FDOT-FHWA SPONSORED RESEARCH PROJECT

FINAL REPORT

Project Title: **Long-term Performance of Epoxy Concrete Filled Open Metal Grate Decking**

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16. 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 149 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 population centers. To alleviate these problems, filling the open grate with an epoxy system with fine aggregate broadcasted on its surface for better skid resistance has been suggested. For new bridges, concrete filling (exodermic deck) has been used, taking the extra weight from the concrete into consideration during the design phase. 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 a necessity in existing decks to remain within the load-carrying capacity of the other components of the bridge. This report represents the results of a series of tests aimed at evaluating the long-term performance of the open grate deck filled with lightweight materials. Experimental results found that the performance of the open filled decks depends on the weather conditions. Based on this study, there is a significant loss of strength as the epoxy material is subjected to a series of temperature cycles. This conclusion is in line with what has been reported in the literature (Sprinkel (1993)). Furthermore the study shows that at elevated temperature there is bleeding of the epoxy. This is likely to lead to durability problems and potential safety hazard since the bleeding may prevent adequate adhesion of the skid resistant sand layer broadcasted on the filled deck. Thermal analysis results showed that the E-bond 526 lightweight materials had a glass transition temperature of about 52°C.(126°F). This glass transition temperature value is low compared to bridge surface temperatures common in hot zones like Florida. Thus, the low glass transition temperature of the epoxy is one of the major problem facing the epoxy filled bridge decks. Furthermore, it can be concluded that the dissimilar materials, which showed significant relative strain between the epoxy and the steel, will lead to durability concerns. This accelerated testing was limited, with temperatures raised to levels that may occur on the filled bridge deck at a limited frequency.

It is the recommendation of the authors that research into finding or developing epoxies with higher glass transition temperatures be conducted if systems of this type are used. Epoxies with low $T_{g,}$, as described in this report, should not be used as fill materials in high temperature zones such as Florida.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
AREA				
in^2	squareinches	645.2	square millimeters	mm^2
ft^2	squarefeet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3

g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb

Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
TEMPERATURE (exact degrees)				
^{o}C	Celsius	1.8C+32	Fahrenheit	^{o}F

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380

DISCLAMER

ACKNOWLEDGEMENTS

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The opinions expressed in this paper are solely of the authors and in no way implicate the sponsors of this work.

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EXECUTIVE SUMMARY

In the Florida State highway system there are 11,100 bridges (6,300 State bridges and 4,800 local bridges). According to the 2007 Bridge inventory, Florida has a total of 149 movable bridges with 91% of which are of the bascule type. The bridge decks of these movable bridges are constructed with steel open metal grate decking to reduce the weight of the superstructure and load carried by the substructure. When traffic traverses 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 population centers. To alleviate these problems, filling the open grate with an epoxy system with fine aggregate broadcasted on its surface for better skid resistance has been suggested.

For new bridges, concrete filling (exodermic deck) has been used, taking the extra weight from the concrete into consideration during the design phase. 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 a necessity in existing decks to remain within the load-carrying capacity of the other components of the bridge. This report represents the results of a series of tests aimed at evaluating the long-term performance of the open grate deck filled with lightweight materials. Experimental results found that the performance of the open filled decks depends on the weather conditions. Based on this study, there is a significant loss of strength as the epoxy material is subjected to a series of temperature cycles. This conclusion is in line with what has been reported in the literature (Sprinkel (1993)). Furthermore the study shows that at elevated temperature there is bleeding of the epoxy. This is likely to lead to durability problems and potential safety hazard since the bleeding may prevent adequate adhesion of the skid resistant sand layer broadcasted on the filled deck. Thermal analysis results showed that the E-bond 526 lightweight materials had a glass

transition temperature of about 52^{o}C.(126^{o}F). This glass transition temperature value is low compared to bridge surface temperatures common in hot zones like Florida. Thus, the low glass transition temperature of the epoxy is one of the major problems facing the epoxy filled bridge decks. Furthermore, it can be concluded that the dissimilar materials, which showed significant relative strain between the epoxy and the steel, will lead to durability concerns. This accelerated testing was limited, with temperatures raised to levels that may occur on the filled bridge deck at a limited frequency.

It is the recommendation of the authors that research into finding or developing epoxies with higher glass transition temperatures be conducted if systems of this type are to be used. Epoxies with low $T_{g,}$, as described in this report, should not be used as fill materials in high temperature zones such as Florida.

CHAPTER ONE

OVERVIEW

Introduction

In the Florida State highway system there are 11,100 bridges (6,300 State bridges and 4,800 local bridges). According to the Florida bridge inventory data for 2007, the State of Florida has a total of 149 movable bridges. Bascule bridges makeup 90.6% of these bridges, while swing and lift bridges constitute 6.7% and 2.7%, respectively. A detailed distribution of these movable bridges, as obtained from the Florida Department of Transportation (FDOT) maintenance office's Bridge Management System Bridge Inventory Report of 2007, is presented in Table 1-1.

Table 1.1: Distribution of Movable Bridges in Florida by District (FDOT 2007)

DISTRICT	TYPE			
	BASCULE	SWING	LIFT	TOTAL
01 - BARTOW	21	2	1	24
02 - LAKE CITY	7	1	1	9
03 - CHIPLEY	1	0	0	1
04 - FT. LAUDERDALE	50	2	0	52
05 - DELAND	11	3	1	15
06 - MIAMI	26	1	0	27
07 - TAMPA	19	1	1	21
TOTAL	135	10	4	149

The decks of these movable bridges are typically 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 population centers. To alleviate these problems, filling the open grate with an epoxy system with fine aggregate broadcasted on its surface for better skid resistance has been suggested. For new bridges, concrete filling (exodermic deck) has been used, taking the extra weight from the concrete into consideration during the design phase. For the older bridges, however, the extra concrete weight was not considered at the design phase. The use of epoxy materials, which are lighter than concrete, to fill existing decks is one way by which the system can remain within the load-carrying capacity of the other components of the bridge.

The use of two dissimilar materials in one structural system always raises issues of compatibility. The issues are more critical when a series of repeated stresses are anticipated such as from either environmental loading and/or applied loads. Over the years, the construction industry has 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, a 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 interfacial forces between the "epoxy prism" and the steel. The only load- 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.

Karbhari, et al. (2004) indicated the primary field conditions which may affect the durability of a polymer composite. These conditions are thermal effects, moisture and alkaline exposure, creep and relaxation, fatigue and ultraviolet light exposure. Moisture diffuses into all organic polymers, leading to changes in physical, mechanical and chemical characteristics. The primary effect of absorption is on the resin itself through hydrolysis and plasticization, which may cause both reversible and irreversible change in the 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.

In summary, the performance of the filled steel decks is defined as its ability to resist cracking, oxidation, chemical degradation, wear and tear under vehicular and environmental loading.

Objective of the Study

The main objective of this study was to address the performance of the filled steel deck systems, subjected to repetitive thermal loads (temperatures below and above normal ambient temperature). Vehicular loading was not considered in this study.

Methodology

In conducting the study, the following tasks were completed:

1. Literature review of current publications, which are related to the behavior and performance of the adhesive resin under different weather conditions.
2. The expected operating conditions that could have an impact on the durability of the epoxy filled open metal grade deck were identified.
3. The results from the literature search along with ASTM E632 procedures were used to determine the parameter test ranges.

Scope of the Project

In order to understand the implications of environmental exposure to the performance of the steel filled deck systems, the impact of each environmental exposure was addressed. This report covers the performance of the filled steel deck system under thermal load exposure. Traffic loading was not included in this study. In reality, traffic loading is expected to be on the deck at the same time as the thermal loading. In this study, this combination was not addressed.

