

FLORIDA STATE UNIVERSITY

FSU-FAMU COLLEGE OF ENGINEERING

LONG-TERM PERFORMANCE OF EPOXY FILLED STEEL GRATE DECKING

By

CATHBERT AKARO

A Thesis submitted to the  
Department of Civil and Environmental Engineering  
In partial fulfillment of the  
Requirements for the degree of the  
Master of the science

Degree awarded:  
Fall Semester, 2006

The members of the committee approve the thesis of Cathbert Akaro defended on August 11<sup>st</sup>, 2006.

---

Primus V. Mtenga  
Professor Directing Thesis.

---

Kamal S. Tawfiq  
Committee Member.

---

John O. Sobanjo  
Committee Member.

Approved:

---

Kamal Tawfiq, Chair Department Civil & Environmental Engineering

---

Ching-Jen Chen, Dean FAMU-FSU College of Engineering.

The Office of Graduate Studies has verified and approved the above named committee Members.

## **ACKNOWLEDGEMENTS**

I would like to thank all those who assisted by the word in the completion of this thesis. To my graduate advisor and committee members, thanks for all your patience and advise. Thanks also to civil engineering department and school of graduate studies for their financial assistance during my course of study. To my fellow graduate students; thank you for your advice, support and the lighter side of engineering.

# TABLE OF CONTENTS

<b>LIST OF TABLES</b> .....	<b>vi</b>
<b>LIST OF FIGURES</b> .....	<b>vii</b>
<b>ABSTRACT</b> .....	<b>ix</b>
<b>1. OVERVIEW</b> .....	<b>1</b>
1.1 Introduction:.....	1
1.2 Goal and Objective:.....	2
1.3 Methodology:.....	2
1.4 Project Scope: .....	3
<b>2. LITERATURE REVIEW</b> .....	<b>4</b>
2.1 Background: .....	4
2.2 Matrix resin:.....	7
2.3 Properties of Epoxy Materials:.....	7
2.4 Type of Adhesive Resin: .....	8
2.4.1 Thermoplastic Resin:.....	8
2.4.2 Thermosetting Resin: .....	8
2.5 Wearing Surface:.....	9
2.6 Polymer Concrete Filled Bridge Decks:.....	10
2.7 Method of Overlay in Bridge Deck:.....	12
2.7.1 Slurry Overlay:.....	12
2.7.2 Multiple Layer Overlay:.....	12
2.7.3 Premixed Overlay: .....	13
2.8 Factors Affecting Bonded Joint:.....	13
2.9 Failure Mode of the Open Bridge Deck: .....	14
2.10 General Trends Regarding Loss of Adhesion: .....	15
2.11 Effect of Temperature and Water: .....	16
<b>3. EXPERIMENT SETUP</b> .....	<b>29</b>
3.1 Introduction:.....	29
3.2 Accelerated Test Terminology:.....	30
3.3 Fabrication of Simulation Chamber: .....	30
3.4 Materials Properties: .....	33

3.4.1	E-Bond 526 Lightweight Materials:.....	33
3.4.2	E-Bond 526 Neat Resin:.....	35
3.4.3	Properties of EP # 5 Modified Aggregates:.....	35
3.5	Sample Preparation:.....	36
3.6	Test Parameters:.....	38
3.6.1	Flexural Test:.....	39
3.6.2	Dynamic Mechanical Analysis (DMA) Test:.....	39
3.6.3	Effect of Cyclic Temperatures to Filled Deck:.....	40
3.6.4	Effect of Combined Low and High Temperatures to Filled Deck:.....	41
3.6.5	Effects of Cyclic Temperatures to E-Bond 526 LW Materials:.....	41
3.7	Instrumentation Setup and Data Collection:.....	41
<b>4.</b>	<b>RESULTS AND DISCUSSION .....</b>	<b>44</b>
4.1	Flexural Test:.....	44
4.2	Dynamic Mechanical Analysis (DMA) Test:.....	47
4.3	Effects of the Cycling Temperatures to Filled Deck:.....	48
4.4	Effect of Combined Low and High Temperature Exposure to Filled Deck: .....	65
4.5	Effects of Cyclic Temperatures to E-Bond 526 LW Materials:.....	67
<b>5.</b>	<b>CONCLUSION AND RECOMMENDATIONS.....</b>	<b>71</b>
5.1	Conclusions:.....	71
5.2	Recommendations: .....	73
	<b>REFERENCES .....</b>	<b>74</b>
	<b>BIOGRAPHICAL SKETCH.....</b>	<b>77</b>

## LIST OF TABLES

Table 2-1: Common Mechanical Properties of Polymer Matrix. -----	9
Table 2-2: Tested Conditions Performed by Kamran, (1993). -----	21
Table 3-1: Physical Properties of E-bond 526 Lightweight System Low Modulus. -----	34
Table 3-2: Properties of E-bond 526 Neat resin Lightweight System. -----	35
Table 3-3: Aggregates Properties and Size Distribution. -----	36
Table 3-4: Sample for Differential Mechanical Analysis (DMA): E-Bond lightweight system. -----	40
Table 4-1: Results for the Stiffness Test Open and Filled With Lightweight Materials. -----	46
Table 4-2: Results for Thermal Properties of E-Bond 526 Lightweight Systems. -----	47
Table 4-3: Effect of Cyclic Weather on Compressive Strength. -----	68

## LIST OF FIGURES

Figure 2-1: Welded Open Steel Grate Deck 4- Ways and 5- Ways Systems. ....	6
Figure 2-2: Open Steel Grate Deck Systems - Jewfish Bascule Bridge. ....	6
Figure 2-3: Effect of the Water Absorption on Glass/epoxy Composite, (Karbhari, et al. 1997).--	19
Figure 2-4: Effect of Environment Exposure on Fracture Toughness, (Dash, et al. 2004).-----	25
Figure 2-5: Effect of Environment Exposure to Mechanical Properties, (Dash, et al. 2004).-----	26
Figure 2-6:Effect of Temperatures to Water absorption- Epoxy Resin, (Jeannie, et al.1998).-----	27
Figure 2-7:Effect of Temperature to Water Absorption –Vinylester Resin,(Jeannie, et al.1998). -	28
Figure 2-8:Effect of Temperature to Water Absorption–Isopolyester Resin,(Jeannie, et al.1998)	28
Figure 3-1: Climatic Chamber With Four Air Conditioners and Ten High-Powered Lamps. ....	31
Figure 3-2: Plan View of Constructed Climatic Chamber and High-Powered Lamps. ....	32
Figure 3-3: Longitudinal Section of Constructed Climatic Chamber. ....	33
Figure 3-4: Pouring of E-Bond 526 LW Materials to Open Steel Grate Decks. ....	37
Figure 3-5: Filled Open Grate Deck with E-Bond 526 LW Materials. ....	38
Figure 3-6: Sensors Connection and Installation to Filled Deck System. ....	43
Figure 3-7: Strain Gauge Type SG-1.5/120-LY11 Used to Build the Sensors. ....	43
Figure 4-1:Flexural Test for the Open and Filled With Lightweight Materials. ....	44
Figure 4-2:Flexural Test for the Open and Filled With Lightweight Materials. ....	45
Figure 4-3:Flexural Test for the Open and Filled With Lightweight Materials. ....	45
Figure 4-4: DMA Test for E-Bond 526 Lightweight Systems. ....	47
Figure 4-5: Surface and Ambient Temperatures From Direct Sunlight. ....	49
Figure 4-6: Ratio of Surface Temperatures from Direct Sunlight to Glass Transion Temperature of LW materials. ....	50

Figure 4-7: Temperatures on the Surface Deck and Ambient Temperatures 2.5 ft from Deck Surfaces-August 18. -----51

Figure 4-8: Temperatures on the Surface Deck and Ambient Temperatures 2.5 ft from Deck Surfaces August 19. -----52

Figure 4-9: Temperatures on the Surface Deck and Ambient Temperatures 2.5 ft from Deck Surfaces August 20. -----53

Figure 4-10: Temperatures on the Surface Deck and Ambient Temperatures 2.5 ft from Deck Surfaces August 21. -----54

Figure 4-11: Ambient Temperatures 2.5 ft from Direct Sunlight-Fort-Lauderdale Station. -----55

Figure 4-12: Effect of Cyclic Temperatures at the Interfacial Region -----56

Figure 4-13: Effect of the Cyclic Temperatures at the Interface -----57

Figure 4-14: Effect of Cyclic Temperatures on the Shear Strain Interfacial Region -----58

Figure 4-15: Effect of Cyclic Maximum Temperature at the Interfacial Region- Top Sensor-----59

Figure 4-16: Effect of Cyclic Loading Temperatures at the Interfacial Region-Top Sensor -----60

Figure 4-17: Effect of Cyclic Loading Temperatures on the Interfacial Region-Bottom Sensor ---61

Figure 4-18: Effect of Cyclic Temperatures on the Interfacial Region – One cycle. -----64

Figure 4-19: Surface Temperatures on the Top and at the Bottom of the Filled Deck System. ---65

Figure 4-20: Effect of Cyclic Temperatures at the Interfacial Region -----66

Figure 4-21: Cyclic Temperatures above and below Glass Transition Temperature. -----68

Figure 4-22: Effect of Cyclic Temperatures to the Compressive Strength. -----69

## **ABSTRACT**

In the Florida State highway system there are 11,100 bridges (6,300 State bridges and 4,800 local bridges). The highway system includes 98 movable bridges, which are located within seven geographic districts. These bridge decks are constructed with steel open metal grate decking to reduce the weight of the superstructure and load carried by the substructure. When traffic traverses on the bridge deck systems, a significant level of noise is generated. This noise has caused some discomfort and has become a nuisance to the public, especially in regard to those bridges located near populated areas. Because of the problem, it has been suggested that filling the open grate with epoxy and fine aggregate broadcasted on it will increase the friction resistance and reduce the noise from bridge deck systems. For new bridges, concrete filling (exodermic deck) has been used, taking the extra weight from the concrete into consideration during the design stage. For the older bridges, however, the extra concrete weight was not considered in the design stage. Thus, the use of epoxy materials, which are lighter than concrete, is necessary in existing decks in order to remain within the load-carrying capacity of the other components of the bridge.

The primary objective of this study was to address the performance of the filled steel deck systems, the behavior and effect of repetitive thermal loads (temperatures below and above normal ambient temperature) to the open steel grid deck systems that were filled with epoxy resin. The deck systems filled with epoxy materials were subjected to accelerated climate chamber to simulate similar or extreme field conditions. Experimental results found that the performance of the open filled decks depends on the weather conditions. Under temperatures above normal ambient temperature, the interfacial region showed severe delamination compared to temperatures below normal ambient temperature. Also the study found that the performances at the interfacial region were affected by the number of cycles for both low and high temperatures.

# CHAPTER ONE

## OVERVIEW

### 1.1 Introduction:

In the Florida State highway system there are 11,100 bridges (6,300 State bridges and 4,800 local bridges). The highway system includes 98 movable bridges, which are located within seven geographic districts. These bridge decks are constructed with steel open metal grate decking to reduce the weight of the superstructure and load carried by the substructure. When traffic traverses on the bridge deck systems, a significant level of noise is generated. This noise has caused some discomfort and has become a nuisance to the public, especially in regard to those bridges located near populated areas. Because of the problem, it has been suggested that filling the open grate with epoxy and fine aggregate broadcasted on it will increase surface friction. For new bridges, concrete filling (exodermic deck) has been used, taking the extra weight from the concrete into consideration during the design stage. For the older bridges, however, the extra concrete weight was not considered in the design stage. Thus, the use of epoxy materials, which are lighter than concrete, is necessary in existing decks in order to remain within the load-carrying capacity of the other components of the bridge.

The use of two dissimilar materials together always raises issues of compatibility, especially when a series of repeated stresses are anticipated (from either environmental loading and/or applied loads). Over the years, the construction industry used steel and concrete as a composite system. However, in normal concrete construction, the steel is usually embedded in the concrete, thus providing sufficient insulation for the steel, which leads to some moderation of the thermal changes that may lead to incompatibility. In some cases where the steel is not embedded, such as in a steel bridge with concrete decking, sufficient numbers of shear studs are provided to transfer loads between the two systems. Filling the open metal grates with epoxy will lead to a series of epoxy prisms in each individual grate cell. In this type of bridge deck there are no shear studs to transfer the loads from the prism to the steel. The only loads-transfer mechanism is the bonding of the epoxy and the flat metal surfaces. The epoxy resin should provide a strong bond at the interface when subjected to traffic and when exposed to climatic changes. Both the epoxy and the steel are subject to

environmental exposures without insulation; these materials behave differently due to their different thermal characteristics. This difference in thermal characteristics raises compatibility issues. Thus, there is a need to identify the long-term consequences of this likely incompatibility.

Bridge decks filled with lightweight materials are subjected to various environmental degradations over their service life. Karbhari, et al. (2004) indicated the primary field conditions which may affect the durability of the polymer composite. These conditions are thermal effects, moisture effects, alkaline effects, creep and relaxation, fatigue and ultraviolet. Thermal effects considered in the section included response changes due to temperatures above the cure temperature, freezing and freeze-thaw conditions, and cyclic temperature variations. Moisture diffuses into all organic polymers, leading to changes in thermo physical, mechanical and chemical characteristics. The primary effect of absorption is on the resin itself through hydrolysis, plasticization, and specifications, which cause both reversible and irreversible change in polymer structure. Composite materials can come into contact with alkaline media through interaction with a variety of sources, including alkaline chemicals, soil or solution diffusing through soil and concrete.

The performance of the filled steel decks is defined as its ability to resist cracking, oxidation, chemical degradation, wear and the effect of unforeseen objects for a specified period of time, under appropriate load conditions, under specified environmental conditions.

## **1.2 Goal and Objective:**

The main objective of this study was to address the performance of the filled steel deck systems, the behavior and effect of repetitive thermal loads (temperature below and above normal ambient temperature) to the systems that were filled with epoxy resin.

## **1.3 Methodology:**

In conducting the study, sequences of tasks were considered. These tasks involved:

1. Research literature reviews for the current publications, which are related to the behavior and performance of the adhesive resin under different weather conditions.
2. Identify the expected operating conditions that will have an impact on the durability of the epoxy filled open metal grade deck.
3. Use the results from literature search and use ASTM E632 procedures to determine the parameter test ranges.

#### **1.4 Project Scope:**

In order to understand the implications of environmental exposure to the performance of the steel filled deck systems, the impact of each environmental exposure will be addressed. The report covered the performance of the filled steel deck systems under thermal loads exposure (temperatures below and above normal ambient temperature).

## **CHAPTER TWO**

### **LITERATURE REVIEW**

#### **2.1 Background:**

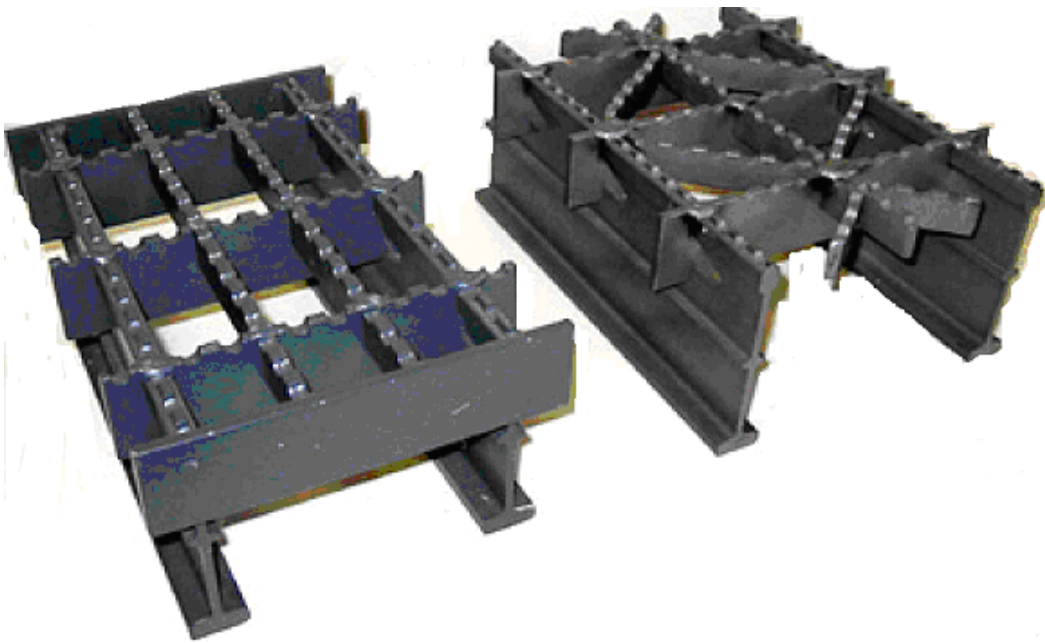
Open steel grid deck systems were first used as a bridge decks in the 1920s and 1930s. These type of bridge decks gained more use in the 1950s. Since that time the open bridge decks have been in service for more than 50 years (Huang, 2002). These types of bridge deck systems are 80% open and do not collect rainwater, snow or ice. The deck systems are primarily used on movable (Bascule) bridges and older bridges that can no longer withstand a heavy dead load. The open steel grid deck may be either welded directly to the supporting members or bolted down with plates.

Traditional steel grid decks are composed of hot-rolled steel members (bar stock and rolled shapes) placed orthogonal to one another through punch-outs and welded at their intersections. Typically, such welded decks are used in concrete filled as well as open grid steel deck applications. Research has shown that welding intersecting members can result in deleterious effects on the fatigue life characteristics within current grid steel deck designs (Klippstein, 1993; Mangelsdorf, 1991). One interesting and recent development is the introduction of open grid steel decks that are weldless.

Typical open steel grid deck systems used in bridge construction are factory-assembled. The decks are made from carbon steel A36 grade and are characterized based on usage and application. The steel grid deck may be grouped into three types. These types are riveted grating, pressure locked grating and welded grating. Riveted grating decks are the stronger than other grating systems. The grating type has bearing bars, which are connected by the truss style crimp bars. Crimp bars distribute load to and between bearing bars and provide lateral support between these bearing bars. This type of grating excels at handling vehicular loading, temperature effects and other conditions that require strength, stiffness and low weight. Pressure locked grating decks are the most versatile grating type. They offer the widest variety of the load bearing bar spacing and can be manufactured effectively in small quantities. The pressure grating can be manufactured of steel or aluminum and are suitable for pedestrians, traffic, grills and architectural applications. Welded grating deck systems are formed by electrically fusing steel load bearing and cross bars. These gratings are recommended for bridge decks and parking applications. There are two types of welded

grating bridge decks used in the bridge deck system. These decks are 5-ways and 4-ways steel grate deck systems (see figure 2-1). The 5-ways steel bridge deck type includes longitudinal, transverse and supplementary steel bars (tertiary bars). Tertiary bars run diagonally from one corner to another and are welded at the intersections. The 4-ways steel grid bridge deck types include two steel bars that are arrayed longitudinally and transversely only. The longitudinal and transverse bars are spaced at the distance of 203 mm (8 in) and 102 mm (4 in) respectively. Between the longitudinal steel plates (main bars) there are steel bars 25 mm (1 in) deep and welded to transverse bars and tertiary bars at the intersection. The longitudinal bars for both types are considered to be thicker and stiffer than the cross bar but the thickness is the same for all types of the gratings.

Huang (2002) studied the behavior of the 4-ways open steel grate deck systems. The study included laboratory tests of full-scale open grate deck systems and individual bars. Static loads were applied on the decks; deflection and behavior of the bearing bars were measured by LVDT and strain gauges respectively. Twenty-one welded strain gauges were used at each deck and were placed at the different locations. The deck was loaded to 44.5KN for three cycles and then loaded to failure. After the decks were loaded to one million cycles, no significant changes in stiffness were observed. All other decks were statically loaded to failure and the results indicated the deck start to be behavior-inelastic, i.e., beyond the elastic limits. The response curves indicated decreased deck stiffness associated with the progressive yielding of the steel bars. Also, the results showed the strain decreases from the center of the deck for both longitudinal and transverse steel bars.



(a) 4-ways open steel grate deck

(b) 5-ways open steel grate deck

Figure 2-1: Welded Open Steel Grate Deck 4- Ways and 5- Ways Systems.



Figure 2-2: Open Steel Grate Deck Systems - Jewfish Bascule Bridge.

## **2.2 Matrix resin:**

In recent years, organic polymers and composite materials have increased their importance in the construction industry. The composite materials provide solution where conventional materials, such as steel or concrete, failed to provide proper performance and service life. The composite materials have been used in civil engineering to retrofit bridges and buildings. The new technology is separated into two main constituents, which are the reinforced and matrix phases. The reinforced phase includes Carbon Fiber Reinforced Polymer (CFRP), Glass Fiber Reinforced Polymer (GFRP) and Aramid Fiber (AF), while the matrix phase includes epoxy, vinyl ester, polyester, polyurethanes and phenolics. In rehabilitation, the resin components and application methods play important roles in determining the performance of a polymer concrete overfill. The contribution of the resin system is the most important factor in relation to the durability under long-term performance. The adverse effects of the environment on the adhesive system can be significantly decreased by application of a proper resin system. The resin has been used in the bridge deck systems to serve as a medium for holding the aggregates together, as well as being a basis for shear load transfer.

## **2.3 Properties of Epoxy Materials:**

Application of epoxy resin began in 1943 and became most used in manufacturing operations and industries in the early 1950s (Wood, 2003). The material shows good performance in corrosion resistance and provides higher strength under normal operation conditions. Epoxy resins can be applied at room temperature and have high surface activity and good wetting properties for a wide variety of materials. Usually epoxy resins are available in a two part systems. These are Component A (adhesive resin) and component B curing agents (hardener). The mixing ratio depends on the application. Studies have been conducted on common adhesive resins (epoxy, polyester and vinylester) under different operational environments. The objectives were to understand the behavior and response of the adhesive resins under different weather exposures. The study found that epoxy matrix has the following advantages over other resins.

1. Epoxy has wide variety of properties because of availability of large number of starting materials, curing agents and modifiers.
2. Epoxy provides higher strength retention under sustained loading compared to the polyester and vinylester.

3. Epoxy resin has low creep and low shrinkage properties.
4. Epoxy material shows good chemical resistance and solvents.
5. The material indicates excellent adhesion properties to a wide variety of fillers, fibers and other substrates.

Jamond and Malvar (2000) tested the specimens that were bonded with three different resins (epoxy, vinylester and polyester) and fabric materials. The specimens were exposed to different operational conditions. After mechanical tests, the specimens bonded with epoxy showed higher moduli of elasticity, compression strength and tensile strength compared to other specimens. Specimens bonded with epoxy resin showed no effect under ultraviolet radiation (UV) exposure compared to vinylester and polyester resin.

## **2.4 Type of Adhesive Resin:**

Adhesive resin is the type of polymer materials, which is in the form of plastic. The applications of the adhesive resin may be grouped based on the chemical and mechanical properties. The common adhesive resins used in civil engineering are thermosetting and thermoplastic resin.

### **2.4.1 Thermoplastic Resin:**

This is types of resins are re-shaped or recycled after heating. The resins falling in this group produced both plastic and elastic deformation when external loads were applied. Thermoplastic resins have higher viscosity than thermosetting resins and they may be crystalline in nature. Thermoplastic resins are more prevalent in aerospace industries due to their toughness and decreased brittleness; they are used mostly with discontinuous fibers. Examples are acylonitrile-nitrile styrene polymers, acrylic (e.g., polymethylmethacrylate, nylon, polyethylene, polypropylene, polystyrene, polyphenyl sulfide, polyvinyl chloride and polyester).

### **2.4.2 Thermosetting Resin:**

Thermosetting resin is another group of resin materials that contains a long chain of molecules. The resins formed in this group create a strong cross-link between the polymer materials. The resins included in this group cannot be re-processed after the cross-link reactions have occurred. Thermosetting resins have no fixed melting temperature and they have higher viscoelastic behavior. The resin under this group carries many beneficial properties such as versatility, good handling characteristics, toughness, high adhesive

properties and low shrinkage. Resins falling into this category are polyesters, vinylester, epoxy, polyurethanes and phenolics. Epoxy resins are workable at room temperature although some of them require heating before mixing. The performances of the epoxy resin depend on the degree of cure. Long cure increases the life of the epoxy performance because it will increase the density of the cross-link and will enhance the chemical inertness that provides resistance to chemical or moisture attack.

Table 2-1: Common Mechanical Properties of Polymer Matrix. Gamma (1999)

Properties	Epoxy resin	Polyester Resin	Phenolics resin
Density (g/cc)	1.1-1.35	1.2-1.4	1.35-1.75
Tensile strength. MPa (ksi)	40-100 (5.8-14.5)	45-90 (6.5-13.0)	45-65 (6.5-9.4)
Compression strength. MPa (ksi)	100-250 (14.5-29.0)	100-312 (14.5-36.2)	90-250 (13-29.0)
Modulus of Elasticity MPa (ksi)	3.0-5.5 (435.1-797.7)	2.5-4.0 (362.5-580.1)	5.5-8.0 (797.7-1160.2)
Poisson ratio	0.38-0.4	0.37-0.4	0.37-0.4
Coefficient of thermal expansion $10^{-6}/^{\circ}\text{C}$	45-65	100-120	30-45

## 2.5 Wearing Surface:

Cuschieri, et al. (1995) conducted a study on noise generated at movable (Bascule) Bridge during traffic flow. The study found that the potential source of noise was the vibrations between the steel grid and the movement of tires over it. To reduce the noise, the authors' suggestion was to fill the open individual cells with epoxy materials and fine aggregates broadcasted on it. The filling process will increase the weight to the superstructures and cause problems to the substructure and foundations. To reduce the weight problem, the authors suggest filling only the wheel paths in the expectation that the entire vehicles would drive on the filled paths.

