the maximum duration of 2 years. The results showed contradiction in the behavior of tensile and shear bond properties after the exposure. The interfacial bond strength degraded asymptotically with the exposure time while the flexural capacity of the FRP sheet bonded to concrete beams increased. However, the transition of failure modes occurred in all cases from concrete cohesion failure to the interface adhesion failure between primers to concrete after the exposure. Till date, the longest duration of such exposure test was performed by Nishizaki and Kato [22] in which the durability of bond between carbon fiber sheet reinforcement polymer (CFRP) and concrete through outdoor exposure in a moderate climate for 14 years. The authors evaluated the adhesive bond properties using the pull-off and peel test methods and found that the pull-off strength was slightly decreased but the residual values still indicated quiet good adhesion properties. In all the cases, the failures occurred in the concrete substrate suggesting that the reduction observed may not be necessarily related to the degradation of the resin bond properties. In contrast, the results of the peel test showed distinct differences in the failure modes after immersion. Benzarti et al. [19] chose 4 different composite systems to perform durability of adhesive bond between concrete and CFRP under accelerated condition (40°C and 95% relative humidity) using pull-off test and single lap shear test. After a year of exposure, even though transition of failure mode was from cohesive concrete failure to the interface for most of the cases, the results from the pull-off test were not always consistent with those of the shear test. Significant reductions in the tensile bond strength were observed for most of the systems while there was an increase in shear bond strength. Similarly, Choi et al. [23] conducted large experimental program to investigate the effects of various exposure conditions (hygrothermal, outdoor and chloride, alkali and UV/water cycles) on concrete beams externally reinforced using different commercially available CFRP composites. Results showed that the flexural strength of the beam specimens were reduced with exposure, but, significant differences in the relative strength loss was observed for different commercial systems indicating that durability is highly dependent on the epoxy system used in the composite. The study also calculated the environmental reduction factor resulting for those exposures and found it close to 85% which was also the suggested factor proposed by ACI (2008) [9]. Recently, Al-Tamimi et al. [24] conducted several single lap shear test on the CFRP precured plates bonded to concrete prisms after being subjected to two marine environment exposures along with the controlled laboratory atmosphere for the comparison. All the specimens were preloaded with 3 and 5 KN of sustained loading and tested after 150 days. The results indicated that the specimens exposed to the sun and saline environments experienced an increase in the bond strength. The reason for such increase in performance was explained by increase in greater polymer crosslinking of adhesive due to exposure in elevated temperature. Finally, Kabir [25] performed some experiments to determine the long term performance of FRP-concrete bond using single lap shear test. The exposure conditions include temperature cycles (5 hours at constant 40°C followed by 7 hours at gradual decrease to 30 °C), wet-dry cycles (1 week wetting at 95% humidity followed by 1 week drying at normal lab condition) and outdoor environment (Sydney) for the maximum period of 18 months. The authors concluded that the outdoor environment turned out to be the most severe case among all, causing degradation of about 15% and 9% in the bond strength for carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP)–

concrete bond respectively. The wet-dry cycles showed only 5% and 6% reduction respectively for the CFRP and GFRP concrete bond whereas the temperature cycle didn't show any adverse effects. All of the above review on the literatures points out that the exposure to moisture coupled with temperature could be harmful to the FRP-concrete bond interfaces, however, the degrees of such effects are vastly dependent on several factors but most importantly the selection of FRP materials along with the epoxy resins.

2.7 TEMPERATURE EFFECT ON EPOXY RESINS AND FRP-CONCRETE BOND INTERFACES

Mostly, thermosetting resins are used which are largely influenced by the service temperature. The property of material changes from a hard and glass like material to a more rubber like material if the service temperature exceeds the glass transition temperature (T_g) [26]. Blontrock *et al.* [26] conducted double face shear tests on concrete elements reinforced with externally bonded CFRP laminates at different elevated temperature values (20, 40, 55 and 70 °C). The authors, considering the test at 20 °C as a reference, noted that the ultimate load increased for the test at 40 °C and 55 °C by 41% and 24% respectively while it decreased at 70 °C by 19%. Klamer *et al.* [27, 28] investigated the influence of temperature on the debonding of externally bonded CFRP laminates by double-lap shear test at different temperature levels (-20, 20, 50, 70, 90 and 100 °C). The results distinguished the effect of temperature into two different zones. In first zone, the failure load increased with increasing temperature (zone 1) followed by decrease in failure load with increasing temperature (zone 2). Such increment in ultimate load was until it reached the temperature around T_g then the load dropped indicating softening of the adhesives. The study also observed two types of failure based on temperature. For low to moderate temperatures (-20°C to 50°C), failure occurred in the concrete whereas for elevated temperature (50°C to 100°C), failure of the adhesive-concrete interface occurred. Klamer *et al.* [29] also tested four beams at three different temperatures at 20°C, 50°C and 70°C. The results showed that the ultimate load and failure modes for both 20°C and 50°C were similar but at 70°C the specimens failed at adhesion-concrete interface with significant decrease in ultimate load. Leone *et al.* [30] conducted double lap shear conducted at different elevated temperatures (50, 65 and 80 °C) and compared with room temperature (20°C). The results showed decrease in maximum bond stress at the temperature above the glass transition point however no such trend could be found for the case of maximum load with temperature. But the failure modes changed from concrete cohesion failure to the concrete-FRP adhesion failure when the temperature changed from 50 °C to 80 °C.

2.8 SUMMARY OF THE CHAPTER

The main objective of this chapter is to present the current understanding on various components of FRP composites including summary of latest studies conducted on the durability of FRP-concrete bond in different moisture and elevated exposure conditions. In addition, the mechanism of moisture degradation of the resin properties and its consequences are also briefly discussed together with the results obtained by some of the researchers in the field. The literatures presented in this chapter highlight many important issues that need to be addressed in the FRP-concrete bonding system. Some of the parameters investigated include FRP composites with different available commercial epoxy resins subjected to various moisture and elevated temperature environmental conditions. The duration of exposure varies from few weeks to 14 years. The studies have shown very serious effects of water on the FRP-concrete bond, significantly decreasing the ultimate bond strength and changing the failure modes after exposure. In contrast, few researchers have reported only minimal or negligible effect of moisture environment. Therefore, there still lies a great mystery of moisture related damages on the FRP-concrete bonding systems. Even though some theories and explanations have been proposed in few of the cases, it still lacks proper evidences to support such claims. The real mechanisms of environmental related deteriorations and the potential FRP materials and conditions are still unclear.

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Chapter 3

3. MOISTURE EFFECT ON DIFFERENT FRP-CONCRETE BOND SYSTEMS

3.1 INTRODUCTION

Carbon fiber reinforced polymer (CFRP) are widely used as reinforcement for strengthening and rehabilitation of structures. Nonetheless, there are still many environmental durability related issues which needs to be determined in order to ensure their performance requirements during their service life. Some of the literatures reviewed in earlier chapters clearly identified the moisture conditions as one of the prime environmental factors which can deteriorate the bond at FRP-concrete interfaces. However, the degrees of such effects are vastly dependent on several factors but most importantly the selection of FRP materials along with their epoxy resins. There are wide varieties commercial fiber reinforcing materials and their epoxy resins for structural applications. The commercial epoxy resin is a unique product due blend of several unknown components with different compositions due to which different responses could be observed when durability related studies are made. The large variation in the results obtained by different researchers are making it even complex to narrow down the true effects of such environmental conditions. One of the solutions could be by using the neat epoxy resin with known compositions but there still lies a great challenge to relate such outcomes with those of the commercial epoxy resins. Therefore, in the context, it is highly necessary to perform many studies on short-term and long-term durability of several available FRP materials and their bonds with concrete under different severe environmental conditions to understand the environmental related deteriorations.

3.2 EXPERIMENTAL OUTLINE

3.2.1 Material description

Altogether 6 commercially available carbon sheet/plate and epoxy resins from different regions of the world were selected for the study. These FRP systems are from the most popular Japanese, European and US based manufactures.

3.2.1.1 Fiber reinforcing material

Three different carbon fiber reinforcing materials are used for the study. They are carbon fiber reinforced polymer (CFRP) plate, carbon fiber strand sheet (CFSS) and carbon fiber sheets (CFS) as shown in the Figure 3-1. The properties of the carbon fiber reinforcing materials used along with their naming system are shown in Table 3-1.



Figure 3-1 Different carbon fiber reinforcing materials used for the study

Table 3-1 The properties of carbon fiber reinforcing materials and their naming system

Description	System-A	System-B	System-C	System-D	System-E	System-F
Type	CFS	CFS	CFS	CFS	CFSS	CFRP
Fiber content	200 g/m ²	200 g/m ²	393 g/m ²	200 g/m ²	600 g/m ²	>68%
Thickness (mm)	0.111	0.111	0.218	0.176	0.333	1.4
Width of plate (mm)	-	-	-	-	-	50
Tensile strength (MPa)	3400	3400	3790	3800	3400	3200
Modulus (GPa)	230	230	230	240	245	210

3.2.1.2 Epoxy resins

All of the epoxy resins were room temperature curing resin for standard applications. For two of the FRP systems, primer layer was used as recommended by the manufacturers before attaching the CFS onto the concrete surface. Detailed chemical information of the resins and their compositions were not disclosed by the manufacturers, however, some of the general information were extracted from the material safety data sheet (MSDS) of the resins. Based on the information given, primary component of the epoxy curing agents used in the current study is modified polyamine which is either aliphatic polyamine or combination of aliphatic polyamine with cycloaliphatic polyamine. The available information of the epoxy resins along with properties are summarized in Table 3-2.

3.2.1.3 Concrete

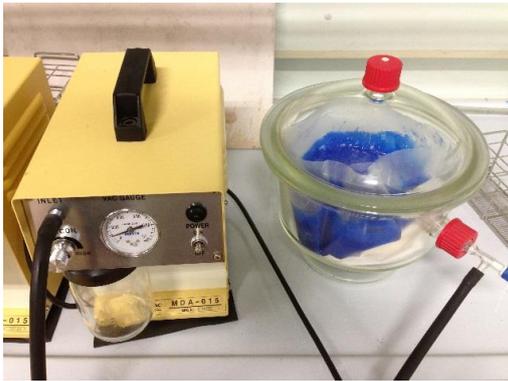
The early strength ready-mix concrete was for this purpose. The mean cylindrical compressive strength was 29.5 MPa after 28 days of curing in standard conditions.

3.2.2 Preparation of the specimens

3.2.2.1 Tensile resin specimens

The dog-bone shaped resin specimens for the uniaxial tensile test were prepared following JIS K 7113 [1]. The specimens were prepared using all the 8 kinds of epoxy resin which include 2 kinds of primer. The Figure 3-2 shows the preparation of tensile resin specimen. The specimens were cured in an ambient room temperature for more than one month before being subjected to any kind of exposure.

Figure 3-2 Preparation of resin samples



Vacuuming out the air from the mixed resin



Pouring the resin into the mold



Tapping the mold to remove trapped air



Specimens put in the room for curing

3.2.2.2 Bond specimens

Schematic details of the shear bond specimen and direct pull-off specimen are shown in Figure 3-3 and Figure 3-4 respectively. For the preparation of bond specimens, concrete prisms were roughened with a disk grinder, cleaned properly with compressed air and FRP sheet/plate was attached on 3 sides on the prism in turn. In two of the systems, primer layer was allowed to harden for a day before attaching the FRP sheet. As it was difficult to control the thickness of the resin layer, the quantity of the resin was measured and applied based on surface area coverage recommendation provided by the manufacturers. After attaching the FRP on all three sides, specimens were put in the laboratory conditions for more than one month as a curing period before giving any kind of environmental exposure. On each surface of the concrete prism, FRP is attached at two different areas to perform both shear and pull-off bond test. The upper part of the concrete prism was used for the shear bond test; whereas the lower part was used for the pull-off test Figure 3-5 and Figure 3-6 illustrates the overall process of bond specimen preparation. The sample for each prepared FRP system is showed in Figure 3-7. The naming system used for the FRPs, epoxy resins and all the specimens are presented in Table 3-3.

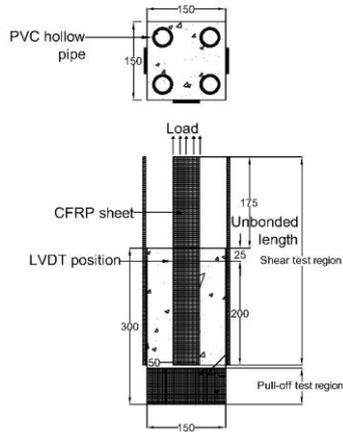


Figure 3-3 Details of bond specimen

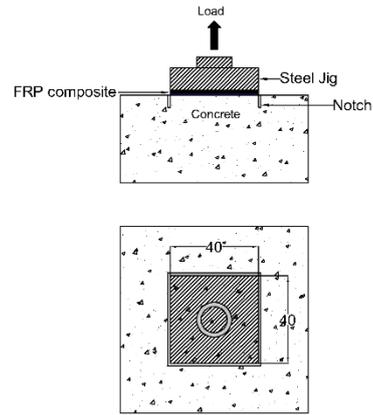


Figure 3-4 Details of direct pull-off test specimen

Figure 3-5 Concrete casting and its surface treatment



Preparation of formwork



Casting of concrete



Concrete prisms after 28 days curing



Surface preparation by disk grinding



Disk grinding machine



Concrete surface before and after preparation

Figure 3-6 Process of attaching FRP composite on the concrete prisms



Arrangement of the concrete prisms



Measurements of the bonding area



Put first coat of the resin



Apply strand sheet and the second coat of resin



Figure 3-7 Sample specimen for each FRP-system

Table 3-3 Naming scheme of the specimens

Composite System	Epoxy	Tensile resin specimens		Shear bond specimens	Tensile bond specimens
		Impregnating resin/ Adhesive	Primer		
A	Epoxy-A	TR-A	TP-A	SB-A	TB-A
B	Epoxy-B	TR-B	TP-B	SB-B	TB-B
C	Epoxy-C	TR-C	-	SB-C	TB-C
D	Epoxy-D	TR-D	-	SB-D	TB-D
E	Epoxy-F	TR-E	-	SB-E	TB-E
F	Epoxy-F	TR-F	-	SB-F	TB-F

3.2.3 Exposure and testing conditions

The specimens were either kept at an ambient condition inside the laboratory until the test which is referred as 0 month (non-immersion case) or completely submerged in water tank maintained at a constant temperature of 20°C for the maximum period of 18 months. Few set of specimens were taken out from the water and tested in every 3 months interval. In order to prevent the loss of moisture, the specimens were quickly transferred into the temporary environmental chamber built around the testing machine in order to keep the exposure and testing conditions similar. Both the shear bond test and resin tensile test were conducted inside the environmental chamber which could maintain the desired temperature and humidity. The schematic of the testing arrangement of the shear specimen inside the controlled chamber along with the specimen during the test is shown in Figure 3-8. Throughout the test period, the temperature of 20 ± 3 °C and humidity over 85% was maintained in order to prevent the loss of moisture from the specimens. As for the direct pull-off test as shown in Figure 3-9, no such arrangement was made to control the temperature and humidity of the testing condition as the setting and testing period was very short which could be assumed to have ignorable effect. At the end of 18 months immersion, one set of each specimen was taken out from the water and put in the laboratory chamber for 4 days maintaining the constant temperature of 28°C for the purpose of drying. The specimens were assumed to be dry when the weight change in a 24 hours was less than 0.1%. The main reason for this is to investigate the irreversible damages caused due to immersion in water.

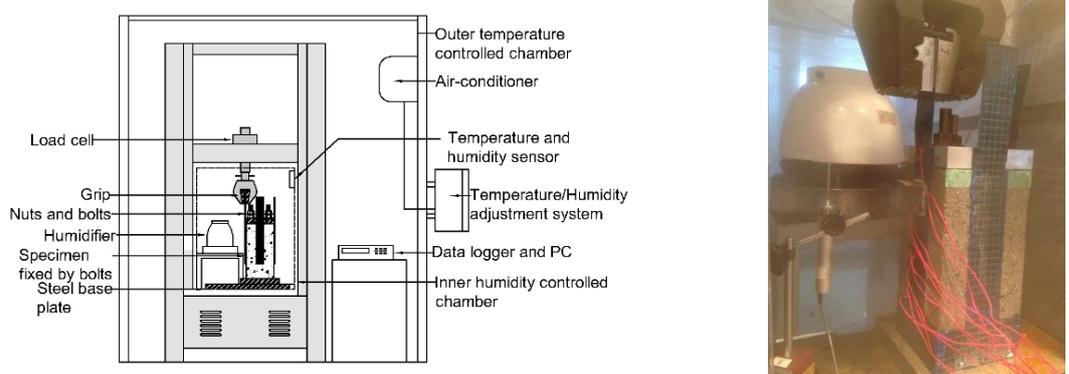


Figure 3-8 Test arrangement schematic for the bond specimen inside the environmental testing chamber (left) and specimen during the test under moisture condition (right)



Figure 3-9 Direct pull-off test

3.2.4 Test Procedures and Instrumentation

Tensile test of the resin samples were conducted with a universal testing machine (UTM) at the loading rate of 2 mm/min. The shear bond specimens were also tested using the same UTM. For the setup of the bond specimens, four long bolts were inserted through the preset plastic pipes inside the concrete prisms and then fixed at the base of the machine. Reaction steel plate was put on top of the concrete prism through the bolts and fixed properly. The specimen was adjusted in position to make sure that the FRP-concrete bond line is aligned with the center line of the upper loading grip. The loading speed of the upper grip was set as 0.2 mm/min. The pull-off test was conducted in accordance to JSCE-E-545 [2]. Manual loading portable adhesion testing device of maximum capacity of 10 kN was used. Loading was applied in the rate of 5-10 kN per minute. Three specimens were tested for each exposure condition in order to ensure the reliability of the obtained results.

3.3 RESULTS AND DISCUSSION

3.3.1 Moisture absorption by epoxy resin specimens and its effect on the mechanical properties

To address the moisture effect on the FRP-concrete bond properties, it is crucial to know the effect on the constituent material properties. In this regard, it is necessary to understand the moisture transportation, absorption characteristics and its influence in the mechanical behavior of the epoxy resins. Therefore, water absorption was monitored in the epoxy samples at different interval of time using gravimetric method. The exponential rising curve showed the closest fitting to represent the relationship between water absorption and the exposure duration in months as shown in Figure 3-10. The regression coefficient in all the cases were greater than 0.98. The diffusion rate of water and the absorption capacities were found to be varied greatly based on the resin type. However, even after 18 months of water immersion, none of the resin specimens are fully saturated. Previous literatures have reported the water absorption by the epoxy resin in the range between 1 to 7% by weight based on their formulations [3]. There are several existing theories on the factors contributing to the moisture absorption. Struik proposed that the quantity of water absorbed is dependent on the amount of free volume which depends on the molecular packing and is affected by the crosslinking density and the physical aging [4]. In contrast, Li et al. proposed that the free volume is not a decisive factor but the polarity of the resin system plays a key role [5]. Soles et al. suggested that the polarity is the significant factor in determining the ultimate moisture uptake, however, the free volume fraction also influences the moisture uptake [3]. The above discussion may also explain the possible reasons of large variation in the moisture absorption capacities shown by the resin specimens. The maximum water absorbed by the resins was found to be in the range of 0.71% to 2.65% after 18 months of immersion in water. Five of the cases (TR-A, TR-B, TP-B, TR-C, TR-D) showed similar water absorption behavior. On the other hand, the resin specimens, TP-A, TR-E and TR-F, showed relatively lower water diffusion rate and the water absorption compared to the other specimens. TR-E and TR-F contain higher filler materials (silica, calcium carbonate etc.) which could have also contributed towards lowering the free volume inside the resin resulting in the lower absorption. Tu and Kruger reported similar nature in which higher filled adhesive showed lower water absorption by the resin specimens [6].

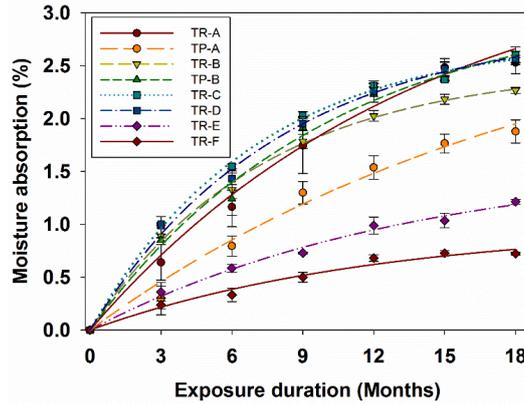


Figure 3-10 Moisture absorption by epoxy resin specimens

Figure 3-11 shows the relationship between average tensile strength and water absorption. Basically two different trend of results could be observed in the figure. Except resins TR-B and TR-C, all the other cases show decreasing trend with the increase in moisture absorption but the degree of its effect varies greatly. The highest reduction in tensile strength occurred in the resin TR-F with an average reduction of around 38% but the overall water absorption was the least (0.71%) compared to the other cases. In contrast, 11% to 22% average tensile strength was reduced for some of other specimens, while the water absorption is greater than 2%. In two of the cases, TR-B and TR-C, no reductions were found despite of absorption of about 2% water by the specimens. Therefore, all the above discussion brings to a point that the durability of the resins are highly dependent on the materials and the amount of water absorption alone cannot be used as an indicator to judge or predict the damages caused by itself.