CHAPTER TWO

LITERATURE REVIEW

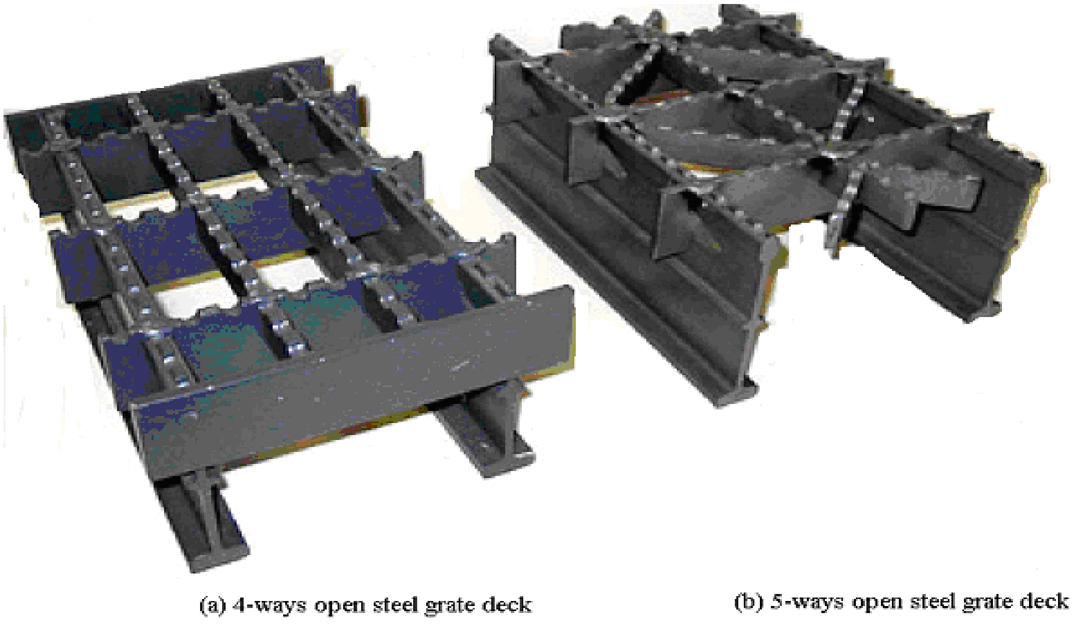
Open steel grid bridge decks have been in service for more than 50 years (Huang et al 2002). They were first used as a bridge decks in the 1920s and 1930s. Steel grid bridge deck systems are 80% open and do not collect rainwater, snow or ice. The deck systems are primarily used on movable (Bascule) bridges and older bridges that can no longer withstand heavy dead loads. 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 (Melhem and Klippstein, 1994,; 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 stronger than other grating systems. This grating type has bearing bars, which are connected by 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 bars and cross stiffening bars. These gratings are recommended for bridge decks and parking structure applications. There are two types of welded grating bridge decks used in bridge deck systems. These decks are 5-way and 4-way steel grate deck systems (see Figure 2-1). The 5-way 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-way 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 grating types.

Huang (2002) studied the behavior of the 4-way open steel grate deck systems. The study included laboratory tests of full-scale open grate deck systems and individual bars. Plots of load-deflection curves indicated decreased deck stiffness associated with the progressive yielding of the steel bars.

Presented in Figure 2-2 is a typical open grate bridge in an open position. As it can be seen from the figure most of the deck surface is open.


(a) 4-ways open steel grate deck

(b) 5-ways open steel grate deck

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


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

Cuschieri, et al. (1995) conducted a study on noise generated on a movable (bascule) bridge during traffic flow. This study found that the potential source of noise was the vibrations between the steel grids as tires traveled over the deck. To reduce the noise, the authors' suggestion was to have the open cells filled with epoxy materials and broadcast fine aggregates to provide skid resistance. To reduce the weight problem, the authors suggested having only the wheel paths filled so as to reduce additional weight on the substructure and the foundation. This solution presupposes that the vehicles would drive only on the filled paths.

Bridge decks require a surface texture to provide skid resistance. In open bridge deck systems, concrete can be properly textured and provide a long-lasting surface. However, for open grid decks filled with epoxy, the long-term performance depends on the type of resin, type of aggregate, 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 skid resistance under any weather condition. 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.

In recent years, organic polymers and composite materials have increased their importance in the construction industry. These composite materials provide structural solutions where traditional structural materials, such as steel or concrete, failed to provide proper performance and service life.

Epoxy resin technology was developed in the 1940s and became widely used in manufacturing operations starting in the early 1950s (Wood, 2003). Epoxy has good performance in corrosive environments. 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 two part systems. These are Component A (adhesive resin) and Component B curing agents (hardener). The mixing ratio depends on the application.

According to a study reported by Jamond and Malvar (2000), the characteristics that give epoxies advantage over other resins include:

1. Wide variety of properties because of availability of large number of starting materials, curing agents and modifiers.
2. Higher strength retention under sustained loading compared to the polyester and vinylester.
3. Low creep and low shrinkage properties.
4. Good chemical resistance.
5. Excellent adhesion properties to a wide variety of fillers, fibers and other substrates.

Presented in Table 2-1 are the characteristics of various resins.

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

Properties	Epoxy resin	Polyester Resin	Phenolics resin
Density g/cc (lbs/in^3)	1.1-1.35 (0.04 – 0.049)	1.2-1.4 (0.043 – 0.051)	1.35-1.75 (0.049 – 0.063)
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 $10^{-6}/^{o}C$	45-65	100-120	30-45

Sprinkel (1993) documented different factors that reduce the performance of the epoxy resin. These factors are salts, acid and alkaline conditions. In addition, exposure to petroleum products reduces 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.

Several studies have been conducted on the durability of composite materials bonded by adhesive resin. Sprinkel (1993) conducted a test on fabric materials bonded with adhesive resin to 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. Results of these studies 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. The polymer expands more than steel or concrete substrate. The differential expansion process develops thermal stresses between the interfacial regions.

Alfred, et al. (1981) studied the change in physical properties of adhesive resin under moisture and temperature exposure. Similarly, Chateauminos, et al. (1993) studied the behavior of adhesive with the objective of investigating the effect of moisture and temperature exposure. These two studies drew very similar conclusion, that is, the intake of moisture leads to a plasticization effect of the matrices, which allows filament buckling to occur easily thus leading to failure of the composite system.

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 the propagation of microcracks in the specimens. Bell et al (1995) performed tests on epoxy resin under water at temperatures of 50^oC and 100^oC. The results showed that the tensile strength decreased from 70MPa at 50^oC to 62MPa at a temperature of 100^oC. Also, the study noted that once the samples were dehydrated, the samples regained their original strength and sometimes became stronger than virgin samples.

There are three common modes of failure of the polymer resin overlays in bridge deck systems. The first mode of failure is delamination or debonding. Delamination is the process by which the polymer 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. 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 in long-term; this failure is affected by the type of aggregates and the strength of those aggregates.

According to Gama (1999) the type of aggregates used to improve skid resistance might affect the durability of the polymer overlay. The percentage of voids, abrasion resistance used and the coefficient of thermal expansion of the aggregates affect the durability of bridge deck systems. Softer, more friable, round or a smaller gradation of aggregates degrade the long-term durability and skid/friction resistance of polymer concrete bridge decks Soft aggregates wear rapidly, friable aggregates will rapidly break down and round aggregates provide poor friction resistance.

Negele and Funke (1996) 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, et al (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) were disrupted immediately and lost intermolecular bond strength. The effect of temperature and water on epoxy resin is an important environmental factor to be considered for 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).

Karbhari, et al. (1996) conducted an experiment to evaluate the behavior of resin systems. From these studies the glass transition temperatures were found to decrease when the epoxies were exposed to the environment.

Han and Drzal (2003) conducted a water absorption test on a hydrophilic polymer matrix of carboxyl functionalized glucose resin and epoxy resin. From these studies it was found that properly cured epoxies were less susceptible to moisture absorption. Chin, et al. (1997) exposed polymer materials to different environmental 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 epoxy specimens 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 11% of their stiffness but other specimens were not affected by dry heat exposure.

Kamran (1993) studied the effect of cyclic temperatures and humidity on the adhesive resin. From this study there was evidence of debonding of the epoxy layer. The author explained that delamination was due to the possibility of higher temperatures that cause differential thermal expansion.

Karbhari, et al. (1997) outlined the degradation mechanism for water molecules to the glass/epoxy composite as presented in Figure 2-3.

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 author suggested the use of Fick's laws to model moisture penetration. According to Fick's first law, the moisture penetration through the joint interface is given by Equation 2-1.

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

The change of the concentration gradient with respect to time is in accordance with Fick's second law as given by Equation 2-2.