Bridge decks require a surface texture to provide abrasion resistance to the wheel transverses during the service life. In open bridge deck systems, concrete can be properly

textured and present a long- lasting surface for many years. However, for open grid deck the long-term performance depends on the type of adhesive resin, aggregate types, environment exposure, construction techniques and workmanship. Aggregates used for surfacing must be especially selected for hardness and wear resistance. The aggregates should be able to provide abrasion resistance under any weathering conditions. Three types of aggregate are most used by the Florida Department of Transportation (FDOT) to improve friction resistance on the open bridge deck systems. These aggregates are EP-5 modified aggregates, manufactured minerals (BT 6 x 10 Basalt (Coarse) Indag #8 Type) and 3-M Company Indag # 8.

There are several techniques used as a wearing surface on bridge deck systems. These techniques are steel wearing surface, asphalt wearing surface and epoxy modified wearing surface. All these techniques should provide the abrasion resistance during the cyclic load, especially during the rainy season.

## **2.6 Polymer Concrete Filled Bridge Decks:**

The polymer concrete overlay consists of adhesive resin as a binder and aggregates to provide abrasion resistance. Epoxy, vinylester and polyester have been used to fill the open steel grid decking cells with aggregate broadcasted materials to increase abrasion resistance. The aggregates used for overlay should have high abrasion resistance to provide good friction resistance. The polymer concrete is the key of the open steel grid deck, which can be slip-resistant during the winter or rain season. Polymer resins, such as epoxy and steel plate, have different mechanical properties. If the system (steel and epoxy) is exposed to temperatures above normal ambient temperature the epoxy resin will expand more than the steel material, also under temperatures of exposure below ambient temperature the epoxy material will contract faster and more than the steel plate. Under to cyclic temperatures, thermal stresses will be created at the interfacial region, which lead to the interfacial failure. The polymer concrete overlay forms a strong bond between the steel and the concrete at the interfaces under normal operation condition. However, the bond strength might be affected by thermal loads and excess load generated from the traffic. Because epoxy materials have adhesive properties, has been used to hold aggregate in place and transfer sustained dynamic and thermal movement to the steel bars.

In the United States, various states have experience with polymer concrete overlays. According to Tarricone (1992), the states that have polymer overlay are California, Virginia, New York, Washington and Ohio. By the 1980s, Virginia realized the benefits of using polymer

concrete. Since then, polymer concrete overlays have been installed on eight to ten bridge decks per year. California started to use premixed polyester overlays in 1982 on Interstate 80 in the Sierra Nevada Mountains in northern California; the reason for overlaying the road was delamination resulting from de-icing salts, heavy tire chain wear and a high traffic volume. The author reported a project in California involving six lanes of the Marina Viaduct approaches to San Francisco's Golden Gate Bridge. Fatigue tests for bond strength, riding surface and delamination were conducted. The results from these tests indicated good performance by polymer materials.

Krauss (1997) reported that the state of Montana has 4,400 bridges. These bridges are exposed to environmental conditions which include temperatures ranging from  $-48^{\circ}\text{C}$  to  $49^{\circ}\text{C}$ , along with heavy snowfall. Corrosion of the reinforcing steel due to the permeating chloride ions, delamination and scaling, and low skid resistance has forced Montana to consider other paving alternatives. The author reported that in 1994 the state decided to overlay  $8,000\text{ m}^2$  of the bridge decks with methyl methacrylate and  $8,500\text{ m}^2$  of bridge deck with epoxy materials. After one year visual inspections of the bridges were conducted; those bridges overlaid with methyl methacrylate showed tears and cracks. Also, after two years the same delamination occurred on another bridge, which was also overlaid with methyl methacrylate. On the other hand, the bridges overlaid with epoxy materials have survived the harsh winters despite the thickness of the epoxy being lower than that of the methyl methacrylate overlays.

Gama (1999) documented the conditions of the Harlem Street Bridge in Chicago, Illinois. The bridge deck is steel grid filled polymer concrete polymer concrete applied in 1994. In 1997 the bridge condition was good but delamination had occurred in some areas. Mendis (1987) reported that New York City began to use polymer concrete overlays in 1980s. The first project to do so was the Queensboro Bridge, followed by the Brooklyn Bridge. The Brooklyn Bridge, connecting Manhattan and Brooklyn, was completed in 1883, with the original bridge deck being made of wooden blocks. After 70 years, the bridge was replaced with a steel grid deck filled with portland cement concrete; a few years later the shear studs were welded to the deck to provide skid resistance. In the 1980s the City Authority decided to rehabilitate the deck with polymer concrete with Flexolith resin. The reasons for the rehabilitation were:

1. The traffic volume of 10,000 cars per day had polished the steel grid and delaminated the portland cement concrete, reducing the skid resistance of the deck.
2. Water and deicing salts caused corrosion of the steel grid.

3. The steel studs created an objectionable noise level.

Sprinkle (1993) documented different factors that reduce the performance of the epoxy resin. These factors are salts, acid and alkaline conditions. Also, petroleum products reduce the bond strength between polymer materials and concrete or steel substrate. Other factors that might affect the interfacial bond strength are surface preparation, materials used and overlaying method.

## **2.7 Method of Overlay in Bridge Deck:**

Gamma (1999) reported three common methods of polymer concrete overlay. These methods are slurry methods, multi-layer methods and premixed methods.

### **2.7.1 Slurry Overlay:**

The slurry overlaying method consists of mixing the polymer resin and gap-graded aggregate in continuous or batch mixing equipment. The gap-graded aggregates consist of different sizes; the proportion of the aggregates in various gap-graded batches are documented by Sprinkle (1995). The blended materials (epoxy and fine aggregates) are distributed on the open-grate deck using gauge rakes, trowels or beam boxes. Aggregates are broadcasted immediately on the blended material before it becomes completely cured. To achieve the required resistance and good abrasion, some overlaying required that a thin layer of the resin be applied on top of the aggregates. Gama (1999) reported that the application of polymer concrete overlaying materials is approximately  $0.41\text{kg/m}^2$  (0.084lb per sq ft) for the primer;  $2.7\text{kg/m}^2$  (0.553lb per sq ft) of a polymer mixed with  $3.8\text{kg/m}^2$  (0.778 lb per sq ft) of silica sand, and  $2.7\text{kg/m}^2$  (0.553lb per sq ft) of silica for the slurry mixture.

### **2.7.2 Multiple Layer Overlay:**

Multiple overlay methods are sometimes called “broom-and-seed overlay.” This method is implemented by applying polymer resin on an existing bridge. Polymer binder is spread throughout the deck by a broom or squeegee, or a roller. The method is suitable for higher viscosity binder systems and when thin overlays are designed. The overlay method is simple and easily implemented because it requires little mechanical equipment and less skilled labor. The aggregates are broadcasted over the polymer binder after the binder material has cured but is still tacky. This process may continue for two or three layers and contains an

overlay thickness of 10 mm for each layer. Sprinkle (1995) reported the application of aggregates on the first layer to be approximately to  $5.4\text{kg/m}^2$  (1.106 lb per sq ft) and  $1.1\text{kg/m}^2$  (0.225 lb per sq ft) of polymer resin. The second layer consists of  $7.6\text{ kg/m}^2$  (1.557 lb per sq ft) and  $2.2\text{kg/m}^2$  (0.45 lb per sq ft) aggregates and polymer resin respectively.

### **2.7.3 Premixed Overlay:**

The premixed overlay technique is implemented by mixing dense-graded aggregates with resin. About 12% by weight of all binder is required for the mixing and the mixing process is performed before it is applied to the bridge deck. A primer coat of about  $0.41\text{kg/m}^2$  (0.084 lb per sq ft) applied on the deck is used to enhance the strong bond between the substrate and mixed materials. To obtain the desired screed skid resistance, the aggregate may be applied on the fresh binder materials on top of the substrate.

## **2.8 Factors Affecting Bonded Joint:**

Several studies have been conducted on the durability of composite materials bonded with adhesive resin. Sprinkle (1993) conducted a test on fabric materials bonded with adhesive resin to the steel and concrete substrate. The main objective of the test was to determine the effect of weather on the durability of the composite materials. The specimens were exposed to different weather conditions, which were temperature, humidity, salt water, hot and cold water. After mechanical tests were conducted, the results showed that the compressive and tensile strength were more highly affected by temperature and humidity than other exposure conditions. The author explained that temperature and humidity/water cause thermal stress within the materials as well as along the interfacial region between the two materials. These stresses could be significantly larger and therefore cause debonding or delamination effects. Also, the author explained that the low strength might be due to the dissimilar thermal coefficients. Both polymer and substrate materials have different thermal expansion: polymer expands more than steel or concrete substrate. The expansion process will develop thermal stresses between the interfacial regions.

Woods (2003) documented that an increase in the operation temperature above the glass transition temperature reduced the bond shearing capacity between polymer and concrete or steel substrate. Molecules in polymer resin become flexible and free to move at a temperature above glass transition temperature. Polymer above glass transition temperature changes its properties from a brittle to a ductile state. Increase in operational temperature may

increase the volume of the system as polymer materials expand more than steel and concrete due to the higher thermal coefficient when compared to steel and concrete. When epoxy is exposed to low temperature, the resins behave differently than in hot weather. If both conditions (water and temperature) act on systems at different time periods, the deck systems will contract and expand. This process of contraction and expansion will create stress on the interfacial region that may lead to cracks and debonding or delamination along the interfaces.

Studies have been performed on the physical and mechanical properties of adhesive resin under environmental exposure. Alfred, et al. (1981) studied the change in physical properties of adhesive resin under moisture and temperature exposure. Also, Chateauminos, et al. (1993) studied the behavior of adhesive with the same objective: the effect of moisture and temperature exposure. The two researchers drew the same conclusion that intake of moisture leads to a plasticization effect of the matrices, which allows filament buckling to occur easily and may lead to failures of the composite materials. Bledzki, et al. (1985) studied the effect of E-glass under the acid solution and the results showed that E-glass/epoxy decreased the load-carrying capacity by 5% when exposed to sulphuric acid. The authors explained that acids penetrate through the matrix and cause cracks, which may result in corrosion at the interfacial region between the fabrics and steel substrates.

Guetta, et al. (1989) conducted studies comparing thermal cyclic to carbon-reinforced polystyrylpyridene (PSP) composites. The results showed that an increase in the maximum temperatures of the cycle decreased the mechanical properties. Also, the studies showed propagation of the microcrack in the specimens. Wimolkiasalk and Bell (1989) performed a test on epoxy resin under water at temperatures of 50°C and 100°C. The results showed that tensile strength decreased from 70MPa to 58MPa at 50°C and decreased to 62MPa at a temperature of 100°C. Also, the studies noted that once the samples were dehydrated, the samples regained their original strength and sometimes became stronger than virgin samples.

## **2.9 Failure Mode of the Open Bridge Deck:**

There are three common modes of failure of the polymer concrete overlay in bridge deck systems. The first mode of failure is delamination or debonding. Delamination is the process by which the concrete layer or adhesive resin materials separate from the near top of the reinforcements. The delamination process may be caused by corrosion produced from the steel materials. Another cause of delamination or debonding is due to the resulting thermal effect, mechanical properties and environmental conditions, or the presence of combinations of

those conditions. Also, improper or inadequate surface preparation (workmanship) and types of materials used may be causes of the delamination effect.

The second mode of failure is the scaling effect, which occurs as the local or peeling of the surface portion of the concrete or aggregate. The scaling effect is caused by contraction or expansion of the materials. The third mode of failure is cracking and loss of the aggregates. Cracks are caused by changes in environmental conditions, such as temperature and humidity. These conditions cause materials to behave differently due to different thermal coefficients. The dissimilarity of these material properties cause the cracks to develop and propagate along the interfaces. Cracks may increase porosity and lead to water intrusion into the interfacial region, which will cause corrosion in the steel bar and expansion of the corrosion products. Nabar (1997) reported that the cracks in overlay could also be induced by fatigue stress at the bond line from excessive flexing of the bridge deck. Also loss of the aggregates may affect the polymer concrete in long-term; this failure is affected by the type of aggregates and the strength of those aggregates.

Gama (1999) documented that the type of aggregates used to determine skid resistance might affect the durability of the polymer concrete overlay. Also, the author documented the factors that affect the performance of the polymer overlay. Percentage of voids, abrasion resistance and quality of the concrete used and the coefficient of thermal expansion all affect the durability of bridge deck systems. Softer, more friable, round or smaller degradation of aggregates affect the long-term durability and skid/friction resistance. Soft aggregates wear rapidly, friable aggregates will rapidly break down and round aggregates provide poor friction resistance.

## **2.10 General Trends Regarding Loss of Adhesion:**

Leidheiser and Funke (1987) reported that the rate of loss of adhesion of thin films to a substrate is dependent on the rate at which water penetrates through the coating to the interface. Water transported and corresponding to the adhesive loss depends on duration of exposure, type of substrate, type of coating materials and temperature changes. Weitsman, et al. (1998) and Weitsman (2000) exposed composite materials to seawater for a period of three years. The results showed that time of exposure and durability were related. Under such prolonged conditions, it is likely that adhesive degradation is a result of a slowly-progressing chemical reaction in the bulk adhesive and/or interface. From these results, the authors concluded that the interfacial strength is controlled by the adhesive and surface preparation. In general, as the temperature increased, the adhesion loss occurred more rapidly. Nguyen

(1995) concluded that when water reaches the interface between an adhesive and an untreated high-energy substrate, the adhesive bonds attributable to secondary molecular interactions (Van der Waals) disrupted immediately and lost intermolecular bond strength.

Takahashi (1998) used Ac-impedance spectroscopy to study the effect of water absorption at the interfacial region. The results showed that at a relative humidity of 80%, increased abruptly, which indicated the formation of water clusters in the bulk and at the interfacial region. Wu, et al. (1995) measured the concentration of water at a polyimide-silicon wafer interface and found that the deuterated water concentration at the interface was 17% compared to 3% in the bulk polyimide adhesive. Kent, et al. (1996) used neutron reflectivity to study the absorption of water at a molybdenum/polyurethane interface. The test results found more than 80% of deuterated water at the interface attributable to debonding.

### **2.11 Effect of Temperature and Water:**

The effect of temperature and water/moisture on epoxy resin is an important environmental factor to be considered on long-term performance of adhesive resin. ACI 440-3.1.3 recommends that FRP materials bonded to a steel or concrete substrate should not be used at temperatures above the glass transition temperature ( $T_g$ ). Sprinkle (1993) reported that temperature above the transition temperature affects the physical and mechanical properties of the adhesive resin. Temperatures above the transition temperature will cause resin molecules to become flexible and free to move, resulting in the delamination and debonding effect. The movement of epoxy molecules may result in low shear strength at the interfacial region. Temperature changes the rate at which moisture penetrates and diffuses into the FRP composite. The moisture penetrates to composite materials modeled by Fick's first law and relationship of the moisture and temperature modeled by the Arrhenius equation

Gama (1999) documented that epoxy; concrete and steel have different mechanical properties such as thermal expansion, stiffness and modulus of elasticity. Change in temperature, moisture and excessive loading will cause differential expansion of the materials and raised compatibility issues.

Sprinkle (1996) reported that the coefficient of thermal expansion for epoxy resin is greater compared to concrete or steel substrate. When the fabric materials are bonded to the concrete or steel substrate with epoxy resin and subjected to temperature or moisture changes, it will undergo volumetric changes. Epoxy resin expands more than concrete or steel due to higher thermal expansion. These changes may create the stresses at the interfacial

region. The cumulative stresses may lead to adhesive failure at the interfaces or shear failure within the concrete or steel substrate.

Karbhari, et al. (1996) conducted tests to evaluate the short-term bond durability before and after environmental exposure. The test includes two resins, Tonen system mixed at ratio 2:1 (resin: catalyst) and commercial epoxy-epon DPL 862 catalyzed by Ancomine 1636, mixed at a ratio of 4:1(resin: catalyst). Both resin samples were cured at a room temperature similar to the field conditions. After thermal analysis, the epoxy-epon system and Tonen resin showed glass transition temperature of 90°C and 54°C respectively. The specimens were tested by dynamic mechanical analysis (DMA) on neat resin after immersion in water for a period of 60 days. The glass transition temperature ( $T_g$ ) of Tonen and Epon epoxy resin system drop by 20% and 12% respectively. It was also noted that ( $T_g$ ) for composite dropped about 11% for both glass- and carbon-reinforced Tonen systems. A 9% drop of glass transition temperature was observed from Epoxy-epon systems after immersion in water for a period of 60 days.

Karbhari and Engineer (1996) conducted an experiment to evaluate the behavior of resin systems. The types of resins used for the tests were symbolized with by letter A and letter B. Dynamic mechanical analyses were performed for both types of resin at a temperature of 23°C and after they had been immersed in water for a period of one week. The results showed that the resin symbolized by letter B had higher glass transition temperature than resin A. Higher glass transition temperature is an indicator that the system B was affected to a lesser degree of exposure than was system A.

Seong, et al. (2003) conducted a water absorption test on a hydrophilic polymer matrix of carboxyl functionalized glucose resin and epoxy resin. The objective of the test was to examine the reaction between water and epoxy resin. Two types of resins were used in this study: epoxy tactics 123 and maleic acid ester vinyl resin (GMAEV). The author noted that epoxy resin reacts with water much more easily in wet environments than does cured epoxy. The weight gain derivation for the GMAEV and epoxy resin showed that the GMAEV increased four times more than the epoxy matrix after immersion in water for a period of 42 days. Also, the results indicate the weight of matrix cured at lower temperatures increased compared to the matrix cured at a higher temperature. A 4% weight gain for both matrixes was observed after immersion in water and for a period of 42 days.

Polymer matrix specimens were immersed in water for 42 days. After the specimens were examined for thermal analysis, the results showed glass transition temperature dropped from 95°C to 82°C and then increased to 98°C. From those results, the authors concluded that absorbed water acts as plasticizer and increases the mobility of the molecule chain and

decreases glass transition temperature. The author documented absorbed water in polymer materials exists in two different types, bound water and free water molecules. Bound water is characterized by the strong interaction with hydrophilic groups on the surface of the matrix. Free water presents in capillary and microvoids within the matrix network. Free water molecules fall into two categories. The first category corresponds to a molecule that forms a single hydrogen bond within the matrix network. Those molecules of water possess lower activation energy and are more easily removed. Those molecules act like plasticizer, which lowers glass transition temperature ( $T_g$ ). The second category of water forms multiples of hydrogen bonds within matrix network. This type of water molecule possesses higher activation energy and is not easy to remove. The molecules in this category increased glass transition temperature ( $T_g$ ) by forming a secondary, cross-linked network with the polymer matrix. The presence of water molecules caused a degradation process such as cutting chain molecules, lowering the reaction of water molecules with the polymer chain and creating vibration of the water molecules. These three effects may lead to the production of shorter chain and effect phase morphology of the cured matrix. The matrixes cured at the lower temperatures have more ductile regions in the shape of globules compared to the matrix cured at higher temperatures.

Chin, et al. (1997) exposed polymer materials to different weather conditions. These conditions were ultraviolet radiation, moisture, heat and high pH. The authors concluded that the most severe exposure conditions were alkaline and saline environments. Jamond and Malvar (2000) exposed the specimen to dry heat conditions of 95°F and 50% relative humidity for a period of four months. The specimens were bonded with four different resins: vinylester, polyester, phonic and epoxy. After the mechanical analyses were conducted for each specimen, the results showed that the specimens bonded with vinylester lost storage modulus by 11% but other specimens were not affected by dry heat exposure.

Karbhari, et al. (1997) outlined the degradation mechanism of water molecules to the glass/epoxy composite by means of the following diagram in figure 2-3 below:

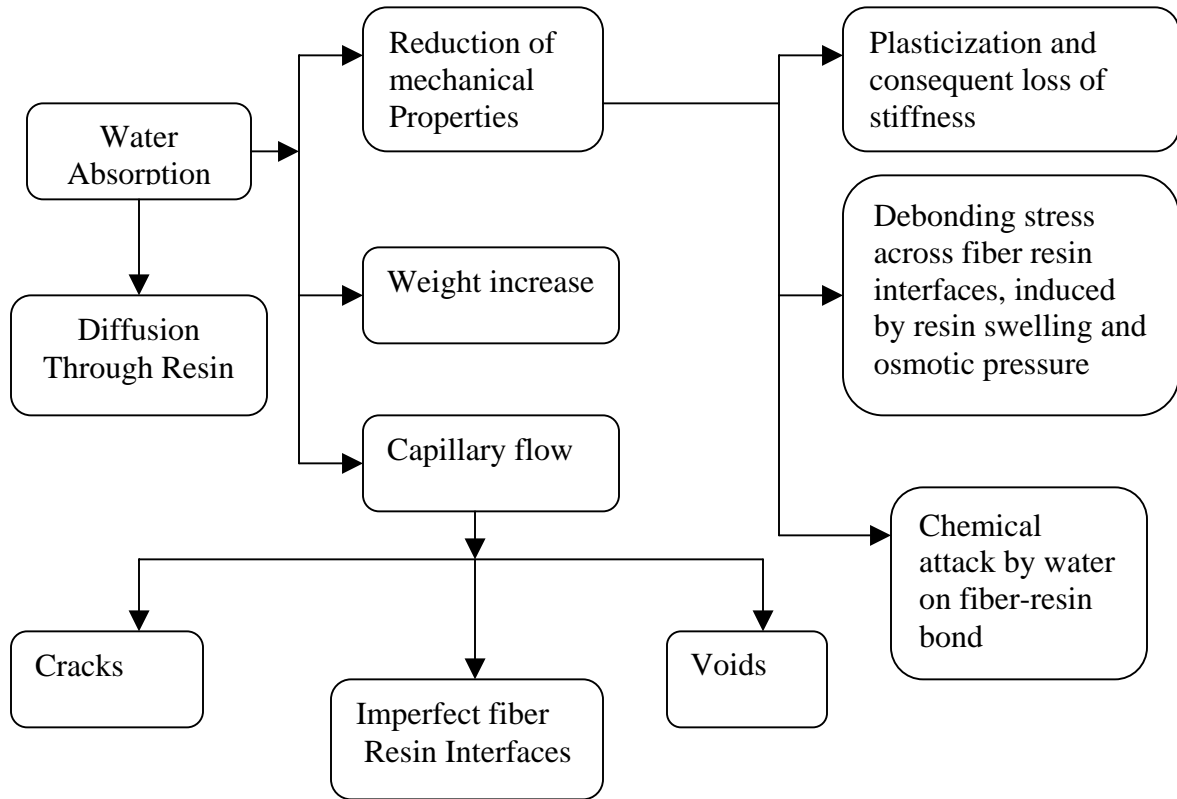


Figure 2-3: Effect of the Water Absorption on Glass/epoxy Composite, (Karbhari, et al. 1997).

Rivera and Karbhari (2001) simulated carbon fiber reinforced and vinylester composite under different field environment conditions. Vinylester resin was catalyzed with 1.5% organic peroxide and cured under ambient conditions of a temperature of 23°C and 50% relative humidity. Two types of the specimens' shapes were prepared: cylindrical and flat plate composite. The specimens were subjected to the three different exposed conditions, which are:

1. Exposed to constant temperature level of -10°C to freezer-thaw conditions in the received state at low humidity level.
2. Exposed to freezer thaw with immersion in deionizer water.
3. Exposed to freezer thaw conditions with immersion in salt solution.

Weight gain analyses were conducted for all specimens. The results showed the weight gain for the specimens immersed in dionized water increased about 36% compared to the samples attained under ambient conditions. Saltwater immersion showed a maximum weight

gain of 80% more compared to the specimens tested under ambient conditions. Results from dynamic mechanical analysis (DMA) indicated that the samples exposed to a temperature of -10°C and dry freeze-thaw exposed increased in stiffness by 27% and 4% respectively compared to the ambient temperature. The modulus of elasticity was compared at each condition. The specimens exposed to deionized water lose storage modulus by 28% compared to the specimens under ambient conditions.

Aminabhavi (1988) performed a weight-gain experiment to the composite bonded with epoxy resin to understand the diffusion phenomenon. The composite materials were exposed to distilled water and salt solution at different temperatures. The main objective was to investigate the diffusion mechanism for the composites. It was observed that the maximum absorptivity depended on the type of filler that was used in the composite. Also, it was observed that the diffusion rate of distilled water was higher than that of salt solution. Whereas in general, the activation energy for diffusion was higher, increase in activation energy for the salt solution was attributed to an increased penetrate size of sodium and chloride ions.

Mukhopadhyaya, et al. (1998) studied the behavior of epoxy on the influence of aggressive exposure conditions. The study involved epoxy adhesive bonded to concrete substrate and glass fiber reinforced polymers (GFRP). Twenty-four concrete prism sizes of 4 in x 4 in x 12 in were used in this study. The specimens bonded with GFRP plates on two opposite faces were 19 in long, 3.5 in wide and 0.138 in thick. Two different concrete strengths were used and they were suitably air entrained. The specimens were subjected to three accelerated aging regimes for a period of nine months. The specimens were exposed to alternate wet-dry cycling in 5% sodium chloride solution, cyclic freeze-thaw at temperatures of 20°C and -17.8°C, and combinations of chloride immersion and freeze-thaw cycles. The specimens were tested to failure after the exposure regime. Load carrying capacity, longitudinal force distribution, shear stress development in the plate, plate end slip, and differential movements between the plate and the concrete substrate were compared. The results showed all the exposure regimes increased the bond transfer length. The combined chloride immersion freeze-thaw cycles produced larger differential movements between the plate and concrete substrate. However, the results were very consistent and showed that accelerated tests could inflict deterioration in the adhesive bonded concrete-GFRP joints.