Figure 3-12 shows the relationship between average tensile strength and the exposure duration. The trends are similar to the relationship between moisture absorption and the tensile strength, as the moisture absorption by the resins increased with the exposure duration. Except for TR-B and TR-C types, reductions in tensile strengths were observed in all cases and the reasons could be due to harmful effect of water on the epoxy resins such as plasticization, hydrolysis, cracking and crazing etc. [7]. In contrast to the tensile strength behavior, the tensile modulus was not significantly affected by the exposure duration as shown in Figure 3-13.

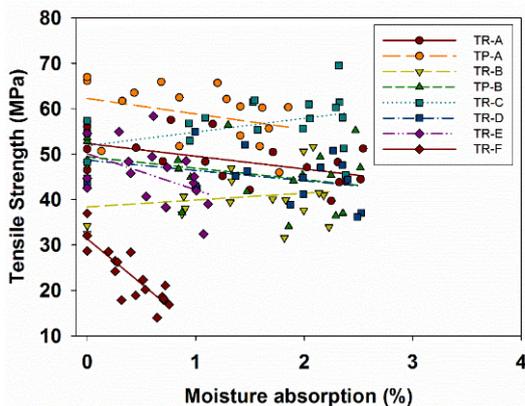


Figure 3-11 Relationship between tensile strength with the moisture absorption by the resins

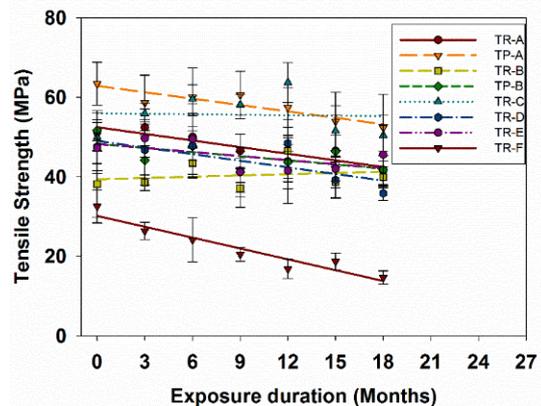


Figure 3-12 Immersion duration effect on the tensile strength of the resins

Figure 3-14 and Figure 3-15 show the comparison of the tensile strength and modulus of the resin specimens respectively tested under wet and dry condition. The results show that drying of the resins after 18 months of immersion in water does not recover the initial mechanical properties indicating that

the exposure to the moisture conditioning caused some irreversible effect in the resin properties. These irreversible effects could be due to loss of crosslinking density and permanent swelling damages due to the exposure in water [8]. It can also be observed that the testing under dry condition after the exposure seems to be more harmful than the wet case which could be due to the shrinkage in epoxy resins initiated due to removal of moisture from the specimens while drying process which further reduced the mechanical properties.

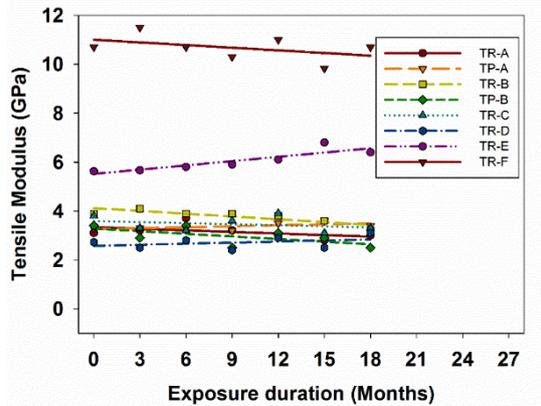


Figure 3-13 Immersion duration effect on the tensile modulus of the resins

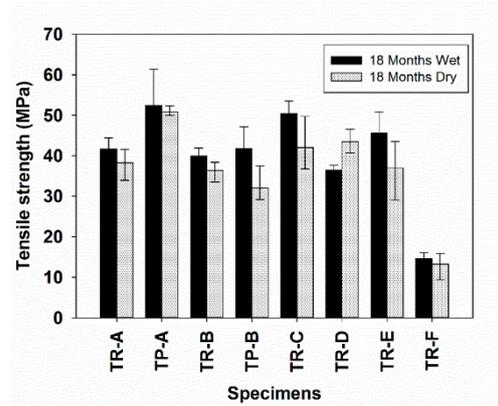


Figure 3-14 Resin tensile strength comparison after 18 months of immersion and different testing conditions

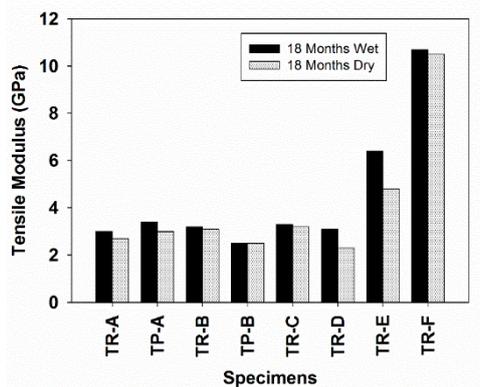


Figure 3-15 Resin tensile modulus comparison after 18 months of immersion and different testing conditions

3.3.2 Effect of moisture on the shear bond failure modes

Mainly three different failure modes were observed, which are cohesion failure at the concrete layer (C) (Figure 3-16a), mixed failure at the concrete and concrete-resin interface (M) (Figure 3-16b) and finally the interface failure between concrete and resin layer (I) (Figure 3-16c). Among above three, concrete cohesion failure is the common mode of failure under normal environmental condition. This failure mode indicates good adhesion bond between the FRP and concrete. This kind of failure mode was mainly observed in specimens SB-A, SB-E and SB-F before exposure. The mixed failure mode here is defined as the partial failure in concrete cohesion and resin-concrete interface adhesion failure. The failure percentage in concrete to the resin-concrete interface even varied within the similar exposure condition among the specimens. Nonetheless, no distinction is made between such cases and generalized into one group as mixed failure mode. Such mode of failures occurred in specimens SB-B and SB-D before exposure. The last failure mode is the adhesion failure at the interface between resin and concrete. This failure mode is the least desired as it implies either insufficient surface preparation or the weak adhesion bonding of the resin with the concrete. The latter could be the reason for this case as similar degree of surface preparation was done in all the systems. Only specimens in SB-C system showed adhesion failure even before exposure.

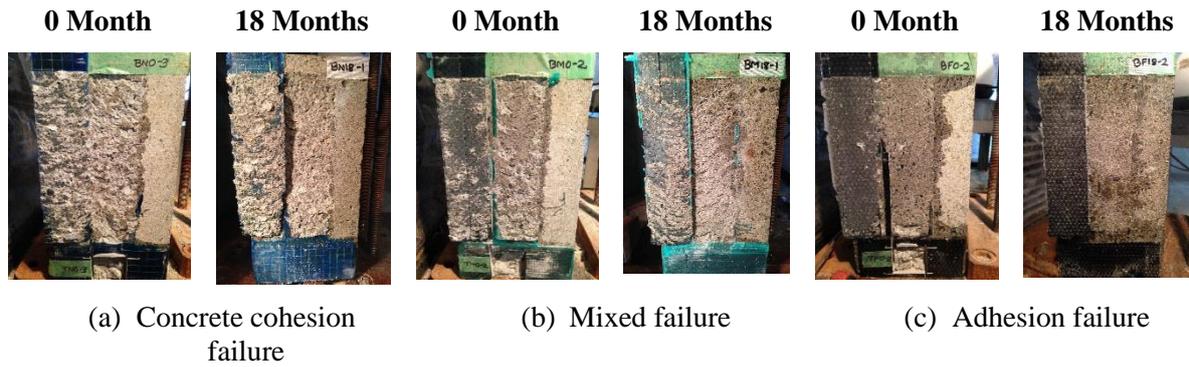


Figure 3-16 Comparison of three typical failure modes before and after 18 months of exposure

Transition of failure mode from the concrete cohesion failure to either mixed or interfacial failure was observed due to effect of immersion in water. Most of the specimens in SB-A, SB-B, SB-E and SB-F showed such transitions after the exposure. Likewise, the mixed failure mode before the exposure either retained the same or changed to interfacial failure in cases like SB-B and SB-D. Lastly, the interfacial failure cases observed in SB-C retained the same failure modes irrespective of the exposure and its duration. Even drying the specimens after 18 months of immersion did not show any differences in failure modes. All the specimens tested under such condition either failed as mixed mode or at the interface between resin and concrete. The above mentioned modes of failures for all the specimens after different exposure durations are summarized in Table 3-4. In general, the propagation of failure occurred from concrete cohesion towards the interfacial failure with prolonged exposure duration.

Table 3-4 Summary of failure modes for the shear bond

Exposure duration (Months)	Testing condition	Failure modes																	
		SB-A			SB-B			SB-C			SB-D			SB-E			SB-F		
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
0	Wet	C	C	C	C	M	C	I	I	I	M	M	M	C	C	C	C	C	C
3	Wet	C	C	C	M	M	C	I	I	I	I	I	I	C	C	C	M	I	C
6	Wet	C	M	C	C	M	C	I	I	I	I	I	I	C	C	C	M	M	M
9	Wet	C	C	C	M	I	M	I	I	I	I	I	I	C	C	C	C	M	M
12	Wet	M	M	C	C	M	I	I	I	I	I	I	I	C	C	M	C	M	M
15	Wet	C	M	M	M	I	M	I	I	I	I	I	I	M	C	C	M	M	M
18	Wet	C	M	M	M	M	I	I	I	I	I	I	I	M	M	M	M	M	C
18	Dry	M	M	M	M	M	I	I	I	I	I	I	I	-	-	-	M	M	M

C=Concrete cohesion; M=Partial concrete cohesion and resin-concrete interface; I=Resin-concrete interface

It can be also be observed that among four different carbon fiber sheet bonding systems, the ones with primer layer showed better adhesion bond at the interface as greater percentages of failures occurred in the concrete layer before and after the exposure. This gives an impression that the primer layer could play an important role in determining the durability of bond between FRP and concrete but no further detailed investigation was carried out to validate this hypothesis. In a separate study [9], the authors confirmed the effect of primer and surface preparation on the FRP-concrete bond interface without any form of environmental exposure. Comparison was made between the specimens with/without the primer layer. The results revealed no additional benefit of applying primer layer in terms of shear bond strength and direct pull-off strength. The failure modes also remained unchanged irrespective of the specimens without the primer layer.

3.3.3 Moisture effect on the shear bond strength

Figure 3-17 shows the variation of the average shear bond strength with the exposure duration. In all of the cases, the exposure seems to have an immediate effect showing reduction in bond strength at 3 months which was retained in most of the cases in extended exposure duration. It is also evident that the bond strength increased significantly in case of SB-F specimens after 3 months of immersion till the 9 months and then remained almost constant till the 18 months. As for SB-E specimen, the bond strength remained fairly unchanged until 9 months exposure period followed by a small increase in 12 month which remained almost constant until the 18 months. For rest of the cases, it is rather difficult to see the clear trend from the figure due to overlapping of data points. Therefore, to get the clearer picture of the changes in relative bond strengths with the exposure duration, the average shear bond strength for immersion cases is normalized by the non-immersion case (0 month case) as shown in the Figure 3-18. Based on the changes in the average bond strength with the exposure duration, results could be categorized into 3 groups.

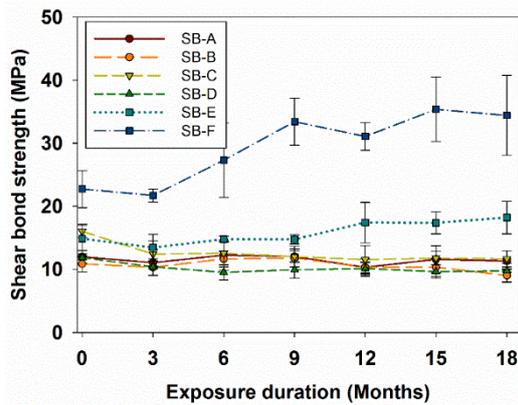


Figure 3-17 Shear bond strength variation with the exposure duration

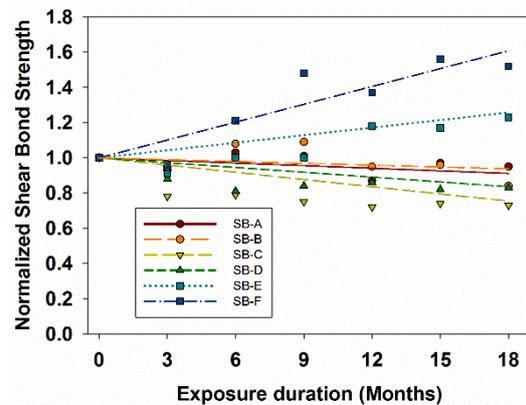


Figure 3-18 Relationship between normalized shear bond strength and the exposure duration

First group includes specimens SB-A, SB-B and SB-E in which the change in average bond strength between the immersion and non-immersion case is less than 5%. Such changes are considered insignificant in terms of overall bond strength and hence categorized as the unaffected by exposure condition. As for the duration of immersion period, there is no strong correlation between the change in the bond strength and the exposure duration. The failure modes for these sets remained either as concrete cohesion or the mixed mode after such exposure.

The second group includes SB-F type specimen which is the FRP plate bonded to the concrete which shows significant gain in bond strength after exposure. Compared to the non-immersion case, the average bond strength increment of 34% was found after immersion case implying some positive effects of water on the bond properties. This increment in the bond strength was mainly initiated after 6 months of exposure duration. This result is in contrast to some of the previous reported results in which the CFRP plates bonded to concrete specimens performed poorer than the sheets [10, 11]. Despite the better properties of FRP plate compared to the sheet, the main reason for such poorer performance is attributed to durability issues of the epoxy adhesives used in such systems. Normally, the adhesive of plate is relatively thicker than the case of sheet bonding, thus making it more vulnerable to the environmental related deteriorations. Even in the present case, the epoxy adhesive used for this system showed significant degradation in the mechanical property but that effect was not reflected in the ultimate bond strength as the failure occurred at concrete cohesion layer. This indicates that the shear strength of the degraded adhesive is still higher than that of the concrete but this still doesn't explain the reason for enhancement in the bond strength. Similar increase in bond strength was also reported by Al-Tamimi et al. and the reason for such increase in strength was attributed to the enhancement of the polymer strength due to the temperature [12]. But in the present case, the temperature from initial curing of specimens to the exposure condition and then the testing temperature was always close to 20°C so such

post curing due to the temperature is highly unlikely. Further, the specimens were cured for more than a month before exposing them into water which was considered as a sufficient period for proper curing of the resins. There are some other possibilities as well which could justify such improvement in the shear bond strength after exposure. The first one could be due to increment in the concrete strength due to better curing conditions provided by curing under water but, the results obtained from the concrete compression test as presented in Figure 3-19 clearly showed that the compression strength remained fairly constant throughout the exposure duration implying no enhancement in concrete properties. In addition to that, despite of being the same batch of concrete, specimens such as SB-A and SB-B did not show any increase in bond strength even though majority of the specimens failed at concrete cohesion as similar to SB-F. Therefore, these explanations totally eliminates any chances for concrete to be the reason for strength enhancement. Other remaining possibilities for improvement in the ultimate bond strength due to increase in the stiffness of FRP or the softening of the resins due to exposure could also be ruled out. The stiffness of FRP didn't change after exposure which was calculated by a strain gauge attached on the unbonded part during the shear bond test and the earlier discussion on the tensile modulus of the resin indicates no significant reduction in the modulus. Thus improving the load transfer mechanism between the FRP and concrete due to exposure is still unknown and under investigation.

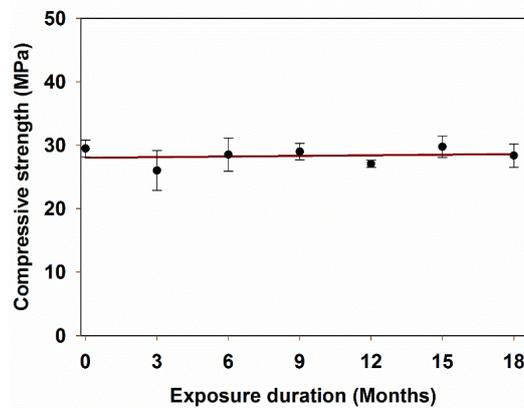


Figure 3-19 Effects of exposure on concrete compressive strength

The third category of the specimens SB-C and SB-D were significantly affected by the exposure in terms of bond strength. The average loss in bond strength after the exposure are 25% and 16% respectively. Significant reductions can be observed in just 3 months of exposure duration which after that remained almost in the same range throughout the exposure duration. This indicates that the effect of moisture on the bond strength can be reflected in a very short duration of time. The failure modes are also distinct in these two systems. In contrast to the remaining systems, which mostly failed by concrete cohesion, specimens SB-C and SB-D showed failure at the interface between concrete and resin layer. Despite the similar degree of surface preparation, the failures at the interface even before the exposure implying weaker adhesion between them. At the interface between concrete and resin, mechanical and chemical bond are two key mechanisms which govern the bond action [13]. The reduction in bond strengths after the exposure indicates that either one or both of the mechanisms are affected by the presence of water. Water at the interface can degrade the mechanical interlocking action or combine with the epoxy components to destroy the adhesion bond at the interface. These two factors may have contributed towards the reduction of the bond strength. The degradation of mechanical interlocking capacity at the epoxy-concrete interface due to absorbed water was also reported by Dolan et al. [11]. In summary, the effect of water is prominent in cases when the surface roughness is not sufficient enough or the adhesion bond between resin and concrete is not stronger enough, resulting in the adhesion failure at the interface. In such condition, significant loss in bond strength could occur after immersion. Similar result was also observed by Shrestha et al. when FRP bonded to high strength substrate concrete failed at the interface after immersion in water [13]. A year of exposure in water resulted in 30% and 32% reduction in average bond strength respectively for two types of specimen with different primer layer. In the same research, such deterioration of bond strength was not observed for normal strength concrete substrate when same FRP systems were used for the same exposure

condition. The failure surfaces in those cases were always mixed type. These evidences and discussions could clearly demonstrate the interfacial failure of bond as the most severe case at which the water deteriorate the bond strength significantly. It also highlights the necessity of proper surface preparation of the substrate concrete and the use of appropriate epoxy resin with higher adhesion strength to ensure stronger bond at the interface than the adjacent layers and remain durable against the moisture environments.

The effect of testing the specimen in dry condition was also examined which was compared with the same duration of immersion as shown in Figure 3-20. About less than 5% recovery of average bond strength was found in specimens SB-C and SB-F whereas over 10% in case of specimen SB-A and SB-B but no such effect was observed in SB-D case. In conclusion, even though recovery of bond strength was noticed in some cases after drying, it could not restore back to the original bond strength which were already deteriorated due to exposure in water.

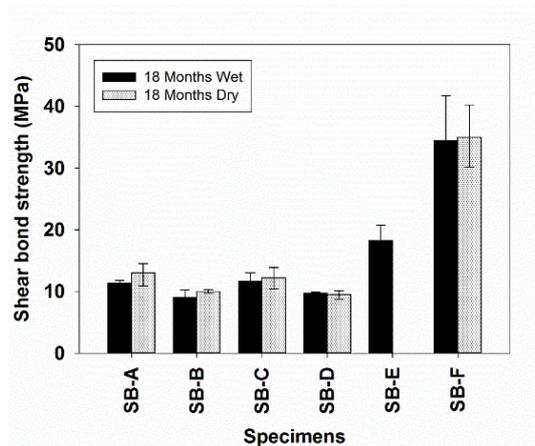


Figure 3-20 Effect of shear bond strength after 18 months immersion and different testing conditions

3.3.4 Moisture effect on the tensile bond strength

The pull-off test method is a simple method to evaluate the quality of tensile bond in the field. This method was used to determine the relative performances of FRP-concrete bond under different durations of immersion in water. The result of the pull-off test is shown in Figure 3-21. Due to large scatter of the data points, it is quite difficult to predict the trend of tensile bond strength with the exposure duration, however, comparison of average tensile bond strength indicates that there are some effects of the water. Few of the data points after exposure are even below the minimum pull-off strength value of 1.4 MPa which is recommended by ACI 440 committee [14]. As also observed in the shear bond test results, the water seems to have affected the tensile bond strength immediately after 3 months of exposure. The tensile bond strengths were significantly reduced for most of the cases. Except specimen type TB-B, the average reduction in the tensile bond strength varied from 19% to 41% in average after the exposure up to 18 months. Some of the other researchers have also observed such reductions in tensile bond strengths after exposure to continuous immersion or wet-dry cycles but in most cases such reductions were accompanied by transition of failure surfaces from concrete to mixed or complete interfacial failures [15-18]. The reason for reduction was simply reported as the adverse effect of water at the interfacial bond between FRP-concrete interfaces. In contrast to the above reported results, no such transition of failure modes occurred after the exposure despite some reductions in the tensile bond strengths. The failures before immersion were in the concrete region (Figure 3-22) and it retained same failure mode even after exposure for most of the cases expect for three specimens. In two of those cases, there was a failure of steel jig bonding indicating improper bonding to FRP and the last one failed partially in concrete and concrete-resin interface. But in overall, it can be concluded that the majority of the failures occurred in the concrete region indicating that the FRP-concrete interfacial bond strength was higher than the tensile strength of concrete.