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

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

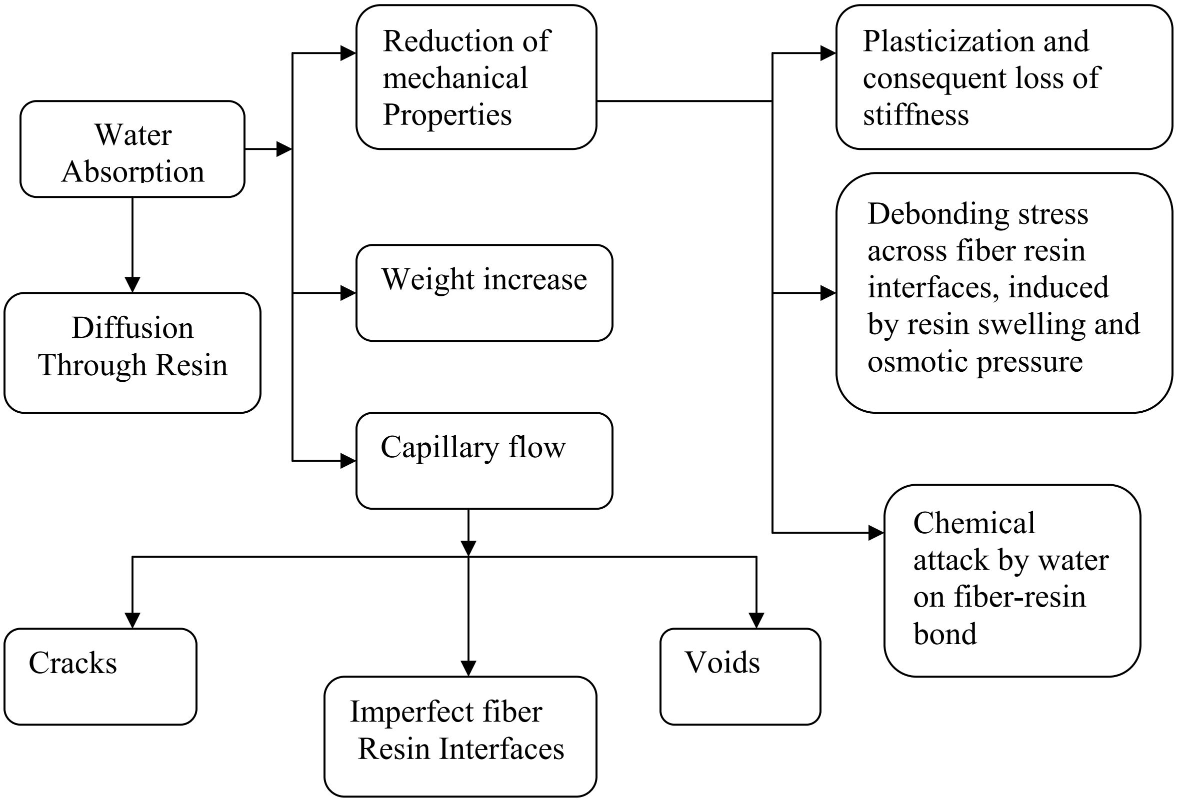


Figure 2-3: Effect of the Water Absorption on Epoxy Composite
(Karbhari, et al. 1997).

Bruijin (1996) and Gijsman, et al. (1996) exposed composite materials to cyclic temperature loading. These cyclic temperature loadings were formed to degrade the bond strength. The authors concluded that these cyclic temperature loadings break the intermolecular bond which reduces the bond strength.

Warren, et al. (1998) conducted laboratory experiments under three environmental conditions to perform durability analysis of carbon fiber reinforced plastic/polymer (CFRP) sheets adhered to plain concrete. After 1190 cycles of temperature loading, all specimens showed visible cracks at the epoxy bond interface.

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 the 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.

Brace (2004) performed a durability test on bonded carbon fiber-reinforced polymer plate and fabric after exposure to environmental conditions. The results showed that beams strengthened with CFRP plate and exposed to 100% humidity and exposed for a period of 415 days showed a 59% lower strength. A 33% strength-loss for the beams strengthened by CFRP plates was observed after 14 months of exposure.

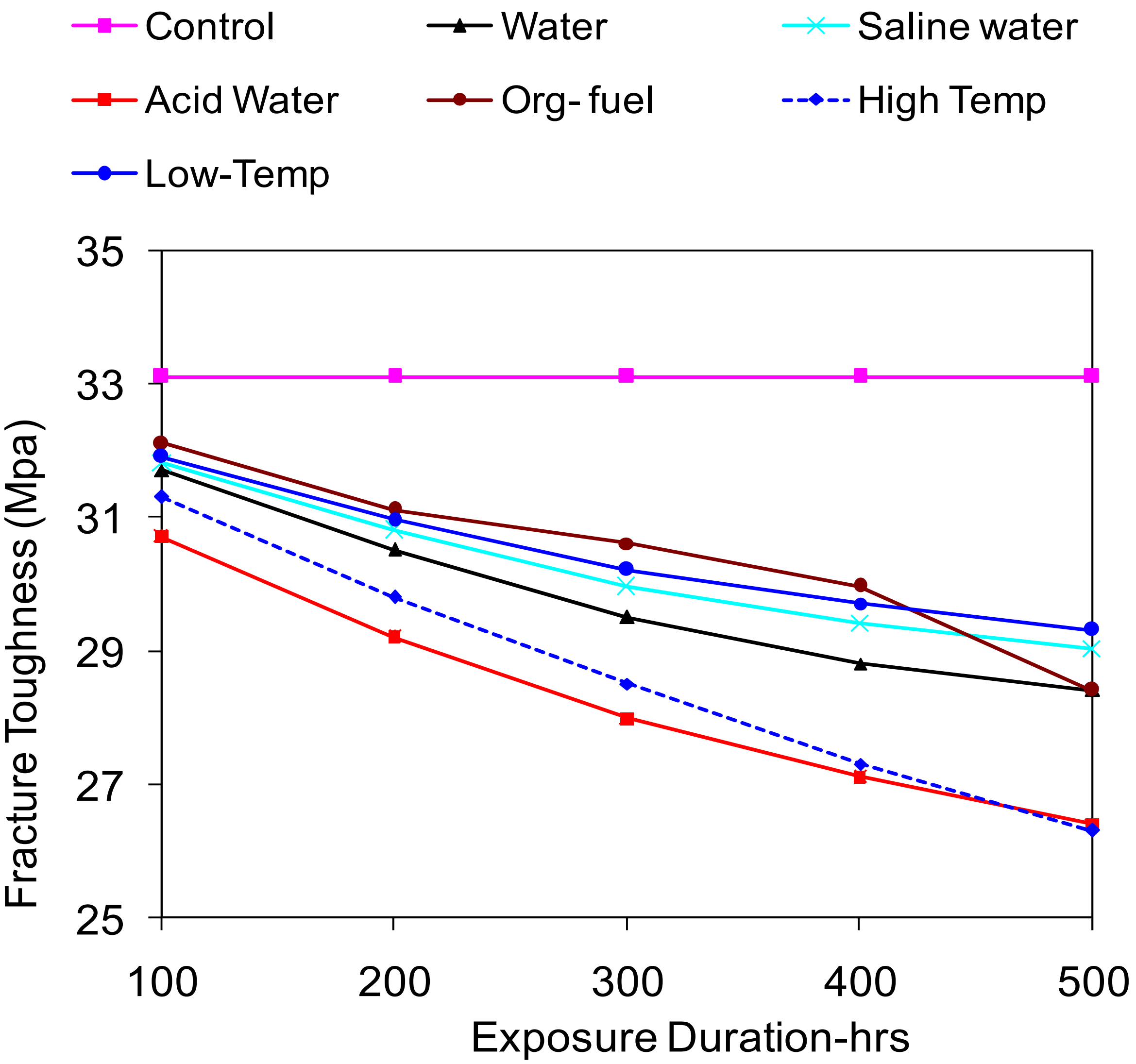


Figure 2-4: Effect of Environment Exposure on Fracture Toughness (Dash and Chatterjee 2004).

Dash and Chatterjee(2004) studied the effect of environmental change on fracture toughness of composite materials. The results of these studies are presented in Figures 2-4 and 2-5. The dissimilar coefficients of expansion were suggested as the cause of the variations presented in these results.