Kamran (1993) studied the effect of cyclic temperatures and humidity on the adhesive resin. The resin type FR-4-epoxy resin board, bis-Maleimide triazine (BT) board and cyanate ester (CE) board were used for this study. All three resins were bonded to E-glass reinforced fiber. Two tests were performed: thermal cyclic and a combination of temperature and

humidity cycles. The thermal cyclic test included three different temperature ranges: from 25°C to 85°C, from 25°C to 150°C and from 25°C to 200°C. In the combination of humidity and temperatures cyclic test, the temperatures ranged from 25°C to 85°C and relative humidity ranged from 20% to 80%. Table 2-2 below summarizes the testing parameters performed by Kamran (1993).

Table 2-2: Tested Conditions Performed by Kamran, (1993).

Exp No:	Low Temp (°C)	High Temp (°C)	$\Delta T$ (°C)	Relative Humidity (%)	Dwell time At High	Dwell time At low	Temp Ramp Time	Total # Cycle
1	25	85	60	20	200hrs	4hrs	10min	10
2	25	150	125	20	50hrs	4hrs	10min	14
3	25	200	175	20	10min	10min	45min	40
4	25	85	60	20 to 85	100hrs	4hrs	10min	13

The results of the thermal analyses showed that the glass transition temperatures of all three resins were above the maximum test temperatures. In Experiment No. 2, only FR-4 was below the maximum transition temperature. For all specimens tested under cyclic temperature, the interfacial debonding occurred after one cycle, which is 54 hours. FR4-PWB exhibited debonding and microcracks along the edge of the bundle and in radial shape.

The results from Experiment No. 3 showed interfacial debonding for all three boards. Also, glass transition temperatures for all resins were above the maximum temperature. The author explained that delamination was due to the possibility of higher temperatures that cause differential thermal expansion. Experiment No. 4 showed the specimens that were subjected to cyclic weather for a period of two months. After visual inspections, the results showed the delamination of fiberglass from epoxy resin at the interfacial region. The researcher explained the delamination effects were due to mismatching of the thermal expansion between the two materials. Secondly, the coupler at the glass-resin interface may have decomposed and lost

adhesion. Another reason was epoxy resin absorbed more moisture than fiberglass materials. This difference may have resulted more swelling in the resin than the fiber and caused interfacial debondment.

Kinloch (1983) performed an experiment to determine the durability of structural adhesive resins. The experiment was performed under high and low humidity and temperature conditions. The test results indicated that the bonded joint exposed to the higher humidity and temperature showed a larger decrease in strength compared to the joint exposed to lower humidity and temperature. The author concluded the lower strength was due to moisture penetrating into the interfacial region through plasticization, hydrolysis, and crack. The moisture penetrated through the joint interface modeled by Fick's first law (Equation 2-1). A change of the concentration gradient with respect to time was modeled by Fick's second law (Equation 2-2).

$$D = \left[ \frac{M_T}{M_{\max}} * \left( \frac{h}{\sqrt{t}} \right) \right]^2 \quad (2-1)$$

First, Fick's law explains the net of the atoms by:

$$J = D \cdot \left( \frac{\Delta C}{\Delta x} \right) \quad (2-2)$$

where J (atom/mm<sup>2</sup>.s) and D (mm<sup>2</sup>/s) are the flux and diffusion coefficient respectively and  $\frac{\Delta c}{\Delta x}$  (atoms/mm<sup>4</sup>) is the concentration gradient. The temperature, activation energy, exposed time and materials can affect the flux of the atom itself.

Bruijin (1996) and Gijsman, et al. (1996) exposed composite materials to temperatures. The composite materials undergo degradation when exposed to the temperature. The authors concluded that the temperature break the intermolecular bond which reduced the bond strength. The diffusion to the composite is assumed to have Arrhenius behavior, which can be expressed in equation 2-3.

$$D = D_0 \left( \exp \left( \frac{-Q}{R.T} \right) \right) \quad (2-3)$$

Where  $Q$  (cal/mol) is defined as activation energy,  $R$  is the gas constant and is given by (1.987cal/mol. K) and  $T$  is the absolute temperature is the constant for a given diffusion of a system.

Gerald, et al. (1999) conducted tests on carbon fiber and epoxy resin to determine the effect of the environmental exposure. The specimens bonded with fiber and epoxy was simulated to the combination of high temperature and humidity in the conditional chamber at a temperature of 80°C and 95% humidity. The specimens included three different laminated products using unidirectional carbon/epoxy tapes. Three types of tests were conducted

1. The weight gain of the materials subjected to the environmental condition.
2. Tensile test.
3. Microscopic analyses of all laminated type.

The results showed that the specimens' weight gain was about 1% for a period of five weeks and ultimate tensile strength showed lower values compared to dry specimens.

Warren, et al. (1998) conducted laboratory experiments under three environmental conditions to perform durability analysis of carbon fiber reinforced plastic/polymer (CFRP) and sheets adhered to plain concrete. The first group of specimens was exposed at a temperature of 46°C (115°F) under salt fog conditions to stimulate extreme waterfront exposure conditions. The second group was exposed to one cycle at a temperature of -23°C (-10°F). The third group was exposed to cyclic temperature at -23°C to 60°C (10°F to 140°F) at an interval of four hours. In addition, two groups of specimens were exposed to a continuous salt fog condition, as per ASTM B 117-94 (standard practical for operating salt spray testing apparatus) at a temperature of 46°C (115°F) for a period of one year. After 762 cycles, the specimens did not show any visible cracks along the interfacial region. However, after 1190 cycles all specimens upgraded by CFRP rods showed visible cracks in the concrete adjacent to the groove filled with epoxy resin. For the specimens exposed to salt fog conditions did not shows any visible deterioration effects.

Buck, et al. (1997) studied the effect of combined weather, temperature and moisture on E-glass/vinylester composite materials. The durability was estimated in terms of ultimate strength of the composite after it had been subjected to combine weather for a period of four months. More severe deterioration effects were observed when the samples were under constant load. This clearly suggests that a combination of moisture and sustained load at a high temperature causes a significant decrease in the ultimate tensile strength, making the material less durable.

Brace (2004) performed a durability test on bonded carbon fiber-reinforced polymer plate and fabric after exposure to environmental conditions. The study presented the effects of adhesive environmental conditions on the deflections and ultimate load carrying capacity. A total of 78 beams were used for the studies. Two beams were un-strengthened and four beams were not exposed to any environmental conditions. Two of them were strengthened with CFRP plate and the remaining beams were strengthened with CFRP fabrics. Thirty-six beams were strengthened with CFRP plate and the remaining 36 were strengthened with CFRP fabrics. Sets of four specimens (two specimens strengthened by CFRP plate and two strengthened by CFRP fabric) were exposed to 100% humidity, dry heat, alkaline solution which contained pH of 9.5, and a seawater solution containing a concentration of 1500 ppm with specific gravity of 1.022. The specimens were exposed for periods of 5 days, 13 days and 417 days at each environmental condition. In addition, sets of four beams were also exposed to 350 and 700 freezing/thawing cycles and 35 thermal expansion cycles. Twelve beams strengthened with CFRP plate and fabrics were subjected to the repeated load cycle. Four beams were used for each of the three repeated load ranges from magnitudes 15%, 25% and 40% of ultimate strength of the un-strengthened beams.

Three points loading were applied for all beams, and ultimate strength and deflections were compared to unexposed beams. The results showed that beams strengthened with CFRP plate and exposed to 100% humidity and exposed for a period of 415 days showed lower strength by 59%. A 33% strength-loss for the beams strengthened by CFRP plates was observed after 14 months of exposure. For the beams strengthened with CFRP plates and exposed to the dry heat condition, ultimate strength dropped by 7% and 13% compared to unexposed beams when exposed for a period of four days and four months respectively. Thirty-five thermal cycles exposure reduced the flexural strength by 15%. Three hundred fifty and 700 freezing and thawing cycles decreased the load carrying capacity of the beams by 3% and 10% respectively. Humidity and salt-water exposure decreased the load bearing capacity compared to unexposed beams. The time of exposure had no significant effect on the beams reinforced with CFRP fabric and exposed to the humidity and salt-water conditions.

Dash, et al. (2004) studied the effect of environmental change on fracture toughness of composite materials. The study involved epoxy resin and eight layers of carbon fabrics. The fabrics were embedded together and fabricated in rectangular plates by the vacuum bag technique under room temperature and pressure. The weather conditions used for this test were.

1. Pure distilled water

2. Saline water
3. Acid water
4. Sulphuric water
5. Organic fuel (kerosene oil)
6. Low temperature (ice temperature)
7. High temperature exposure at 60°C.

After the specimens were exposed to the accelerated environments for a period of three weeks, six different fracture toughness tests were conducted. The exposed results are summarized in Figures 2-4 and 2-5 below.

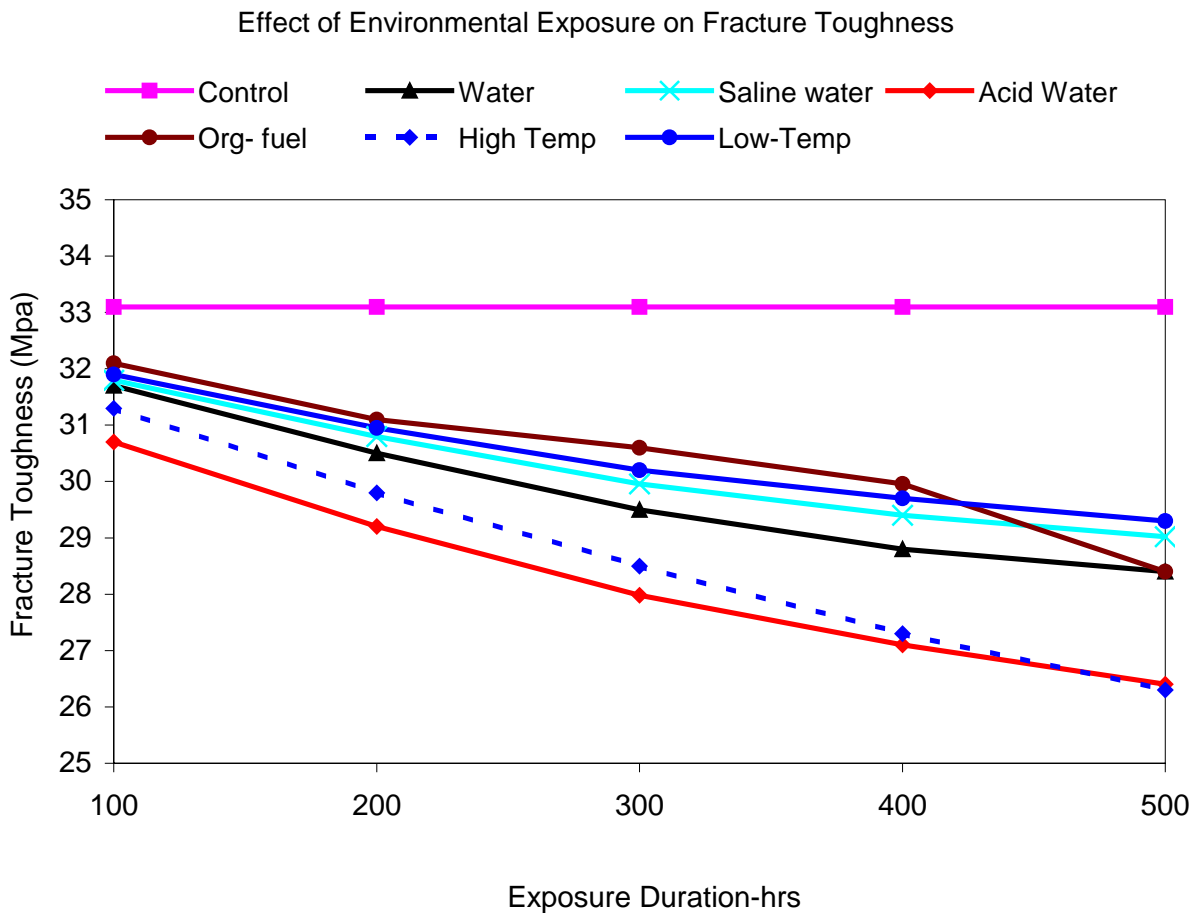


Figure 2-4: Effect of Environment Exposure on Fracture Toughness, (Dash, et al. 2004).

### Effect of Environmental Exposure to Mechanical Properties

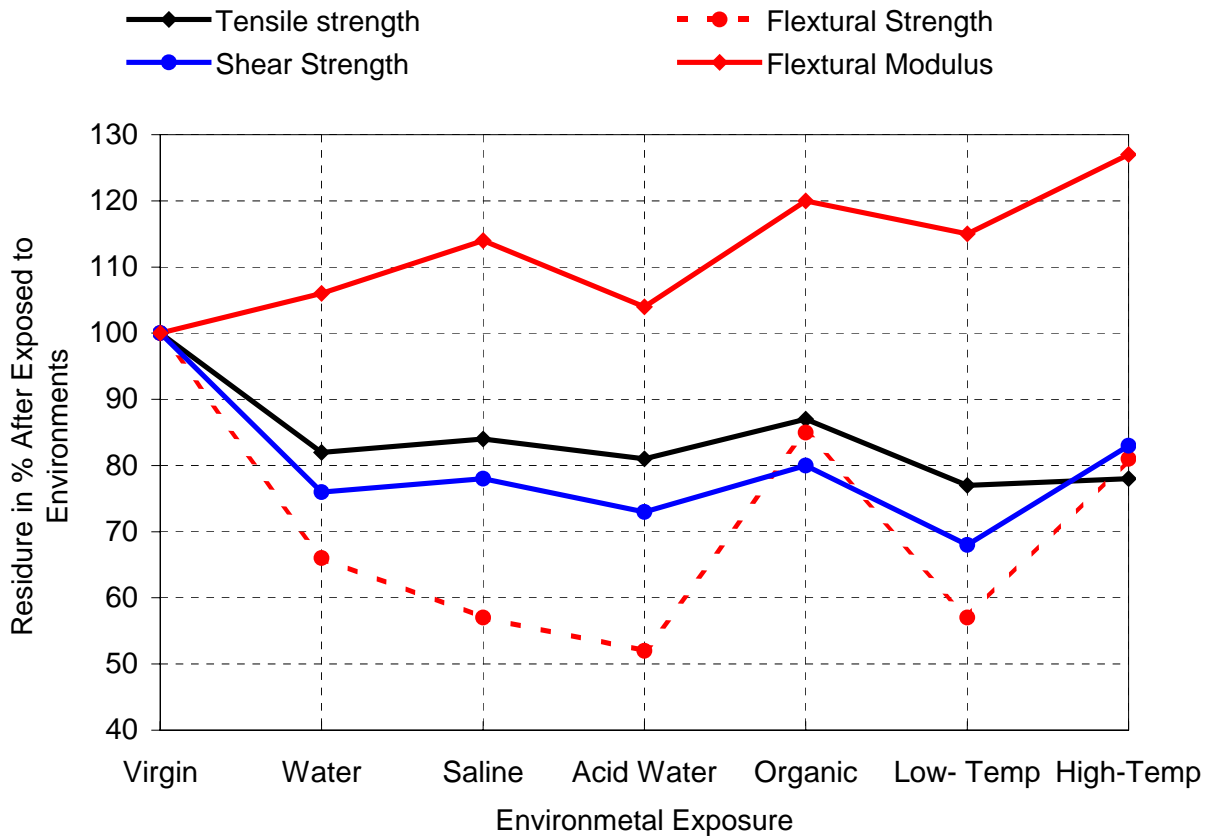


Figure 2-5: Effect of Environment Exposure to Mechanical Properties, (Dash, et al. 2004).

After the specimens were subjected to different environmental conditions, fracture toughness was tested at an interval of four days (Figure 2-4). The results indicated that the specimens exposed to low temperatures had higher degradation than those exposed to higher temperatures for the all environments tested. The author explained that the low temperatures caused shrinkage of the constituent value phases of the woven carbon/epoxy composite. In hot air at a temperature of 60°C, only 1% weight loss was recorded after three weeks of exposure. The specimens subjected to high temperature fracture toughness dropped by 12%, but low temperature drop by 20%. The author concluded that dissimilarity in the thermal coefficient caused differential expansion and contraction characteristics.

Jeannie, et al. (1998) simulated the effects of absorption and diffusion of distilled water, saltwater and concrete pore solution in composite matrix. The test included three epoxy, polyester and vinylester resins. The vinylester resins were prepared by mixing 3% by mass of methylethyl ketone peroxide and catalyzed by 9% of oxygen and silicone deforming agent “less than 0.5%”. Epoxy resins were prepared by mixing 100 parts of EPON 828 with 42 parts of jeffamine. The polymer films (having a square dimension of 25 mm) were immersed in distilled water and salt-water solutions to simulate marine environments. The salt-water solutions were prepared by mixing 0.58mol/L sodium hydroxide in distilled water with a pH of 6.7 and 0.23 mol/L potassium hydroxide. Thermal analysis and water absorption tests were conducted on each resin. Epoxy resin showed lower glass transition temperature for both methods (thermal analysis and absorption tests). Also, epoxy resin showed a higher absorption compared to vinylester and isopolyester resins at any temperature. The figure 2.6 through figure 2.8 below indicated the effects of the temperature to water absorption for different adhesive resins.

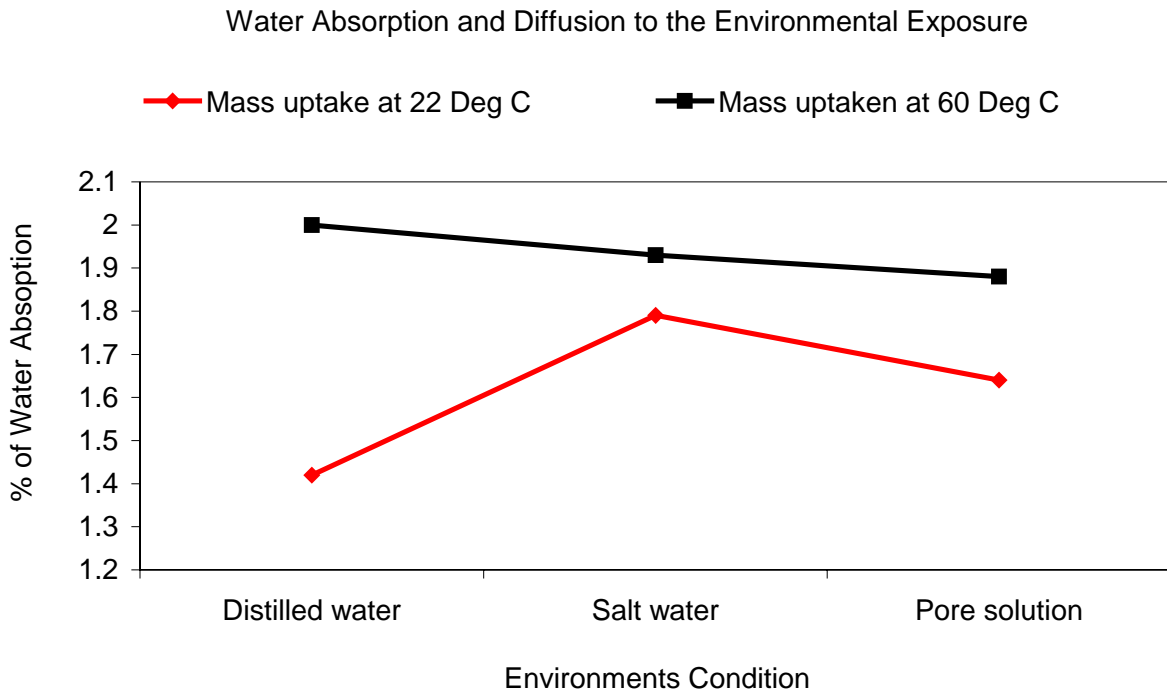


Figure 2-6:Effect of Temperatures to Water absorption- Epoxy Resin, (Jeannie, et al.1998).

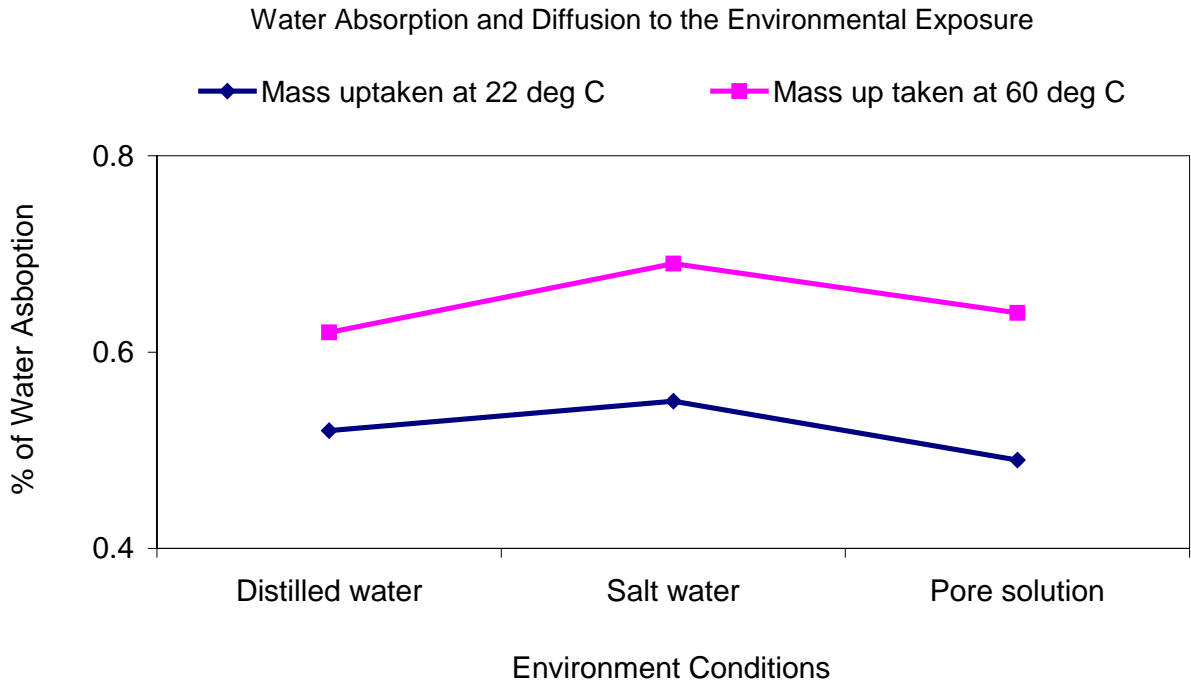


Figure 2-7: Effect of Temperature to Water Absorption –Vinylester Resin, (Jeannie, et al. 1998).

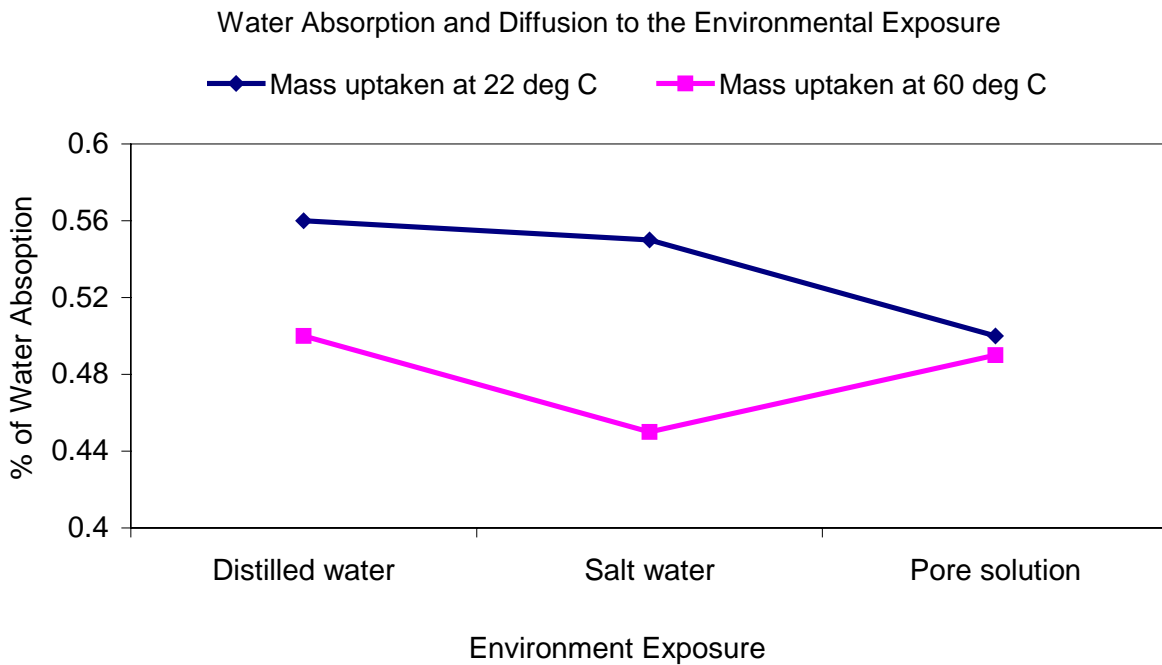


Figure 2-8: Effect of Temperature to Water Absorption –Isopolyester Resin, (Jeannie, et al. 1998)

## CHAPTER THREE

### EXPERIMENT SETUP

#### 3.1 Introduction:

Accelerated test is a procedure in which conditions are intensified to reduce the time required to obtain a deteriorating effect similar to normal conditions. The procedures are conducted in order to quantify the life characteristics of the product, system, or component under normal operating conditions. Over the years, the term accelerated life testing has been used to describe and to observe failure modes of a product or system and its life characteristics. To understand the mode of failure, the products have been forced to fail more quickly than they would under normal operating conditions.