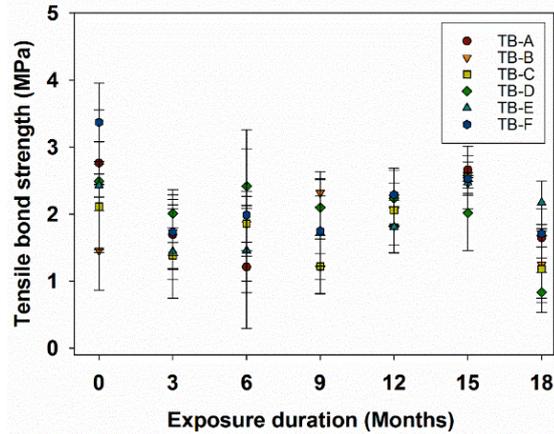


Figure 3-21 Variation of tensile bond strength due to exposure

Figure 3-23 shows tensile bond strength comparison tested under wet and dry condition after 18 months of exposure in water. Similar to the shear bond behavior, drying process helped recovery of the tensile bond strength but was not able to retain back the original state except specimen TB-B in which it was higher than the original strength. Even in the failure modes, no distinction could be made between those conditions as most of them failed in concrete.

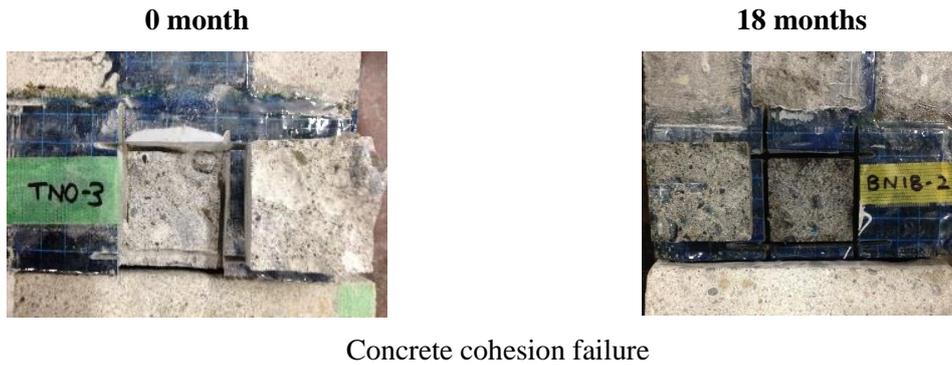


Figure 3-22 Comparison of typical failure mode before and after 18 months of exposure

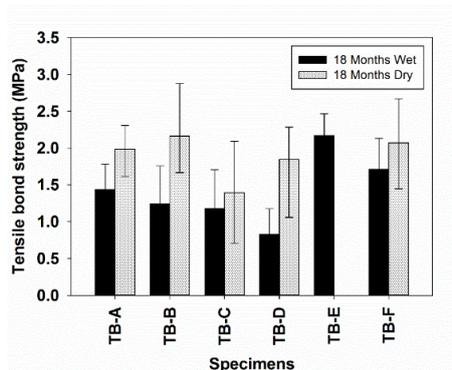


Figure 3-23 Effect on tensile bond strength after 18 months immersion and different testing conditions

The results obtained from shear bond behavior and the tensile bond behavior does not correlate with each other. The shear bond tests showed three different set of behavior in response to moisture condition whereas the pull-off tests showed deterioration in most of the cases. Similar results were also reported by Nishizaki and Kato when durability of bond was confirmed after 14 years of exposure [19]. The

authors found reductions in tensile bond strength after the exposure but similar to the current results, all the failures occurred at the concrete. The authors argued that the slight decrease in the tensile bond strength does not necessarily indicate a change in adhesive properties of the bond between carbon fiber sheet (CFS) reinforcement and concrete, but could rather be due to a change in the mechanical properties of the concrete substrate. On the other hand, the peel characterizations were much more discriminant and showed large differences both in peel forces and failure modes.

In summary, the effect of exposure in water caused significant reductions in tensile bond strengths in most of the cases despite no obvious distinction between the failure modes. Continuous exposure in water for a long duration could cause some serious deterioration in the tensile bond properties which could be recovered to a certain extent after drying process. Failures mostly in the concrete regions and large scatter in data make this test inappropriate to fully understand the true mechanism of moisture related deteriorations in the tensile bond behavior. Nevertheless, the tensile bond strengths obtained here can be used as an indicative values to compare the relative changes in the performances over different environmental conditions.

3.4 CONCLUSIONS

The durability of FRP-concrete bond interfaces for six commercially available FRP systems were evaluated with single lap shear bond test and direct pull-off test together with moisture absorption and tensile test of resin. Based on the observed results of immersion for the period of 18 months, following conclusions can be drawn:

1. The water absorption capacities of the resin varied greatly from 0.71% to 2.65% after 18 months of immersion in water at 20°C. The water absorption by the resin proved to be harmful affecting the tensile strength in most of the cases but no strong relationship was found between amount of moisture absorption and the tensile strength. In contrast to the strength behavior, the modulus was not much affected by such exposure.
2. In response to moisture exposure, the shear bond behavior either showed no effect, positive effect or significant reductions in the bond strength depending on the FRP systems. There was an increase in average bond strength of about 34% in case of SB-F type but in contrast, there were reductions of 16% and 25% respectively in SB-C and SB-D types. Less than 5% change in bond strength was observed for remaining specimen types SB-A, SB-B and SB-E after the exposure. It can also be concluded that longer duration of exposure does not necessarily mean greater effect. At the later stages of exposure duration, the bond strengths almost remained constant.
3. As for the failure modes in shear bond tests, three typical failure modes were observed, which are concrete cohesion failure, partial concrete cohesion and resin-concrete interface failure and lastly interface failure between resin and concrete. As an effect of water immersion, transition of failure modes occurred from concrete cohesion to mixed mode or interface failure but significant reductions in bond strength were observed only in cases of complete interface failures. This emphasize the importance of proper surface preparation required in substrate concrete and use of the resin with good adhesion bond strength with concrete to ensure durability of FRP-concrete bond against moisture related damages.
4. Tensile bond strengths obtained from direct pull-off tests were reduced significantly in most of the cases after exposure, but the failure modes, which were concrete cohesion failures remained unchanged. This fact suggests that there are some harmful effects of water immersion in tensile bond properties.
5. Comparisons were made for specimens exposed to 18 months in water and then testing them under wet and dry conditions to evaluate the irreversible damages occurred due exposure. In general, the results revealed that the mechanical properties of the resins were further deteriorated after drying, but in contrast, both the shear and tensile bond strengths were partially

recovered but the original strengths were not restored. These results indicate that the damages caused due to exposure in moisture are irreversible.

6. Durability evaluation of 6 FRP-systems revealed that the environmental related deteriorations are highly dependent on the materials under investigation. From the current set of systems, the wet-layup systems performed poorly than the factory impregnated systems.

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Chapter 4

4. MOISTURE EFFECT ON THE FRP-CONCRETE INTERFACE BOND WITH DIFFERENT SURFACE PREPARATION METHODS

4.1 INTRODUCTION

FRP is widely being used as a strengthening material all around the world due to its various advantages over other strengthening methods such as high strength, light weight and ease in construction. Numerous studies have already proved wide applicability of FRP in strengthening of concrete structures. Now the focus has shifted towards making this existing method more efficient and economical. This is possible by improving the bond behavior between substrate and the FRP composite by efficiently utilizing the high strength material properties. The bond interface properties are influenced by many factors such as resin, concrete strength, surface treatment method (i.e. surface roughness) etc. In presence of proper adhesion bond between substrate and FRP, the bond strength usually increases with the concrete strength and there are already some existing relations between bond strength and the concrete strength showing such behavior [1, 2]. However, surface preparation is one of the critical factors which can affect the bond behavior between FRP and concrete but it is often the most debatable issues among the researchers. There exists several different concrete surface preparation methods and usually the assessment of the surface roughness is performed qualitatively by visual inspection which varies greatly on the assessing person. Due to this reason, several quantitative techniques have been developed to measure the concrete surface roughness which are briefly reviewed by Santos et al. [3]. The most practical method was proposed by the International Concrete Repair Institute (ICRI), in which the surface is visually compared with the nine standard concrete surface profiles (CSP) of increasing roughness [4] (Figure 4-1). As for the required concrete surface roughness for FRP application, ACI Committee 440 [5] suggests the CSP of minimum 3 and recommends abrasive or water blasting method. In a study conducted by Al-Tamimi et al. [6], the effect of surface preparation method and the degree of surface roughness was investigated on CFRP-concrete bonding systems by pull-off test. Grinding method was recognized as the best among several other methods such as hammer and chisel, sand blasting and shot blasting. The optimum level of surface roughness was recommended from level 6 to 8 on ICRI samples. However, the above conclusions are based on only three CSP levels (4, 6 and 8) and failures in most of the cases were governed by the concrete cohesion strength. Iovinella et al. [7] performed shear test and pull-off test to determine the effect of different roughness levels and surface preparation procedures. The quantitative evaluation of the surface roughness is performed by the laser profilometer which analyzes a finite number of linear profiles and provides amplitude and slope of different parts along the profile. A single roughness parameter is introduced which is able to incorporate the amplitude and angularity of the surface. The authors were also able to establish relationship between roughness parameter with bond strength where, greater bond strengths were obtained for higher roughness values. Among different methods, bush-hammering and sand blasting methods were found to be the most effective than grinding and brushing. In contrast to these results, Yalim et al. [9] did not find any significant effect of surface roughness on the overall performance when flexural test of beams strengthened with two different FRP systems and three different surface roughness levels were carried out. The three different chosen surface profiles were CSP 1, CSP 2-3 and CSP 6-9 among which the smoothest and the intermediate surface profiles were achieved by grinding while the roughest one was obtained by the pressure washing. The study recommends CSP 2-3 level as a conservative measure even though CSP 1 was adequate according to the results.

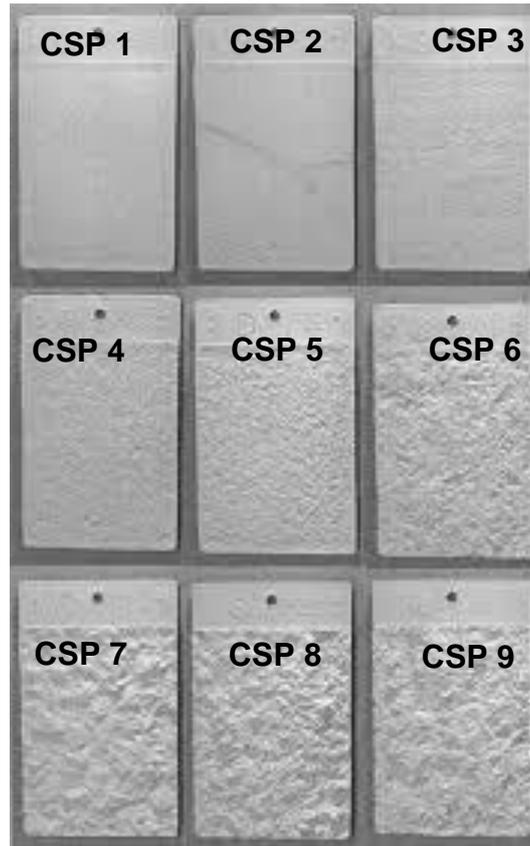


Figure 4-1 Plastic models concrete surface profile (CSP) by ICRI

As a brief summary of above literatures, it is clear that there have been quite a bit of study on the degree of surface roughness and the methods to understand their effects on the FRP-concrete bond behavior. However, those tests were only limited under laboratory conditions without any consideration of the external environmental actions which are usually experienced during its service life. Some of the previous literatures have reported transition of failure mode from concrete cohesion (Figure 4-2) to mixed failure between concrete cohesion and interface (Figure 4-3) after exposure in moisture conditions indicating that the bonds at the interface are affected by such exposures. This indicates that the interface between concrete and FRP is of prime importance under such conditions and it is necessary to understand the mechanisms associated with it. Basically, at the interface there exist two bond mechanisms which are chemical bonding and the mechanical bonding. Chemical bonding is due to hydrogen bonding and mechanical bonding is due to surface roughness conditions. The main objective of this chapter is to determine how the different surface roughness conditions affect the durability of FRP-concrete bonds with introduction of exposure to moisture conditions.

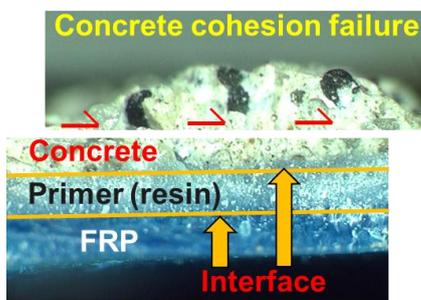


Figure 4-2 Failure without environmental effect

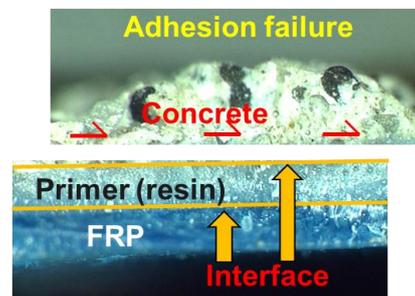


Figure 4-3 Failure after subjecting to environmental effect

4.2 EXPERIMENTAL OUTLINE

In order to generate concrete substrates of different surface roughness, the experiment is grouped into two parts based on the substrate surface preparation method. The first part includes shear bond durability of FRP-concrete with normal and high-strength concrete substrates treated with disk-grinding method. Whereas, the second part includes shear bond behavior between FRP and high strength-concrete treated with sand-blasting method.

4.2.1 Preparation of specimens

Early strength ready-mix concrete was used for this purpose of the mean cylindrical compressive strength of the concrete was 39.4 MPa. ASTM C39 [10] was followed to obtain compressive strength of cylindrical concrete specimens but the strength was calculated from the mean strength of one specimen tested at different ages (0, 1, 2, 3, 4, 6 months). The age of 0 month refers to 28 days after casting and remaining durations were in reference to this time.

For the high-strength concrete, several trial mixes were casted in the laboratory with an addition of liquid superplasticizer in order to get a balance between required strength and workability of the concrete. Around 140 liters of concrete was casted in two separate batches. The water/cement ratio was reduced to 0.22 by adding 1% superplasticizer (Rheobuild SP8HU) by the weight of the cement. Mix proportion for 140 liters of concrete is shown in Table 4-1. ASTM C39 [10] was followed to obtain the compressive strength of the concrete which was 88.6 MPa. The compressive strength was calculated from the mean strength of one specimen tested at different ages (0, 3, 6 months). The age of 0 month refers to 28 days after casting and remaining durations were in reference to this time.

Table 4-1 Mix proportion for high-strength concrete (140 liters)

Gravel	Sand	Cement	Water	Admixture
Kg	Kg	Kg	Kg	Kg
124.9	98.5	108.2	23.8	1.1

Two groups of concrete prisms were prepared of the dimension 150x150x300 mm. The first group of concrete prisms was treated with disk-grinder which includes both normal and high strength concrete, whereas, the second group consists of only high-strength concrete treated with sand-blasting method to obtain greater degree of surface roughness. Figure 4-4 shows the final prepared surfaces by both of the methods. Disk grinded method yielded CSP level 4 whereas the sand-blasted surface was equivalent to CSP level 7.

After the proper surface preparation of the concrete prisms, one layer of carbon fiber sheet was attached to the concrete for first group and two layers for the second group. The reason for putting two layers of FRP is to prevent the rupture failure of the FRP [11]. The same carbon fiber sheet along with the matrix (Epoxy-R) and primers (Epoxy-E and Epoxy-F) were used for this study. Properties of the FRP materials and the preparation of bond specimens are illustrated in earlier chapters. An additional epoxy putty layer was used in case of specimens treated with sand-blasting method in order to smoothen the bonding surface after applying the primer layer. The bond specimens in the first group were prepared with both the primer types, whereas, the second group the specimens were prepared with only Epoxy-F primer.

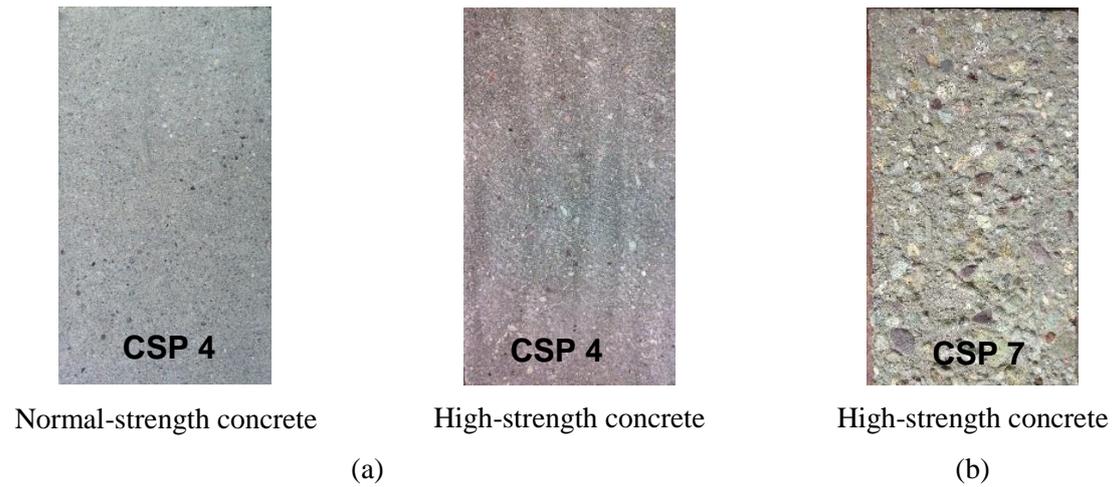


Figure 4-4 Concrete surface treated with (a) disk-grinding method (b) sand-blasting method

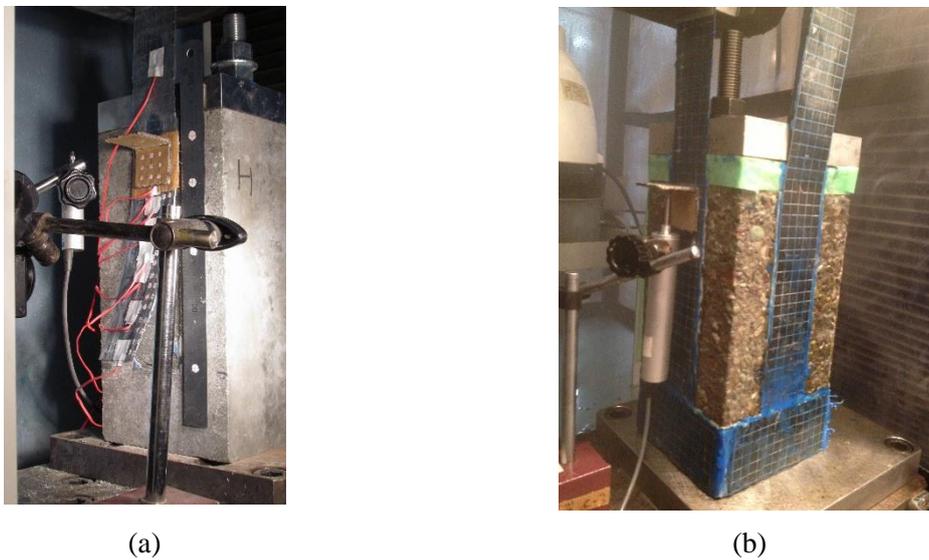


Figure 4-5 Demonstration of sample specimen during test for (a) Group-1 and (b) Group-2

4.2.2 Exposure and testing conditions

Both group of specimens were immersed in a water tank at 20 °C for different durations of time. The first group specimens were tested at laboratory conditions, whereas, the second group specimens are test in an environmental chamber which can control desired humidity and the temperature. Humidity over 85% and temperature $20\pm 3^{\circ}\text{C}$ was maintained during the test in the latter case. The detailed parameters along with number of tested specimens for each case are shown in Table 4-2.

Table 4-2 Parameters and number of specimen details

Exposure duration (months)	Number of specimens		
	Group-1		Group-2
	Normal-strength	High-strength	High-strength
	Type-E/F	Type-E/F	Type-F
0	3	3	3
1	1	-	-
2	1	-	-
3	1	1	3
4	1	-	-
6	1	1	3
9	1	-	3
12	1	1	3
15	1	-	3
18	1	-	-
24	1	-	-

Group 1: Disk-grinded substrate/single layer of FRP/testing environment not-controlled

Group-2: Sand-blasted substrate concrete/ 2 layers of FRP sheet/ high humidity temperature controlled testing environment

4.2.3 Measurement of roughness

To quantify the surface roughness of the concrete surface treated by different methods, a small 30x30 mm was scanned by three dimensional scanner (Figure 4-6) and roughness was calculated. The roughness is quantified by arithmetic mean value (Ra) which is the difference between the average height of the peaks and the average height of the valleys from an arbitrary baseline based on JIS standard (Figure 4-7) [12].