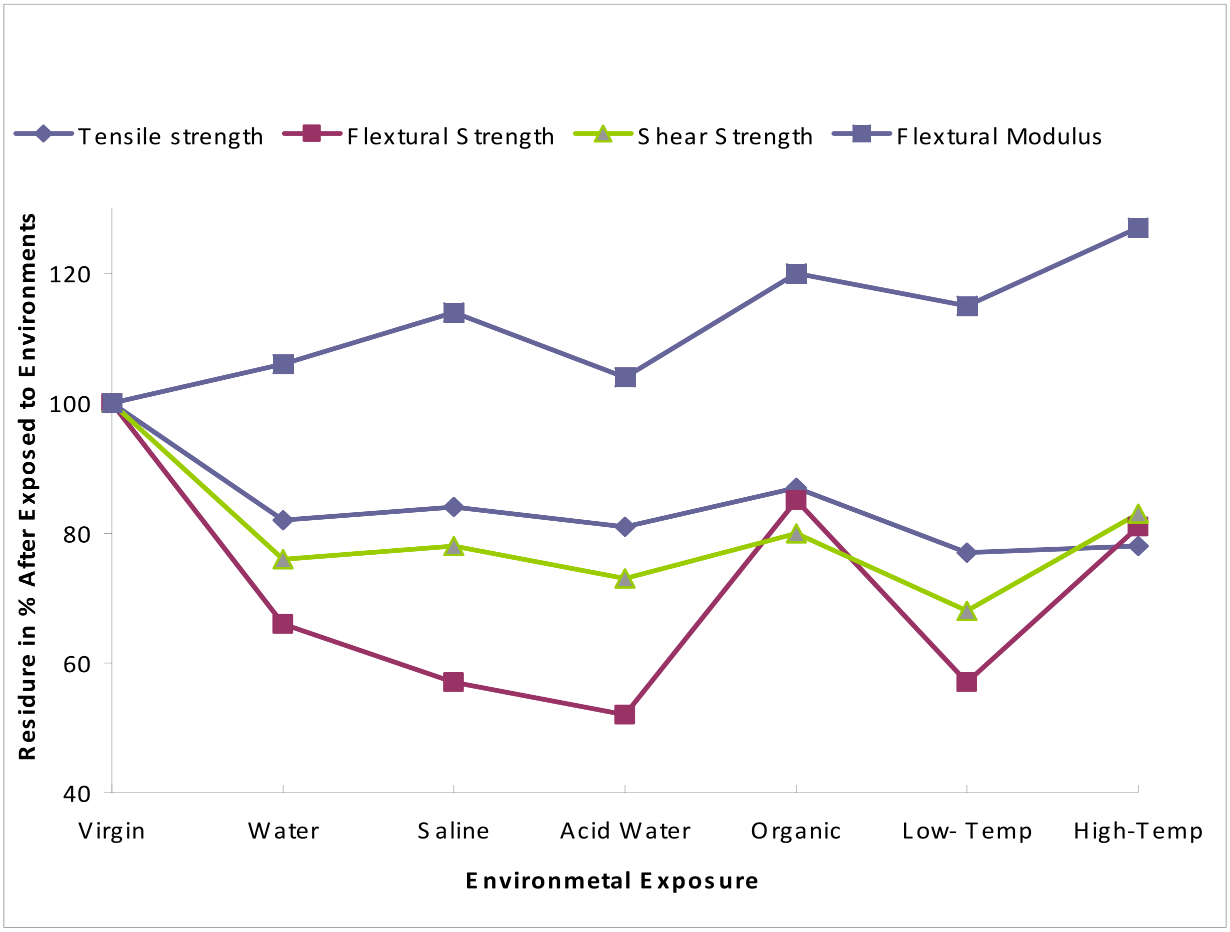


Figure 2-5: Effect of Environment Exposure on Mechanical Properties

(Dash and Chatterjee. 2004).

In summary, concerns of environmental impact on the epoxy performance are supported by the literature as documented above. This is the primary reason that the focus of this study was on the thermal loading on the filled grate system.

CHAPTER THREE

EXPERIMENT SETUP

Introduction

Accelerated testing is a procedure in which conditions are intensified to reduce the time required to obtain deteriorating effects that are similar to what is expected in normal operational conditions. The procedures are conducted in order to predict the failure mode and to quantify the life expectancy of a product, system, or component under normal operating conditions.

Accelerated testing can be divided into two types: qualitative accelerated testing and quantitative accelerated testing. In qualitative accelerated testing, the interest is mostly in identifying failures and failure modes. Qualitative tests do not quantify the life expectancy of the product under normal use conditions; however, they provide valuable information on the level of stress that can be tolerated. On the other hand, quantitative accelerated life testing is mostly interested in predicting the life of the product under normal use conditions. Qualitative tests are performed on small samples subjected to either a single severe level of stress, or to a number of stress levels, or to a time-varying stress. The stresses exceeding those encountered 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 conditions such as extreme temperatures, humidity, alkaline or acidic exposure, and pressure. These test conditions can be applied either separately or in various combinations thereof. The stresses exceeding those encountered 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 conditions such as extreme temperatures, humidity, alkaline or acidic exposure, and pressure. These test conditions can be applied either separately or in various combinations. If the specimens fail, appropriate actions will be taken to improve the product's design in order to change the cause(s) of failure as may be found desirable for the intended use of the product or system.

A good qualitative test quickly reveals those failure modes that will occur during the life of the product under normal conditions.

Accelerated Testing Terminology

Understanding of failure mechanisms is essential in conducting successful accelerated tests. Failure mechanisms of a product are categorized into overstress failure and wear out failure. Overstress failure occurs 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 referred to as wear out failure. Wear out mechanisms are expected during the life cycle of a product or the system. If products are subjected to weathering loads the wear out rate of failure may increase. In this study the wear out failure accelerated testing is applicable. Open grid deck samples, filled with an epoxy system and fine aggregate broadcasted on its surface for better skid resistance, were subjected to thermal effects in a climatic chamber to evaluate general performance of the systems under simulated weather exposure.

Bridge deck temperatures vary by times of the day and by seasons. For example, in Florida the ambient temperature varies from 10^{o}C (50^{o}F) to over 38^{o}C (100^{o}F) on a summer day. With these ambient temperature variations the bridge deck temperature variations will be much higher since the material has some heat storage capacity. In this study these temperature variations were determined by exposing some samples in the weather outside the laboratory.

Fabrication of the Simulation Chamber

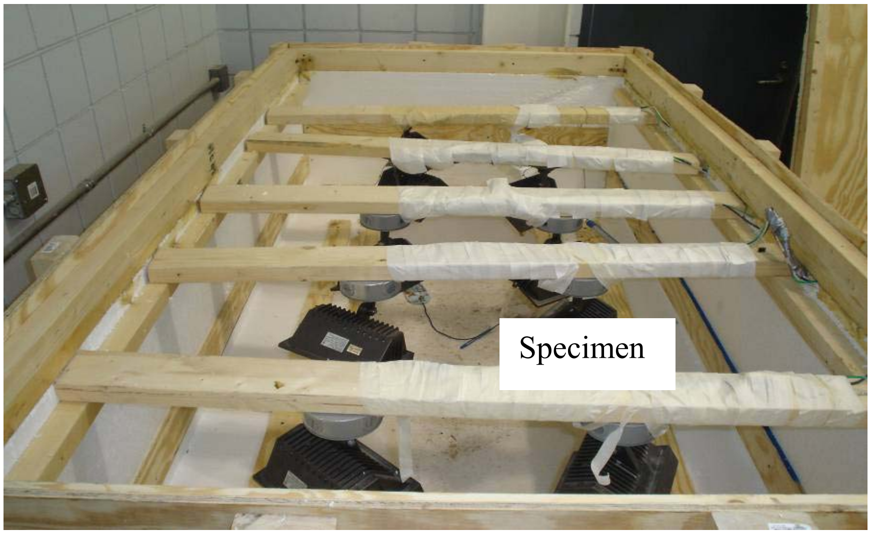
A climate chamber capable of producing extreme cold and hot conditions was fabricated. Cold and hot conditions were created to simulate temperature changes under field conditions similar to summer and winter seasons. The simulation chamber size was 2.4 m x 1.2 m x 1.2 m (8 ft x 4 ft x 4 ft). It was constructed using pressure-treated lumber (2 in x 4 in) framing with 1-inch plywood sheathing. 2-in thick fiberglass insulation was adhered on the inner sides of the chamber walls to provide better control of the temperatures inside the chamber. 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 environmental variations inside the chamber.

This support platform consist of a horizontal frame with an opening [2.1 m by 0.6 m (7 ft by 2 ft)]. It was constructed such that when the specimen is in place two distinct zones are created within the chamber. These two zones were thermally separated from each other by installing fiberglass at the separation level. The insulation was placed such that there was complete thermal isolation when the specimen is in position. These zones were created so as to allow the simulation of different temperatures between the bottom side of the deck, which is protected from direct sunlight exposure, and the top surface of deck, which is exposed to direct sunlight and thus likely to attain higher temperature rises. The bottom zone (cold zone) in the chamber was equipped with a cooling mechanism so as to allow the lowering of the temperature. The upper zone (hot zone) was equipped with heating elements, thus the ability to raise the temperature as desired. 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).