Accelerated test involves acceleration of failures with the single purpose of quantification of the life characteristics of the product under normal use conditions. This test procedure can be divided into two types: qualitative accelerated testing and quantitative accelerated life testing. In qualitative accelerated testing, the interest is mostly in identifying failures and failure modes without attempting to make any predictions as to the product's life under normal use conditions. Quantitative accelerated life testing is mostly interested in predicting the life of the product under normal use conditions. This procedure of qualitative tests is performed on small samples subjected to a single severe level of stress, to a number of stresses, or to a time-varying stress. If the specimens fail, appropriate actions will be taken to improve the product's design in order to eliminate the cause(s) of failure.

Qualitative tests are used primarily to reveal probable failure modes. However, if not designed properly, they may cause the product to fail as the result of modes that would never have been encountered in real life. A good qualitative test quickly reveals those failure modes that will occur during the life of the product under normal use conditions. Qualitative tests do not quantify the life characteristics of the product under normal use conditions; however, they provide valuable information on level of stresses tolerated.

To determine the quantitative test the product will be stimulated to fail in a life test. This is accomplished by applying stress that exceeds the stress a product will encounter under normal use conditions. The time-to-failure data obtained under these conditions are then used to extrapolate normal use condition data. In addition, accelerated life tests can be performed under extreme weather conditions such as high or low temperature, humidity, alkaline or acid

exposure, and pressure and vibration exposure, and the tests can be performed under a combination of these use conditions.

### **3.2 Accelerated Test Terminology:**

Understanding the concept of failure mechanisms is essential for conducting successful accelerated tests. Failure mechanisms of a product are categorized into overstress failures and wearout failures. Overstress failures occur if the stresses applied to the product exceed the strength of the materials. In contrast, failure due to accumulation of increased damage in excess of the material's endurance limit is termed wearout failure. For this study the term-accelerated test refers to a test that accelerated wearout failure mechanisms. Wearout mechanisms are expected during the life cycle of a product or the system. When the systems; if products are subjected to weathering loads the wearout rate of failure may increase. In this study open grid deck samples filled with epoxy and broadcast aggregates were subjected to thermal effects in a climatic chamber to evaluate general performance of the systems under weather exposure.

### **3.3 Fabrication of Simulation Chamber:**

Bridge deck systems filled with epoxy and broadcast aggregates are subjected to weather changes during their service life that vary between low and high temperatures. A fabricated climatic chamber is capable of producing extreme cold and hot conditions. Cold and hot conditions were created to simulate temperature changes under field conditions similar to summer and winter seasons. The simulation chamber sizes were 2.4 m x 1.2 m x 1.2 m (8 ft x 4 ft x 4 ft) and were constructed of pressure-treated lumber (2 in x 4 in) then completely covered with 1-inch plywood. The chamber was designed to include working space for the investigators. Fiberglass insulation 2 in thick was placed inside the walls and adhesive resin was used to seal edges at corners in order to minimize temperature loss. L-angle and T-angle steel brackets were fixed to each corner between studs and horizontal members to increase stability of the chamber and to prevent distortion caused by internal pressures.

Two zones were created within the climatic chamber, a hot zone and a cold zone. The zones were separated by plywood and insulated with fiberglass on both sides. These zones were created to simulate different temperatures between the bottom and the running surface of deck systems. The size of the cold zone was 2.4 m x 1.2 m x 0.4 m (8 ft x 4 ft x 1.3 ft) while the hot zone was 2.4 m x 1.2 m x 0.9 m (8 ft x 4 ft x 3 ft). Four air conditioners of 844 kilojoules

(8,000 BTU) each were spaced 1.2 m (2 ft) apart. Between the zones there was a rectangular opening 2.1 m (7 ft) long x 1.2 m (2 ft) wide. The opening was located at the center to accommodate specimens during testing. The steel grate deck systems filled with lightweight materials with broadcast aggregates were placed in the space provided between the zones, resting on a strong support. After the specimen was in place, the sides between the specimen and the plywood were sealed to minimize temperature loss. A pressure gauge was located in the cold zone to control and release pressure created during testing.

A hot zone was created on the upper side of specimens by introducing a series of ten high-power lamps. The lamps were mounted on the frames and connected in parallel. The frames were designed to be adjusted and moved to any position. Each lamp of 500W x 125 V was used to simulate hot conditions and was mounted at a height of 9 in from the running surface of the deck sample. Between the top cover and chamber frame there was a rubber gasket to ensure a tight fit between the cover chamber frames. The completely accelerated chamber is shown in figures 3-1 and 3-2. Figure 3-3 shows longitudinal cross section of accelerated chamber.



Figure 3-1: Climatic Chamber With Four Air Conditioners and Ten High-Powered Lamps.



Figure 3-2: Plan View of Constructed Climatic Chamber and High-Powered Lamps.

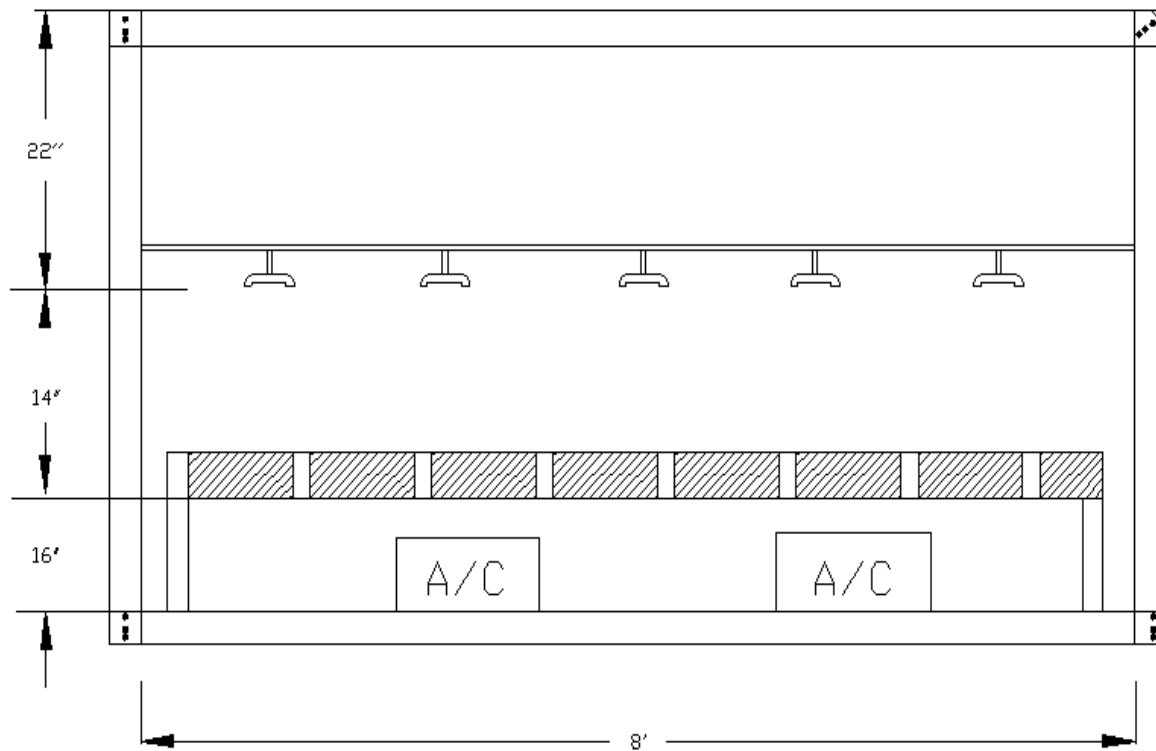


Figure 3-3: Longitudinal Section of Constructed Climatic Chamber.

### 3.4 Materials Properties:

Three different materials were used to fill open steel grid deck systems. E-bond lightweight system low modulus, E-bond neat resin, and EP # 5 modified aggregates.

#### 3.4.1 E-Bond 526 Lightweight Materials:

E-bond 526 low modulus is the product of two components, E-bond 526 epoxy resin part A and hardener, E-bond 526 part B (curing agent). The two components are mixed together to form E-bond lightweight systems, which have adhesive properties. The mixed E-bond lightweight systems have been used in open bridge and parking steel grid deck systems with the aim of transferring loads from the traffic flow to the steel bearing bars.

The E-bond lightweight system is a multipurpose system suitable for a wide range of applications in both structural and nonstructural materials, and it has the following advantages:

1. The E-bond lightweight system low modulus weighs less and is recommended where weight is a serious consideration.
2. The E-bond lightweight system low modulus is easy to mix and systems have long pot life even at high ambient temperatures.
3. The E-bond lightweight system is moisture insensitive compared to vinylester and polyester.
4. The E-bond lightweight system low modulus provides excellent adhesion to most structural and nonstructural components.
5. E-bond lightweight systems are flexible, have higher creep resistance, and are resistant to chemical attack from acids, bases, fuels, and others.

Table 3-1: Physical Properties of E-bond 526 Lightweight System Low Modulus.

Properties	Value	Test method	Conditions
Viscosity	1.6 kg/(m.s)	ASTM D 2393	-
Bond strength	1500 psi	ASTM C881	14 days
Modulus of elasticity	695 psi	ASTM D 695	7 days
Compressive strength	1800 psi	ASTM C881-90	4 hours
	6400 psi		48 hours
Tensile strength	2571psi	ASTM D638-91	7 days
Elongation break	41%		
Glass transition temperature	113-118°F.	ASTM E1356	25°C (75°F)
Absorption	0.15%	ASTMD570-81 (88)	7 days
Adhesive strength	310 psi	ACI 5038	7 days

**3.4.2 E-Bond 526 Neat Resin:**

E-Bond neat resin has been used in bridge deck and parking systems as a waterproofing material. The resin materials have adhesive properties and are used to hold the aggregate on the concrete or steel substrate to provide abrasion resistance during traffic flow. The net resins were mixed at a ratio of 1:1 as per manufacturer recommendations and were fixed until the mixture became homogenous. The blended resins were applied to the E-bond lightweight before the pot life expired.

Table 3-2: Properties of E-bond 526 Neat resin Lightweight System.

Properties	Value	Test method	Conditions
Viscosity	1kg/(m.s) to 2kg/(m.s)	ASTM D 2393	@ 75°F
Bond strength	1500 psi	ASTM C881	14 days moist
Compressive strength	1300 psi	ASTM C-579-91,	3 hrs @ 75°F
	1700 psi		3.25 hrs @ 75°F
	2200 psi		3.5 hrs @ 75°F
	6800 psi		48 hrs @ 75°F
Tensile strength	2000 psi	ASTM D-638	7 days
Elongation break	50% min		
Absorption	0.15%	ASTMD 570-81 (88)	7 days

**3.4.3 Properties of EP # 5 Modified Aggregates:**

EP #5 modified aggregates were used in this study to provide skid resistance. The aggregates were investigated if they contained dust or laitance. The applied aggregates met the requirements specified in Table 3-3.

Table 3-3: Aggregates Properties and Size Distribution.

S/n	Property	Specification	Mesh size	% of pass
1	Hardness	6 to 7 Mohs	4.75 mm / #4	100
2	Specific gravity	1.44	2.36 mm / #8	30-75
3	Abrasion index	1.412	1.18 mm / #16	0-5
4	Friability index	78.0	600 m / #30	0-1

### 3.5 Sample Preparation:

Welded steel grating decks 5-way decking systems were used in this experiment. Six specimens filled with lightweight materials were prepared, the deck bars sizes includes main bars 100 mm x 6 mm (5 in x 0.24 in), cross bars 50 mm x 6 mm (2 in x 0.24 in) and supplementary bars 25 mm x 6 mm (1 in x 0.24 in). The main bars were spaced at a distance of 203 mm (8 in) and between the bars an extra bar was placed at the center. Transverse steel bars perpendicular to the main bars were spaced at a distance of 101 mm (4 in). Each individual cell included two tertiary bars connected from one corner to another corner. The layout and geometry of the welded deck is shown in Figure 3-4 and figure 3.5 indicated completely cured filled specimens with E-Bond 526 LW materials.

Multilayer overlay methods were used to prepare deck samples and were performed under ASTM C 1486 guidelines. The preparation procedures were executed at three stages:

1. Application of the E-bond 526 lightweight systems to each individual cell. The lightweight materials were poured into a grid cell after a plastic sheet was placed underneath.
2. Application of E-bond 526 neat resin. This process was done after the LW material has been completely cured. Two coats of resin were applied to the running surface. The first coat was applied three hours after epoxy resin had been applied and cured. Application was done at a rate of approximately 40 sq.ft per gallon. The second coat was applied one hour after the first coat at a rate of 20 sq ft per gallon. This was done after cleaning the top surface.

3. The third and final stage was application of the wearing surface. EP #5 modified aggregates were broadcast immediately after E-bond 526 neat resin was applied. The aggregates were applied in two lifts to provide an approximate wearing surface of 1/3–3/8 in thickness. The aggregates were applied at a rate of 1.1lb per sq ft for the first coat and 2.2 lb per sq ft for the second coat. Plastic sheets were used to cover the specimens for two days to maintain constant temperatures before exposure to the weather chamber.



Figure 3-4: Pouring of E-Bond 526 LW Materials to Open Steel Grate Decks.



Figure 3-5: Filled Open Grate Deck with E-Bond 526 LW Materials.

### 3.6 Test Parameters:

To achieve the objective the following tests were conducted:

1. Flexural test.
2. Dynamic mechanical analysis (DMA) test.
3. Effect of cyclic temperature to filled decking.
4. Effect of combination low and high temperatures.
5. Effect of cyclic Temperatures to E-bond 526 LW.

### **3.6.1 Flexural Test:**

Bridge deck systems are designed to carry the dead load and the live load from traffic flow. Dead loads for open grid deck systems are small compared to those for concrete deck systems. AASHTO recommends that design of the live load to the bridge should be calculated as specified in articles 3.6.1.2.2–3.6.12.4, which is truckload, tandem, or lane load. In order to understand the behavior of open steel grid filled with lightweight materials under static loads, the flexural tests were performed prior to and after filling with lightweight materials. Three-point loading was applied to the open deck and filled deck. Three dial gauges were used to measure the midspan deflections and were located at the center and outside edges of the deck midspan.

### **3.6.2 Dynamic Mechanical Analysis (DMA) Test:**

Dynamic mechanical analysis (DMA) is a thermal analysis technique used to measure changes in the viscoelastic response of a material as a function of temperature, time, or deformation frequency. DMA is commonly used to determine quantitative flexural storage and loss moduli, tan delta, and the dynamic complex viscosity of materials. The technique also is useful for qualitatively characterizing the glass transition temperature ( $T_g$ ) of polymer and composite materials. DMA tests were performed to determine the maximum temperature at which the E-bond lightweight system changes from brittle to ductile characteristics. Changing in characteristics loss adhesive properties of the polymer materials. DMA tests were conducted at room temperature after the samples were completely cured. The test measured glass transition temperature of the polymer materials or plastic.

A simplified explanation of the DMA technique may be described as follows. Typically, a sample is clamped into the DMA apparatus and subjected to an oscillatory deformation while being heated or cooled at some controlled rate. The resonant frequency of the sample and mechanical clamp assembly is continuously monitored as a function of temperature. As the viscoelastic response of the material changes over some temperature range, the electrical energy required to maintain a constant level of sample deformation also changes and is continuously monitored. Quantitative analysis routines are used to calculate the modulus (stiffness) and viscoelastic loss characteristics of a specimen as a function of temperature or time. Transition temperatures are readily obtained by determining the peak temperatures of the loss moduli or tan delta profiles. Polymer samples generally exhibit at least two distinct material phases. Since the mechanical loss characteristics of a material are directly related to

molecular level motions, the DMA damping signal is particularly sensitive to a material's glass transition process. Determining the glass transition temperature and the flexural storage and loss moduli of composite materials is a common DMA application. Composite samples exhibit dramatic changes in damping (loss) profiles and display characteristic peaks as they pass through the glass transition temperature range. The test specimen was clamped between the movable and stationary fixtures, and then enclosed in the thermal chamber. Frequency, amplitude, and a temperature range appropriate for the material being tested were the inputs. Then torsional oscillation to the test sample was applied while the temperature was slowly moved through the specified range. The rate of temperature change used for the thermal analysis was 5°C per minute. Four different specimens of E-bond lightweight system were prepared and tested per ASTM D 5023. The specimen was connected to the DMA instrument and output data such as Elastic Modulus (E') versus temperature, or strain, Viscous Modulus (E'') versus temperature, Damping Coefficient (Tan Δ) versus temperature, frequency, or strain were recorded by the computer and analyzed for glass transition temperature.

Table 3-4: Sample for Differential Mechanical Analysis (DMA): E-Bond lightweight system.

Sample number	Sample sizes		
	Length mm (in)	Width mm (in)	Thickness mm (in)
EBS-1	60 (2.4)	11.580 (0.456)	5.176 (0.204)
EBS-2	60 (2.4)	11.633 (0.458)	5.177 (0.204)
EBS-3	60 (2.4)	11.660 (0.459)	5.178 (0.204)
EBS-4	60 (2.4)	11.600 (0.457)	5.168 (0.203)

### 3.6.3 Effect of Cyclic Temperatures to Filled Deck:

Cyclic temperatures were used to test durability and behavior at the interfacial region between epoxy/steel. The deck sample filled with epoxy lightweight materials was exposed to extreme cyclic temperatures over a given period of time in the accelerated chamber. The

weather tests were performed under ASTM D1151 guidelines (standard practice for effect of moisture and temperature on adhesive bonds). Polymer concrete overlay experienced thermal loads such as temperature and moisture/water during the summer and winter seasons, respectively. High temperature exposure affects interfacial bond strength between steel plate and epoxy resin and changes mechanical properties of adhesive resin.

#### **3.6.4 Effect of Combined Low and High Temperatures to Filled Deck:**

Bridge decks experience high temperatures on their surfaces from direct sunlight. But underneath the deck systems the temperatures are low compared to the running surfaces. To simulate existing situations both low and high cyclic temperatures were employed in the accelerated chamber to create temperatures different between the deck surfaces and underneath of the deck surface.

#### **3.6.5 Effects of Cyclic Temperatures to E-Bond 526 LW Materials:**

The effects of cyclic weather on compressive strength were tested on specimens that experienced cyclic temperature. Epoxy cylinders were subjected into two types of temperature ranged, cyclic temperatures below and above glass transition temperature and cyclic temperatures below glass transition temperatures. The aim of the tests were to determine the effect of cyclic temperatures to E-bond 526 lightweight system. A total of 42 cylindrical specimens measuring 100 mm (4 in) diameter x 200 mm (8 in) were prepared for the compression test. The sample preparation and testing procedures were performed under ASTM D 695 guidelines. 36 cylinders were subjected to low and high cyclic temperatures, 18 cylinders were subjected to low temperatures, and the remaining cylinders were subjected to cyclic temperatures and 6 cylinders remain unexposed. The specimens remained under room temperature for a period of six hours before being tested in the compressive test machine at a rate of 0.05 in per min to determine compressive strength.

### **3.7 Instrumentation Setup and Data Collection:**

A crucial problem in the study was instrumentation setup. Several techniques were considered to model the behavior of the epoxy at the interfacial region. Strain gauges were selected to capture the response of the epoxy at the interfaces to weather changes. Thermocouples were used to obtain temperature of deck surfaces and at interfacial regions. Thermocouples and strain gauges were selected according to specimen size and test

conditions. Each specimen involved six channels in its setup, four channels for the thermocouples and two channels for the strain gauges. Strain gauges type SG-1.5/120-LY11 and thermocouples SRTC-TT-T-30-72 with temperature ranges from -200°C to 400°C were chosen to capture delamination of the epoxy from the interface under extreme weathering. Each strain gauge channel had four gauges, two in tension and two in compression, and were connected to form a bridge circuit. Two gauges, one in tension and one in compression, were soldered on top of the aluminum bracket. The other two gauges were soldered to the bottom of each bracket. Arrangements and gauge connections are detailed in Figure 3-5.

Each channel was calibrated prior to fixing it to the steel plate. There were two methods of performing calibration, one-point calibration and two-point calibration via LogView software. One-point calibration was used to calibrate thermocouple wires because it is more accurate for thermocouples than for strain gauges. One-point calibration was performed by putting thermometer and thermocouple wires into an ice bath for 30 minutes. Both thermometer and thermocouple wires showed no differences in temperature readings. Two-point calibration was performed on the strain gauges and was used to convert raw voltage readings into accurate calibrated strain readings. Two known values were applied to aluminum brackets and entered into the LogView software. The software calculated the calibration offset and calibration scale, which was used to calculate the actual sensor reading.

After the calibration was completed the aluminum brackets with gauges and thermocouples connected were fixed to steel bars before E-bond lightweight systems were poured. Other thermocouples were fixed at the top and bottom of the deck to capture the temperature profile between the deck surfaces. These brackets were mounted to the steel bars by using strong adhesive resin. One bracket was bonded at a height of 6.4 mm (0.25 in) from the running surface and another bracket at a height of 6.4 mm (0.25 in) from the bottom of the deck. Collection of data was done electronically using a 6-channel logbook system 300 data acquisition system, which consisted of a PC containing the strain software and thermocouple.

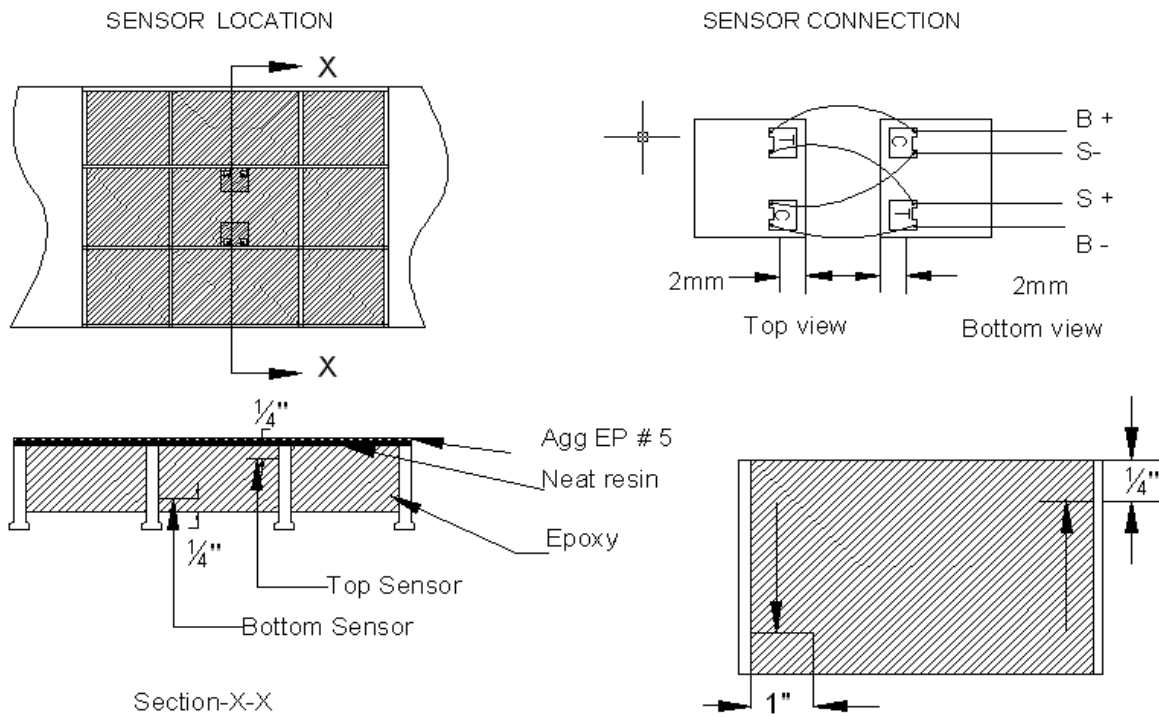


Figure 3-6: Sensors Connection and Installation to Filled Deck System.

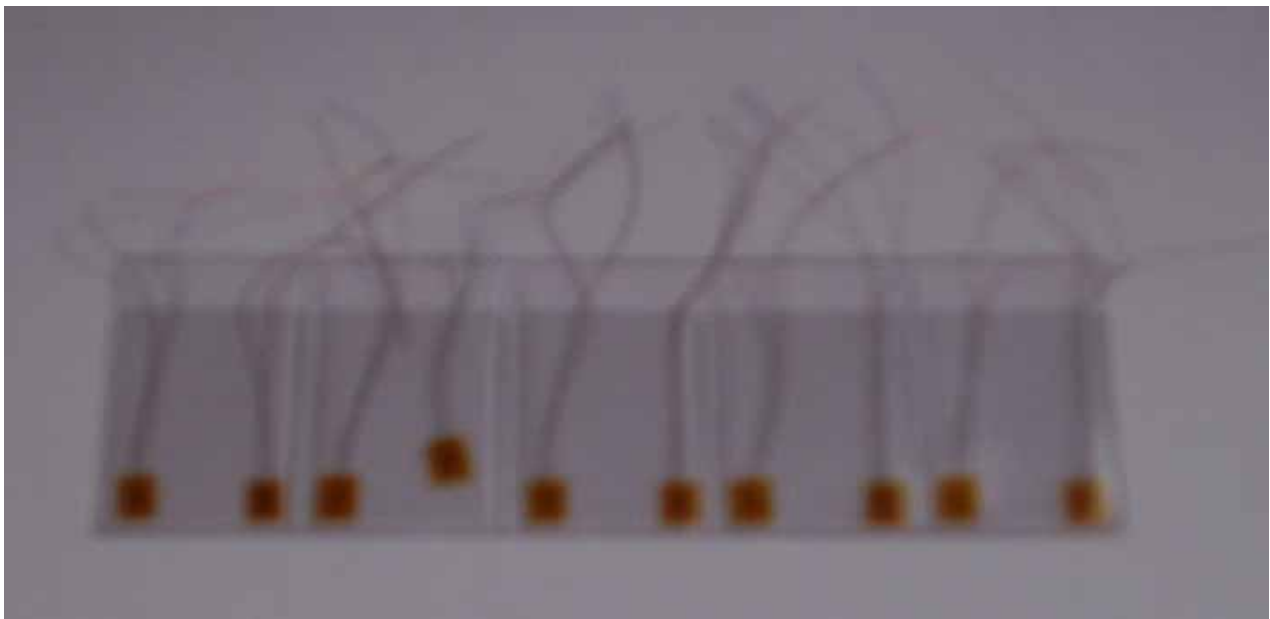


Figure 3-7: Strain Gauge Type SG-1.5/120-LY11 Used to Build the Sensors.