Figure 4-6 3D scanner to quantify the roughness

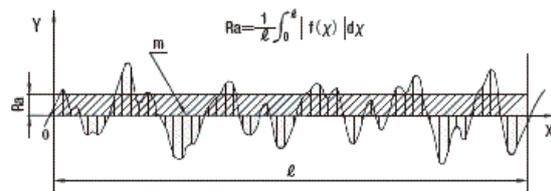


Figure 4-7 Evaluation of roughness

4.3 RESULTS AND DISCUSSIONS

4.3.1 Effect of the surface preparation method on the bond strength

Figure 4-8 shows effect of the surface preparation method on the shear bond strength. The concrete surfaces prepared with the disk-grinded method showed comparable bond strength irrespective of primer type and concrete strength. The high-strength concrete did not yield greater bond strength which is usually the case when the failure occurs by concrete cohesion. The failure modes in the normal-strength cases were by concrete cohesion indicating good adhesion between primer and concrete but the high-strength cases showed mixed failure with greater percentage of failure surface by adhesion at the interface. Such failure mode indicates that the adhesion bond between primer and concrete is

relatively weaker due to insufficient surface roughness. Figure 4-9 shows the surface profile of concrete generated by different methods of preparation. The arithmetic mean roughness (Ra) in high-strength concrete were calculated as 0.11 mm and 0.54 mm respectively for disk-grinded and sand-blasted surfaces [11], whereas, in the normal-strength case, it was 0.09 mm. The surface roughness by disk-grinding method showed very similar roughness values in both normal and high strength concrete case whereas the sand-blasting method generated substantially rougher surface. The average bond strength in the sand-blasted case was 30.27 MPa which is almost more than 2 times greater than the disk-grinded case. This is primarily due to greater mechanical interlocking effect as a result of higher surface roughness, but the contribution of 2 layers of FRP in the latter case cannot be denied. In order to negate that effect of stiffness and to see the sole effect of the roughness, this bond strength was reduced by 1.41 factor obtained from theoretical expression to get equivalent load for the one layer of FRP. This still yields 110% increase in bond strength compared to the disk grinding method. Disk grinding method was able to remove the top weak layer of mortar however, due to high strength nature of concrete, the grains were closely packed with fewer voids resulting in a comparatively smoother profile than necessary for high strength concrete. This induced premature debonding of the FRP from the concrete surface without utilization of the high strength property of the concrete. As a consequence, the failure occurred almost in the adhesion layer at primer-concrete interfaces, however, some concrete debris could be observed on the failed FRP sheets. This indicates premature interface failure due to inadequate bond between the primer and concrete. Whereas, for the sand-blasted case, its surface has lots of exposed aggregates and greater roughness due to which friction and mechanical interlocking effect increases because of increase in bonding surface area. This proves the importance of proper surface preparation required in case of high strength concrete.

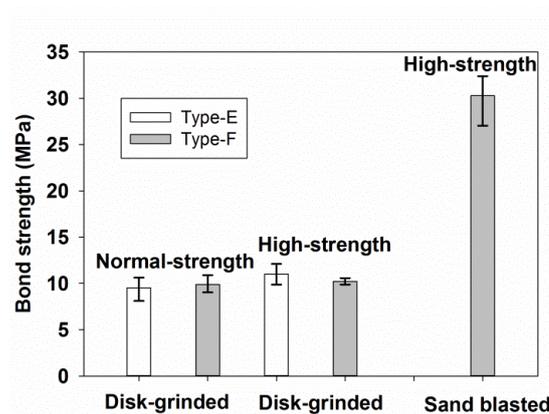


Figure 4-8 Effect of surface preparation method on the bond strength

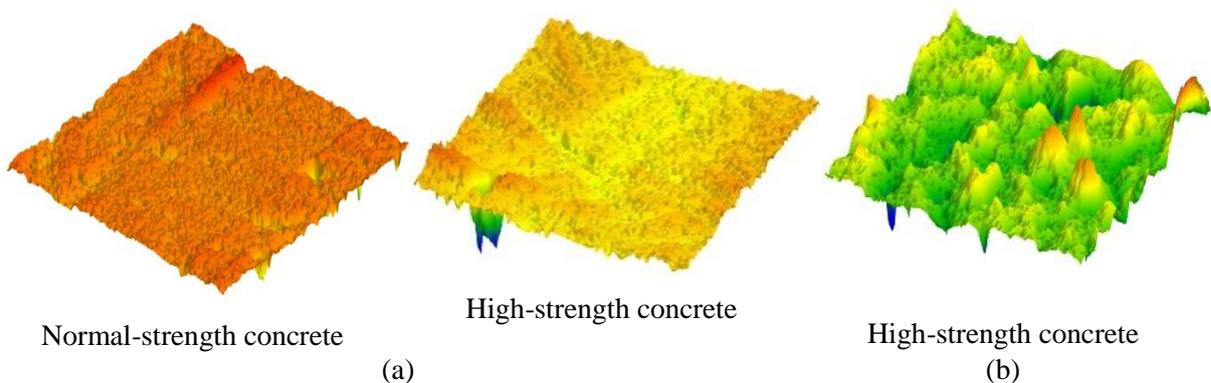


Figure 4-9 Concrete surface profiles in (a) disk-grinded surface (b) sand-blasted surface

4.3.2 Relation between shear bond strength and surface preparation method in moisture conditions

In high-strength concrete specimens treated with disk-grinding method, both Type-E and Type-F specimens showed greater loss in bond strength with the increase in immersion duration. As seen in Figure 4-10, the maximum bond strength reduced up to 32% after a year immersion into water. A similar decreasing trend was confirmed for Type-F specimens with reduction of 30% after a year of water immersion. The average reduction in bond strength after exposure for both the cases was around 28%. In contrast, the same high-strength specimens treated with sand-blasting method showed better bond durability despite use of the same FRP and the resins. As shown in the Figure 4-11, the effect of immersion did not significantly affected the bond strength. The average reduction in bond strength was less than 7% after 15 months of exposure in water. Similarly, the disk-grinded normal-strength concrete substrate cases also showed less than 7% reduction in bond strength in average after 24 months of exposure (Figure 4-12). In order to explain the effect of moisture and surface treatment of the bond strength, it is necessary to understand the adhesion mechanism at the interface.

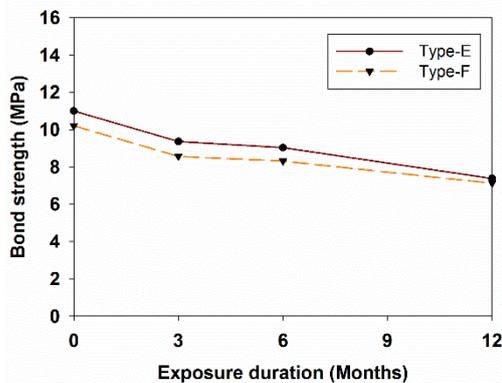


Figure 4-10 Effect of moisture on the bond strength for high-strength concrete treated with disk-grinder

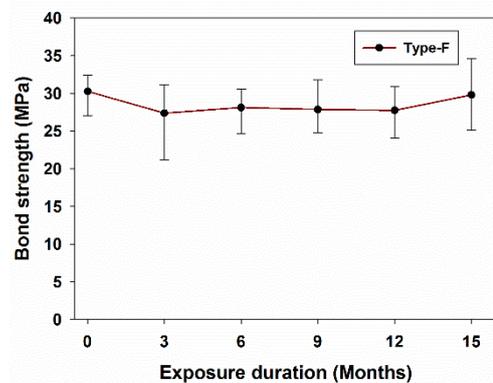


Figure 4-11 Effect of moisture on the bond strength for high-strength concrete treated with sand-blasting

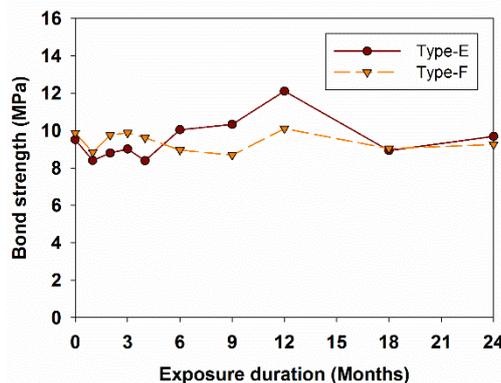


Figure 4-12 Effect of moisture on the bond strength for normal-strength concrete treated with disk-grinder

There are two key mechanisms which govern the bond between FRP composite and the concrete substrate at the interface. The first is the mechanical bond which is the function of degree of surface roughness, while the other one is the intermolecular forces or chemical bonds formed as a result of reaction between epoxy components (mainly hydroxyl group) with the substrate concrete. The amount of hydroxyl groups is dependent on the epoxy resins so use of same resin on both the surfaces eliminates the possibility of making such difference thus making the mechanical bond as the primary concern.

Mechanical bond works by forming interlocking action formed by penetration of resins into the pores, defects and surface roughness in concrete. Numerous articles have been published on the effect of surface preparation on the bond strength [6, 13]. Even though surface roughness is not the only governing parameter, usually surface having higher roughness yields greater strength due to larger bonding area. Therefore, in presence of good mechanical interlocking bond, the exposure due to water seems to have lesser harmful effects at the interface. Despite degradation of chemical bonds at the interface due to water, presence of mechanical interlocking action could still retain the bond strength between the concrete and FRP. In case of high-strength disk-grinded specimens, there is a weakening of adhesion bond at the interface by water but due to ineffective mechanical bond action, such large reduction in bond strength was observed. The failure mechanism in these two groups can be visualized as shown in Figure 4-13. This can be verified by observing the failure patterns before and after the exposure to the moisture environments. Figure 4-14 shows the influence of moisture in the failure modes for the high-strength concrete treated by different methods. The failure patterns in both the groups are distinctly different. In case of first group, both Type-E and Type-F showed weaker adhesion between concrete and primer resulting in the almost interface failure even before exposure in water. However, little concrete could be seen on the FRP sheets making it a mixed mode which is partial concrete cohesion and primer-concrete interface. This failure mode changed to complete adhesion failure at the interface after exposure in water for 3 months and retained same mode till the 12 months. This indicates harmful effects of water at the adhesion bond between concrete and the resin. The second group showed relatively good adhesion bond at the interface as a result of rougher surface. The mixed mode of failure could be observed before the exposure which remained almost similar throughout the exposure duration of 15 months. Nevertheless, very little concrete or aggregates could be seen for longer exposure duration cases.

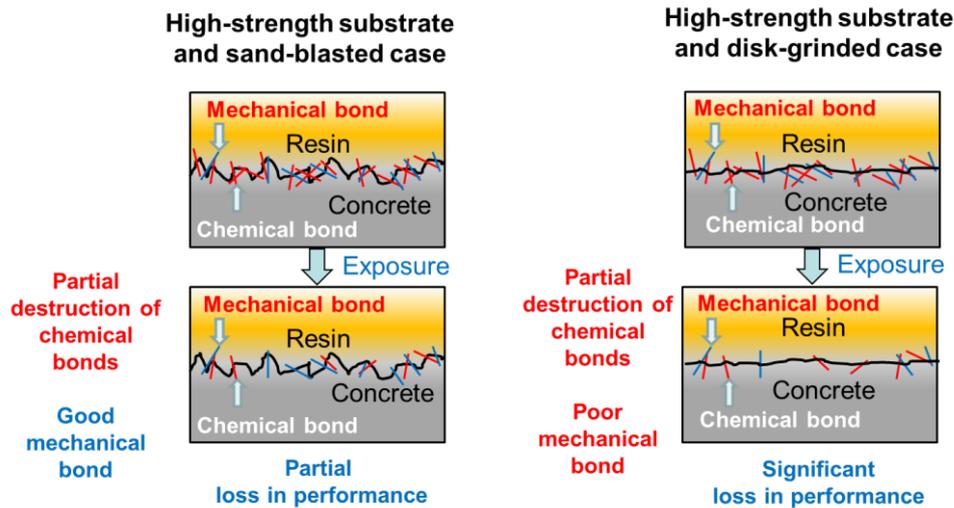


Figure 4-13 Visualization of bond failure mechanism before and after exposure in high-strength concrete substrate treated by disk-grinding and sand-blasting method

Exposure duration	Group-1 (Type-E)	Group-1 (Type-F)	Group-2 (Type-F)
0 Month			
	Mixed failure	Mixed failure	Mixed failure
3 Months			
	Adhesion failure		Mixed failure
6 Months			
	Adhesion failure		Mixed failure
9 Months			
			Mixed failure
12 Months			
	Adhesion failure		Mixed failure
15 Months			
			Mixed failure

Figure 4-14 Comparison of failure surfaces at different exposure duration for the high-strength case

In the normal-strength case (Figure 4-15), despite some effects of water, presence of good mechanical bonds prevented from such greater reductions of bond strength. There is a transformation of failure modes from concrete cohesion to mixed mode of failure after exposure but none of the cases failed at complete adhesion failure like high-strength case. This indicates that disk-grinding method of surface roughness was adequate in the normal-strength case.

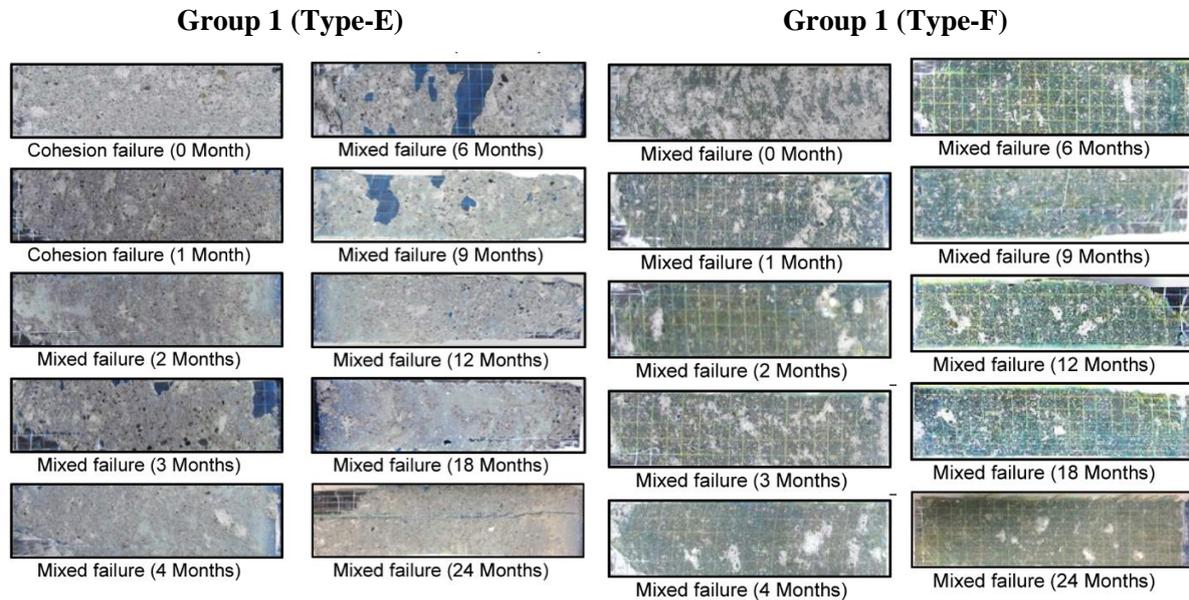


Figure 4-15 Influence of immersion duration in failure of normal-strength concrete substrate

4.4 CONCLUSIONS

The role of surface preparation in determining the durability of the bond between FRP and concrete under moisture conditions was examined for both normal and high-strength concrete. Following conclusions can be drawn out:

1. To ensure better bonding action between FRP and high-strength substrate concrete, sand-blasting method of surface preparation seems to be more appropriate than the disk-grinding method. The higher degree of roughness value can be obtained through the former method, thus increasing the mechanical interlocking action at the interface. Disk-grinding method to produce CSP level 4 or arithmetic mean roughness value of 0.09mm is found sufficient for the normal strength concrete (<40 MPa) whereas, for the high-strength concrete (90 MPa), sand-blasting method to generate arithmetic mean roughness of over 0.54 mm or CSP level-7 would ensure good bond between FRP and concrete.
2. The minimum surface preparation of CSP level 3 provided by ACI 440.2R may not be sufficient in all the concrete substrate cases. The high-strength concrete requires greater degree of roughness to fully utilize the material property effectively. More research is required to address the minimum surface preparation in such cases.

The unique relationship between the deterioration in the shear bond strength and the adhesion failure modes due to moisture condition was confirmed in the high-strength substrate case. The comparison of the results after water immersion test at 20 °C for 12 months duration confirms that the average bond strength reduction was around 30% for disk-grinded case whereas, the average bond strength reduction was only about 7% in case of sand-blasted specimens. As expected, failure mode changed to adhesion from mixed after exposure in case of insufficient roughness due to disk-grinded case but the mixed failure mode was retained in case of sand-blasted case when the surface roughness was sufficient. Presence of good mechanical bonds due to sufficient surface roughness could retain the bond strength despite some destruction of chemical bonds at the interface by water.

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Chapter 5

5. ANALYTICAL BOND-SLIP MODELS FOR FRP-CONCRETE BOND INTERFACE IN MOISTURE CONDITIONS

5.1 INTRODUCTION

A large number of bond tests for the FRP-concrete interfaces under shear have been carried out in the past. Basically, debonding failure models are categorized into three groups [1] 1) empirical models derived from a large amount of experimental data, 2) theoretical fracture analysis models, and, 3) fracture-mechanics based models with empirically derived parameters. Most of the test falls under first category with different bond testing methods such as single lap pullout test, double lap pullout test, shear bending tests etc. These studies have yielded several empirical bond stress-slip relationships which is the most important interface law that can determine the overall performance of the bonded members. Some of the empirically proposed bond stress-slip relations are given as follows:

1. Model based on Popovic's expression by Nakaba et al. (2001) [2]:

Nakaba et al. proposed local bond stress slip relation using Popovic's formula. The present model was derived based on relationship between the maximum bond stress average and the concrete compressive strength.

$$\frac{\tau}{\tau_{max}} = \frac{s}{s_{max}} \frac{n}{n - 1 + \left(\frac{s}{s_{max}}\right)^n}$$

where,

$$\begin{aligned}\tau_{max} &= \text{maximum local bond stress} = 3.5f'_c{}^{0.19}, \\ n &= \text{Popovic constant} = 3 \\ s_{max} &= \text{slip at } \tau_{max} = 0.065 \text{ mm} \\ f'_c &= \text{concrete compressive strength}\end{aligned}$$

2. Shear softening model by Sato et al. (2001) [3]:

Sato et al. considered effect of concrete strength and FRP stiffness in this local bond stress-slip relation. The bond stress-slip model consists of separate ascending and descending expressions.

$$\tau = \frac{\tau_{max}}{s_{max}} G_o D^* s \quad (s \leq s_{max})$$

$$\tau = \tau_{max} \exp(-10(s - s_{max})) \quad (s \leq s_{max})$$

where,

$$s_{max} = 0.8 \times 10^{-12} (E_f t_f)^{2.4} f'_c{}^{0.2} + 0.021 \quad (E_f t_f < 38.4 \text{ GPa} - \text{mm})$$

$$s_{max} = \frac{3100}{E_f t_f} f'_c{}^{0.2} + 0.034 \quad (E_f t_f \geq 38.4 \text{ GPa} - \text{mm})$$

$$G_o = 1 + \frac{25500}{E_f t_f} \quad (E_f t_f \geq 38.4 \text{ GPa} - \text{mm})$$

$$\tau_{max} = 9.1 f_c^{0.2} E_f t_f \times 10^{-5} \leq 3.49 f_c^{0.2}$$

$$D^* = 1 - \exp \left[\alpha \left(\frac{s}{s_{max}} \right)^{-\beta} \right]$$

$$\alpha = \ln \left(1 - \frac{1}{G_o} \right)$$

$$\beta = 0.2665 (E_f t_f)^{0.083} \leq 0.64$$

$E_f t_f = \text{stiffness of FRP}$

G_o, D^*, α, β are emperical constants

3. Hyperbola model obtained by regression proposed by Guo et al. (2005)[4]:

The hyperbola model was obtained by the regression of the ascending and descending branches of the measured bond stress-slip curves respectively. Separate equations were proposed for ascending and descending branches as follows.

$$\left\{ \begin{array}{l} \frac{\tau}{\tau_{max}} = 1.114 \left(\frac{s}{s_{max}} \right)^{0.488} \quad s \leq s_{max} \\ \frac{\tau}{\tau_{max}} = 1.3424 e^{-0.2578 \frac{s}{s_{max}}} \quad s > s_{max} \end{array} \right\}$$

where,

$$\tau_{max} = 0.7512 f_c^{0.5}$$

4. Model considering shear stiffness of the adhesives by Dai et al. (2005) [5]:

Dai et al. derived simple bond stress-slip relationship based on two parameters, the interfacial fracture energy and interfacial ductility index which take into account the effects of shear stiffness of the adhesives, stiffness of the FRP and the concrete compression strength.

$$\tau = 2B G_f (\exp(-Bs) - \exp(-2Bs))$$

where,

$$G_f = 0.446 (G_a/t_a)^{-0.352} f_c^{0.236} (E_f t_f)^{0.023}$$

$$B = 6.846 (E_f t_f)^{0.108} (G_a/t_a)^{0.833}$$

In case of common adhesives,

$$G_f = 0.514 f_c^{0.236}$$

$$B = 10.4$$

$\frac{G_a}{t_a} = \text{the shear stiffness of the adhesives}$

5. Savoia et al. (2003) [6]:

$$\tau = \tau_{max} \frac{s}{s_{max}} \frac{2.86}{\left(1.86 + \left(\frac{s}{s_{max}}\right)^{2.86}\right)}$$

$$\tau_{max} = 3.5f_c^{0.19}$$

$$s_{max} = 0.051$$

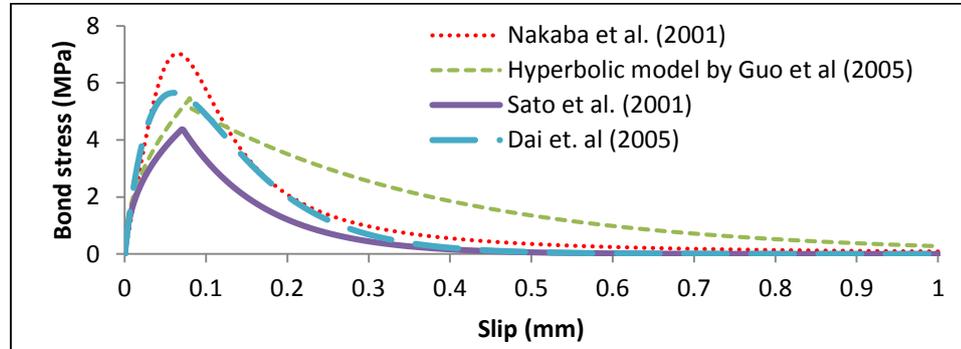


Figure 5-1 Different existing bond stress-slip models

All the models shown in Figure 5-1 shows quite variation in bond stress-slip shapes. These variations are caused due to use of dissimilar materials, different empirical constants, consideration of various governing parameters, way of formulation etc. Some of the most considered parameters by the researchers to formulate the bond stress-slip relationships are FRP stiffness, concrete strength, fracture energy, maximum bond stress and its corresponding slip value, adhesive shear stiffness etc.