The cold zone was provided with four window air conditioner units of 844 kilojoules (8,000 BTU) each spaced 0.6 m (2 ft) apart. Between the zones there was a rectangular opening 2.1 m (7 ft) long by 0.6 m (2 ft) wide. Pressure release valves were provided so as to avoid explosion of the chamber when the cooling system was in operation.

A series of ten high-power lamps, each rated as 500W, was installed in the hot zone of the chamber. The lamps were mounted on a frame and connected in parallel. The frame was designed in such a way that it was possible to adjust the positions of the lamps in three directions (plan dimensions and height wise). A chamber cover fitted with rubber gaskets was provided so as to achieve a total climate-controlled environment after the placement of the specimen. Pictures of the constructed chamber are presented in Figure 3-1.

b) Climate Controlled Chamber Showing Cooling Units for Cool Zone



b) Climate Controlled Chamber Showing Heating Units for Hot Zone

Figure 3.1: The Constructed Chamber Showing the Cooling and Heating Systems.

Presented in Figure 3-2 is a sketch of a longitudinal cross section of the chamber.

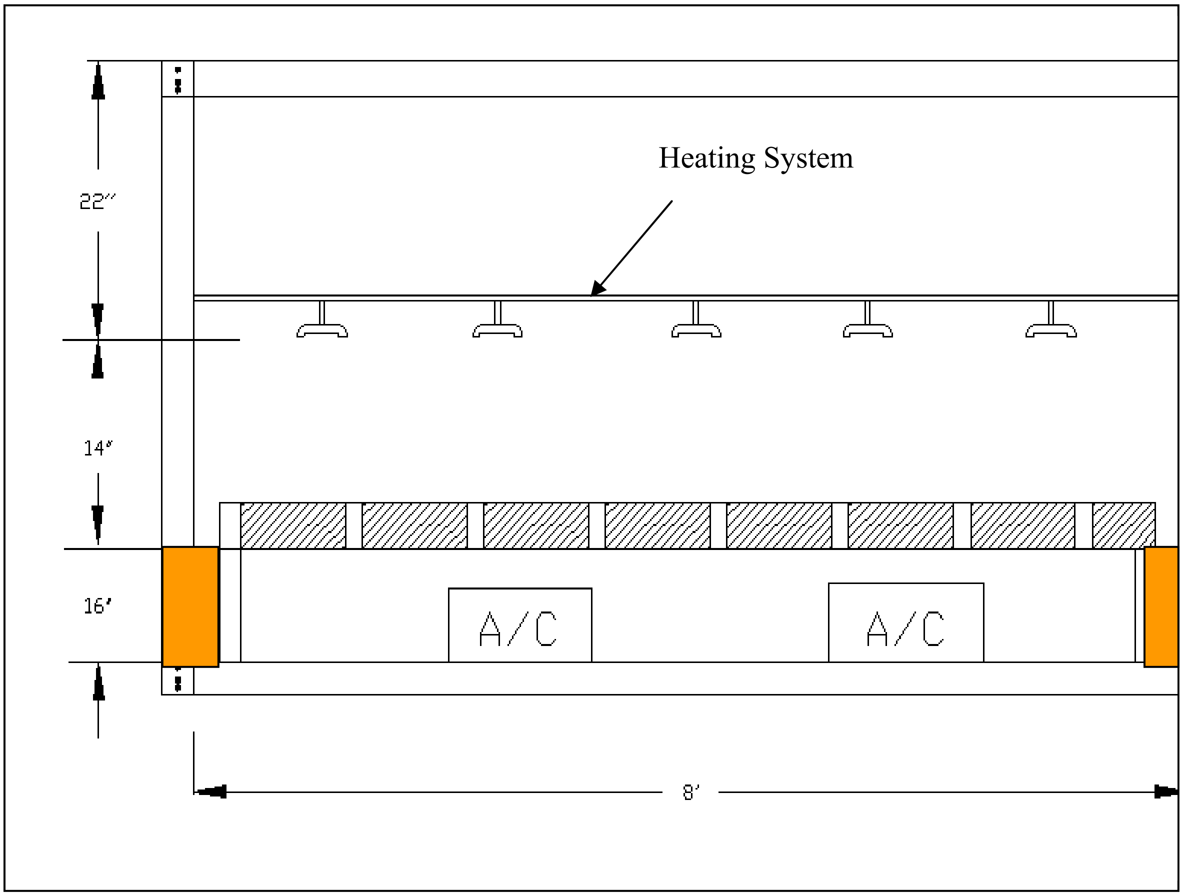


Figure 3-2: Longitudinal Section of Constructed Climate Chamber.

Material Properties:

The epoxy system used in this study consisted of the two part E-Bond 526 low modulus epoxy, which is produced by mixing a base material (Part A) and a hardener or curing agent (Part B). This E-bond lightweight system is multipurpose, suitable for a wide range of applications in both structural and nonstructural materials, and it has the following advantages:

1. Lightweight thus allowing applications where weight is of concern.
2. Easy when mixing with long pot life even at high ambient temperatures.
3. Moisture insensitive unlike other systems such as vinylester and polyester systems.
4. Provides excellent adhesion to most structural and nonstructural components.
5. Low creeping
6. Resistant to chemical attack from acids, bases, fuels, and others.

Important properties of the E-Bond 526 lightweight system (as specified by the manufacturer) are presented in Table 3-1.

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

Properties	Value	Test method	Conditions
Viscosity	0.09 lb/(in*s)	ASTM D2393	-
Bond strength	1500 psi	ASTM C881	14 days
Modulus of elasticity	695 psi	ASTM D695	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^oC (75^oF)
Absorption	0.15%	ASTMD570-81 (88)	7 days
Adhesive strength	310 psi	ACI 5038	7 days

The wearing surface consisted of EP #5 modified aggregates. These modified aggregates were broadcasted onto the surface after coating the surface with E-Bond Neat resin. The properties of the E-Bond Neat resin as supplied by the manufacturers are presented in Table 3-2.

Table 3-2: Properties of E-Bond 526 Neat Resin Lightweight System.

Properties	Value	Test method	Conditions
Viscosity	0.06 to 0.11 lb/(in*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%	ASTM D570-81 (88)	7 days

The properties of EP #5 modified aggregates as provided by the manufacturer are presented in Table 3-3.

Table 3-3: Aggregates Properties and Size Distribution (As per manufacturer specifications).

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

Sample Preparation

A total of six (6) samples of open welded steel grating deck (5-way decking systems) were cut. The gross dimensions of each sample were approximately 2.1 m by 0.6 m (7 ft by 2 ft). The sample bar sizes include: main bars of dimensions 100 mm x 6 mm (4 in x 0.24 in), cross bars of dimensions 50 mm x 6 mm (2 in x 0.24 in) and supplementary bars of dimensions 25 mm x 6 mm (1 in x 0.24 in). The main bars were spaced at 203 mm (8 in) on center (thus 4 main bars per specimen, refer to Figure 3.3). Transverse steel bars (cross bars) installed perpendicular to the main bars were spaced at 101 mm (4 in). Each individual cell formed by intersection of the main and the cross bars had an additional two tertiary bars connected from one corner to the other corner of the cell. The layout and geometry of the welded deck is shown in Figure 3-3.

The filling of the open grate system was done using the multilayer overlay method and performed in accordance to ASTM C1486 guidelines. The filling was implemented as follows:

1. All desired embedded sensors, thermal couples and strain gages, were attached to the open grate deck samples.
2. The open grate system sample was placed upside-down on a sheet of plastic paper (Figure 3.3). Spacers, 6mm (0.25-in) high, were placed between the plastic sheet and the metal deck. This was to allow the epoxy system to flow under the steel, thus providing an epoxy cover over the metal.
3. The E-Bond 526 were mixed in accordance to manufacturer's specifications.
4. The E-Bond 526 lightweight system was filled in each individual cell.
5. Application of E-Bond 526 Neat resin. This process was done after the LW material had 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.
6. 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 1/4 to 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.

Presented figure 3.4 are the E-Bond 526 lightweight (LW) material filled samples after complete curing.

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

Figure 3-4: Filled Open Grate Deck with E-Bond 526 LW Materials.

Test Parameters

In order to achieve the objectives of this study the following tests were conducted:

1. Flexural test.
2. Dynamic mechanical analysis (DMA) test.
3. Temperature cycling on filled decking.

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 the live load to be calculated as specified in Articles 3.6.1.2.2–3.6.1.2.4, 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.

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. DMA tests were conducted at room temperature after the samples were completely cured. The tests measured the glass transition temperature of the polymer materials.