## CHAPTER FOUR

### RESULTS AND DISCUSSION

This chapter presents the results of all the experiments in this study. The chapter also includes the implications of all the results.

#### 4.1 Flexural Test:

The Flexural tests (load versus deflection) were conducted for an open grid deck and for a deck filled with E-bond lightweight systems. The results presented below show the stiffness test for the open deck and for the deck filled with lightweight materials.

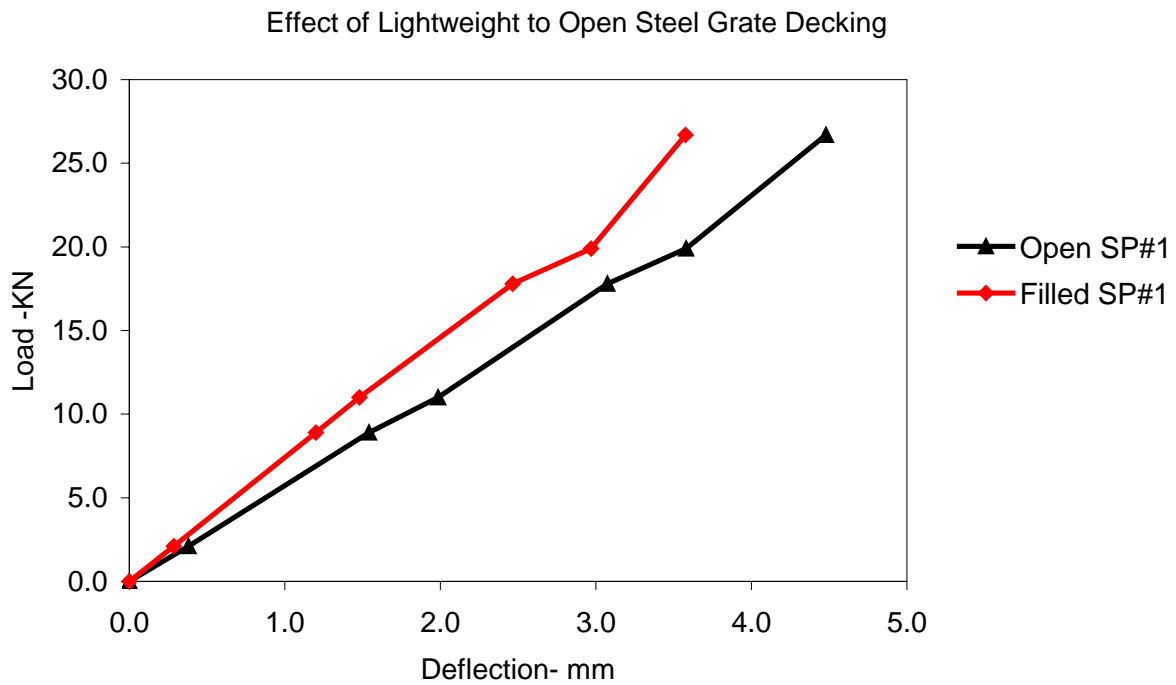


Figure 4-1: Flexural Test for the Open and Filled With Lightweight Materials.

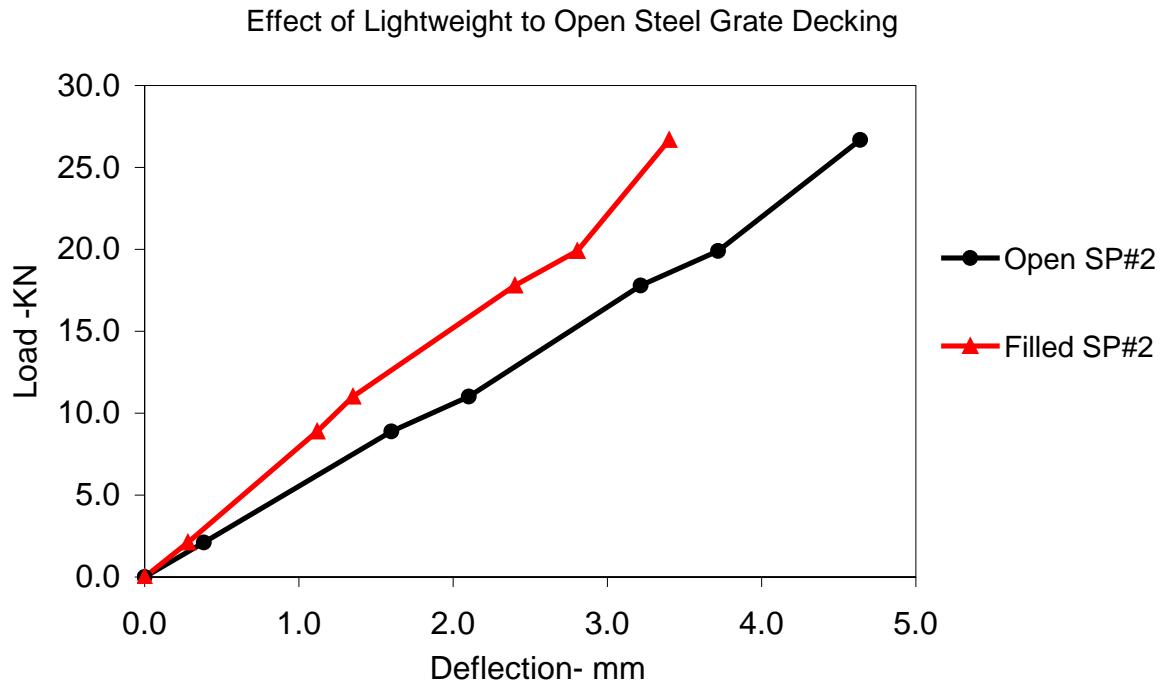


Figure 4-2: Flexural Test for the Open and Filled With Lightweight Materials.

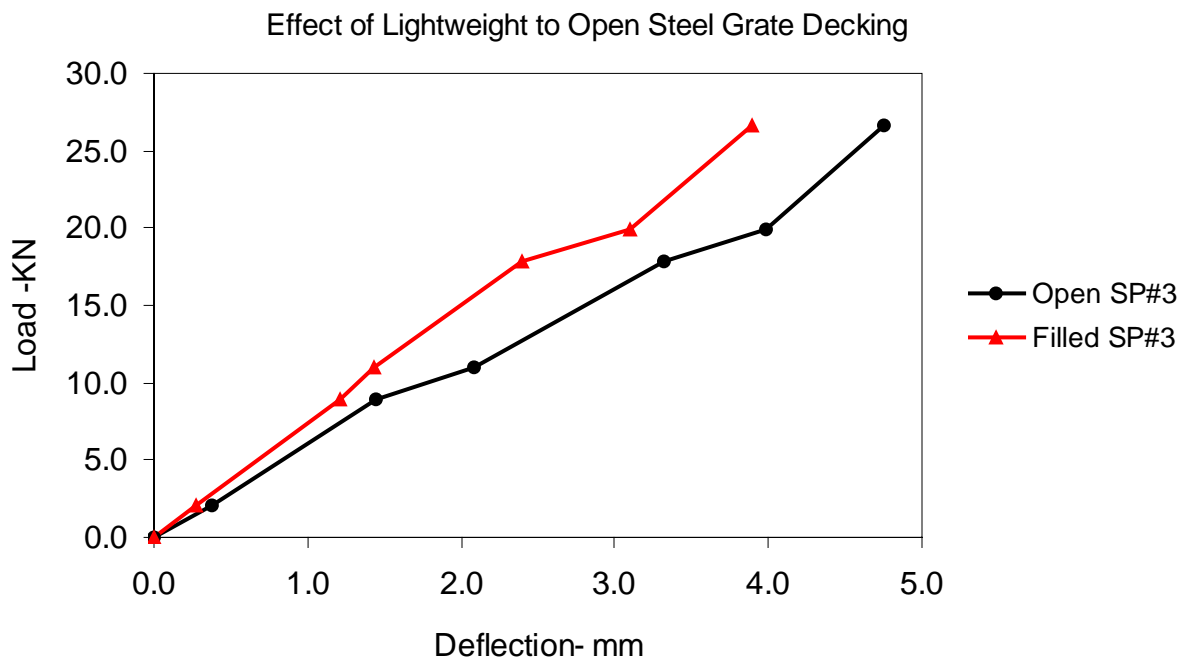


Figure 4-3: Flexural Test for the Open and Filled With Lightweight Materials.

Table 4-1: Results for the Flexural Test Open and Filled With Lightweight Materials.

		Specimen # 1		Specimen # 2		Specimen # 3	
S/n	Load KN (Kip)	Deflection mm		Deflection mm		Deflection mm	
		Open deck	Filled deck	Open deck	Filled deck	Open deck	Filled deck
1	0.000 (0.000)	0.000	0.000	0.000	0.000	0.000	0.000
2	2.113 (0.475)	0.381	0.285	0.384	0.280	0.378	0.268
3	8.896 (2.000)	1.541	1.200	1.600	1.119	1.441	1.210
4	11.009 (2.475)	1.985	1.480	2.101	1.350	2.485	1.430
5	17.792 (4.000)	3.095	2.465	3.215	2.401	3.320	2.400
6	19.905 (4.475)	3.580	2.969	3.718	2.804	3.980	3.100
7	26.688 (6.000)	4.479	3.576	4.639	3.400	4.756	3.889

The test results show that the lightweight materials increased the stiffness of the open steel grid deck systems by showing low midspan deflection compared with open filled deck system. The lightweight materials within the individual grid cells experienced compressive and tensile stress under a wheel load. E-bond lightweight materials increased the compressive strength of the steel plates and reduced the bending strain of the steel plates caused by the live load, as indicated in figure 4-1 through figure 4-3 above.

#### 4.2 Dynamic Mechanical Analysis (DMA) Test:

The table 4-2 below represents the results for the DMA test of the lightweight materials.

Table 4-2: Results for Thermal Properties of E-Bond 526 Lightweight Systems.

Sample Number	Glass Transition Temperature $T_g$ °C	Dynamic Modulus (MPa) at Temperature $T_g$ °C	Tan Delta	Dynamic Modulus (MPa) Temperature 25 °C
EBS-1	51.68	238.427	0.5366	1150
EBS-2	51.21	233.761	0.5554	1350
EBS-3	50.39	238.409	0.5554	830
EBS-4	53.39	259.079	0.5221	1361

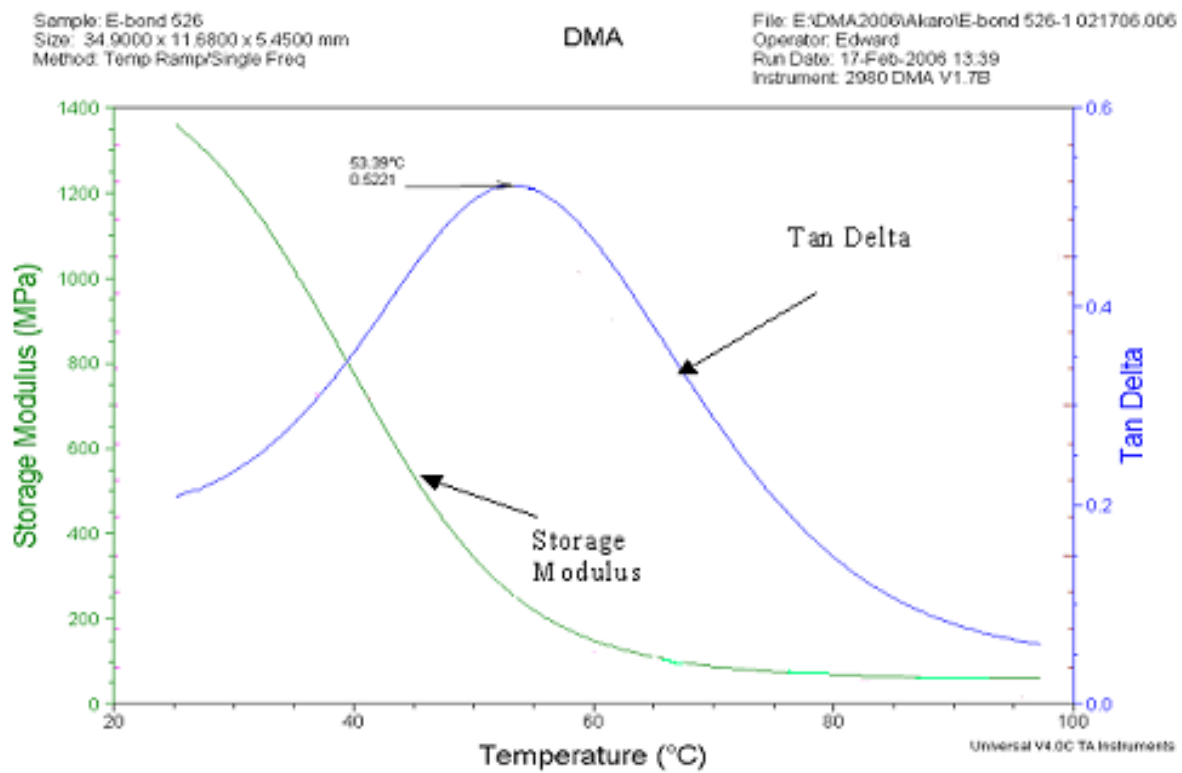


Figure 4-4: DMA Test for E-Bond 526 Lightweight Systems.

Figure 4-4 above indicated the glass transition temperature measured by DMA test. DMA test is an indicator of chemical changes to the adhesive resin. An increased glass transition temperature ( $T_g$ ) of the epoxy resin weakens the intermolecular bond between them. The glass transition temperature ( $T_g$ ) of E-bond lightweight materials was obtained by using the peak of the damping coefficient or Tan delta ( $\text{Tan } \Delta$ ) as the determinator. The test results showed a glass transition temperature of about 52°C, which was interpreted from figure 4-4. With the glass transition temperature ( $T_g$ ) indicated above, the polymer changed mechanical properties, especially the storage modulus and viscoelastic behavior. These two properties contributed to the performance of the bond strength at the interfacial region and within the adhesive matrix.

The Tan delta coefficients were used in the DMA output to interpret the glass transition temperature ( $T_g$ ). The glass transition temperature is the reversible change in an amorphous polymer from (or to) a viscous or rubbery condition to (or from) a hard and relatively brittle one. At low temperatures, the rubbery condition of the polymer becomes hard and stiff, and the rubbery condition changes its properties and becomes elastic when the temperature increases.

It should be noted that during the rehabilitation schemes it is important to select a resin system with a higher glass transition temperature. Above the glass transition temperature, the resin will become formable and the molecules will be free to move. When the adhesive resin is exposed to temperatures above the glass transition temperature, the resin will not be able to transfer the shear stresses to the interfacial region between the epoxy and steel or concrete substrate.

#### **4.3 Effects of the Cycling Temperatures to Filled Deck:**

Bridge decks are subjected to direct sunlight over their service life. The magnitude and intensity of the sunlight varies over the course of the year and depends on the season as well. During the summer seasons the temperatures are quite high than the Glass Transition Temperature of 54°C (129°F), which may affect the performance of the deck systems. In order to estimate the range of temperatures to be used for the accelerated test, the bridge deck systems that were filled with lightweight materials and aggregated broadcasted were exposed to direct sunlight for a period of 2 hours, from 1:00pm to 3:00pm. Figure 4-5 shows the maximum temperature of 94 °C (201°F), which was recorded on July 22.

Ambient and Surface Temperatures on Filled Deck System in Two different Days

▲ Surface temperatures July 21    ◆ Surface temperatures July 22  
◆ Ambient temperature July 21

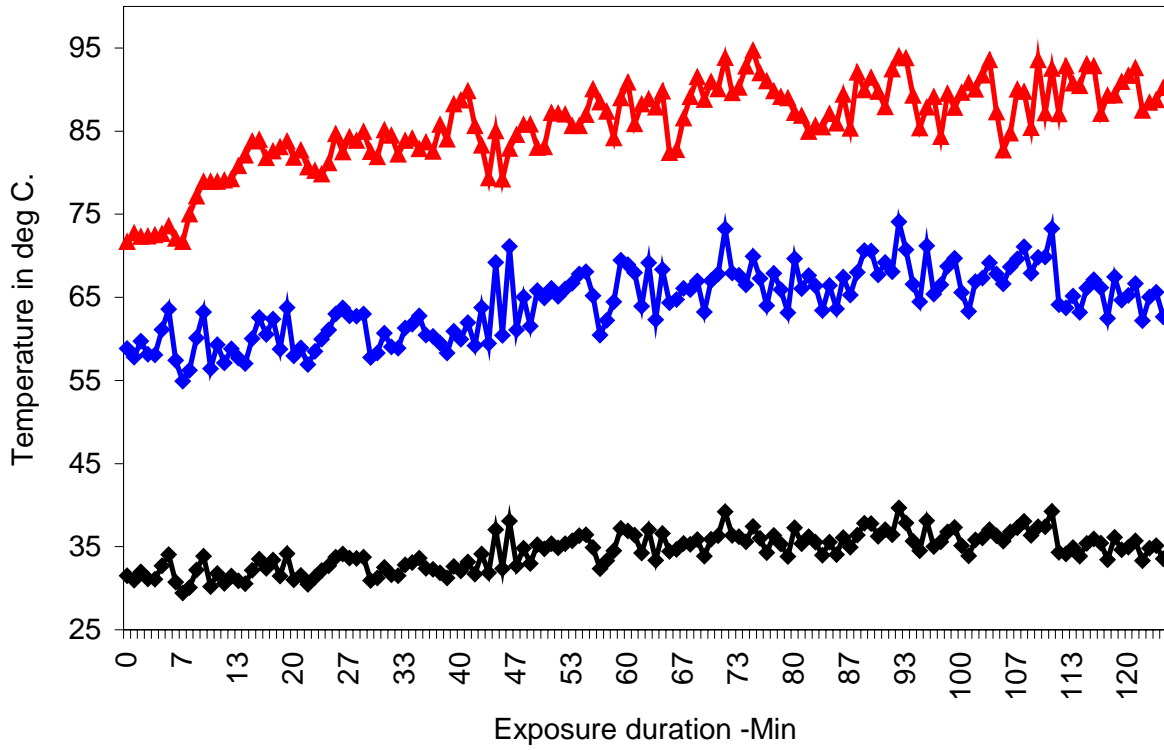


Figure 4-5: Surface and Ambient Temperatures From Direct Sunlight.

Ratio of Surface Temperatures to the Filled Deck to Glass Transition of LW Materials ( $T_s/T_g$ )

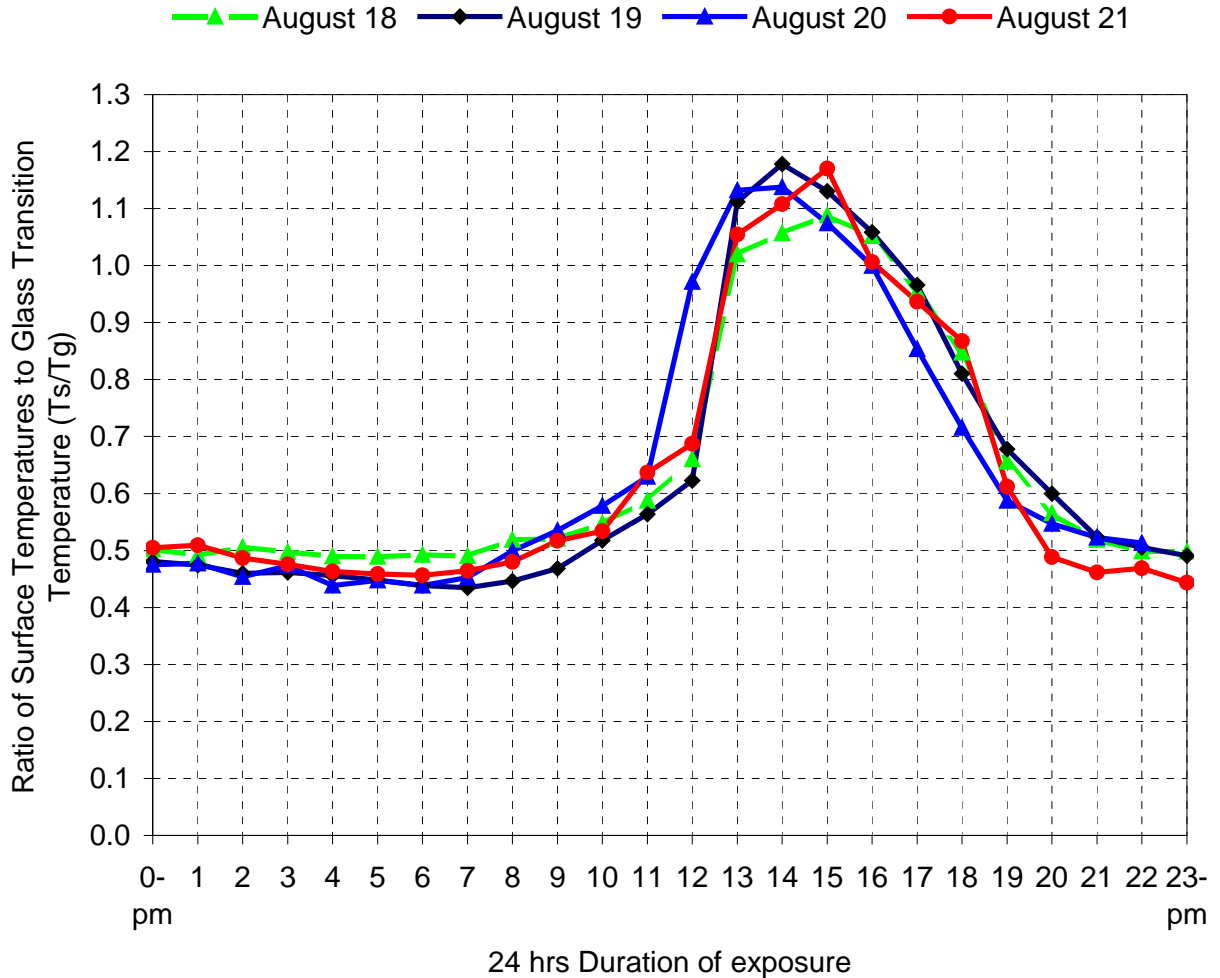


Figure 4-6: Ratio of Surface Temperatures from Direct Sunlight to Glass Transition Temperature of LW materials.

The above figure 4-6 above indicates the ratio of surface temperatures on the filled deck systems to the glass transition temperature of the LW materials when subjected direct to the sunlight. The aim of the temperatures recording process was to find how many hours in a day the deck systems will be subjected to the temperatures above glass transition temperature. The temperatures were recorded in August 2006 in four different days. The

recording process shown that, the surface temperatures on the filled deck systems was higher than glass transition temperature of LW materials for about four hours a day, which started from 1 am to 4pm. E-bond 526 LW materials loss adhesive characteristics when subjected to temperatures above the glass transition temperature. Increases of temperatures of exposure above glass transition Increasing viscosity of the E-bond 526 LW materials, reduced shear strength and lower storage modulus of the materials during that time the shear strength at the interfacial will be lower than other time in a day.

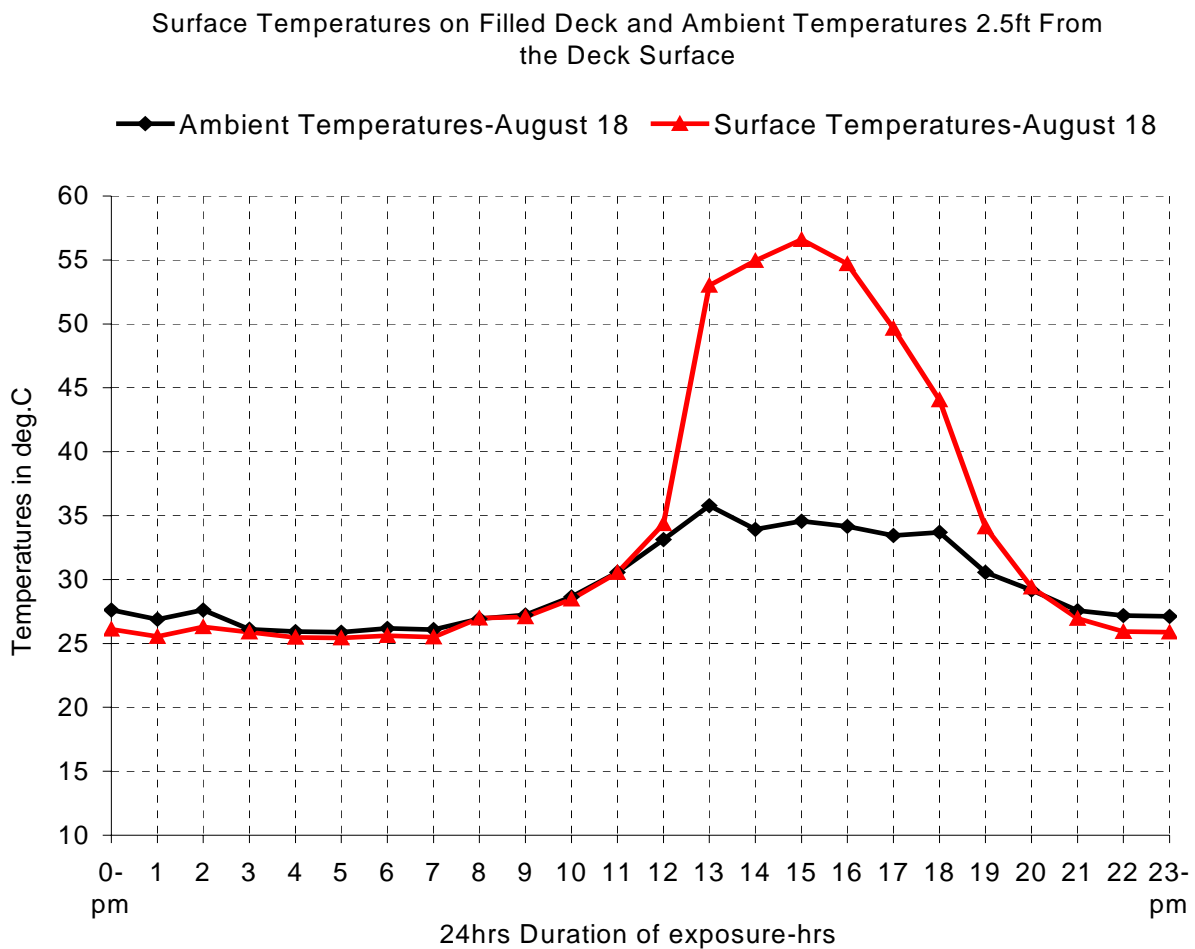


Figure 4-7: Temperatures on the Surface Deck and Ambient Temperatures 2.5 ft from Deck Surfaces-August 18.