In order to incorporate such scatter, Dai [7] proposed the analytical method of determining the nonlinear bond stress-slip model which has been widely accepted and used by other researchers. The proposed model is simple to use and can predict the ultimate pull-out load pretty well. However, the model does not incorporate the influence of environmental actions whereas during the service life of the structure, it undergoes through several different types of mechanical and environmental actions. Moisture is one of the key issue in case of marine environment. Past studies have reported some effects on the FRP bond and material properties. There are only few limited bond models incorporating moisture and other environmental effects.

Silva et al. [8] investigated the effect of moisture, salt fog and temperature cycles on the CFRP/GFRP-to-concrete joints for maximum period of 10,000 hours. The authors compared several indicators such as maximum bond stresses, ultimate slip, fracture energies, effective bond length before and proposed bond stress-slip laws taking in account of those effects. The authors followed similar approach proposed by Dai et al. [7] to predict the bond stress-slip curves but later introduced the environmental reduction factors to take care of different exposure conditions and FRP types. The proposed reduction factors for CFRP were similar as ACI 440 but higher in case of GFRP laminates. In another study, [9] identified the interface region relative humidity (IRRH) as the primary factor that affects the bond fracture energy of FRP concrete specimen in moist environment and the ultimate bond performance. From the experiment, IRRH and interfacial fracture energy at different durations were determined for the maximum period of 8 weeks, and based on the bond mechanism, a deterioration model was developed to describe the local relation between the interfacial fracture energy and the IRRH in moist environment [10].

Dai et al. [11] developed nonlinear bond-slip model for FRP laminates externally bonded to concrete at elevated temperature considering the existing test data of FRP-concrete bonded joints at temperatures ranging from 4-180°C. The authors modified the two parameter bond-slip model to account the influences of both temperature induced thermal stress and temperature induced bond degradation. The interfacial fracture energy was found to be decreasing after approaching the glass transition temperature of the bonding adhesive.

Yun et al. [12] developed an analytical model for bond-slip relationship similar to Dai et al. [7] but the authors used the measured slip distribution to propose bond-slip relation. According to the model, if the bond length is sufficient then the bond-slip relation for that region does not vary along the bonded area whereas, if the bond length is not sufficient then the bond-slip relation varies with the location. The same model was applied in case of freeze-thaw cycling and the curves were proposed in respect to the number of freeze-thaw cycles.

Ouyang and Wan [10] proposed a nonlinear deterioration model for bond interfacial fracture energy of FRP-concrete joints in moist environments. The authors correlated the bond interface region relative humidity (IRRH) in a moist environment to the bond fracture energy. IRRH was determined through diffusion analysis as a function of the moisture exposure time and environmental relative humidity.

All the above literatures points out that the bond stress-slip models incorporating the effects of moisture conditions are extremely limited. The main objective of this chapter is to propose bond-slip models incorporation the effects of moisture conditions.

5.2 ANALYTICAL APPROACH

5.2.1 Dai's approach

Dai et al. [7] developed a simple method to determine the local bond stress-slip relationships of FRP sheet-concrete interfaces which requires loaded end slip and strain in FRP. Based on the method, the authors proposed a simple interfacial τ -s relationship with only two parameters; interfacial fracture energy (G_f) and interfacial material constant B . The applicability of the method has already been verified with the experimental results and by comparison of the proposed τ -s relationship with other researchers. Brief theoretical background in presented hereafter.

The expression is given below:

$$\tau = 2BG_f(e^{-Bs} - e^{-2Bs}) \quad (1)$$

The above expression is derived by considering the relationship between the strain of FRP sheet and interfacial slip assuming the boundary condition of zero free end slip and sufficient effective bond length. The derivation of the above expression is shown in brief.

The relationship between FRP strain and interfacial slip at any location of FRP-concrete interface subjected to a pull load at the free end is given by

$$\varepsilon = f(s) \quad (2)$$

Where, ε is the strain of FRP sheets at any location; s is the corresponding slip at that location.

Dai et al. [7] used a simple mathematical function as given in Eqn. (3) which proved to represent the ε -s behavior with a good accuracy when compared with the experimental results.

The relation between strain and slip is given by:

$$\varepsilon = f(s) = A(1 - e^{-Bs}) \quad (3)$$

Where, A and B are experimental parameters obtained from the non-linear regression between the plot of strain versus slip relation. The physical meaning of A corresponds to the maximum strain in the FRP provided the bond length is sufficient and B can be regarded as the brittle index which controls the shape of the bond-slip curve [11].

In the FRP sheet-concrete interfaces, the interfacial bond stress can be expressed as:

$$\tau = E_f t_f \frac{d\varepsilon}{ds} = E_f t_f \frac{df(s)}{ds} f(s) \quad (4)$$

Differentiating Eqn. (4) with respect to s ,

$$\frac{df(s)}{ds} = AB e^{(-Bs)} \quad (5)$$

Substituting, Eqn. (5) in Eqn. (4), the bond stress-slip relation would be as follows

$$\tau = A^2 B E_f t_f e^{(-Bs)} (1 - e^{(-Bs)}) \quad (6)$$

The interfacial fracture energy G_f is defined by

$$G_f = \int_0^\infty \tau ds \quad (7)$$

By substituting Eqn. (6) into Eqn. (7) and simplifying, the following equation can be obtained.

$$G_f = \frac{1}{2} A^2 E_f t_f \quad (8)$$

$$A = \sqrt{\frac{2G_f}{E_f t_f}} \quad (9)$$

Finally, substituting (9) into (6) we get,

$$\tau = 2B G_f (e^{(-Bs)} - e^{(-2Bs)}) \quad (10)$$

The relationship for the ultimate pull-out load is given by

$$P_{max} = b_f \sqrt{2E_f t_f G_f} \quad (11)$$

The above approach was used to verify in case of different fiber sheet bonding cases. However, the validity was not yet confirmed for the strand sheet and plate bonding cases. Therefore, in this study applicability of Dai's methodology was confirmed in case of all three different external bonding reinforcements (CFS, CFSS and CFRP) systems in ambient condition. Table 5-1 show fairly good ratio of predicted ultimate load and experimental ultimate load. Dai's methodology was only developed for the ambient environment conditions, however, the applicability of the method in the case of other environmental exposures are still unknown. Therefore, the experimental data obtained from the shear test conducted at different moisture conditions were used to predict the ultimate load to check its applicability at different environment condition. Figure 5-2 shows the comparison of predicted and experimental ultimate loads. The figure clearly show over prediction of the ultimate load signifying that the moisture effect cannot be well incorporated. This could be mainly be due to inability of the method to capture the local deteriorations due to water at the interface. Therefore, the method needs to be modified in case of moisture conditions.

Table 5-1 Verification of Dai's approach using different FRP bonding systems

Fiber material	System	A	B	R ²	E _f (N/mm ²)	t _f (mm)	(P _{ana.})	(P _{exp.})	P _{ana./P_{exp.}}
CFS	SB-A-0	0.0077	10.96	0.948	230000	0.111	9.78	11.57	0.84
CFS	SB-B-0	0.0065	14.46	0.954	230000	0.111	8.33	9.82	0.85
CFS	SB-C-0	0.007	10.73	0.967	230000	0.218	17.52	15.81	1.11
CFS	SB-D-0	0.006	11.81	0.952	240000	0.176	12.65	11.77	1.07
CFSS	SB-E-0	0.0034	14.4	0.968	245000	0.333	13.71	12.49	1.1
CFRP	SB-F-0	0.002	17.44	0.969	210000	1.4	29.55	26.06	1.13

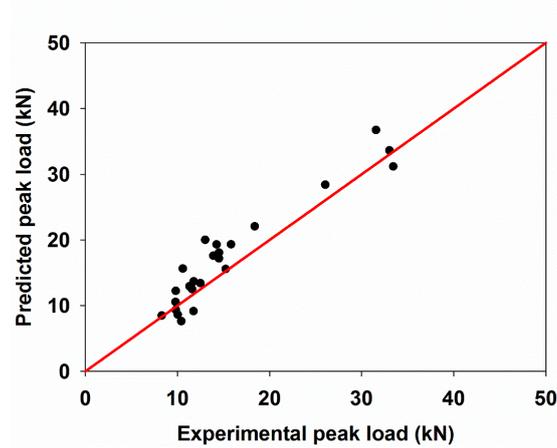


Figure 5-2 Comparison of predicted and experimental ultimate loads using Dai’s method

5.2.2 Modified approach to determine the bond-slip relations in moisture conditions

The brief steps to determine the bond-slip relations in moisture condition is shown in Figure 5-3. In the expression for ϵ -s, Dai used a single ϵ -s at the loaded end of the FRP to determine the experimental values of A and B by non-linear regression. However, in this study, the local responses at different locations were measured by the strain gauges and the corresponding slips at those locations were calculated by integration of those strain results. The obtained ϵ -s relations in such different locations were regressed using the same mathematical function as given in Eqn. (3) to determine a single regressed curve that could capture the average response of the ϵ -s distribution throughout the bonded length. The ϵ -s curves were determined in all the 6 FRP systems at different exposure durations by non-linear regression analyses which are shown in Figure 5-4 to Figure 5-9. The regression coefficients in all the cases along with their correlation factor are shown in Table 5-2. As it can be seen that, the value of correlation factor lies within the range of 0.92 to 0.97 showing a very good agreement between the proposed shape function and the experimental behavior. The figures clearly demonstrate differences in behavior of ϵ -s curves in response to the moisture exposure. The variations are in response to the different load transfer behavior between FRP composite and concrete. Specimens SB-C and SB-D show the greatest reduction in the peak strain values and increase in interfacial slip after exposure whereas specimens SB-E and SB-F show increase in peak strain after exposure. The effect is not clear in SB-A case and a small reduction in SB-B case.

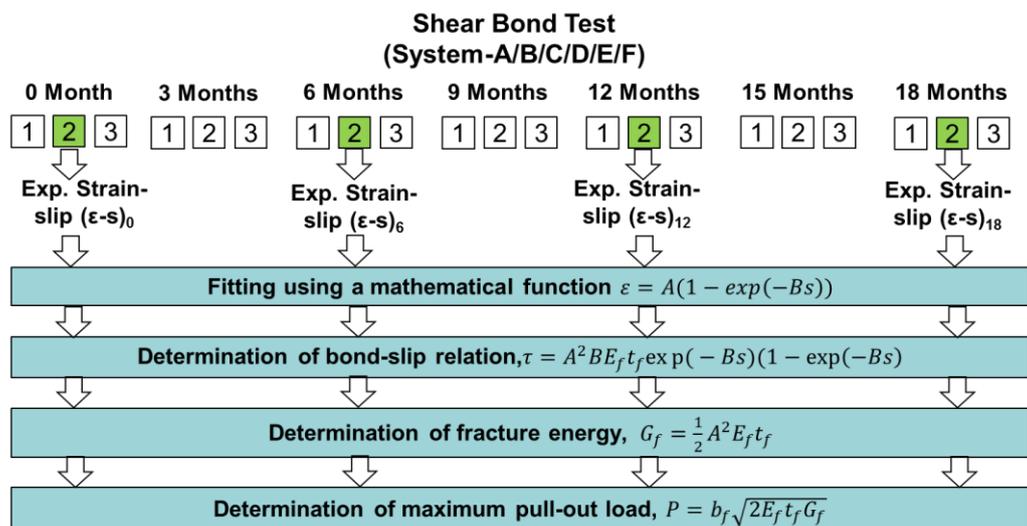


Figure 5-3 Brief procedure to determine bond-slip relations in moisture conditions

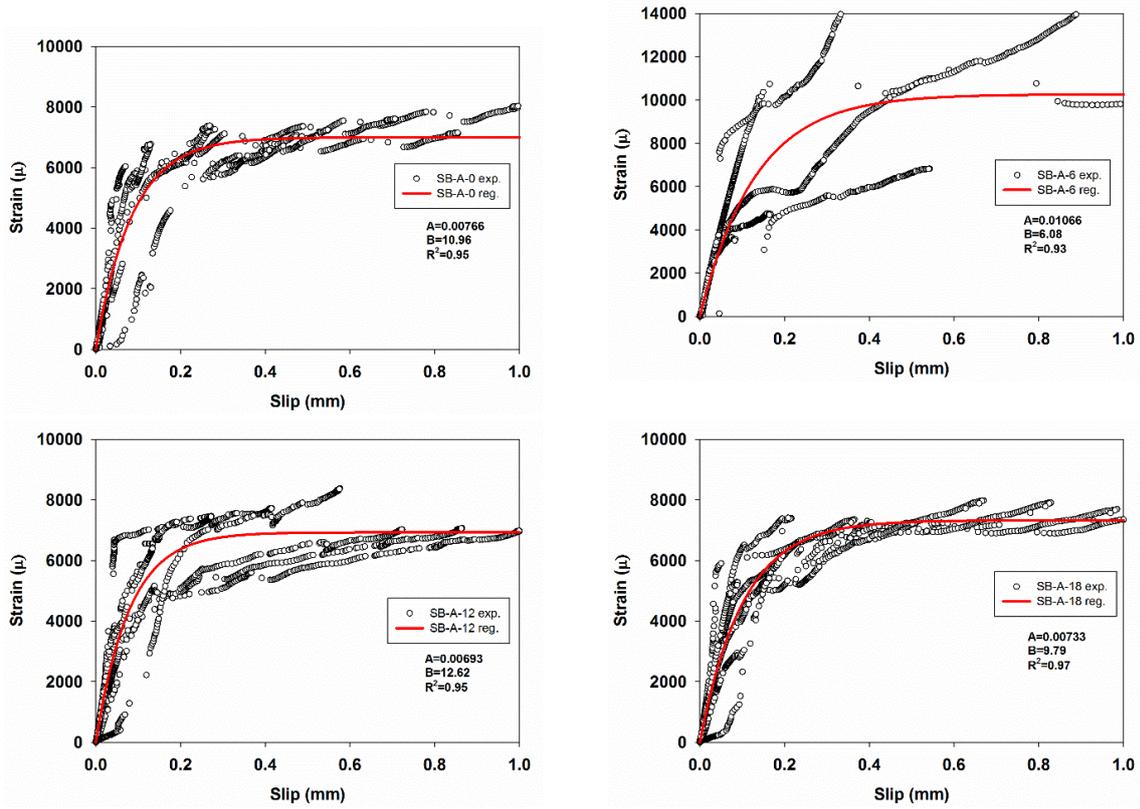


Figure 5-4 ϵ -s relations for SB-A systems at 0, 6, 12 and 18 months respectively

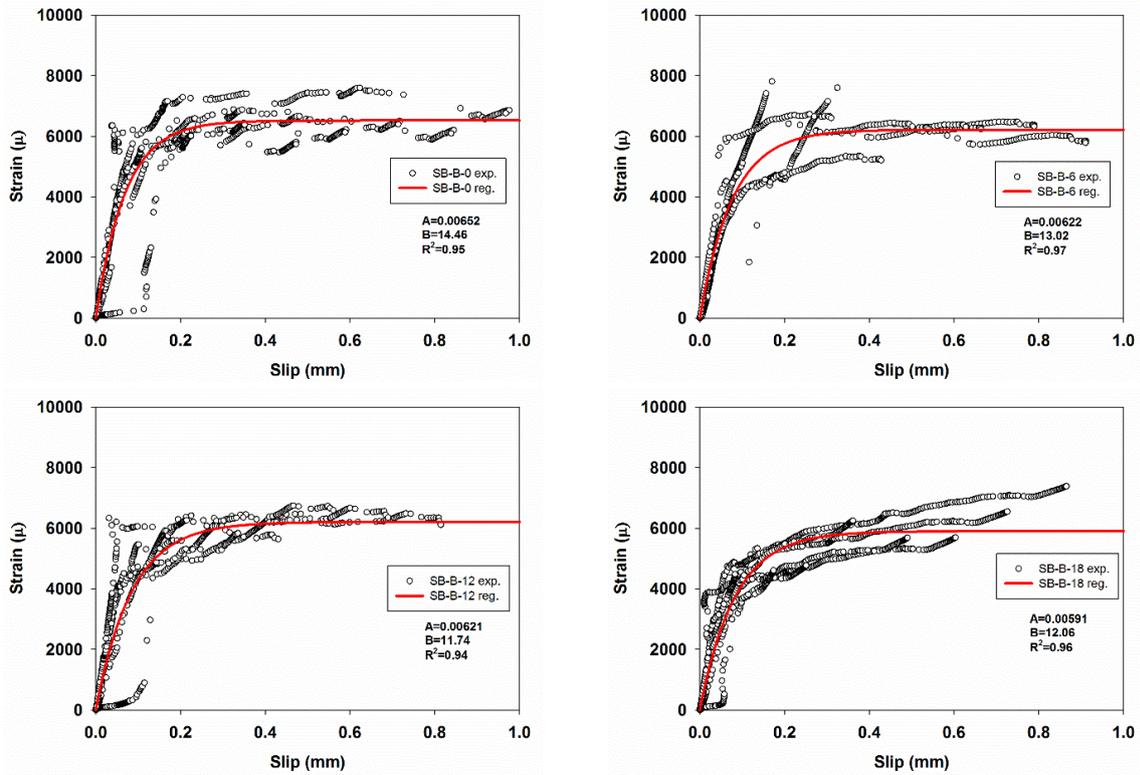


Figure 5-5 ϵ -s relations for SB-B systems at 0, 6, 12 and 18 months respectively

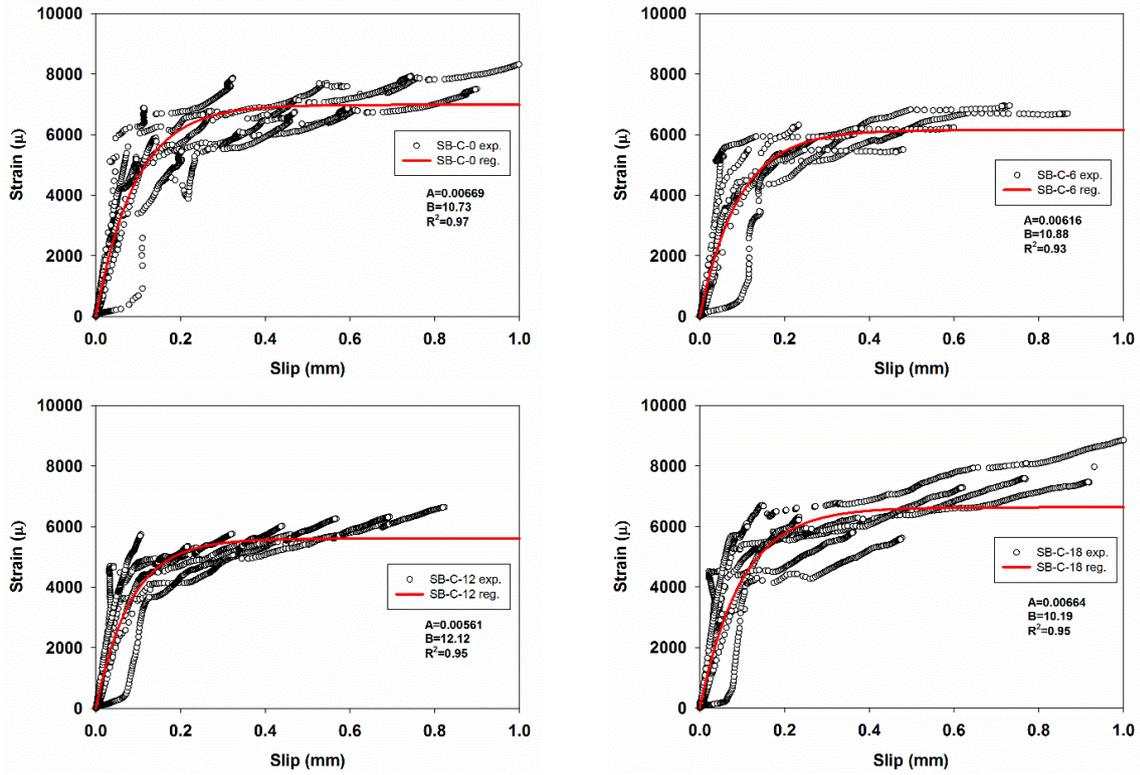


Figure 5-6 ϵ -s relations for SB-C systems at 0, 6, 12 and 18 months respectively