In a DMA, 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 are 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 changes. Quantitative analysis routines are used to calculate the modulus (stiffness) and viscoelastic characteristic losses with respect to temperature and time. Changes in mechanical characteristics of a material are directly related to molecular level motions, which in turn lead to damping of DMA signal. Thus signal damping is affected by the material glass transition point. Composite samples exhibit dramatic changes in damping (loss) profiles and display characteristic peaks as they pass through the glass transition temperature range.

In this study, the test specimen was clamped between the movable and stationary fixtures of the DMA apparatus, and then enclosed in the thermal chamber. Torsional oscillation was then applied while slowly raising the temperature. The rate of temperature change used in this test was 5^{o}C per minute. Four different specimens of E-Bond lightweight system were prepared and tested per ASTM D5023.

Presented in Table 3-4 are the dimensions of the specimens prepared for the DMA tests.

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)

Cyclic Temperatures Tests

The epoxy filled deck samples were placed in the climate chamber one at a time and subjected to a regime of temperature variations. These tests were performed in accordance to ASTM D1151 guidelines (standard practice for effect of moisture and temperature on adhesive bonds). The temperature ranges used in these tests were very similar to temperature and moisture/water experienced by bridge decks during the summer and winter seasons.

In a separate testing, E-Bond 526 cylinders were subjected to cyclic temperatures. A total of 42 cylindrical specimens measuring 100 mm (4 in) in diameter and 200 mm (8 in) in height were prepared for this test. ASTM D695 guidelines were used in conducting this test. Out of the 42 cylinders, a total of six cylinders were used as control specimens and not subjected to thermal loading. The remaining 36 cylinders were subjected to cyclic temperature exposure, half of them being subjected to low temperatures, and the other half subjected to high cyclic temperatures. The specimens remained under room temperature for a period of six hours before being tested in compression at a rate of 0.05 in per min to determine compressive strength.

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 the temperature of the 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 type SRTC-TT-T-30-72 with operational temperature ranges of -200^{o}C to 400^{o}C were chosen to monitor stains and temperatures.

Two customized gages were installed in a grate cell to monitor the relative movement of the epoxy and the steel. These gages were made up of aluminum brackets with four strain gages attached. These strain gages were placed such that two of them were on the tension side and two in compression side of the aluminum bracket, thus allowing a full wheatstone bridge sensor. These custom made sensors were placed in the cell such that one was 6-mm (1/4-in) from the top surface of the fill and the other was 6-mm (1/4-in) from the bottom surface of the fill. Details of the sensor placement are presented in Figure 3.5. The logic behind the customized sensor was as follows: The aluminum bracket (L-shaped) had one of the legs glued to the steel grate cell wall prior to the filling. The strain gages were installed on the cantilevered leg. Upon filling the cell the cantilevered leg was surrounded by epoxy. As the epoxy expanded relative to the steel cell walls the cantilevered leg would flexes with it , thus causing strain in the gages. The magnitudes of these strains will depend on the shear source developed by the expansion of the epoxy relative to the steel.

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 LabView 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 the customized sensors and entered into the LabView software. The software calculated the calibration offset and calibration scale, which was used to calculate the actual sensor reading. Upon completion of the calibration the sensors and thermocouples were installed prior to filling the grate.

After filling and hardening of the epoxy, additional thermocouples were installed at the top and bottom of the deck to capture the temperature profile on the deck surfaces. Data from all these sensors was acquired electronically using a 6-channel logbook system 300 data acquisition system.

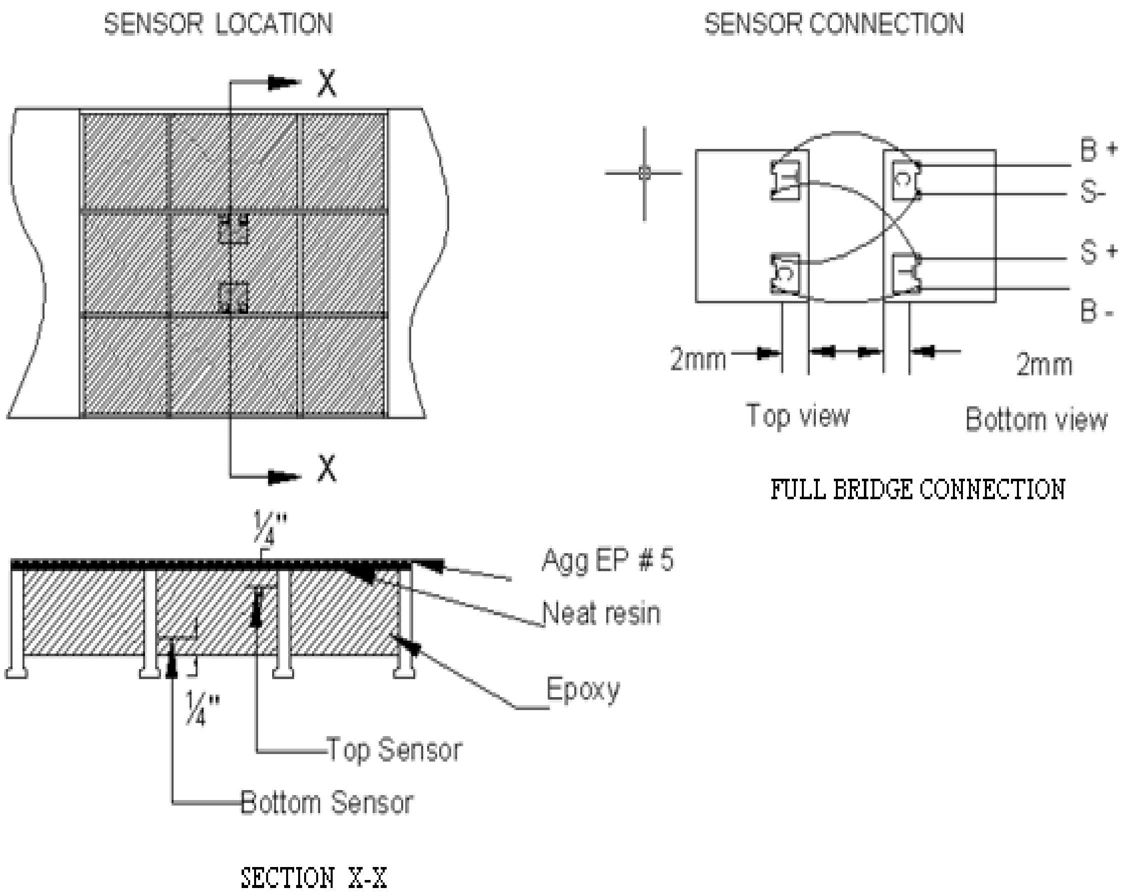


Figure 3-5: Sensors Connection and Installation to Filled Deck System.

CHAPTER FOUR

RESULTS AND DISCUSSION

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

Flexural Test

Presented in Table 4.1 are the results of the flexural loading conducted on three deck specimen before and after epoxy filling.

Table 4-1: Flexural Test Results for the Open and Filled Deck System.

	Specimen # 1		Specimen # 2		Specimen # 3	
Load KN (Kip)	Deflection mm (in)		Deflection mm (in)		Deflection mm (in)	
	Open deck	Filled deck	Open deck	Filled deck	Open deck	Filled deck
0.000 (0.000)	0.00 (0.00)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)
2.113 (0.475)	0.381 (0.015)	0.285 (0.011)	0.384 (0.015)	0.28 (0.011)	0.378 (0.015)	0.268 (0.011)
8.896 (2.000)	1.541 (0.061)	1.2 (0.047)	1.6 (0.063)	1.119 (0.044)	1.441 (0.057)	1.21 (0.048)
11.009 (2.475)	1.985 (0.078)	1.48 (058)	2.101 (0.083)	1.35 (0.053)	2.485 (0.098)	1.43 (0.056)
17.792 (4.000)	3.095 (0.122)	2.465 (0.097)	3.215 (0.127)	2.401 (0.095)	3.32 (0.131)	2.4 (0.094)
19.905 (4.475)	3.58 (0.141)	2.969 (0.117)	3.718 (0.146)	2.804 (0.110)	3.98 (0.157)	3.1 (0.122)
26.688 (6.000)	4.479 (0.176)	3.576 (0.141)	4.639 (0.183)	3.4 (0.134)	4.756 (0.187)	3.889 (0.153)

The average load-deflection relationship as obtained in the in the flexural tests of open grid deck and filled deck system are presented in Figure 4.1. The solid lines are the linear regression lines for the respective data. As shown, the R^2 values for these regression lines are very high (close to 1.0), thus indicating a very good correlation. The slopes of the regression lines are 31.6 kip/in and 41.2 kip/in for the open deck and filled deck respectively.