Surface Temperatures on Filled Deck and Ambient Temperatures 2.5ft  
From the Deck Surfaces

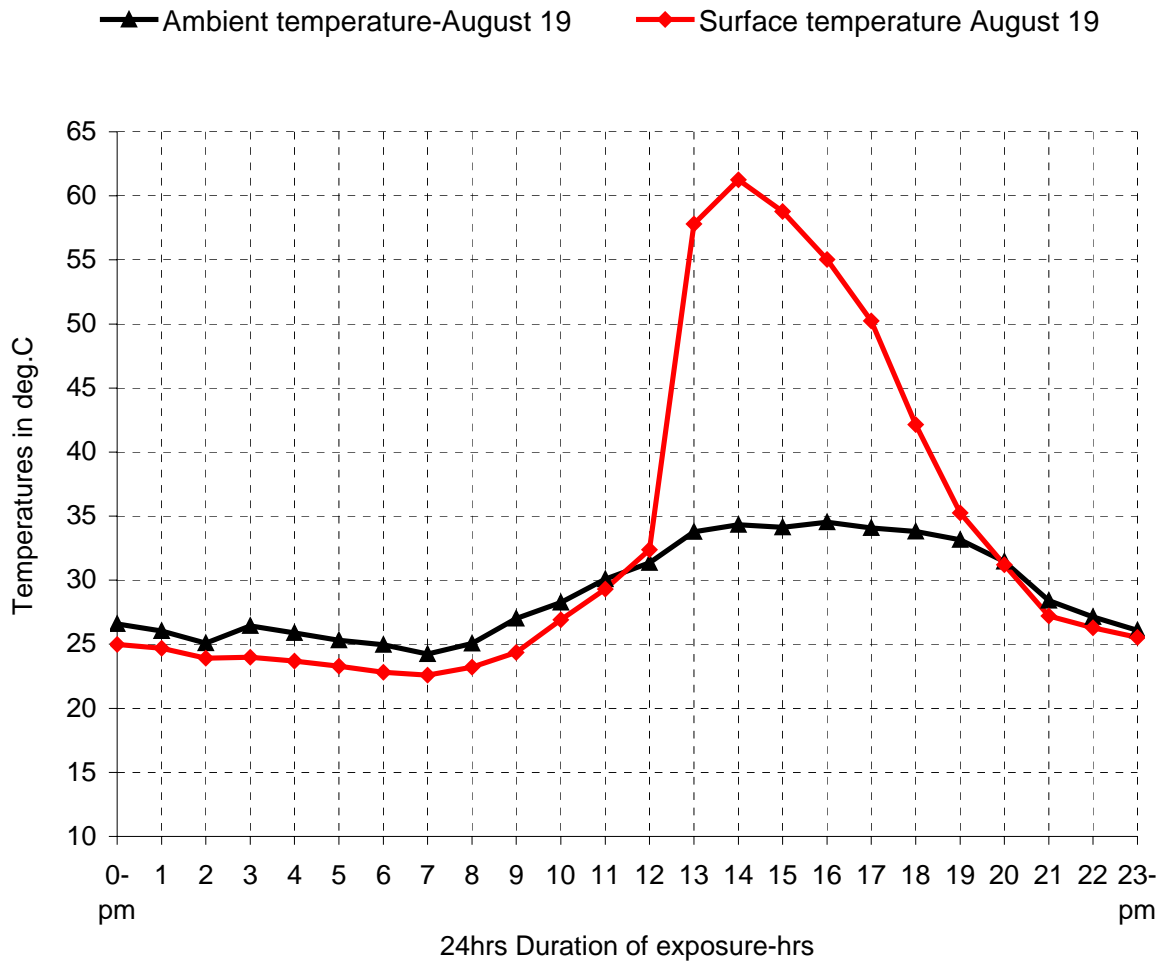


Figure 4-8: Temperatures on the Surface Deck and Ambient Temperatures 2.5 ft from Deck Surfaces August 19.

Surface Temperatures on Filled Deck and Ambient Temperatures 2.5ft  
From the Deck Surfaces

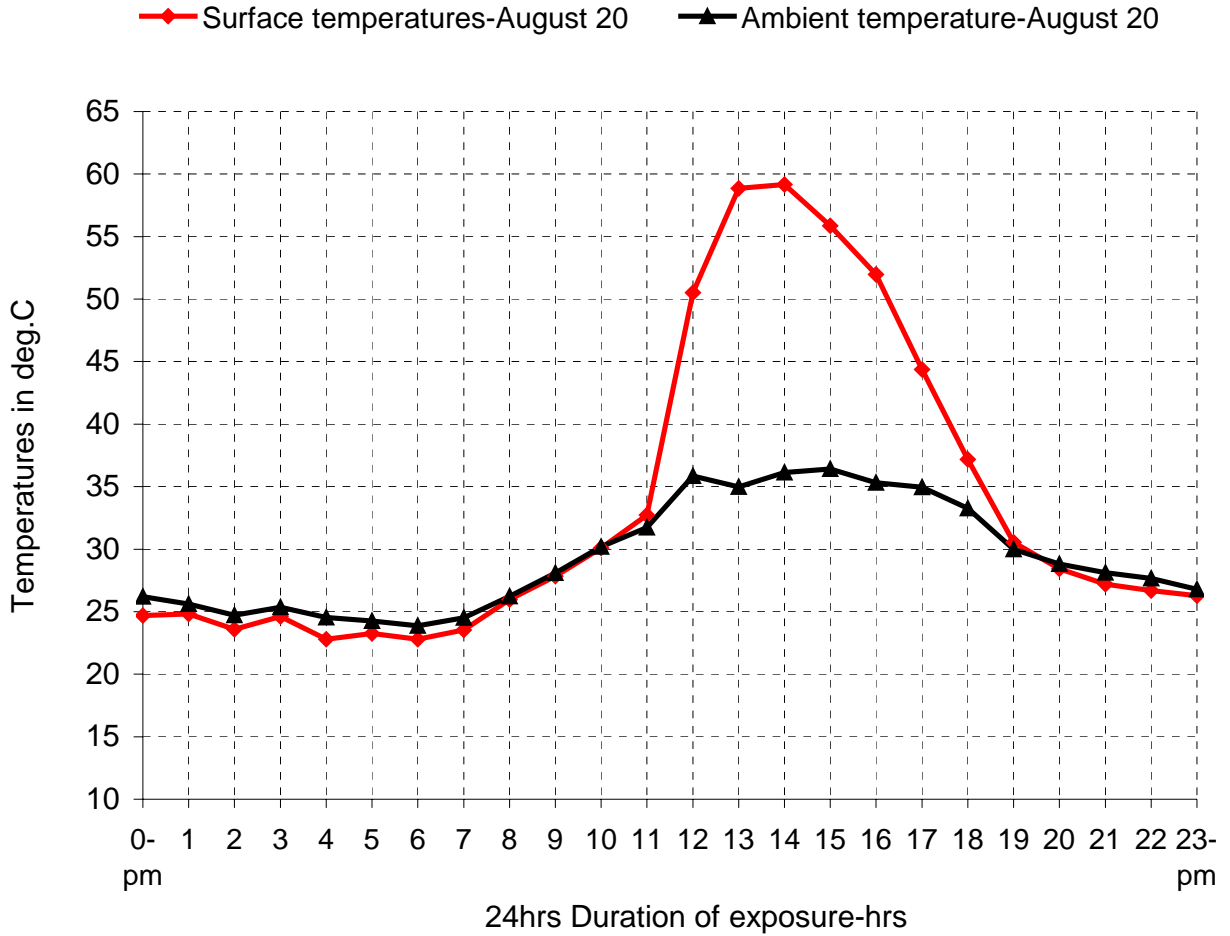


Figure 4-9: Temperatures on the Surface Deck and Ambient Temperatures 2.5 ft from Deck Surfaces August 20.

Surface Temperatures on Filled Deck and Ambient Temperatures 2.5ft  
From the Deck Surfaces

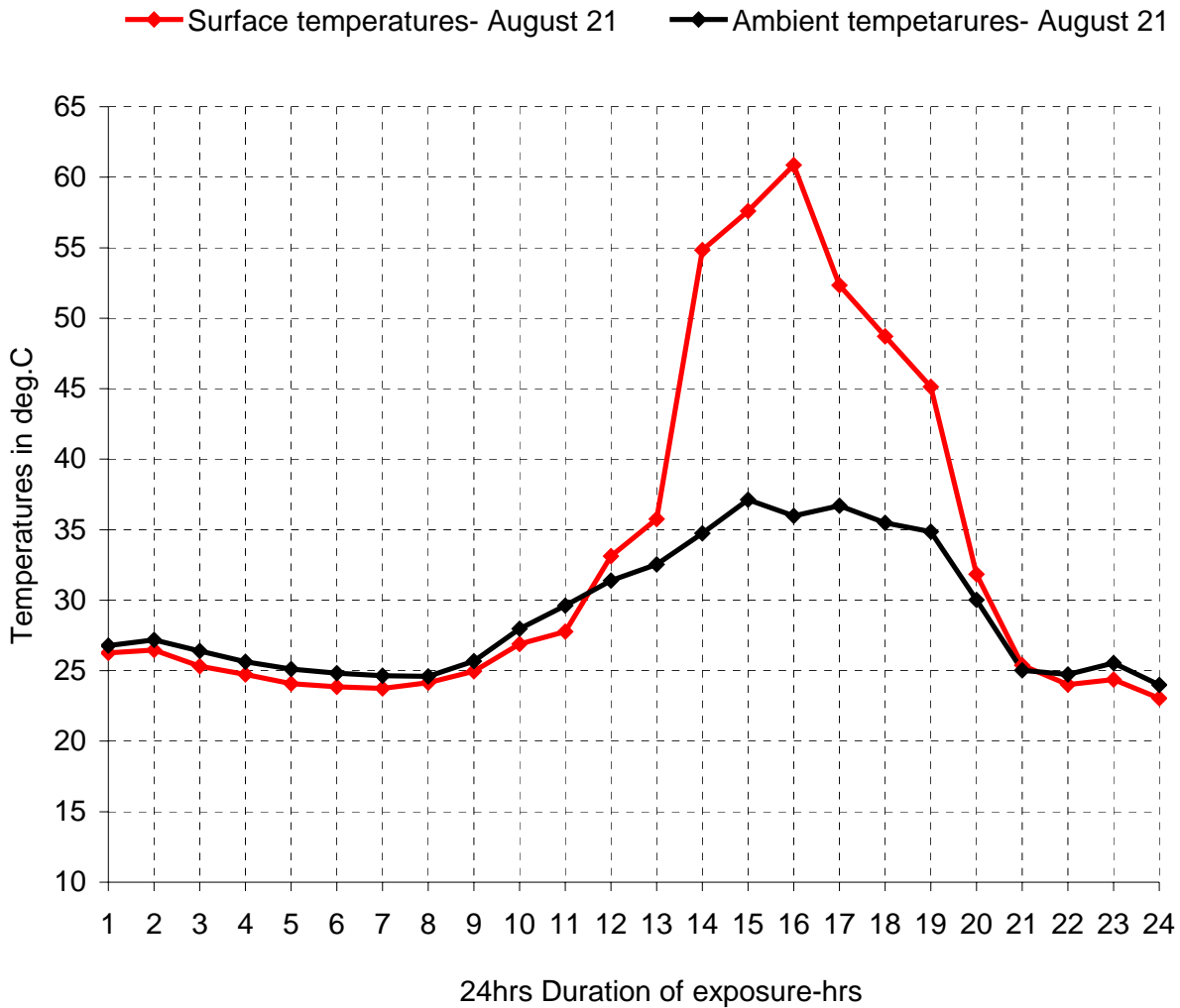


Figure 4-10: Temperatures on the Surface Deck and Ambient Temperatures 2.5 ft from Deck Surfaces August 21.

Figure 4-7 through figure 4-10 shows the surface temperatures recorded on the filled deck and ambient temperatures 2.5 ft from the filled deck surfaces for four different days. The figures indicated that the temperatures on the deck surfaces are depending on the intensity of the ambient temperatures and duration of exposure. Figure 4.11 below the maximum ambient temperatures measured direct form sunlight for each month.

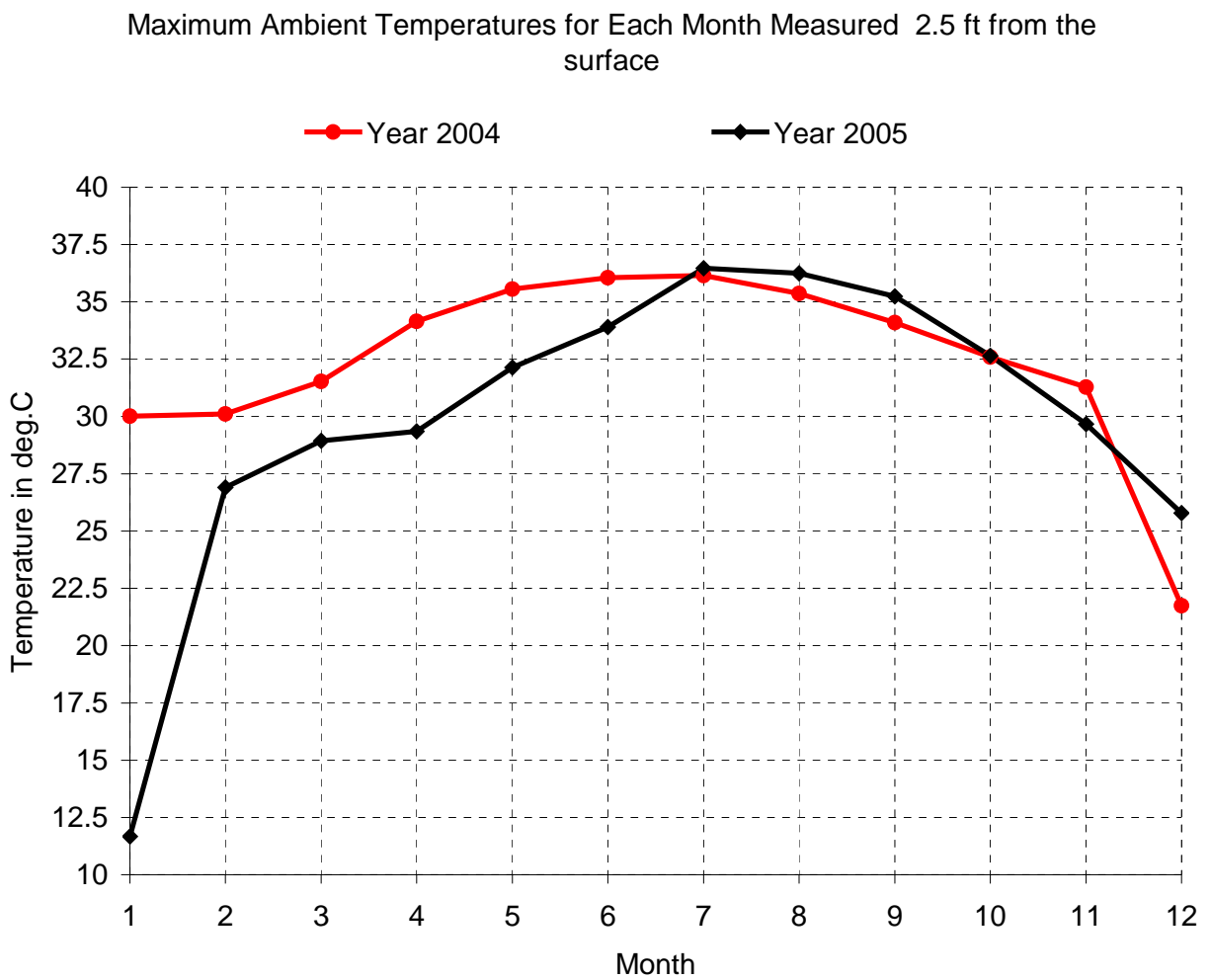


Figure 4-11: Ambient Temperatures 2.5 ft from Direct Sunlight-Fort-Lauderdale Station.

Open steel decks filled with lightweight materials and aggregates broadcasted were subjected to cyclic temperatures. The cyclic temperatures ranging from above and below normal ambient temperatures and were generated on the top deck as well as underneath the deck. Visual inspections of each specimen were conducted prior and after exposure to the cyclic temperature to determine whether there were physical defects between the epoxy and the neat resin. The only major defects observed during the loading were scaling and bleeding of the neat resin.

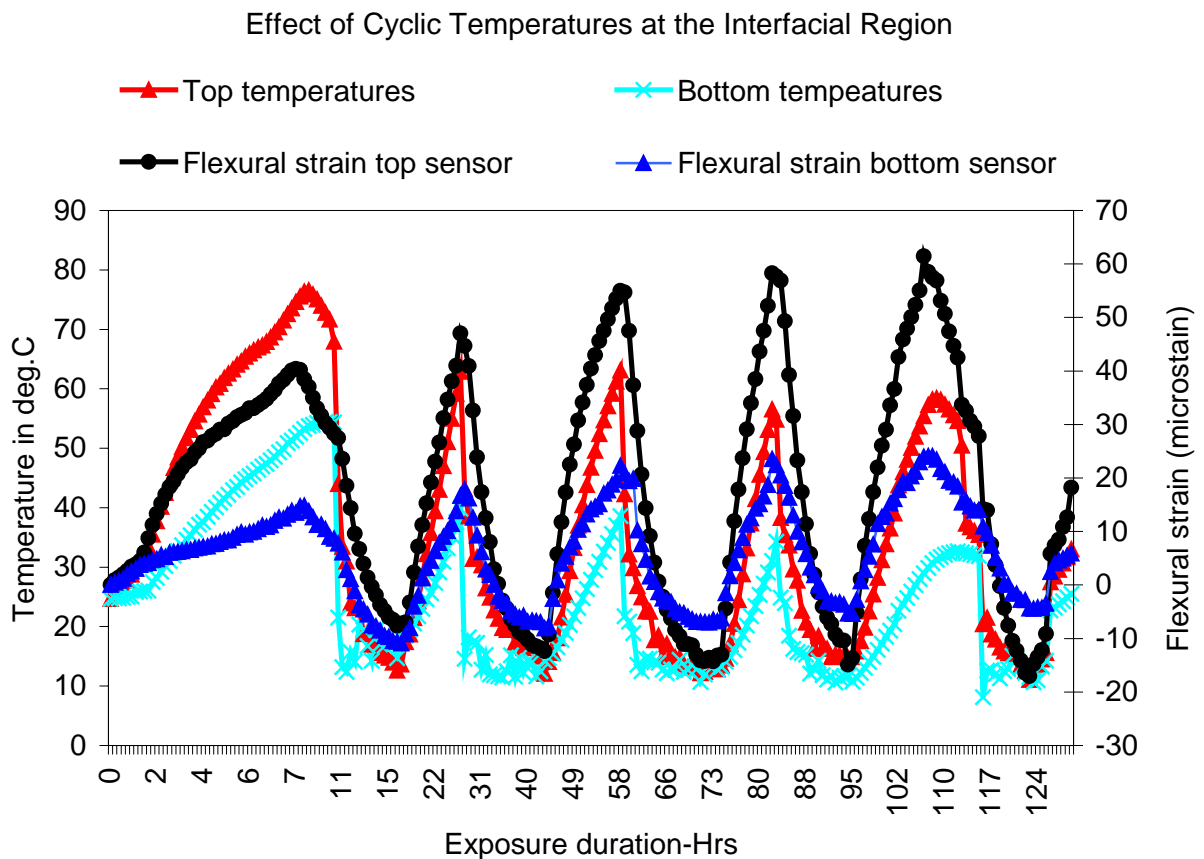


Figure 4-12: Effect of Cyclic Temperatures at the Interfacial Region

Scaling effects were observed at the interface between the neat resin and the epoxy. This effect was due to the expansion and contraction of the epoxy materials and neat resin even though the specimens exposed under direct sunlight (the neat resin) became softer and lost their adhesive properties. The bleeding effects reduced the performance of the neat resin

by reducing the bond strength between the aggregates and the neat resin, and between the epoxy and the neat resin. Also, the bleeding effects might have caused the cracks and loss of aggregates on the running surfaces, which led to low abrasion resistance.

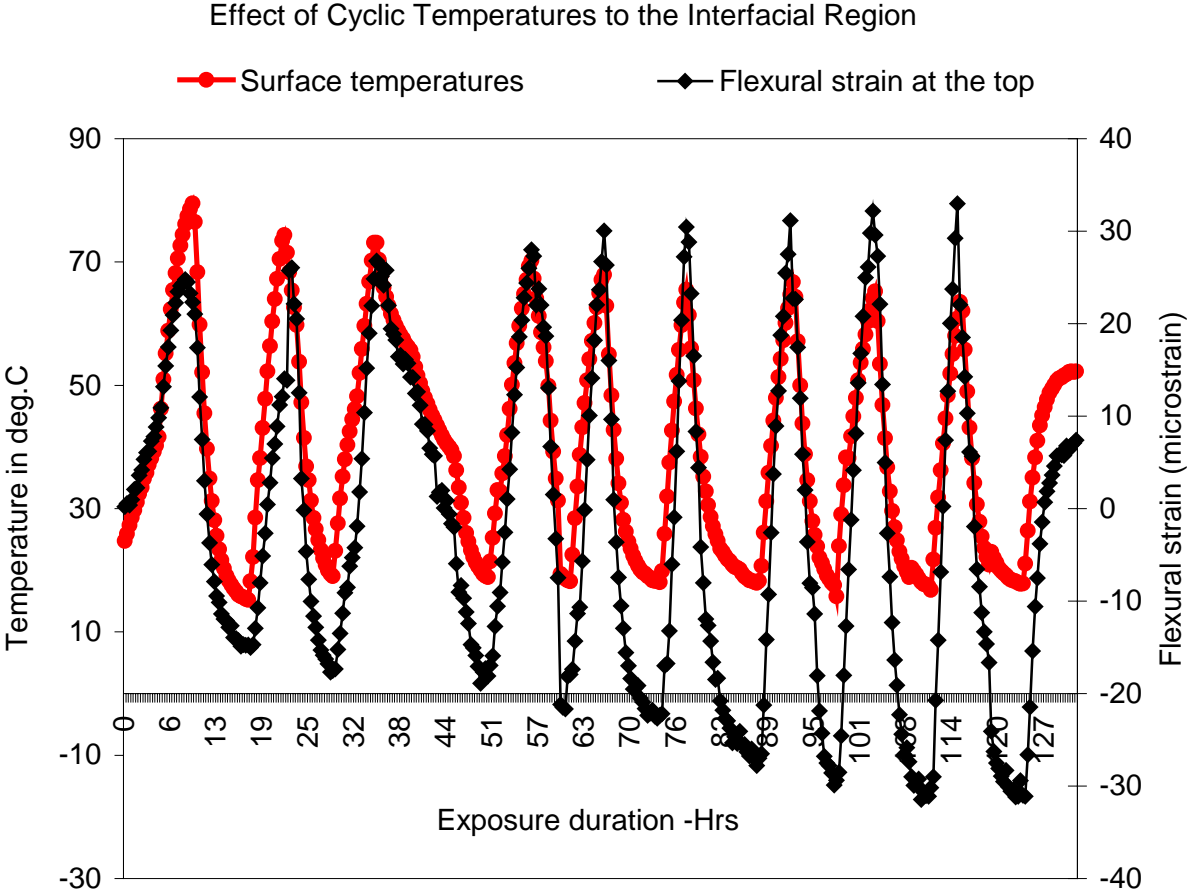


Figure 4-13: Effect of the Cyclic Temperatures at the Interface

Effect of Cyclic Temperatures to the Interfacial Region.