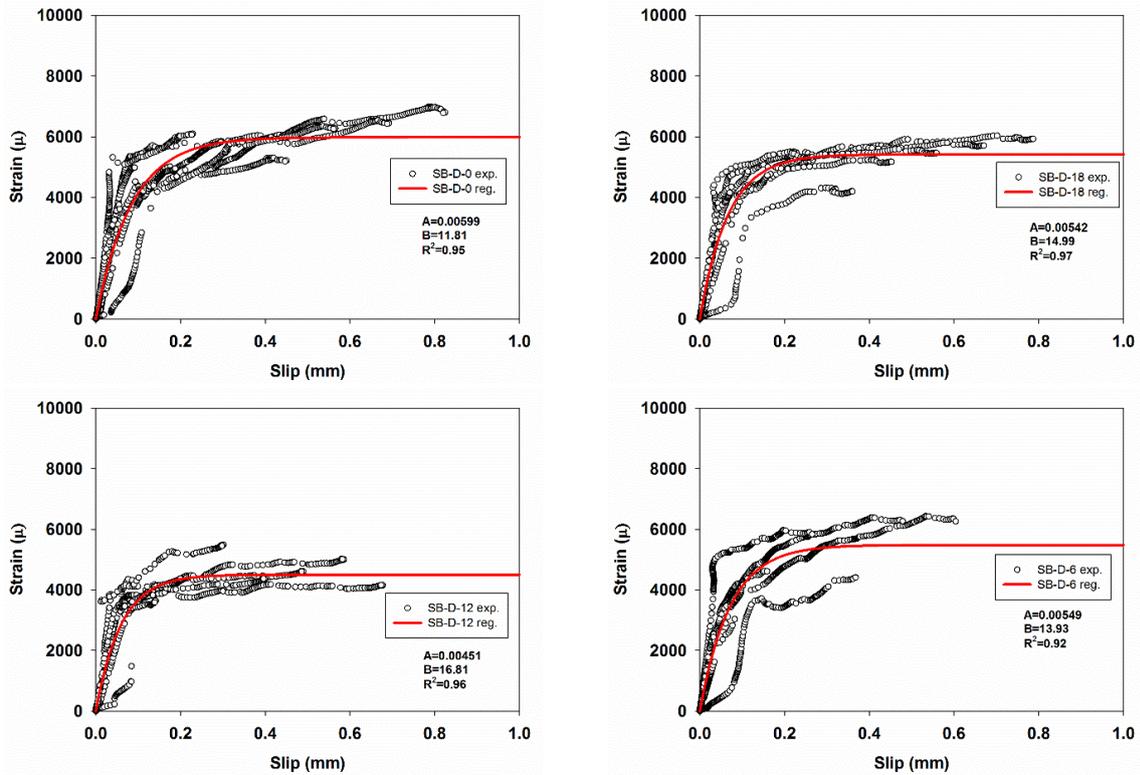


Figure 5-7 ϵ -s relations for SB-D systems at 0, 6, 12 and 18 months respectively

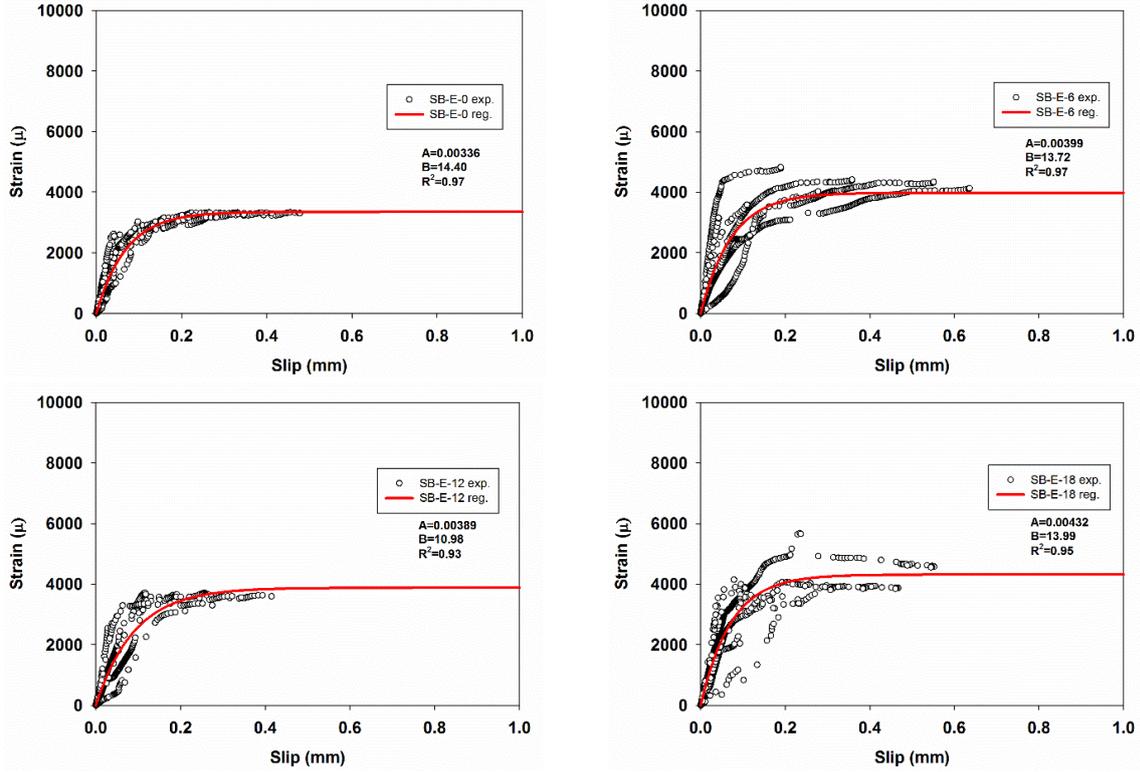


Figure 5-8 ϵ - s relations for SB-E systems at 0, 6, 12 and 18 months respectively

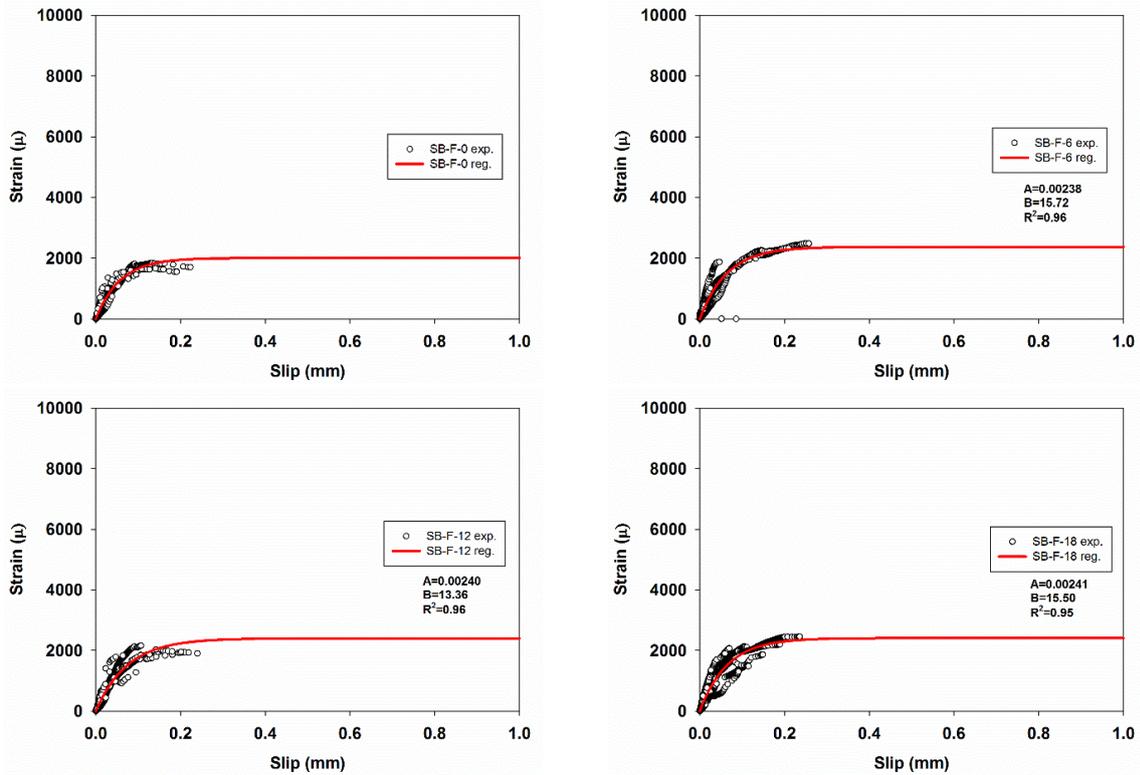


Figure 5-9 ϵ - s relations for SB-F systems at 0, 6, 12 and 18 months respectively

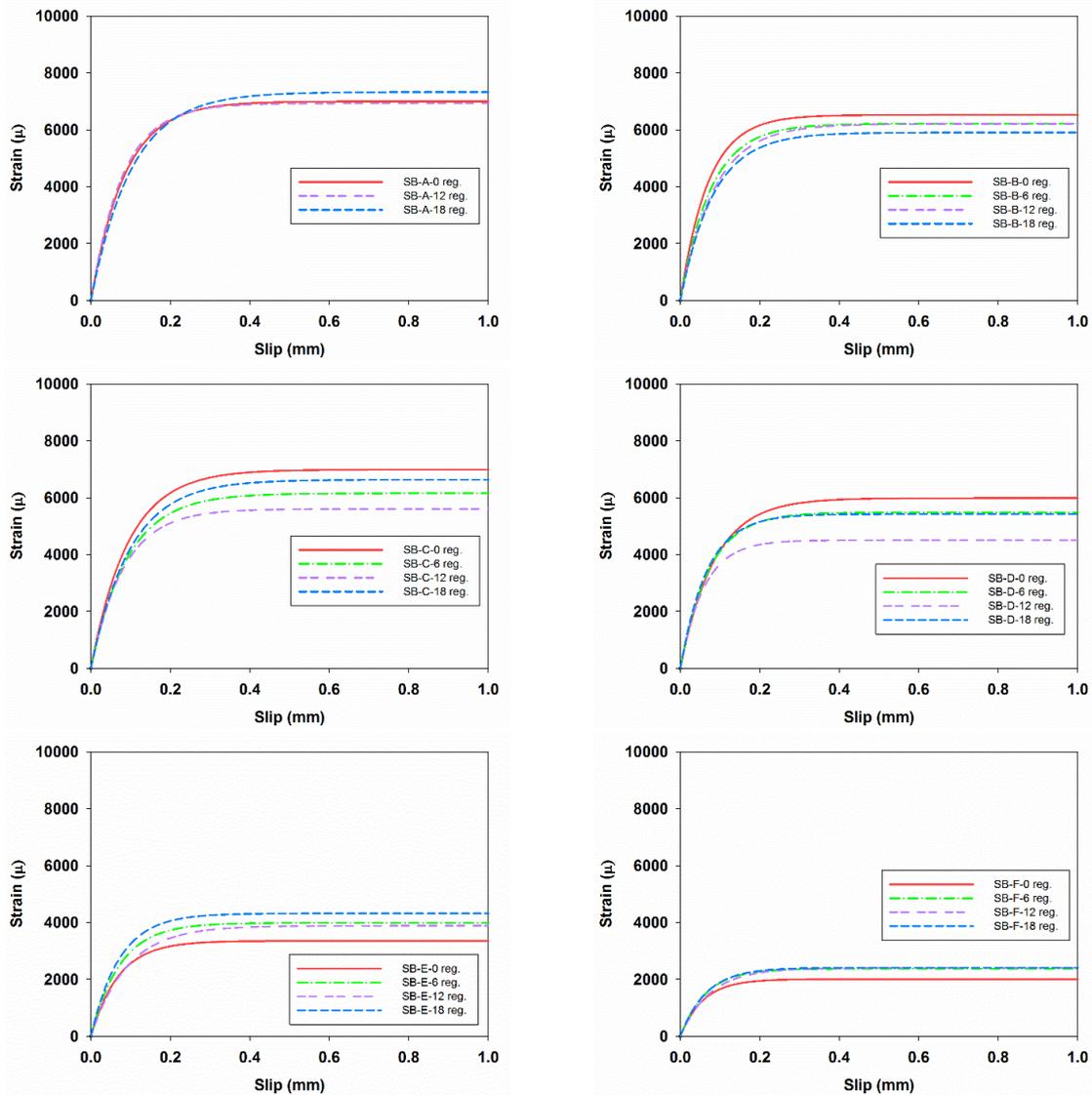


Figure 5-10 Regressed ϵ -s relations for all the 6 FRP systems

Using the obtained values of A for different cases, the fracture energies are calculated using Eqn. (8). Throughout all the calculations, it is assumed that the exposure conditions did not affect the stiffness of the FRP composites and the values provided by the manufactures are used. This assumption seems to be fair in case of CFRP composites as the carbon fibers mostly governs the mechanical properties which is highly durable material against environment. Even though some degradation could occur in epoxy resin binding these fibers, its overall contribution towards the ultimate strength and stiffness would be small. Both Nguyen et al. [13] and Sciolti et al. [14] have found similar negligible effect of immersion in water on the tensile modulus of the CFRP when exposed for 1 year and 30 weeks respectively.

All the calculated fracture energies along with the regressed values A and B are shown in the Table 5-2. The relation between the fracture energy and immersion duration is presented in Figure 5-11. As the fracture energy and the bond strength are closely inter-related, their response to the moisture exposure duration are similar in all 6 systems. The loss/gain in the bond strengths after immersion can be explained by reduction/increment in fracture energy due to degradation/improvement in the bond properties from exposure in water. Even though many of the previous studies have observed higher degradation with the increase in exposure duration, it was not true for all the cases. Two contrasting responses were observed due to exposure and its duration, therefore all the systems cannot be generalized into a common framework. Nevertheless, to understand the effect of exposure, the

immersion cases are simply grouped as one, irrespective of the exposure duration and then compared with the reference or non-immersion condition. Figure 5-12 shows such relative changes in both bond strengths and fracture energies in all the 6 systems. It is evident that the significant reductions were observed in SB-C and SB-D cases whereas small changes in SB-A and SB-B. Nevertheless, such loss in bond strengths and fracture energies are mainly due to degradation caused by moisture conditions. In contrast to such behaviors specimens SB-E and SB-F showed significant gain in performance after exposure.

Table 5-2 Regression coefficient values and fracture energies of all the specimens

Specimens	Exposure duration (months)	E (N/mm ²)	Thickness (mm)	A	B	R ²	G _f (N/mm)	Normalized G _f
SB-A-0	0	230000	0.111	0.00766	10.96	0.95	0.749	1.00
SB-A-6	6	230000	0.111	0.01066	6.08	0.93	1.451	1.94
SB-A-12	12	230000	0.111	0.00693	12.62	0.95	0.614	0.82
SB-A-18	18	230000	0.111	0.00733	9.79	0.97	0.686	0.92
SB-B-0	0	230000	0.111	0.00652	14.46	0.95	0.543	1.00
SB-B-6	6	230000	0.111	0.00622	13.02	0.97	0.494	0.91
SB-B-12	12	230000	0.111	0.00621	11.74	0.94	0.493	0.91
SB-B-18	18	230000	0.111	0.00591	12.06	0.96	0.446	0.82
SB-C-0	0	230000	0.218	0.00699	10.73	0.97	1.225	1.00
SB-C-6	6	230000	0.218	0.00616	10.88	0.93	0.952	0.78
SB-C-12	12	230000	0.218	0.00561	12.12	0.95	0.790	0.64
SB-C-18	18	230000	0.218	0.00664	10.19	0.95	1.106	0.90
SB-D-0	0	240000	0.176	0.00599	11.81	0.95	0.758	1.00
SB-D-6	6	240000	0.176	0.00549	13.93	0.92	0.637	0.84
SB-D-12	12	240000	0.176	0.00451	16.81	0.96	0.430	0.57
SB-D-18	18	240000	0.176	0.00542	14.99	0.97	0.621	0.82
SB-E-0	0	245000	0.333	0.00336	14.40	0.97	0.461	1.00
SB-E-6	6	245000	0.333	0.00399	13.72	0.92	0.650	1.41
SB-E-12	12	245000	0.333	0.00389	10.98	0.93	0.618	1.34
SB-E-18	18	245000	0.333	0.00432	13.99	0.95	0.762	1.65
SB-F-0	0	210000	1.4	0.00201	17.44	0.97	0.594	1.00
SB-F-6	6	210000	1.4	0.00238	15.72	0.96	0.833	1.40
SB-F-12	12	210000	1.4	0.00240	13.36	0.96	0.847	1.43
SB-F-18	18	210000	1.4	0.00241	15.50	0.95	0.854	1.44

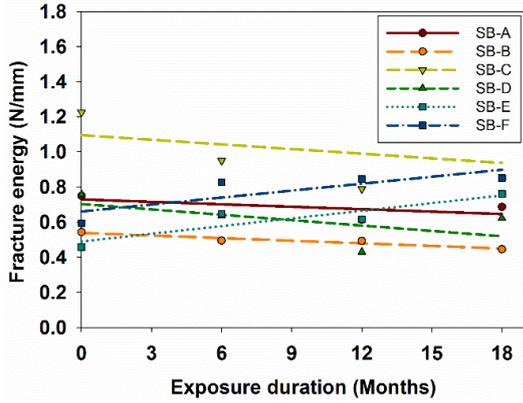


Figure 5-11 Relationship between fracture energy and exposure duration

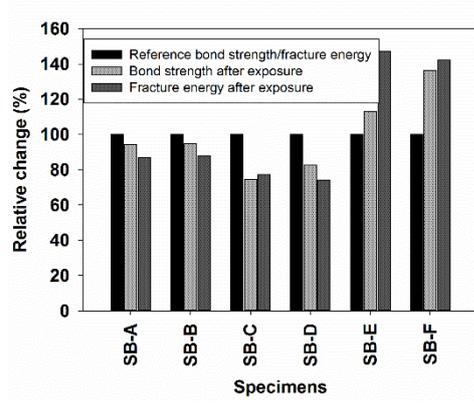


Figure 5-12 Relative change in bond strength and fracture energy after exposure

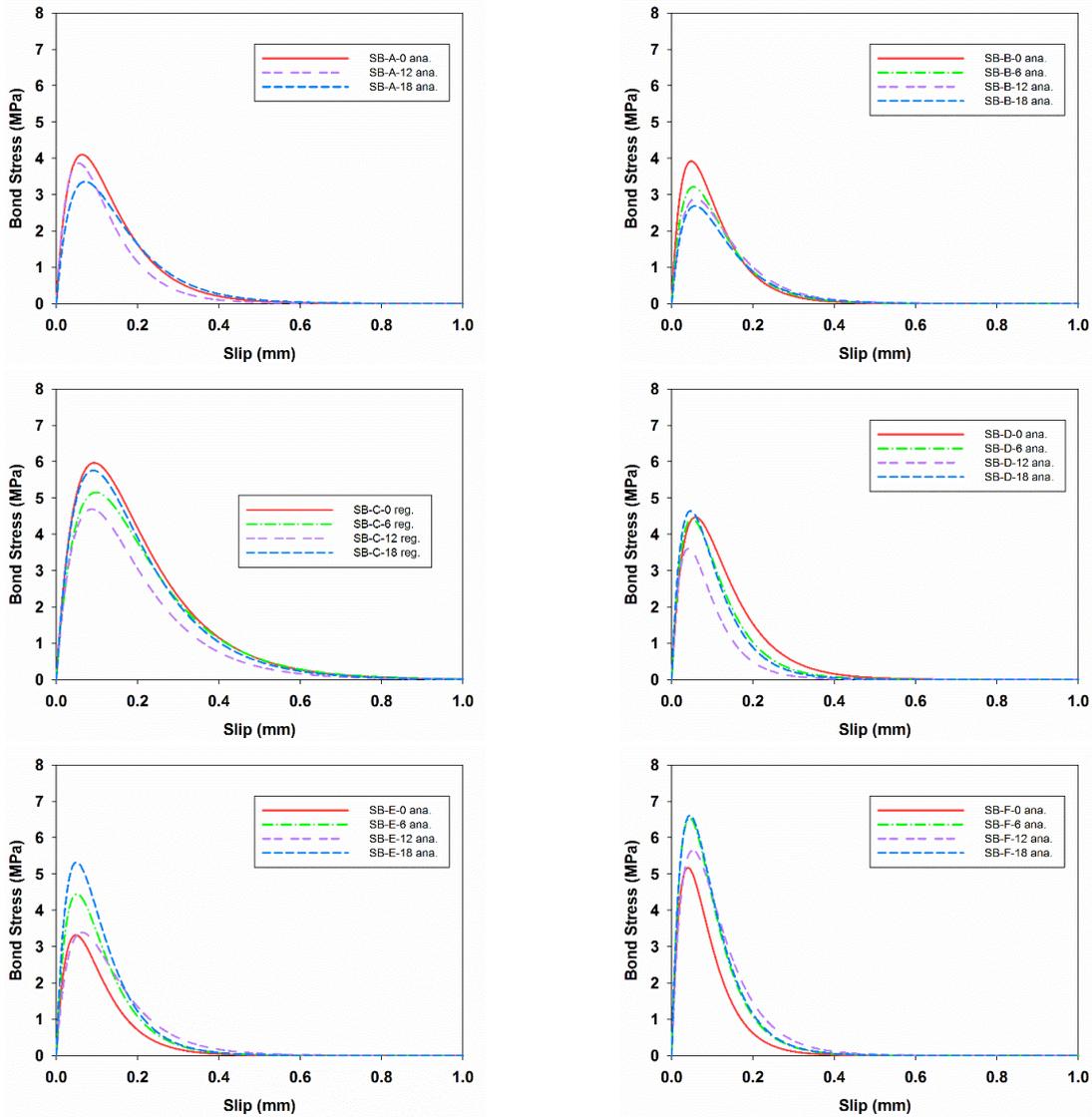


Figure 5-13 Comparison of bond-slip curves at different exposure durations

From Eqn. 10 bond-slip curves were plotted for all the 6 systems at different immersion duration as shown in Figure 5-13. The analytical bond-slip models are compared with the experimentally obtained

local bond-slip curves at locations as shown in Figure 5-14. The predicted model show fair agreement showing average response with the experimental data.