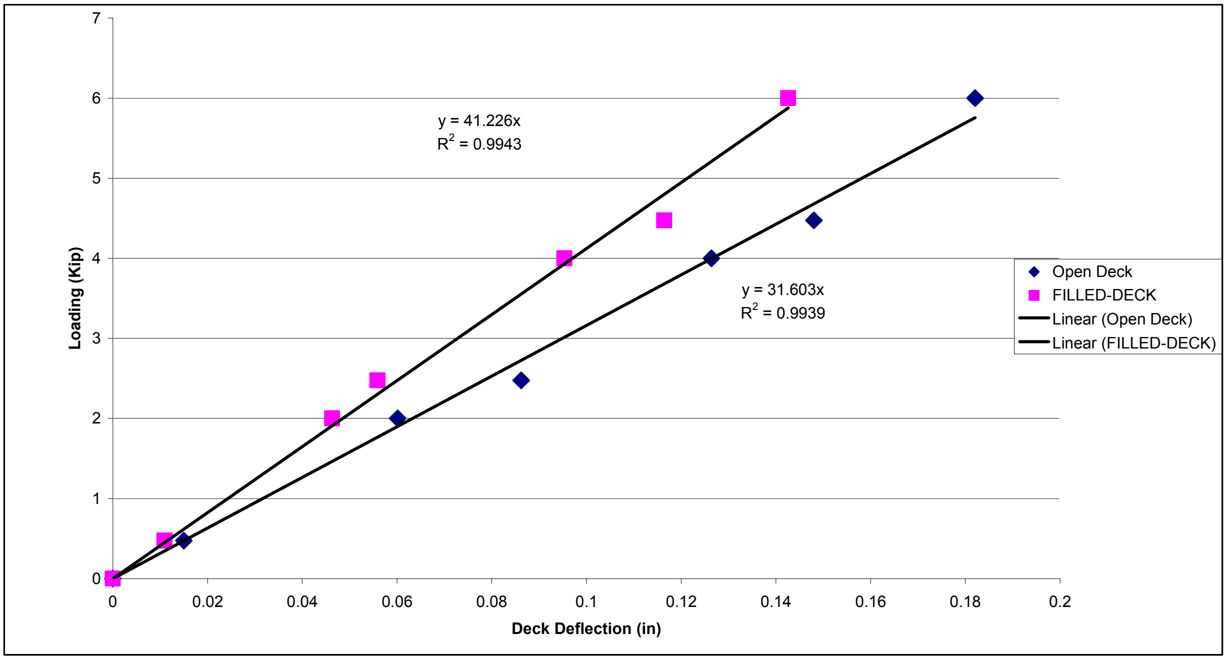


Figure 4-1: Specimen/ Flexural Test for the Open and Filled Deck System

These results shows that the epoxy fill increases the stiffness of the deck by 30%. This is a significant increase of the deck-system stiffness.

Dynamic Mechanical Analysis (DMA) Test

Presented in Table 4-2 are the results for the DMA test conducted in this study. The average glass-transition temperature of the tested samples was 51.67^{0}C (125^{o}F). At the same time there was a 78.5 % average loss in material modulus when the samples tested at room temperature assumed to be 25^{o}C

(77°F) were compared to samples tested at the sample glass transition temperature. As per the definition of glass transition point, the material starts to undergo plastic deformation, i.e, starts to flow, thus an explanation for the large loss of modulus.

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

Sample Number	Glass Transition Point T_g °C (°F)	Modulus MPa (KSI) at Tg Point	Tan Delta	Modulus MPa (KSI) At 25 °C (77°F)	Change in Modulus (%)
EBS-1	51.68 (125.0)	238.4 (34.58)	0.5366	1150 (166.8)	-79.3
EBS-2	51.21 (124.2)	233.8 (33.90)	0.5554	1350 (195.8)	-82.7
EBS-3	50.39 (122.7)	238.4 (34.58)	0.5554	830 (120.4)	-71.3
EBS-4	53.39 (128.1)	259.1 (37.58)	0.5221	1361 (197.4)	-81.0
Averages	51.67 (125.0)	242.4 (35.16)	0.542	1173 (170.1)	-78.5

Figure 4-2 indicates the glass transition temperature measured by DMA test. The glass transition temperature or point (T_g) is defined as the temperature at which the TanDelta curve reaches a peak point. As shown in the plot, the modulus of the system at such point is very low, i.e., the material is starting to flow. DMA test is an indicator of chemical changes in the epoxy. A temperature above the glass transition point (T_g) weakens the intermolecular bond of the epoxy. In turn, the weakening leads to changes in mechanical properties, especially the storage modulus and viscoelastic characteristics. These two properties contributed to the performance of the bond strength at the interfacial region and within the adhesive matrix. Based on the test results, glass transition temperature of the E-Bond system was found to be around 52°C (125°F).

The glass transition temperature is a reversible change in an amorphous polymer. At low temperatures the polymer becomes hard and stiff. At elevated temperature the polymer changes its properties and becomes elastic and start flowing (plastic behavior) for temperatures higher than the glass transition point (T_g).

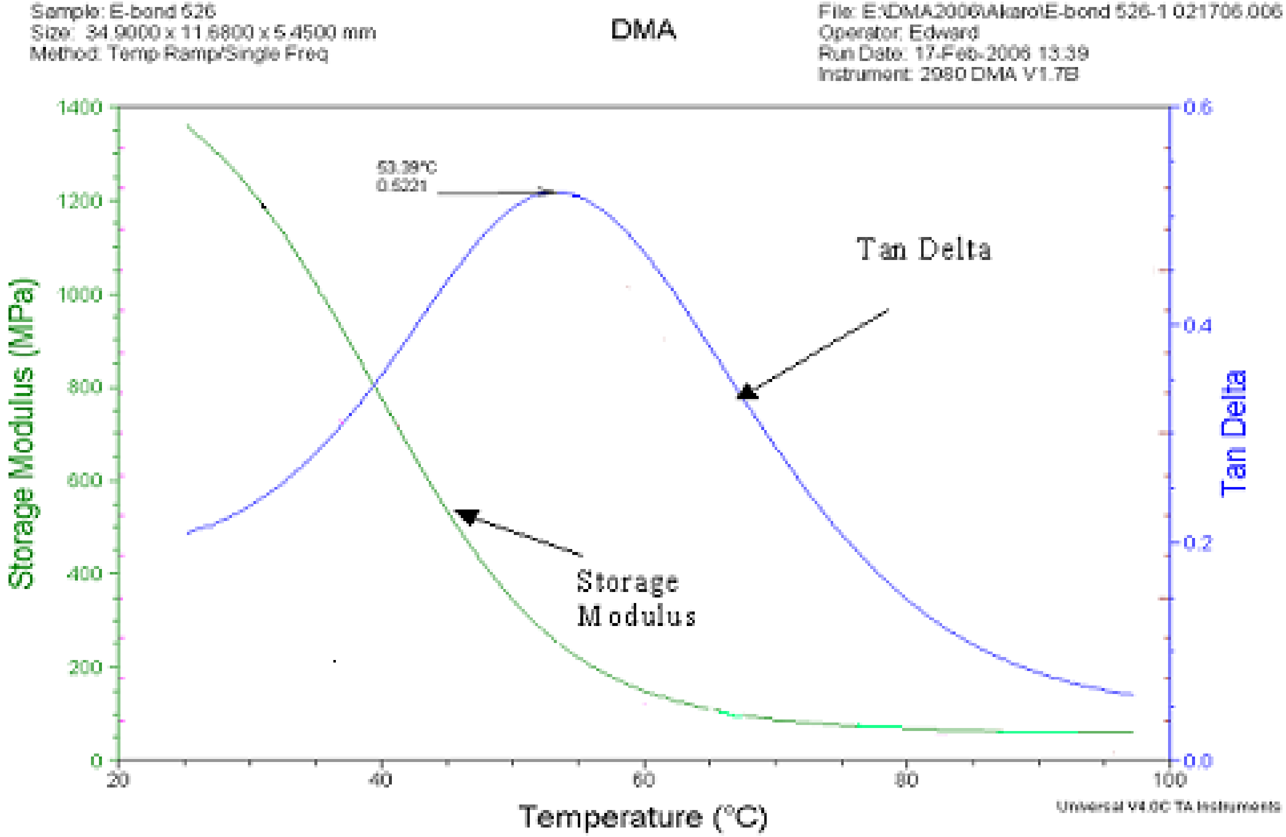


Figure 4-2: DMA Test for E-Bond 526 Lightweight Systems.