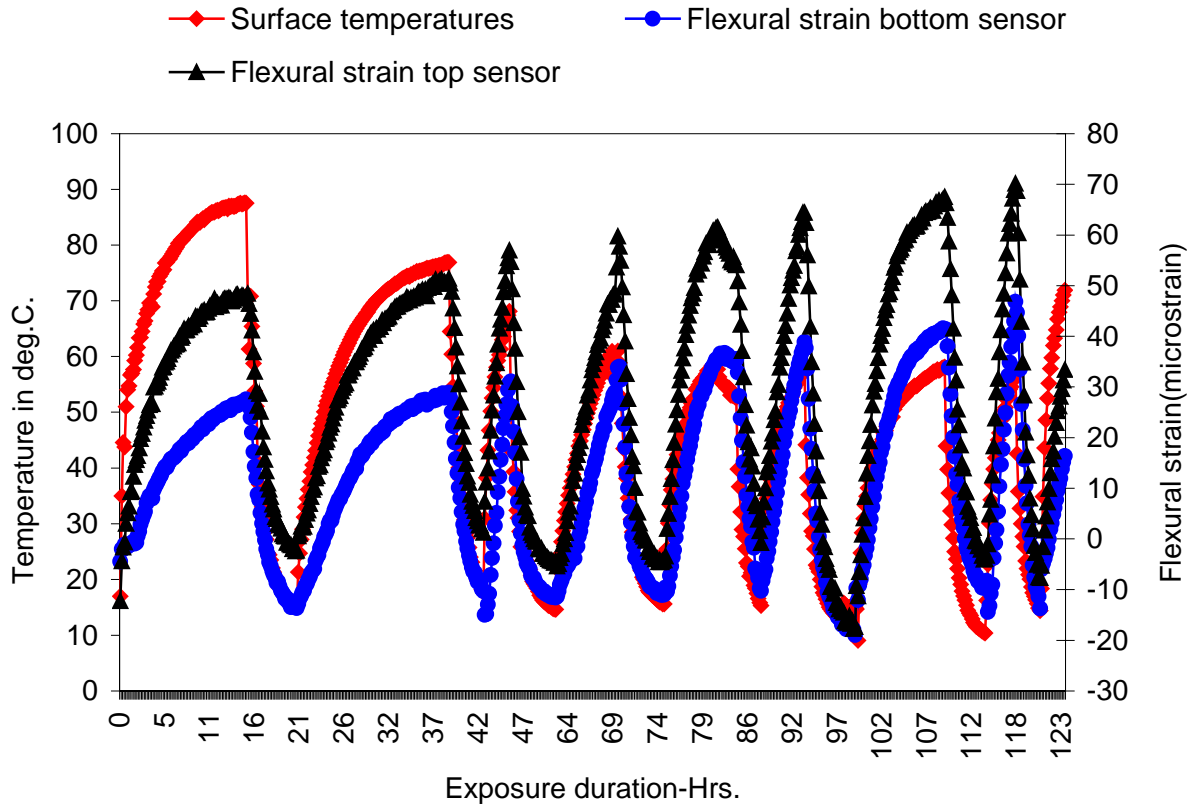


Figure 4-14: Effect of Cyclic Temperatures on the Shear Strain Interfacial Region

Figures 4-12, 4-13, and 4-14 above summarize the effects of the temperature exposure on the interfacial region between a steel plate and epoxy resin. The figures above show that delamination is greatly effected by temperatures; they also show the relationship between delamination at the interfacial region and weather exposures. Owing to the loading and unloading temperatures, the epoxy molecules at the interfacial region expand and contract. The expansion and contraction processes weaken the bond strength between the epoxy and steel plates.

Effect of the Maximum Cyclic loading Temperatures -Top Sensor

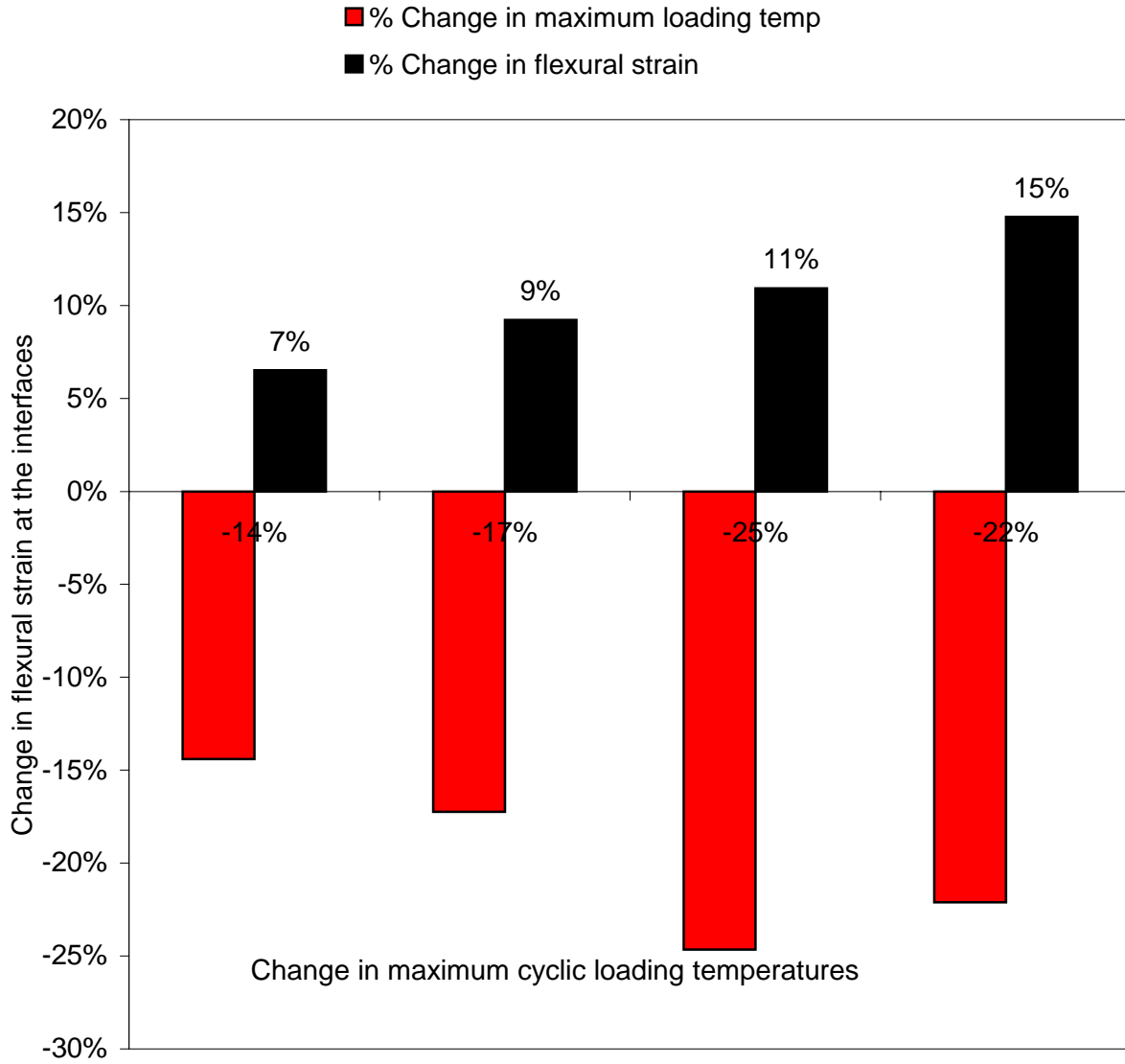


Figure 4-15: Effect of Cyclic Maximum Temperature at the Interfacial Region- Top Sensor

### Effect of the Maximum Cyclic Loading Temperatures -Top Sensor

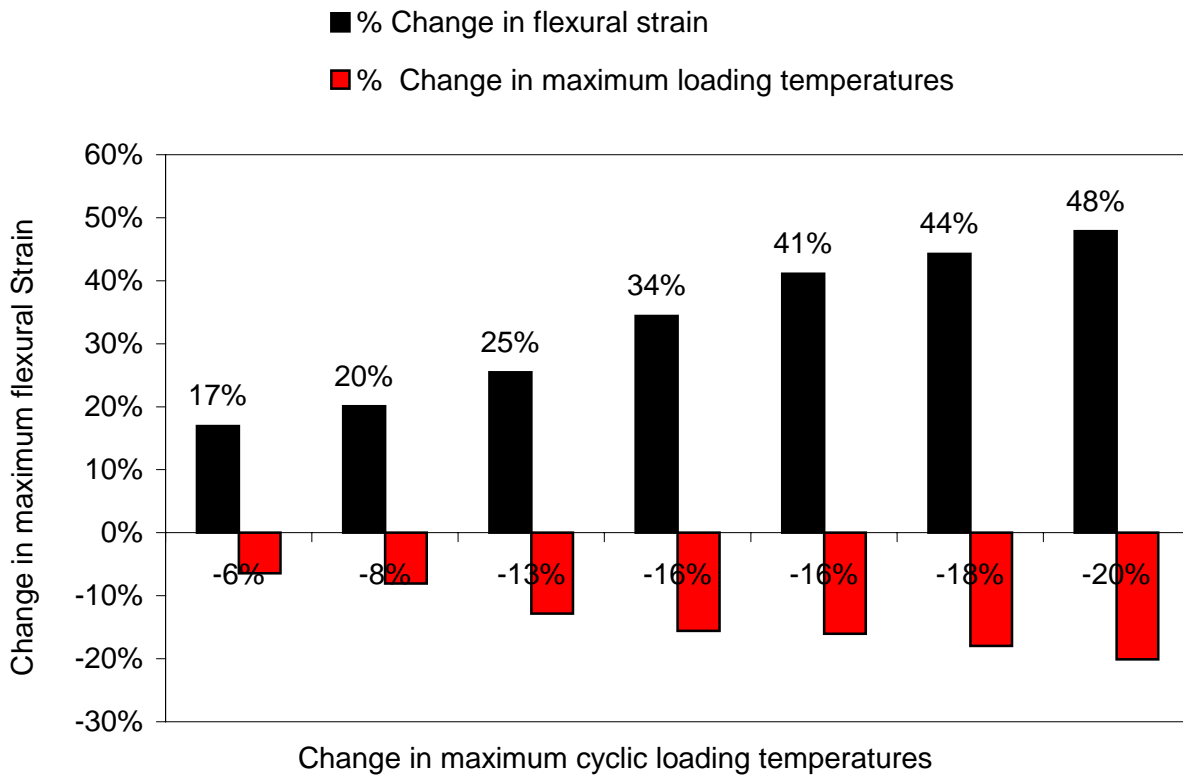


Figure 4-16: Effect of Cyclic Loading Temperatures at the Interfacial Region-Top Sensor

Figures 4-15 and 4-16 shows the effects of cyclic weather on the interfacial region between a steel plate and epoxy resin for the different tests. In the first test (figure 4-12), the maximum loading temperature for the first cycle was 75°C (167°F) and the loading temperature dropped by 14% in the second cycle. The change in temperature increased the flexural strain of the sensor about 7%. With the third cycle, the temperature dropped by 17%, but the flexural strain increased by 9%. After the fifth loading cycle the maximum temperature dropped by 22%, but the delamination increased by 15%.

Figure 4-16 shows the effects of cyclic weather on the interfacial region between a steel plate and epoxy resin (see figure 4-13). The maximum loading temperature for the first cycle was 79°C (174°F) and the loading temperature dropped by 6% in the second cycle. The change in temperature increased the flexural strain of the sensor about 17%. With the third

cycle, the temperature dropped by 8%, but the flexural strain increased by 20%. After the seventh loading cycle the maximum temperature dropped by 20%, but the delamination increased by 48%. The increase in the flexural strain was due to induced fatigue stresses caused by thermal loads. Under fatigue stresses, the materials lose their storage modulus and bond strength characteristics.

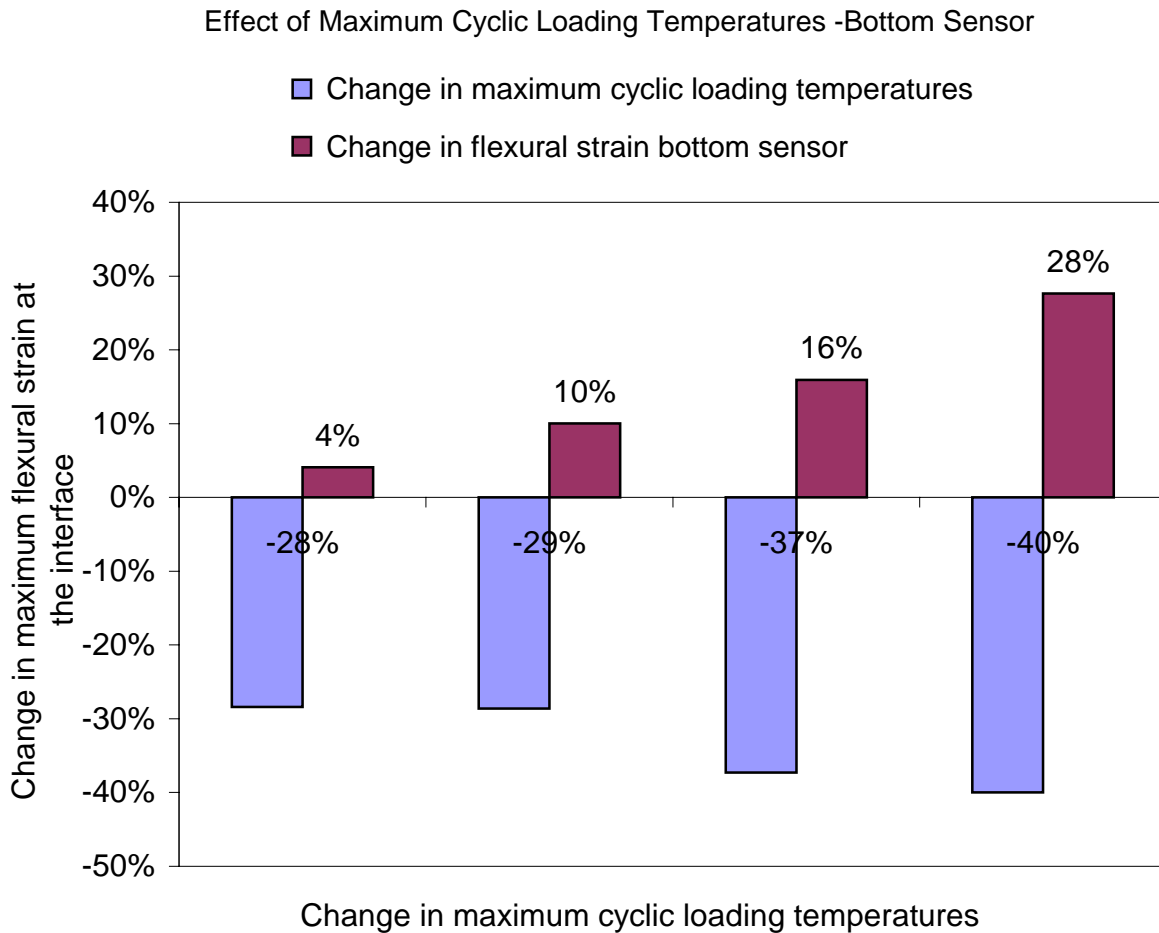


Figure 4-17: Effect of Cyclic Loading Temperatures on the Interfacial Region-Bottom Sensor

Figure 4-17 above summarizes the effects of cyclic weather underneath the deck. The thermocouple positioned underneath the deck showed maximum loading temperatures for the first cycle, which was about 54°C (129°F) figure 4-12. In the second loading the temperatures dropped by 28%, but delamination at the interface increased by 4%. The figure indicated that

delamination at the interfacial region was affected by cyclic weathering. An increase in cyclic weather exposure might affect the performance of the open grid deck systems in the long run.

The experimental results show that the performance of the filled grid deck systems depends on weather exposure. The degradation effect increased at the interfacial region, but this in turn depended on the increase in temperature. On running surfaces the effect increased linearly as the temperature increased to 31°C (88°F) (figure 4-18); it increased dramatically when temperatures were above 30°C (86°F). But at low temperatures the flexural strain increased linearly to the glass transition temperature, and then the strain to the sensor increased dramatically. The rapid changes in flexural strains were due to increased viscoelasticity and the reduction of mechanical properties at the interface and within the matrix.

Operation temperatures above the glass transition temperature caused epoxy molecules to become more flexible and free to move. These movements caused re-arrangements of the epoxy molecules and changes in resin morphologies. The process led to the degradation of the intermolecular forces between the particles and reduced the storage modulus of the elastic. Woods (2003) documented that an increase in the operation temperature above the glass transition temperature changes the mechanical properties of polymer and reduces the shearing capacity between the polymer and the concrete or steel substrate. At the interfaces between the steel plate and the epoxy, there were temperature gradients along the depth between the epoxy and the steel plate. The temperatures varied linearly, with a higher temperature on the running surface and a decreased temperature along the interfaces. The difference in temperature gradients caused the shear strain to change as well.

The presence of free water molecules within the matrix network was another reason for the increase in strains to the sensors. Free water molecules exist in capillaries and microvoids within the matrix; this type of water split into two categories. Category one corresponded to molecules that formed a single hydrogen bond within the matrix network. These molecules possess lower activation energy and can be removed easily in low temperature conditions. The molecules in this category act like a plasticizer, which lowers the glass transition temperature ( $T_g$ ) and increases the viscoelasticity of the materials. The second category of water forms multiple hydrogen bonds within the matrix network. This type of the water molecule possesses a higher activation energy level and cannot be removed easily in low temperature conditions. The molecules in this category increase the glass transition temperature ( $T_g$ ) by forming a secondary cross-linked network with the polymer matrix. In high temperature conditions, the molecules will be displaced and allow free water to escape from the matrix network. The

process leads to the creation of voids between the matrix networks and affects the phase morphology of the cured matrix.

Bridge deck systems filled with epoxy and aggregates broadcasted experienced cyclic weather (loading and unloading) in daily operation. Changes in the weather load may cause the delamination of materials at the interface and changes in the materials' properties. Under repeated weather loads, thermal stresses will develop at the interfacial region and cause delamination at the interface in the long run. Guetta et al. (1985) reported that an increase in temperature lowered the mechanical properties and increased the crack propagation along the interfaces. The cumulative microcracks will affect long-term performance at the interfacial region. If the specimens employ under loading and then unloading, the molecules will occupy new positions when loading weather is applied; when the unloading process occurs the molecules will either re-occupy new positions or return to their original position. The reversible processes weaken and lose their mechanical properties and change the morphologies of the adhesive materials.

High temperature exposures are major environmental factors affecting the performance of the open deck filled with lightweight materials. During the first cyclic weather condition, the maximum temperature exposure at the top deck was 33% higher compared to the bottom deck. The temperature difference shows a 63% greater shear strain compared to the bottom of the deck. However, when there was low temperature exposure on the deck surface, the temperature was 5% higher than at the bottom deck. The difference in temperature caused an 8% increase in shear strain at the top of the deck compared to the bottom. The study concludes that the high flexural strain was due to the presence of the empty voids that remained after the free water molecules escaped when exposed to a high temperature.

Another reason for the low flexural strain to the sensors is due to the hydrogen bond that exists within the polymer materials. The hydrogen bonds formed by the free water molecules were not completely removed due to the low temperature. In low temperature conditions the molecules contract and park together, and the contraction process increases the intermolecular force between molecules, which requires more energy to break the interfacial bond. Although Seong et al. (2003) reported that water molecules caused the degradation process of polymer materials such as cutting chain molecules; the reaction of the water molecules with the polymer chain and vibration of the water molecules was lower. These three effects may have led to the production of a shorter chain. Water may also affect the phase morphology of the cured matrix. A matrix cured at lower temperatures has more ductile regions in the shape of globules compared to a matrix cured at higher temperatures.

Kinloch (1987) documented that moisture is often regarded as the primary agent in the reduction of service life and the reliability of adhesive joints and composites. Moisture affects the performance of nearly all adhesives because water is ubiquitous in the atmosphere and has a substantial affinity for both organic and inorganic materials. The dramatic reduction in adhesion strength has been attributed to both physical and chemical changes resulting from moisture absorption in either the bulk of the adhesive or at the interface between the adhesive and substrate. Brewis et al. (1990) and Cognard (1984) proposed that degradation of the interface is the basic cause of the loss of adhesion strength. The authors concluded that bonds attributable to secondary forces at the interface are broken up by moisture and temperature exposure.

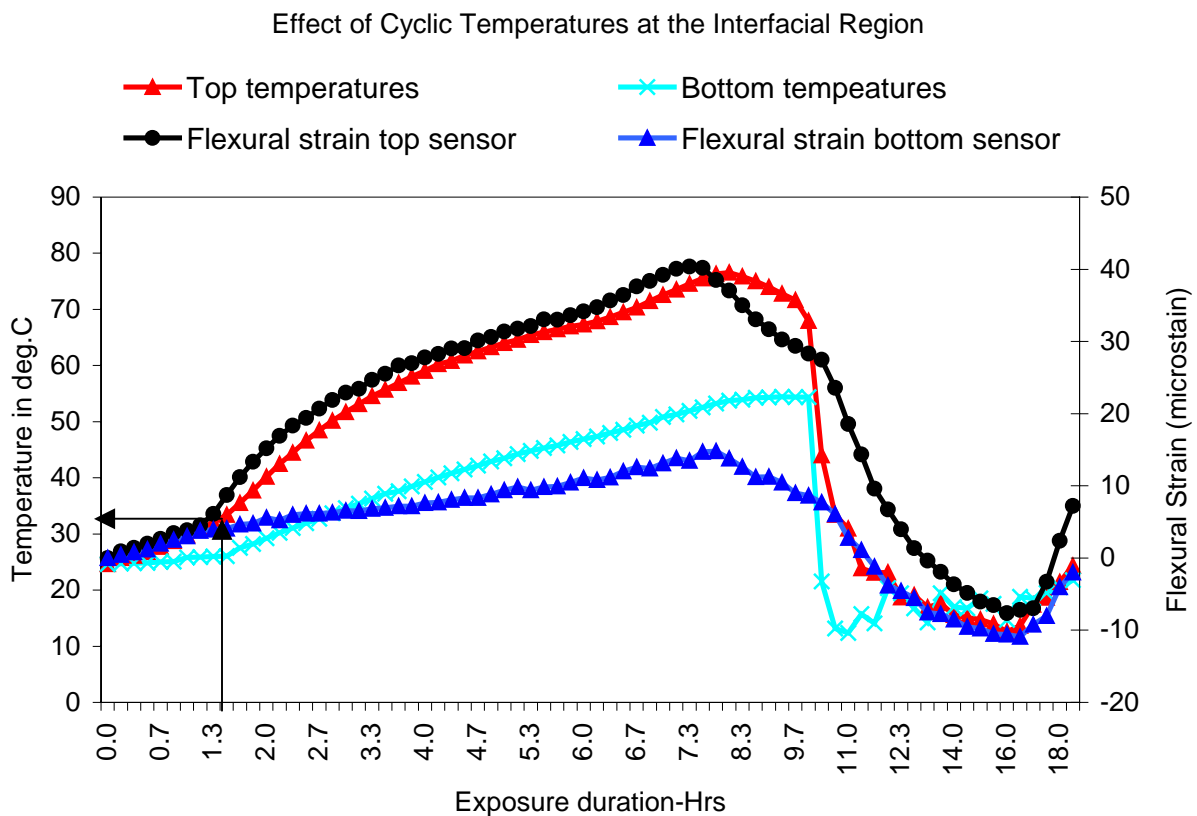


Figure 4-18: Effect of Cyclic Temperatures on the Interfacial Region – One cycle.

#### 4.4 Effect of Combined Low and High Temperature Exposure to Filled Deck:

Both low and high temperature above cured were employed in the climatic chamber to simulate field conditions. The low condition was introduced to simulate a low temperature underneath the sample and a high temperature on the upper deck. The results from the study are summarized in figure 4-19 below.

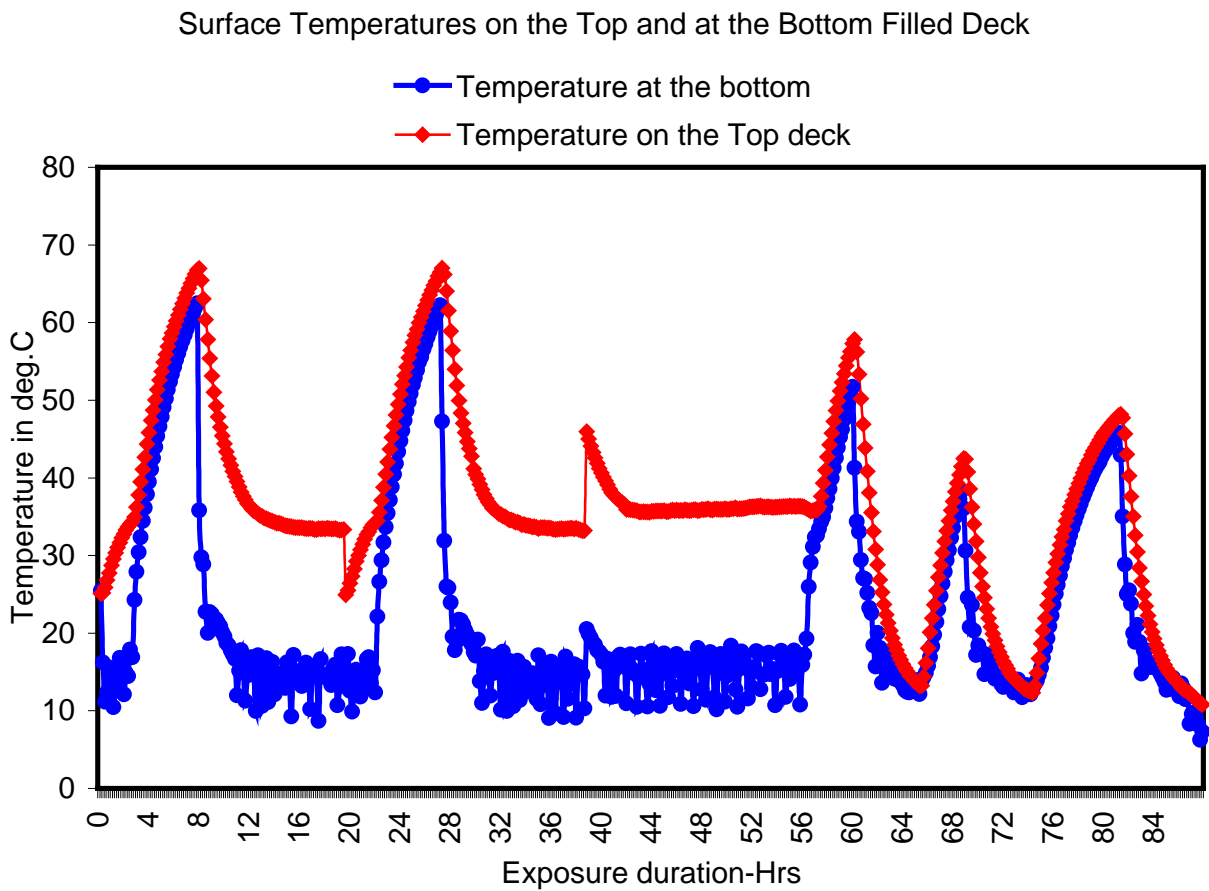


Figure 4-19: Surface Temperatures on the Top and at the Bottom of the Filled Deck System.