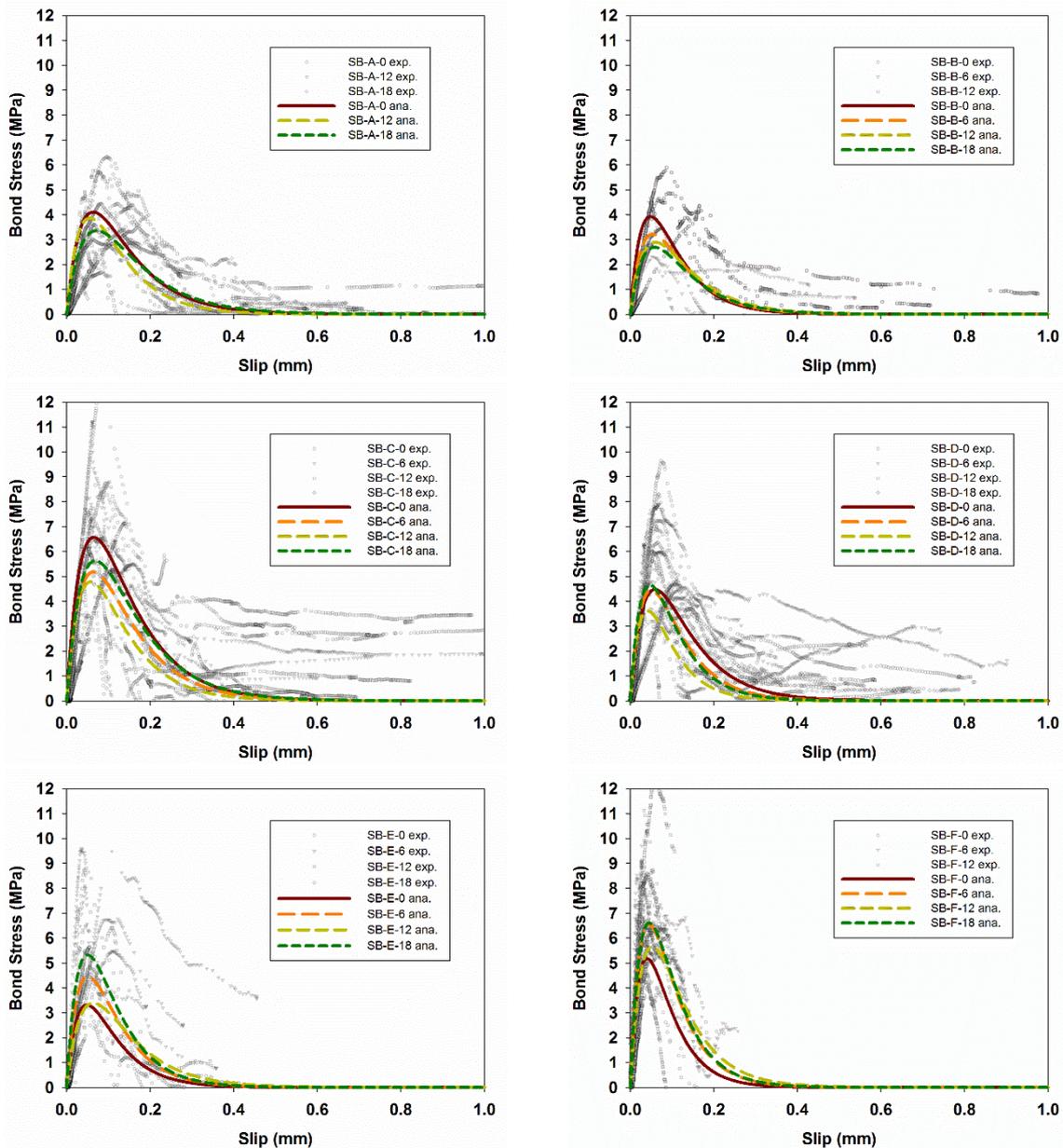


Figure 5-14 Comparison of predicted bond-slip curves with the experimental curves

5.2.3 Modified bond-slip models for moisture conditions

Dai et al proposed simple two parameters bond-slip model which includes interfacial fracture energy (G_f) and ductility index (B). The same approach was used to predict the bond-slip models in moisture conditions in 6 FRP systems. However, there is a need of a common approach which could predict the behavior in the in such conditions. Therefore, influence of moisture conditions and immersion duration was related to normalize interfacial fracture energy (G_f) and ductility index (B) separately.

Based on the response to moisture conditions, all the systems are divided into two systems. The first system are the wet-layup FRP composite that includes SB-A, SB-B, SB-C and SB-D which showed either small or large reductions in fracture energy due to exposure. Whereas, improvement in the fracture energy due to immersion is grouped in to another category which include SB-E and SB-F. Both of these are pre-impregnated systems. Effect of exposure duration on the ductility index (B) are for both

the categories are shown in Figure 5-15 and Figure 5-16 respectively. The expression after regression are given below.

For wet-layup case,

$$B_t^{Env.} = B_0(1.05 - 0.05e^{-0.40t}) \quad (12)$$

For pre-impregnated case,

$$B_t^{Env.} = B_0(0.85 + 0.15e^{-0.25t}) \quad (13)$$

Similarly, effect of exposure duration on the interfacial fracture energy (G_f) for both the categories is shown in Figure 5-17 and Figure 5-18 respectively. The regressioned curves show that in both of the cases, the interfacial fracture energy seems be almost constant after 6 months of immersion. The expression are given below.

For wet-layup case,

$$G_{f_t}^{Env.} = G_{f_0} (0.8 + 0.2e^{(-0.38t)}) \quad (14)$$

For pre-impregnated case,

$$G_{f_t}^{Env.} = G_{f_0} (1 + 0.45(1 - e^{(-0.20t)})) \quad (15)$$

Using the Eqns. (12)-(15), the values of $B_t^{Env.}$ and $G_{f_t}^{Env.}$ are calculated for all the specimens as shown in Table 5-3.

Thus, the 2 parameter bond-slip relation shown in eqn. 10 can be rewritten incorporating the effect of moisture exposure duration as:

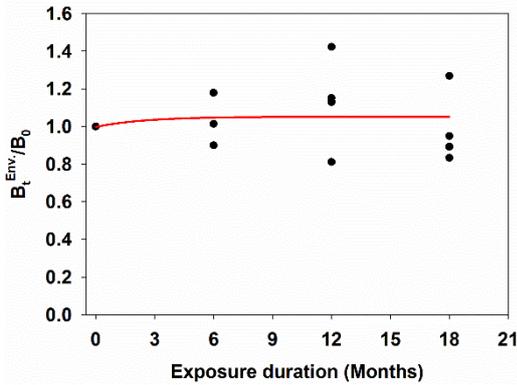
$$\tau_t^{Env.} = 2B_t^{Env.} G_{f_t}^{Env.} (e^{(-B_t^{Env.} s_t^{Env.})} - e^{(-2B_t^{Env.} s_t^{Env.})}) \quad (16)$$

Where, t is the duration in months.

Using Eqn. (16), the bond-slip models for all the systems are prepared for different exposure durations as shown in Figure 5-19.

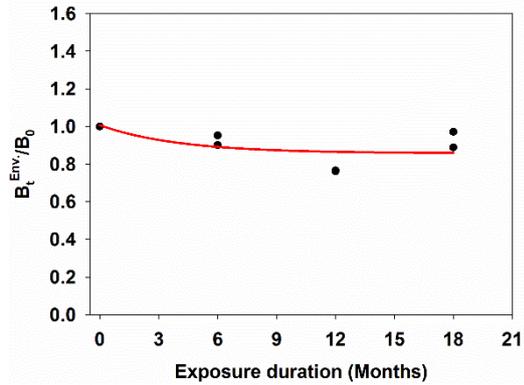
Table 5-3 Calculated values for $B_t^{Env.}$ and $G_{f_t}^{Env.}$

Specimen	Exposure duration (Months)	$B_t^{Env.}$	$G_{f_t}^{Env.}$	Specimen	Exposure duration (Months)	$B_t^{Env.}$	$G_{f_t}^{Env.}$
SB-A-0	0	10.96	0.75	SB-D-0	0	11.81	0.76
SB-A-3	3	11.34	0.65	SB-D-3	3	12.22	0.65
SB-A-6	6	11.46	0.61	SB-D-6	6	12.35	0.62
SB-A-18	18	11.51	0.60	SB-D-18	18	12.40	0.61
SB-A-24	24	11.51	0.60	SB-D-24	24	12.40	0.61
SB-B-0	0	14.46	0.54	SB-E-0	0	14.40	0.46
SB-B-3	3	14.97	0.47	SB-E-3	3	13.26	0.56
SB-B-6	6	15.12	0.45	SB-E-6	6	12.72	0.61
SB-B-18	18	15.18	0.43	SB-E-18	18	12.26	0.67
SB-B-24	24	15.18	0.43	SB-E-24	24	12.25	0.67
SB-C-0	0	10.73	1.23	SB-F-0	0	17.44	0.59
SB-C-3	3	11.10	1.06	SB-F-3	3	16.06	0.72
SB-C-6	6	11.22	1.01	SB-F-6	6	15.41	0.78
SB-C-18	18	11.27	0.98	SB-F-18	18	14.85	0.86
SB-C-24	24	11.27	0.98	SB-F-24	24	14.83	0.86



$$B_t^{Env.} = B_0(1.05 - 0.05e^{-0.40t})$$

Figure 5-15 Effect of exposure duration on the normalized B for wet-layup system



$$B_t^{Env.} = B_0(0.85 + 0.15e^{-0.25t})$$

Figure 5-16 Effect of exposure duration on the normalized B for pre-impregnated system

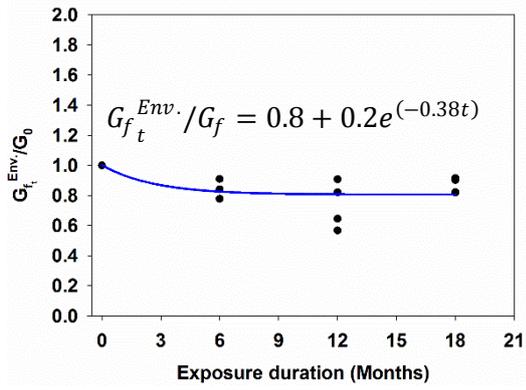


Figure 5-17 Effect of exposure duration on the normalized G_f for wet-layup system

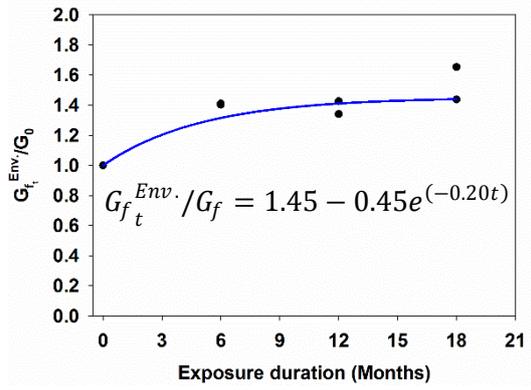


Figure 5-18 Effect of exposure duration on the normalized G_f for pre-impregnated system

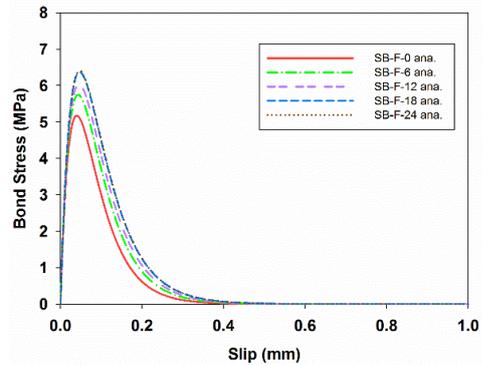
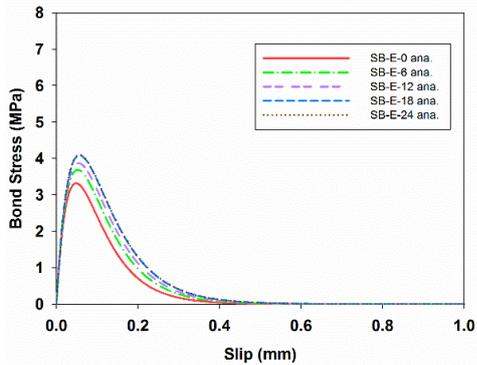
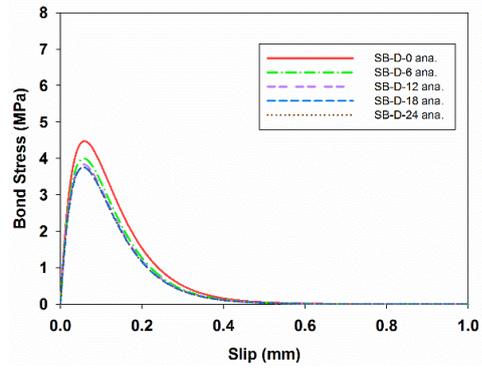
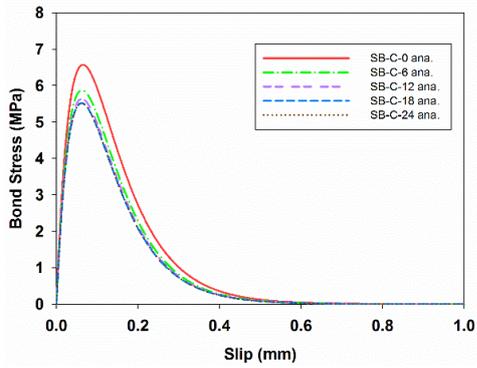
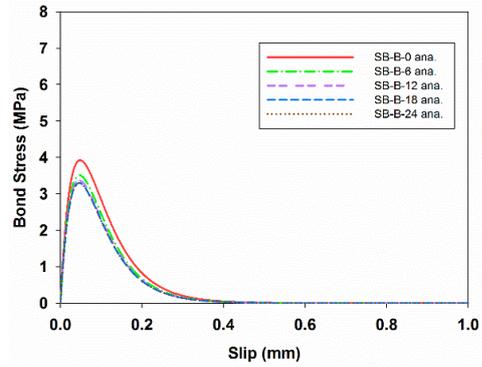
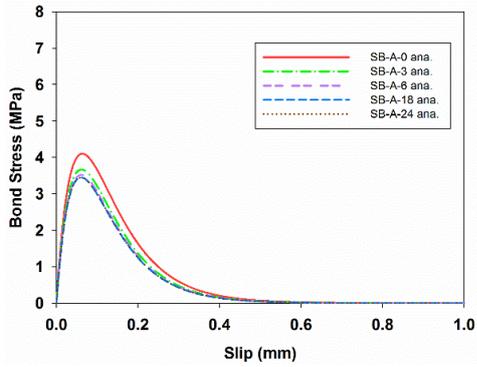


Figure 5-19 Modified bond-slip models incorporating moisture effect

5.2.4 Verification of the model

The expression for ultimate load transfer can also be modified with the interfacial fracture energy for environmental condition as:

$$P_t^{Env.} = b_f \sqrt{2E_f t_f G_{f_t}^{Env.}} \quad (17)$$

In the above equation, calculated fracture energies for the exposed cases are used to determine the ultimate loads. Figure 5-20 shows good agreement of the predicted and average experimental ultimate loads at 0, 6, 12 and 18 months.

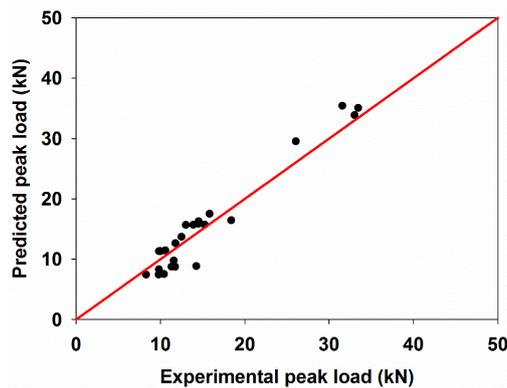


Figure 5-20 Comparison between predicted and experimental ultimate loads at 0, 6, 12 and 18 months taking all the 6 FRP systems

5.3 CONCLUSIONS

From the analysis of the strain results, following conclusions can be drawn:

1. Dai's approach was modified for the moisture conditions cases. The modified approach was applied to derive bond-slip models in all the systems for moisture conditions and normal temperature range.
2. The effect of moisture on the FRP systems can be categorized into two different cases based on the observation of average interfacial fracture energies and bond strength after exposure. In general, wet-layup systems showed reduction in interfacial fracture energy and the ultimate bond strength after exposure whereas pre-impregnated systems showed improvement. These two contrasting behavior are compared with the experimental local bond-slip models.
3. The effect of exposure duration was related with the two parameters interfacial fracture energy (G_f) and ductility index (B) separately for two categories. In both of the cases, the effect of moisture seems to affect the bond properties until the period of 6 months after which further exposure does not significantly affect these parameters.
4. Bond-slip models are determined using modified fracture energy $G_{f_t}^{Env.}$ and ductility index $B_t^{Env.}$ to incorporate the effect of moisture condition and duration of exposure.
5. The predicted ultimate loads were compared with the experimental loads at different exposure duration taking all the 6 FRP systems. The results show fair agreement between predicted and the experimental values.

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Chapter 6

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

The durability of FRP-concrete bond interfaces was investigated under influence of moisture conditions. Following general conclusions can be drawn out:

1. The water absorption capacities of the epoxy resin varied greatly which proved to be harmful, affecting mainly the tensile strength in most of the cases but no strong relationship was found between amount of moisture absorption and the tensile strength. In contrast to the strength behavior, the modulus was not much affected by such exposure.
2. Durability evaluation of 6 FRP-systems revealed that the environmental related deteriorations are highly dependent on the materials under investigation. From the current set of systems, the wet-layup systems performed poorly than the factory impregnated systems. In response to moisture exposure, the shear bond behavior either showed no effect, positive effect or significant reductions in the bond strength depending on the FRP systems. It can also be concluded that longer duration of exposure does not necessarily mean greater effect. At the later stages of exposure duration, the bond strengths almost remained constant.
3. As for the failure modes in shear bond tests, three typical failure modes were observed, which are concrete cohesion failure, partial concrete cohesion and resin-concrete interface failure and lastly interface failure between resin and concrete. As an effect of water immersion, transition of failure modes occurred from concrete cohesion to mixed mode or interface failure but significant reductions in bond strength were observed only in cases of complete interface failures. This emphasize the importance of proper surface preparation required in substrate concrete and use of the resin with good adhesion bond strength with concrete to ensure durability of FRP-concrete bond against moisture related damages.
4. The normal-strength concrete substrate preparation by disk-grinding was sufficient to retain the appropriate mechanical bond even in moisture conditions whereas, sand-blasting method was more effective in the high-strength concrete substrate case. The higher degree of roughness value can be obtained through the former method, thus increasing the mechanical interlocking action at the interface.
5. The degree of roughness greatly affects the durability of bond between high-strength concrete and FRP. There was significant loss in bond strength after the exposure for the disk-grinded cases whereas, such losses were much lower in sand-blasted cases. Presence of good mechanical bonds due to sufficient surface roughness could retain the bond strength despite some destruction of chemical bonds at the interface by water. Transition of failure modes to adhesion at the interface after exposure seems to have greater effect on the bond strength than other failure modes. By increasing the surface roughness, adverse effects of the moisture conditions can be minimized at the bond interfaces.
6. Comparisons between wet and dry testing conditions revealed that the mechanical properties of the resins were further deteriorated after drying, but in contrast, both the shear and tensile bond strengths were partially recovered but the original strengths were not restored. These results indicate that the damages caused due to exposure in moisture are irreversible.
7. Tensile bond strengths obtained from direct pull-off tests were reduced significantly in most of the cases after exposure, but the failure modes, which were concrete cohesion failures remained

unchanged. This fact suggests that there are some harmful effects of water immersion in tensile bond properties.

8. The approach determined by Dai was modified to develop bond-slip models applicable for moisture conditions and normal temperature range. The effect of moisture on the FRP systems can be categorized into two different categories based on the observation of average interfacial fracture energies and bond strength after exposure. In general wet-layup systems showed reduction in interfacial fracture energy and the ultimate bond strength after exposure whereas pre-impregnated systems showed improvement. These two contrasting behavior are compared with the experimental local bond-slip models.
9. The effect of exposure duration was related with the two parameters interfacial fracture energy (G_f) and ductility index (B) separately for two categories. In both of the cases, the effect of moisture seems to affect the bond properties until the period of 6 months after which further exposure does not significantly affect such parameters. Bond-slip models are determined using modified fracture energy ($G_f^{Env.}$) and ductility index ($B_t^{Env.}$) to incorporate the effect of moisture condition and duration of exposure. The predicted ultimate loads were compared with the experimental loads at different exposure duration. The results show fair agreement between the predicted and the experiments.

6.2 RECOMMENDATION

6.2.1 Proposal of bond deterioration factor for moisture conditions

The current available guidelines on the external bonded FRPs does not clearly addresses the environmental durability related issue due to lack of available research in the field. However, all of the guidelines agree that degradation to environment is one of the important issues which needs to be considered while designing the structures. In this regard, ACI 440.2R has introduced an environmental reduction factor to consider long-term exposure effect due to various types of environments on the tensile properties, creep-rupture and fatigue endurance of FRP laminates. The environmental factor is chosen based on appropriate fiber type and exposure condition. This reduction factor reduces the ultimate design tensile strength and limits the design rupture strain of FRP materials. However, this research confirms that reduction in the FRP material properties may not be sufficient in all the environmental exposure cases and the degradation of bond between FRP and concrete under moisture conditions should be considered separately.

From investigation of six of the commercial FRP-concrete bonded systems in shear and tension, different durability behavior is observed. Even though, much degradation due to exposure is observed in the case of tension bond evaluated by the direct pull-off test, the big variation obtained in the results despite of similarly conditioned specimens cannot be well explained. Due to failures governed by the concrete cohesion and limited information obtained from the tests, the tensile bond deterioration is not considered for the computation of the bond deterioration factor. On contrary, the moisture effect on the shear bond behavior is much clearer in terms of the bond strength and its relationship with the failure modes with the exposure conditions. Therefore, only shear bond results are considered for determining the bond deterioration factor for moisture condition.

The relationship between shear bond strength and the exposure duration is divided into two groups. The first group consists of four FRP wet layup systems whereas the second group consists of two pre-fabricated FRP systems. As the bond deterioration was only observed in the wet-layup cases, the results of the pre-fabricated cases are not included in determination of the bond deterioration factor. In addition, the effect of exposure duration was found significant until 9 months of immersion after which the change in shear bond strength due to the length of exposure was minimal. Such state can be considered as the lower bound case after which no further deterioration is possible due to moisture in the given temperature range. Therefore, the bond degradation factor in the wet-layup system is defined as the average ratio between the shear bond strength after moisture exposure to the shear bond strength without moisture exposure. While considering only the wet-layup systems, the results of 75 shear bond

specimens were taken with the maximum exposure duration of 18 months period and the bond durability factor is calculated as 0.88. This factor could be used as an additional reduction factor in the member resistance to consider the bond degradation between FRP and concrete due to the moisture dominant environment condition in the field applications. However, this factor should be limited only to the bond critical applications for strengthening with the wet-layup CFRP system under normal temperature range of 20 °C.

6.2.2 Recommendations for future study

There are still lot of work that needs to be done which are briefly described as below.

1. The availability of wide range of products in the market and large variation in the durability results obtained by different researchers are making it too complex to narrow down the true effects of such environmental conditions. Such variability in durability resistance is mainly due to use of wide variety of the commercial epoxy resin products available in the market. Commercial epoxy resin is really unique in itself and distinct from one another due to blend of many complicated components and compositions that are not revealed. Due to these reasons, the durability performance and resistance against different environmental conditions varies and the true mechanism is usually unknown. Therefore, it is somehow necessary to identify such key components of the commercial epoxy resins and relate the environmental related effects with the chemical compositions of the resins.
2. In the study, effect of moisture and elevated temperature were investigated separately. However, the coupled action may yield different durability results. Therefore, it is necessary to investigate such effect of moisture at different temperature range to clearly understand the combined behavior.
3. The direct pull-off test does not give much information about the interfaces between FRP and concrete as the failures are governed by the concrete properties rather than the interface in majority of the cases. Such kind of test with small test area can only represent a local behavior of the bond and the results are usually affected by many factors resulting in a big scatter in the data. Therefore, environmental effect on the tensile bond properties needs to be investigated further by different approach which can give more information about the interface region.
4. There is a great necessity to develop standardized test methods for such durability tests. Lack of such standards and guidelines are making it quite difficult to understand environmental effects due to wide variation in results obtained by different researchers.

APPENDIX (ELEVATED TEMPERATURE EFFECT ON THE FRP-CONCRETE BONDS)

A.1. INTRODUCTION

One of the major disadvantages of the FRP-concrete bonded system is recognized as its poor resistance to the fire and elevated temperature due to softening of the epoxy resins. At the glass transition temperature, the epoxy resins quickly loses mechanical properties thus affecting the bond performance as well. The standard glass transition of the epoxy resins used for structural applications are between 45°C-82 °C. It is quite likely that such temperatures could be reached at the surface of concrete which could potentially affect the bond between FRP and concrete. But the degree of such temperature effects could vary depending on the FRP and resins systems. There are different commercial FRP and resin systems available in the market with unique properties. Therefore, it is necessary to investigate the effect of elevated temperature on different existing FRP systems to understand the behavior in elevated temperature.

A.2. EXPERIMENTAL OUTLINE

The experiment includes tensile test of the epoxy resins and the FRP-concrete bond tests for both shear and tension. Altogether 6 commercial systems were investigated in elevated temperature. The FRP material properties and the preparation of the specimens are given in earlier chapter. All the specimens were tested at 3 temperature ranges which are $20\pm 3^{\circ}\text{C}$, $40\pm 3^{\circ}\text{C}$ and $50\pm 3^{\circ}\text{C}$. The arrangements for testing the specimens are elevated temperatures are shown in Figure A-1, Figure A-2 and Figure A-3 respectively for the resin tensile test, shear bond and tension bond. By putting different heat sources around the chamber, the temperature was elevated to the desired value which was continuously monitored by a sensor attached on the surface of the specimen. The number of specimens with their parameters are summarized in Table A-1.



Figure A-1 Elevated temperature testing arrangement for the resin tensile test

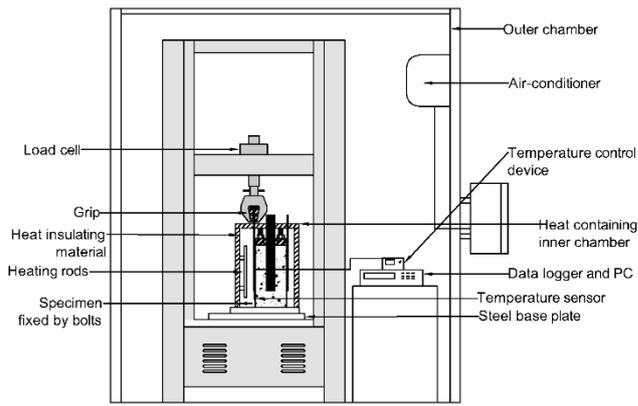


Figure A-2 Elevated temperature testing arrangements for the shear bond specimens

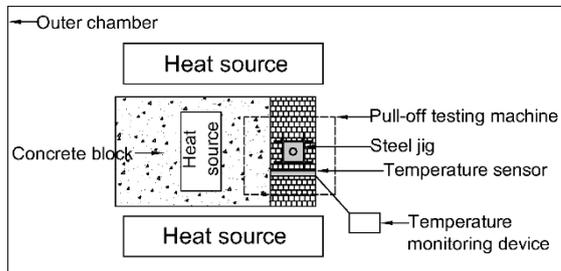


Figure A-3 Elevated temperature testing arrangements for the tension bond specimens

Table A-1 Number of specimens tested at different temperatures

Specimen	Resin tensile test		Shear bond test			Tension bond test		
	20 °C	40 °C	20 °C	40 °C	50 °C	20 °C	40 °C	50 °C
SB-A	3	1	3	2	1	3	2	1
SB-B	3	1	3	2	1	3	2	1
SB-C	3	1	3	2	1	3	2	1
SB-D	3	1	3	2	1	3	2	1
SB-E	3	1	3	2	1	3	2	1
SB-F	3	1	3	2	1	3	2	1

A.3. RESULTS AND DISCUSSIONS

A. Effect of elevated temperature on the tensile properties

Figure A-4 and Figure A-5 shows the effect of temperature on the tensile strength and modulus of the resins respectively. The reduction of the strength occurred in all of the resins at 40 °C from 7% to 78% depending on the resins. The highest deterioration occurred in specimen TP-B with overall 78% decrease in the tensile strength and 25% reduction in the modulus. In none of the cases, glass transition

temperature was exceeded but despite of that such large reductions occurred in the mechanical properties of the resin.

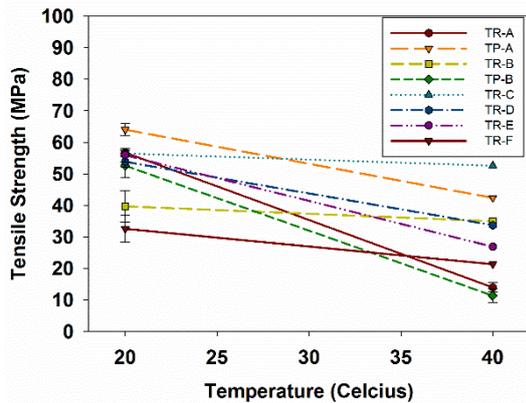


Figure A-4 Effect of temperature on the tensile strength of the resins

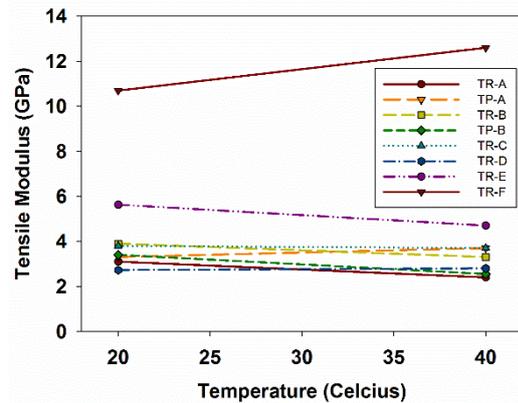


Figure A-5 Effect of temperature on the tensile modulus of the resins

B. Effect of elevated temperature on the shear bond properties

The effect of temperature on the results of shear bond test is shown in Figure A-6. The effect of temperature on the peak load is insignificant for wet lay-up systems (SB-A, SB-B, SB-C and SB-D) until 40 °C. The failure modes in all the cases were similar to the reference case (20 °C). The failures were mostly concrete cohesion or the mixed failure which is partial failure at concrete cohesion and resin-concrete interface (Figure A-7 to Figure A-11). Only one of the specimens (SB-B) failed at the interface between primer and matrix (Figure A-8). In that particular primer case there was drastic reduction of the tensile strength and modulus of the primer at 40 °C. Despite of such reduction in the resin properties, the peak load was similar as the reference case. The effect of temperature in these cases are more distinguish at 50 °C. The failure in all the cases occurred by rupture of the FRP at the loads much lower than the ultimate capacity of the FRP composites. This indicates that the temperature could have affected the resin properties lowering the ultimate capacity of the FRP composites.

The effect of temperature on the two of the pre-impregnated FRP systems (SB-E and SB-F) showed improvement in the bond properties due to higher temperature of 40 °C. The increment in the peak loads were 144% and 51% respectively for specimens SB-E and SB-F. These enhancements in the peak loads were slightly lowered at 50 °C to 83% and 34% respectively which could be possible due to effect of temperature closer to glass transition temperature of the resins. Similar increment in the ultimate load was also observed by Blontrock et al. [1] when temperature was elevated from 20 °C to 40 °C and 55 °C. Gao et al explained such increase in ultimate load mainly due to the thermal stresses generated by increase in temperature which could resist the part of the pull load in a bonded joints [2]. For the specimen SB-E, failure mode at 20 °C and 40 °C were either at the concrete cohesion or the mixed failures. But at 50 °C, the failure mode turned to complete interface failure between resin and concrete interface. The peak load for this case was comparatively lower than at 40 °C. In case of specimen SB-F, the failure mode remained unchanged as the concrete cohesion despite the increase in the temperature (Figure A-10 and Figure A-11). Unlike the wet-layup cases, rupture of FRP composite didn't occur which could be mainly due to greater ultimate capacity as a result of greater stiffness and higher quality of FRP due to factory impregnation.

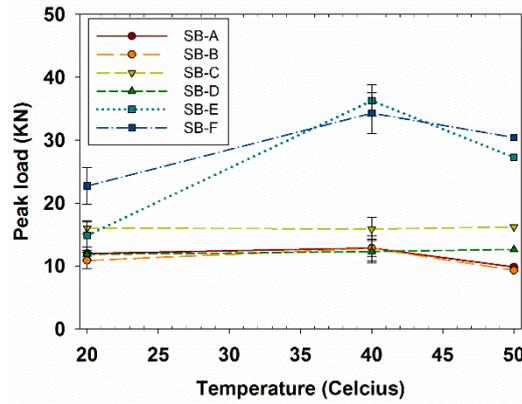


Figure A-6 Effect of temperature on the peak load

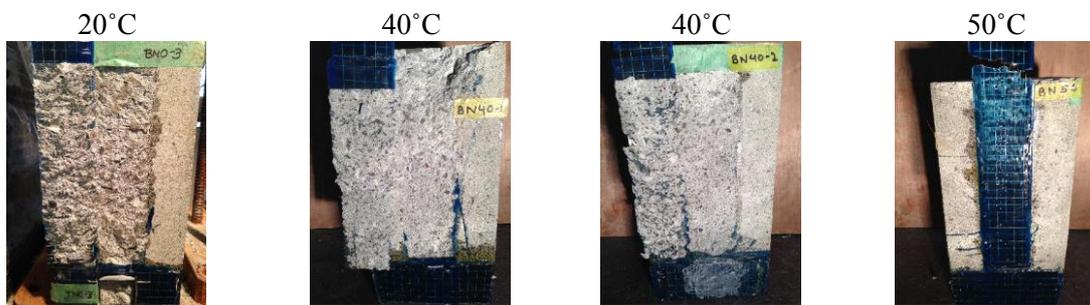


Figure A-7 Comparison of failure modes at different temperatures for SB-A specimen

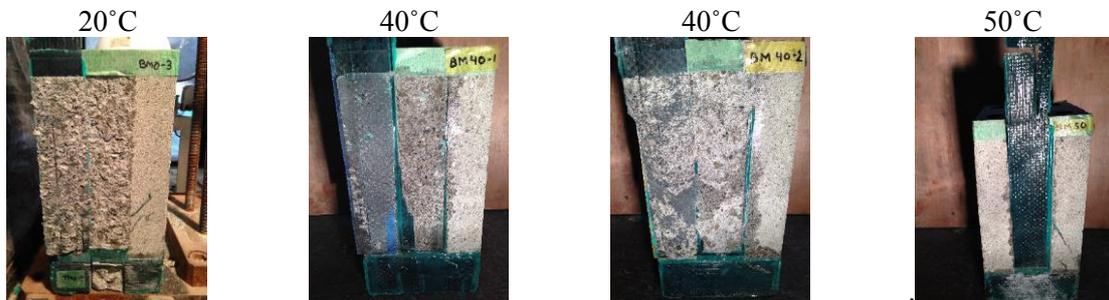


Figure A-8 Comparison of failure modes at different temperatures for SB-B specimen

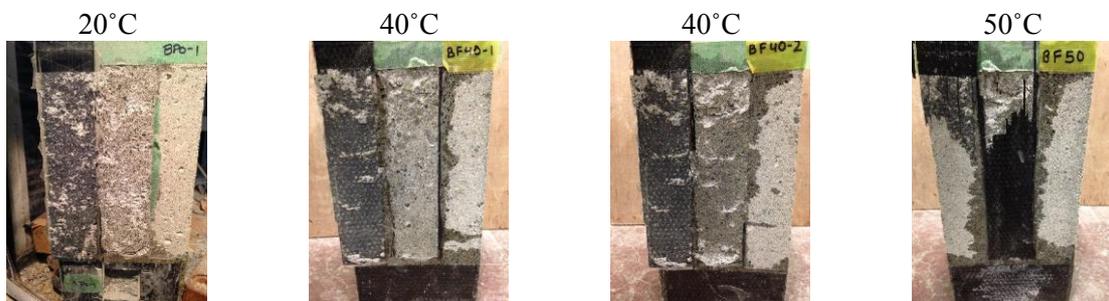


Figure A-8 Comparison of failure modes at different temperatures for SB-C specimen

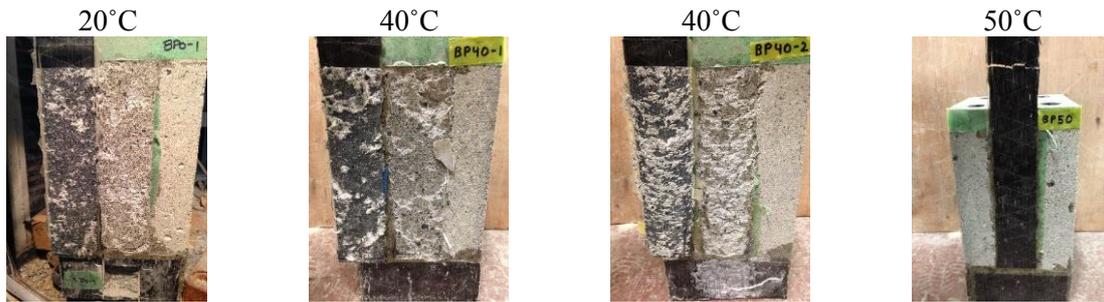


Figure A-9 Comparison of failure modes at different temperatures for SB-D specimen

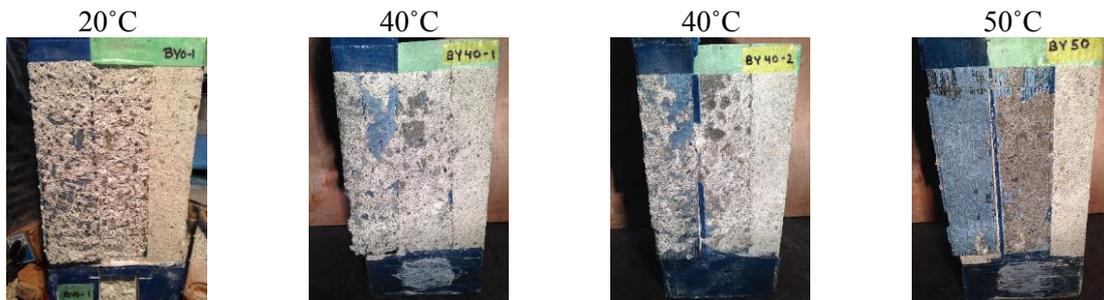


Figure A-10 Comparison of failure modes at different temperatures for SB-E specimen

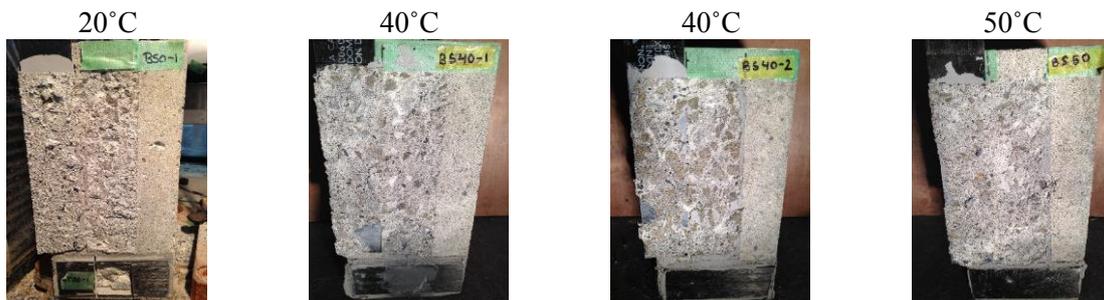


Figure A-11 Comparison of failure modes at different temperatures for SB-F specimen

C. Effect of elevated temperature on the tensile bond properties

The effect of temperature on the tensile bond properties is shown in Figure A-12 and representative failure modes at each temperature for one of the specimens in Figure A-13. From the comparison of tensile bond at different temperatures, it can be confirmed that most of the cases remained unchanged or slightly reduced till 40 °C followed by improvement at the temperature of 50 °C. The failures in all the cases occurred by concrete cohesion irrespective of the exposure temperature. This indicates that the temperature below the glass transition temperature is not severe for the tensile bond between FRP and concrete.

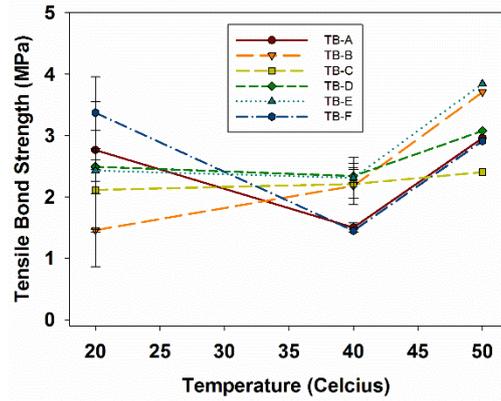


Figure A-12 Effect of temperature on the tensile bond strength



Figure A-13 Failure modes at 20 °C, 40 °C and 50 °C temperature respectively

A.4. CONCLUSIONS

The effect of temperature on the FRP-concrete bond interfaces were evaluated by shear and tensile bond tests in 6 FRP systems. The results can be summarized as following.

1. Even at a temperature below the T_g of the resin, it could still affect the mechanical properties of the resin. Some of the resins showed large reduction in the strength and the modulus at 40 °C but this needs to be confirmed by more such tests at different temperatures.
2. The shear bond properties of FRP and concrete interface were evaluated at different temperatures of 20 °C, 40 °C and 50 °C. Comparison of ultimate load and failure patterns with the reference (20 °C) indicates that there is no adverse effect on bond properties for the wet-layup systems at 40 °C. However, at 50 °C despite of similar load levels, all the specimens failed by rupture of the FRP composite suggesting that such temperature could affect the fiber-matrix bond. In contrast to this, factory impregnated systems showed better resistance against such temperature ranges which could be possibly due to better quality of impregnation. Interestingly, there is a large improvement in the bond properties reflected by increment in the ultimate load capacity at higher temperatures which could be possibly due to post-curing of the epoxy resins due to increase in temperature.
3. The effect of temperature on the tensile bond properties was confirmed by the pull-off test. At the tested temperature, no severe effects were confirmed in terms of tensile bond strength and failure modes. Failures in all the cases were governed by the concrete cohesion indicating good bond at the interfaces.

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