After a period of 40 hours, the temperatures were kept constant for a period of 17 hours. Both sensors showed/ recorded the constant delamination under constant temperatures (figure 4-15). After cyclic temperatures, the delamination increased linearly, and the sensor at the bottom of the deck showed high delamination despite a lower cyclic temperature. Severe delamination under a lower temperature exposure was caused by a hydrogen bond within the molecules. If water molecules exist within the polymer materials, the water molecules will react with the steel plate. The reaction forms oxide surfaces on the steel plates, which lead to the loss of bond strength between the steel plates and adhesive resin.

Tianbao (2001) reported that moisture can enter to interfacial region either by diffusion through the bulk of the epoxy or may be transported by metal/epoxy interfaces. The moisture forms a hydrogen bond and it is believed to lower the performance of the bond strength between steel and epoxy under dry conditions. The moisture increases the glass transition temperature of the adhesive resin by forming a secondary cross-link between the polymer materials. Water molecules are very strong hydrogen bond agents; when they reach the interfacial region in a wet environment, they can break the bond and form a new hydrogen bond with the hydrated oxide surface of the metal. Also, the adhesive may lose its mechanical properties when the hydration of aluminum oxides are involved. Before water is introduced, the aluminum exists in an amorphous phase; after water is introduced, hydration ( $\text{Al}_2\text{O}_3$ ) and boehmite  $\text{AlOOH}$  are formed. The second step of hydration consists of nucleation and the growth of bayerite  $\text{Al}(\text{OH})_3$  crystallites.

#### **4.5 Effects of Cyclic Temperatures to E-Bond 526 LW Materials:**

Compression tests were performed to understand the behavior of compressive strength under cyclic weathering. The specimens were categorized into four groups and subjected to different cyclic weather loads: cyclic temperatures above and below glass transition temperature and cyclic temperature below glass transition temperature. The specimens subjected to above and below glass transition temperature were subjected to the cyclic temperatures ranged from  $75.6^\circ\text{C}$  ( $168^\circ\text{F}$ ) to  $17.4^\circ\text{C}$  ( $63.3^\circ\text{F}$ ), while those specimens subjected to the cyclic temperatures below glass transition temperature were subjected to cyclic temperatures ranged from  $44.3^\circ\text{C}$  ( $112^\circ\text{F}$ ) to  $6.6^\circ\text{C}$  ( $43.9^\circ\text{F}$ ) as indicated on the figure 4-21 The specimens were exposed to the cyclic temperatures different exposed duration. The specimens were tested after were exposed to the cyclic temperatures below and above normal ambient conditions at an interval of seven cyclic temperatures as indicated in table 4-3 and figure 4-22.

### Temperatures Profile

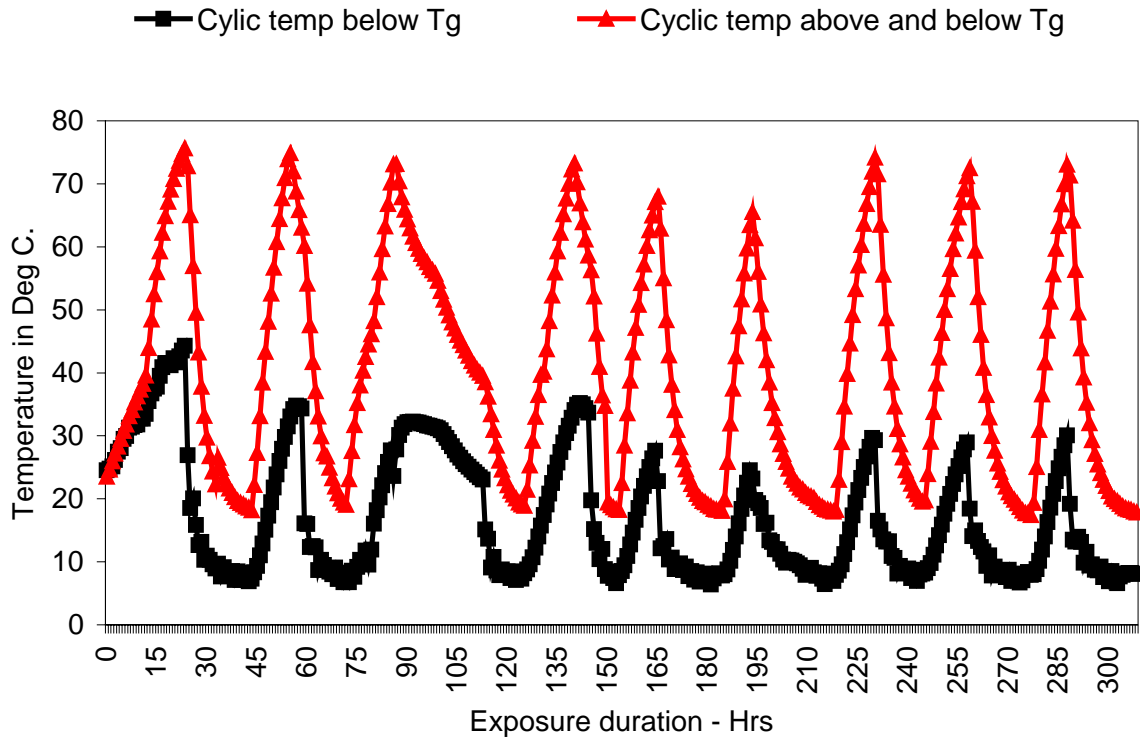


Figure 4-21: Cyclic Temperatures above and below Glass Transition Temperature.

Table 4-3: Effects of Cyclic Temperatures on Compressive Strength.

Cycle	Low-Temperature exposure			High Temperature exposure			Duration Days
	Load- lb	Area, sq-in	Strength in -psi	Load- lb	Area, sq-in	Strength in -psi	
Virgin	12990.10	12.56	1190.88	12990.10	12.56	1190.88	0
7	11115.11	12.56	844.96	10471.03	12.56	833.68	10
14	8392.40	12.56	668.18	7935.64	12.56	631.82	22
28	7373.53	12.56	587.06	5709.65	12.56	510.44	30
35	6892.64	12.56	548.78	6488.67	12.56	516.60	40

### Effect of Cyclic Temperatures to the Compressive Strength

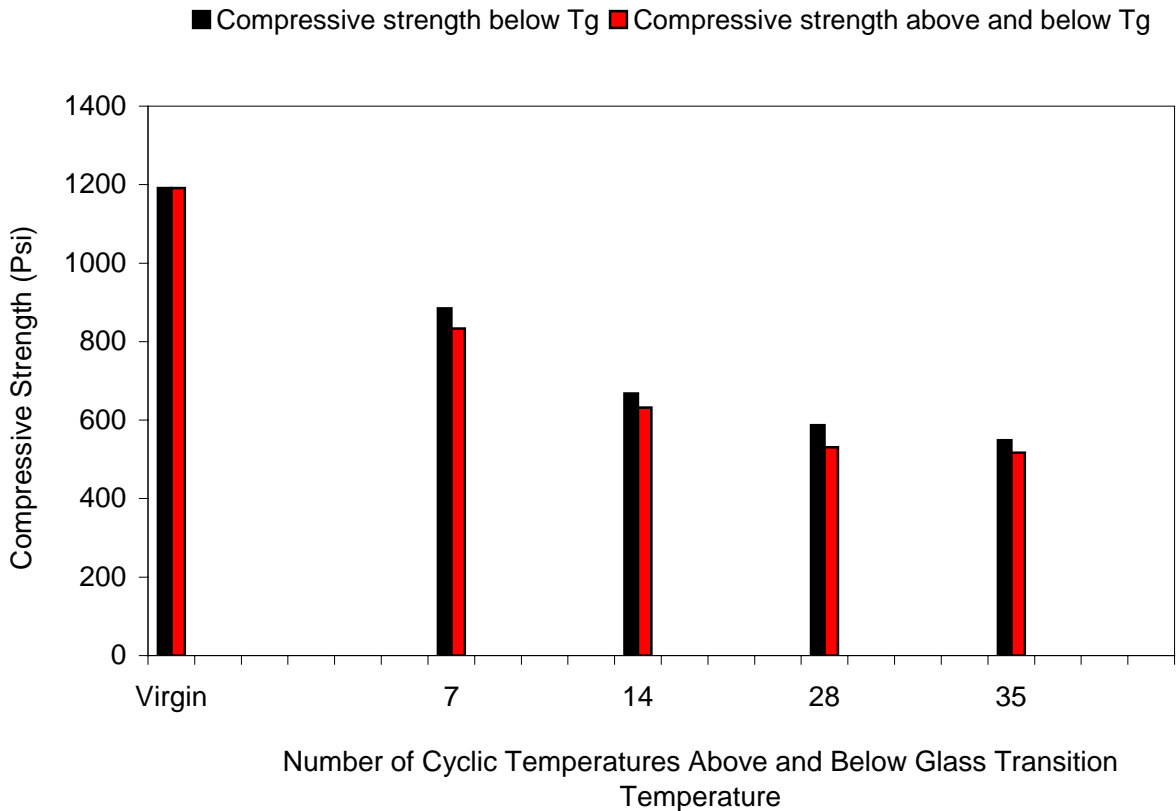


Figure 4-22: Effect of Cyclic Temperatures to the Compressive Strength.

The results figure 4-22 shows that the low compression strength for the specimens undergo high cyclic weather changes compared to other specimens. The specimens exposed to seven cycles of high or low temperatures showed low compression strength compared to virgin specimens. A loss in strength of about 29% and 30% was observed in the specimens exposed to seven cycles of low and high temperature respectively. The specimens exposed to high temperatures for seven cycles showed about a 6% loss in strength compared to the specimens that were exposed to a low temperature range. After the specimens were exposed to 28 cycles of low and high temperatures, the specimens lost about 51% and 57% in compression strength respectively. The specimens exposed to high temperatures for 28 cycles lost about 13% in strength compared to those exposed to low temperatures. After the specimens were exposed to 28 weather cycles at high or low temperatures, the specimens lost about 12% and 19% in

strength respectively compared to the specimens that were exposed to fewer than 14 weather cycles. For 35 cycles the specimens exposed to temperature below and above glass transition temperature lost about 13% in strength compared to those exposed to temperatures temperature below glass transition temperature.

Low compressive strength is caused by a breakdown of the intermolecular force. Also, molecules become formable, flexible, and free to move. Higher temperature exposure leads to an increase in viscoelastic behavior and a lower storage modulus of polymer materials (figure 4-4). For these two reasons, adhesive resins may lose their adhesive properties, which leads to weakened interfacial bond strength. Woods (2003) and Sprinkle (1993) documented that the temperature above the transition temperature affects the physical and mechanical properties of polymer materials. Above the glass Transition temperature, the polymer materials lost their adhesive properties and bond strength characteristics, and the adhesive resins changed from a brittle to a ductile state above the glass transition temperature. Another reason for the low compressive strength was the escape of the free water molecules and changes in phase morphology of the cured matrix and lowers the compression strength of the cured matrix.

## CHAPTER FIVE

### CONCLUSION AND RECOMMENDATIONS

This chapter includes the conclusion and makes recommendations based on the results of the study. The aim of this research was to investigate and determine the longevity of an open metal grate decking filled with epoxy under field conditions. The investigation focused on the accelerated test of a steel grid deck filled with epoxy resin and aggregates broadcasted. The accelerated test was conducted under extreme weather conditions to simulate field conditions. The testing variables in these tests were low and high temperatures, which were performed in a laboratory according to ASTM D-1151 guidelines (Standard Practice for Effect of Moisture and Temperature on Adhesive Bond). Several tests were conducted; these tests included the stiffness test for an open and filled system, the effect of cyclic weather on compressive strength, the performance of the filled deck systems under cyclic temperatures, and the effect of combined weather on the filled deck systems.

#### 5.1 Conclusions:

Based on the study, the following conclusions were drawn from the results of the experiment.

1. E-Bond 526 lightweight material loss bond strength characteristics above normal ambient temperature compared to below ambient temperature. The decks exposed to high temperatures showed more flexural strain at the interface between the steel and epoxy resin. The strain was induced by the rapid changes in the epoxy's physical and mechanical properties.
2. The results from the cyclic temperatures showed that delamination decreased along the interfaces. The difference in flexural strains was influenced by the temperature gradient along the interfaces. Also, the results showed that the degradation of materials that were exposed to high temperatures was affected more than the epoxy at the bottom of the deck. The materials that were near the running surfaces were affected more and become softer than those exposed to lower temperatures underneath the deck.
3. Thermal analysis results showed that the E-bond 526 lightweight materials had a glass transition temperature of about 52°C. This glass transition temperature value

was low compared to the operation temperatures, to which the systems are exposed. Based on the recorded temperatures (i.e., the direct sunlight on the deck systems), the results showed that the surface temperature on the bridge deck was about 94°C (201°F) and could become higher during the summer season; this also affects the performance of the deck system.

4. When exposed to cyclic temperatures the flexural strain for the sensors increased linearly as temperatures dropped below 31°C (88°F). They then increased dramatically as the temperature went above 31°C (88°F). A rapid increase in shear strains is a result of the epoxy becoming soft and losing its shear strength. Epoxy resin showed excellent bond performance below 31°C (88°F); above that temperature, the epoxy molecules become softer and lost their adhesive properties.
5. The results for the low and high temperature tests showed that both conditions affected the bond performances at the interfaces. But no severe delamination was observed at both low and high temperatures. Polymer materials expand and contract according to changes in the weather. Under low temperature conditions, the molecules packed together and reduced the volume of the epoxy materials. When the adhesive resin was exposed to temperatures above 31°C (88°F), the molecules expanded and increased the volume of materials. The compression test proved that high cyclic temperatures affect the performance of open filled deck systems. The compressive strength was lower for all specimens that were subjected to high cyclic temperatures.
6. The study found that cyclic weather contributes to the performance of deck systems. An increase or decrease in temperature affects the cyclic load and contributes to the delamination at the interfacial region.

## **5.2 Recommendations:**

In order to characterize the durability of the bridge deck systems filled with lightweight materials, other weathering loads should be considered to evaluate the general performance of open decks filled with lightweight materials. Bridge deck systems filled with epoxy are exposed to ultraviolet rays, as well as alkaline and saline conditions every year. UV exposure often results in surface oxidation, as evidenced by the increase in oxygen-containing functional groups. The effect will increase the cracking of polymer materials and will affect the long-term performance of the epoxy resin.

Bridge deck systems experienced various weather loads and wheel loads in daily operation and in their life span. The combination of the wheel loads and the weather loads enhanced the performance of the filled deck systems. Therefore, the usefulness of the findings will be enhanced by the long-term performance of the filled system under a combination of critical loads. A complete understanding of the degradation mechanisms under various exposure and loading conditions will not only enhance material performance, but will also facilitate the design of the accelerated aging schemes for the service life prediction.

## REFERENCES

- 1 Alfred, R.E (1981). "The temperature and moisture content on the Flexural Response of Kevlar/Epoxy Laminates: Part 1. [0/90] filament orientation". Journal of composite materials.15 p 117-1981.
- 2 Aminabhavi, T.M (1988), "Liquid Diffusion into Epoxy-Resin Composites". Journal of Applied Polymer Science, 35, p.1251-1256.
- 3 Alfred, R.E (1981). "The temperature and moisture content on the Flexural Response of Kevlar/Epoxy Laminates: Part II. [+ Or - 45,0/90] filament orientation". Journal of composite materials.15 p 117-1981.
- 4 Akira Kuraishi (2001). "Durability analysis of composite structure using accelerated testing methodology" Dissertation submitted to the Faculty of the department of civil engineering and engineering mechanics –University of Arizona.
- 5 Birger, S. Mashonov, A. and. Kening, S (1989). "The effect of the thermal and hydrothermal aging on the failure Mechanisms of Graphite-Fabric Epoxy Composites subjected to the Flexural Loading". Composite, 209 -341.
- 6 Bledzki, A, Spaude R and Ehrenstein, G.W (1985). "Corrosion Phenomena in Glass Fibers and Glass Fiber Reinforcement Thermosetting Resins". Composite Science and Technology, 23,p 263,1985.
- 7 Brewis, D. M, Comyn, J, Raval, A. K.; Kinloch, A. J. International Journal of Adhesion and Adhesives 1990, 10, 247-253.
- 8 Bremner (2001). "Accelerated test of plain and epoxy coated reinforcement in simulated seawater and chlorine solutions".
- 9 Chateauminois, A. Chabert, B.Soulier, J, P and Vincent, L (1993). "Hydrothermal Aging Effects on the Static Fatigue of Glass/Epoxy composite". Composite 24.P 547.
- 10 Chin, J.W, Martin, J and Nguyen, T (1997). "Effect of Ultraviolet (UV) radiation"-Gap analysis for fiber reinforced polymer composite in civil infrastructure.
- 11 Cuschieri, J.M, Gregory, S and Tournour, M (1995). "Open grid bridge noise from grid and tire vibrations". Center for Acoustics and Vibration Department of Ocean Engineering Florida Atlantic University Boca Raton Florida 22320 USA.
- 12 Cognard, J. Journal of Adhesion 1994, 47, 83.
- 13 Dash, P.K and Chatterjee, A.K (2004). "Effects of Environment on Fracture Toughness of Woven Carbon/Epoxy Composite". Department of Space Engineering and Rocketry, Birla Institute of Technology Mesra 835215.
- 14 Gao, J. and Weitsman, Y. J. (1998). University of Tennessee Report MAES 98-4.0-CM.
- 15 Gerald (1999). "Hydrothermal effects on the Tensile Strength of Carbon/Epoxy laminates with molded edges". Institutes of technology Brazil.
- 16 Gohari, Kamran (1993). "Effect of temperature and humidity cycling on FR-4, Bis Maleimide Triazine and Cyante Ester printed wiring boards". Master thesis Department of Mechanical engineering University of Maryland.

- 17 Grace (2004). "Evaluate the durability of externally bonded carbon fiber-reinforced polymer plate and fabric exposed to the environment".
- 18 Guetta, (1989). "Effect of Thermal Spiking on Carbon Toray 300B Reinforced Polystyrylphyrine Composite". A Kinetic Spectroscopic and Mechanical Study", Composite, 20 p 46.
- 19 Hartwig, A, Schneider and Luhring, A (2002). "Influence Of Moisture On The Photochemical Induced Polymerization Of Epoxy Group In Different Chemical Environment".
- 20 Huang, Haoxiong (2001). "Behavior Of Open Steel Grid Decks for Bridges". Department of Civil and Environment Engineering, University of Delaware, Newark, DE 19716, USA.
- 21 Jeannie (1998). "Sorption and diffusion of water, Salt Water and concrete pore water solution in Composite Matrices". National Institute of standards and technology, Gaithersburg, Maryland 20899.
- 22 Malvar, L.J. Hoffard, T.A. Novinson, T and Jamond, R.M (2000). "Composite in simulated marine environments". Naval Facilities Engineering Service Center Port Hueneme, California 93.43-4370 Special publication SP-2083-SHR.
- 23 Karbhari, V.M and Engineer (1996). "Effect of Environmental Exposure on the External Strengthening of Concrete with Composite Short-term Bond Durability". Journal of Reinforcement Plastics and Composite.Vol.15 .pp 1195-1216.Division of structure engineering (MC0085) university of California, San Diego 9500 Gilman Drive La Jolla 9209.
- 24 Karbhari, V.M and Engineer M and Eckel II, D.A (1996). "Durability of composite rehabilitation schemes for the concrete: Use a Plate Test". Department of applied mechanics and engineering sciences mail code 0085 University of California, san, Diego La Jolla. CA92093.
- 25 Karbhari, V.M and Engineer (1996). "Investigation of Bond between Concrete and Composite: Use a Plate Test". Journal of Reinforcement Plastics and Composite.Vol.15.pp 208-227.Department of applied mechanics and engineering sciences mail code 0085 University of California, san, Diego La Jolla. CA92093.
- 26 Karbhari, V.M. Murphy, K and zhang, S (1993). "Effect of concrete based Alkali solutions on short term durability of E glass/Vinylester Composite".
- 27 Klippstein, H. (1993). "Static and Fatigue Strength Determination of Design Properties for Grid Bridge Decks, Volume III – Fatigue Tests and Strain Measurements on Grid Decks". Research Report ST-14, Department of Civil Engineering, University of Pittsburgh.
- 28 Kinloch, A, J (1983). "Durability of Structural adhesive". Applied science publishers LTD.
- 29 Kinloch, A. J (1987). Adhesion and Adhesives: Science and Technology; Chapman and Hall: New York.
- 30 Krauss, P and Mendis, N (1997). "Recent performance problems of MMA-Based on polymer Concrete Bride Deck Overlay in Montana". CSES-SCGS international conference of engineering materials. Ottawa Canada, June pp 433-446.
- 31 Leidheiser, H.; Funke, W (1987). Journal of Oil Color Chemists' Association.
- 32 Mangelsdorf, C.P. (1991) "Static and Fatigue Strength Determination of Design Properties for Grid Bridge Decks. Volume II – Plate Stiffness Summary and Strain Measurements on Grid Decks". Research Report ST-10, Department of Civil Engineering, University of Pittsburgh.

- 33 Malvar, L.J (1998). "Durability of Composite in Reinforced Concrete". CDCC first International conference on Durability of composite for construction Sherbrooke Canada.
- 34 Mendis, P (1987). " A polymer Concrete Overlays". Concrete international Design and Construction, Vol 9 no 12.dec pp 54-56.
- 35 Micelli, F, Nanni, A., La Tegola, A. (2001). "Effects of Conditioning Environments on GFRP Bars". 22<sup>nd</sup> SAMPE Europe International Conference, CNIT Paris, pp. 1-13.
- 36 Mukhopadhyaya, U. P, Swamy, R.N and Lynsdale, C.J (1998). "Influence of aggressive exposure conditions on the behavior of adhesive bonded concrete-GFRP joints". Department of Mechanical Engineering, Center for Cement and Concrete, Structural Integrity Research Institute, University of Sheffield, Mappin Street, Sheffield S1 3JD, UK.
- 37 Nguyen, T (1995). "Journal of Adhesion", 48, 169-194.
- 38 Richard A. Zimmer (2002). "Method for friction testing of open graded steel bridge decks". Texas transportation institute research report.
- 39 Rivera, J and Karbhari, V.M (2001). "Cold temperature and simultaneous aqueous environment related degradation of carbon/Vinylester composite". Department of structure engineering university of California, an Diego, MC 0085, la Jolla CA 92093 0085, USA.
- 40 Seong Ok Han, Lawrence Drzal, T (2003). "Water Absorption effects on hydrophilic polymer matrix of carboxyl functionalized glucose resin and epoxy resin".
- 41 Sprinkle, M.M (1993), "Polymer Concrete Bridge Overlays", Transportation Research Record, no 1393.pp.107-116,
- 42 Sprinkle, M.M (1995), Chair, Guide Specification for Polymer Concrete Bridge Deck Overlays, AASHTO-AGC-ARTBA-Task 34,L.D Evans, Ed pp 63.
- 43 Takahashi, K. M.; Sullivan, T. M. J. Applied. Phys. 1989, 66, 3192.
- 44 Tarricone (1992). "Overlays on Deck". Civil engineering, Vol.62 no.9 pp.42-45.
- 45 Tannours, F and Saadatmanesh (1999). "Durability of AR Glass Fiber Reinforced Plastic Bars". ASCE Journal of Composites for Construction, Vol. 3 No.1, pp. 12-19.
- 46 Tianbao Du (2001). "Durability of polymer metal interfaces under cyclic loading". Department of materials science and engineering, university of Illinois at Urban-Champaign.
- 47 Warren, G., Burke, D., Harwell, S., Inaba, C., and Hoy, D (1998). "A limited marine durability analysis of CRFP adhesive to concrete". Second International Conference on the concrete under severe conditions environmental and loading, CONSEC `98 Thomson, Norway, pp 1381-1362 Naval Facilities Engineering Service Center, Port Hueneme.CA USA.
- 48 Weitsman, (2000). Mechanics of Time Dependent Materials, 4, 107-126.
- 49 Wimolkiatisak, A, S. and Bell, J.P (1989). "Interfacial Shear strength and failure modes of interface-Modified Graphite Epoxy composite". Polymer Composite, 10 p 16.
- 50 Wu, W. L. Orts, W. J. Majkrzak, J. Hunston, D. L (1995). Polymer Science and Engineering, 35, 1000-1004.
- 51 Woods, M (2003). "Accelerated testing for bond reliability of fiber-reinforced polymer (FRP) to concrete and steel in aggressive environments".

## **BIBLIOGRAPHY SKETCH**

Cathbert Akaro was born on November 1974 Moshi, Tanzania. He completed his Bachelor Degree from University of Dar es salaam, Tanzania from November 2002. Cathbert obtained his Master of Science Degree in Department of Civil and Environmental Engineering at FAMU-FSU College of Engineering in Tallahassee, Florida.