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 following seasonal changes. Presented in Figure 4-3 and figure 4-4 are the 24 hours surface temperatures recorded on the filled deck and ambient temperatures at 2.5 ft from the filled deck surfaces for four different days under a Tallahassee sun exposure. Whereas the highest ambient temperature was measured to be about 35^{o}C the measured deck surface temperature was measured to be over 60^{o}C. These results shows there is a significant difference between the ambient temperature and the deck surface temperatures.

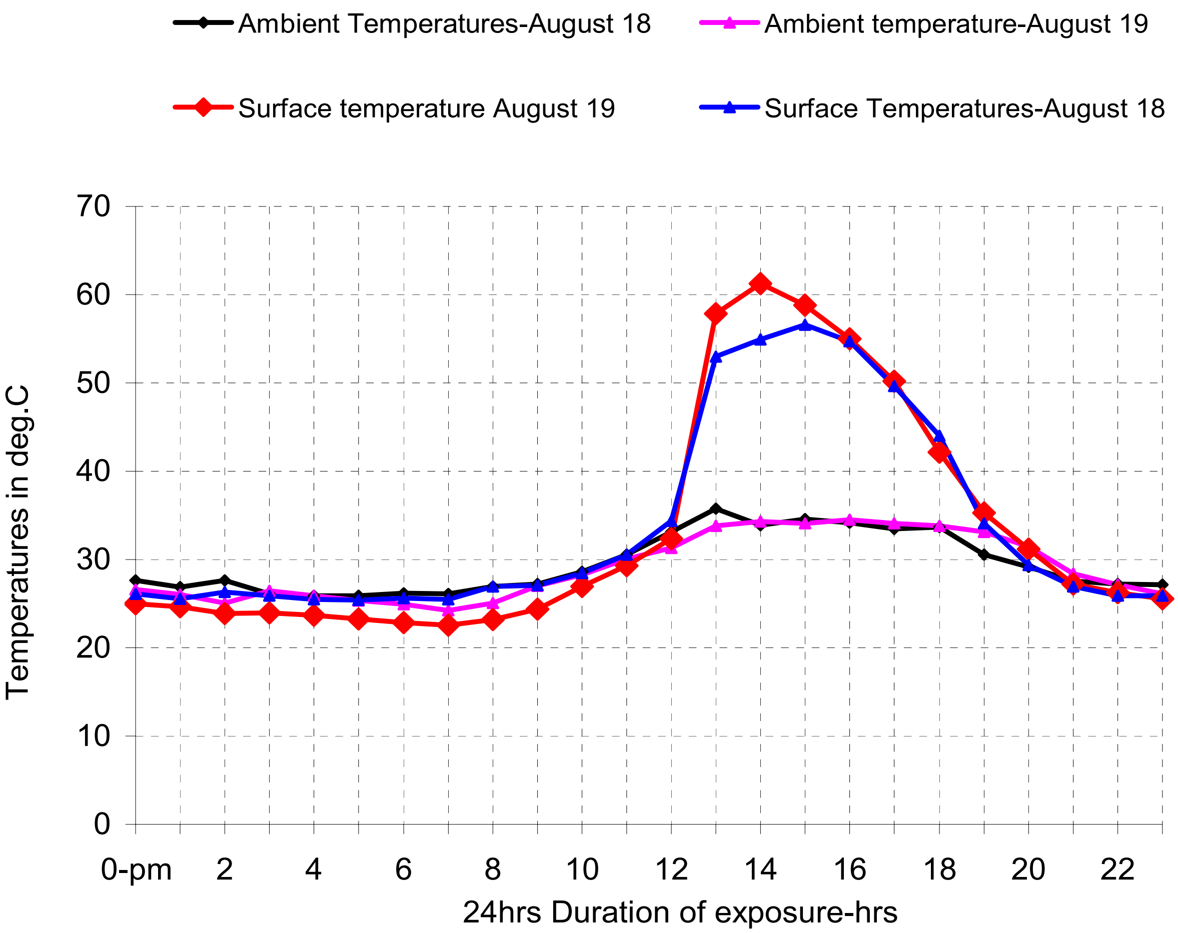


Figure 4-3: Temperatures on the Deck Surface and Ambient Temperatures at 2.5 ft from Deck Surface Measured August 18 and 19, 2006 .

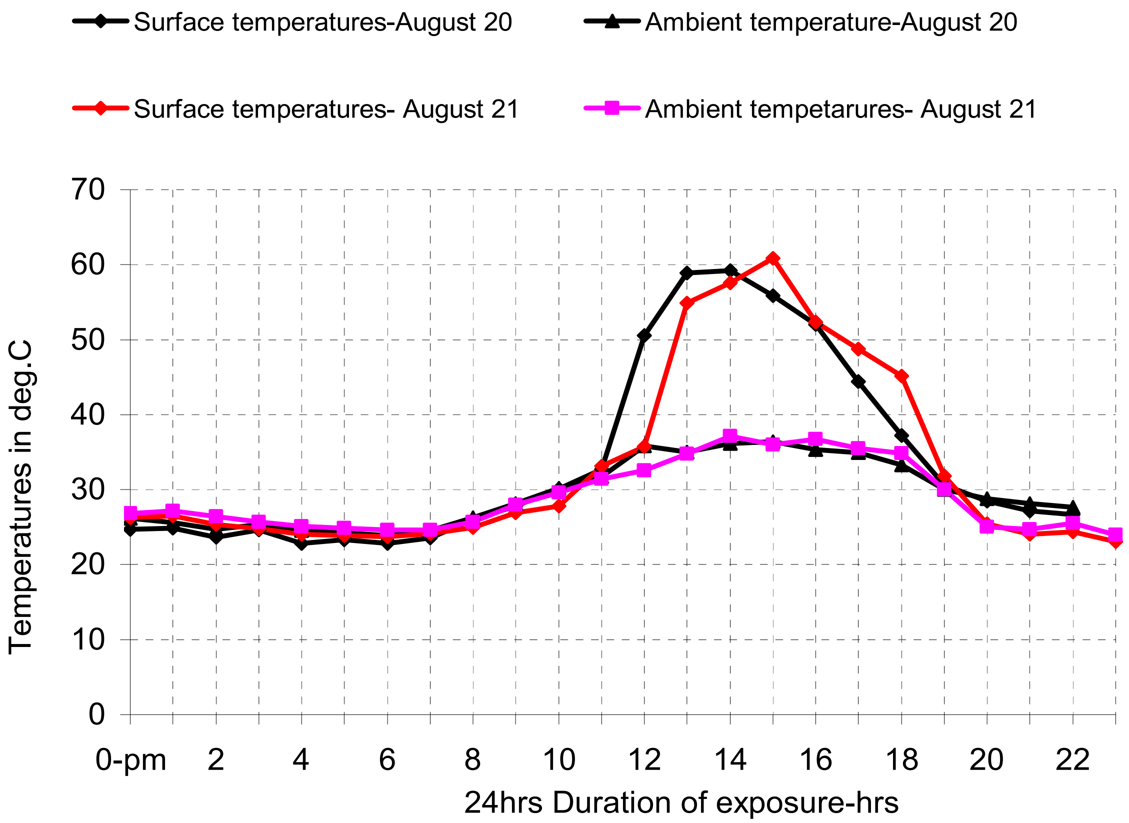


Figure 4-4: Temperatures on the Deck Surface and Ambient Temperatures at 2.5 ft from Deck Surface Measured August 20 and 21, 2006 .

Presented in Figure 4-5 are the ratio of the measured surface temperatures on the filled deck systems to the glass transition temperature of the E-Bond 526 epoxy. The aim of the temperatures recording process was to find how many hours in a day the deck systems will be subjected to temperatures above the epoxy glass transition temperature. The data shows that, the surface temperatures on the filled deck systems was higher than glass transition temperature of the E-Bond 526 for about four hours a day, from 1 am to 4pm for the period of August 18 to 22, 2006.

As was shown by the DMA tests mechanical properties of the epoxy, such as the modulus are reduced considerably when temperatures are close or above the glass transition point. This definitely has negative impact on the durability of the system. In the testing conducted in this study no loads were applied to simulate vehicular loading at the time the epoxy was in a “flowing” state. It is very plausible that if vehicular loading is applied at this state there will be some considerable deformation of the highly pliable epoxy.

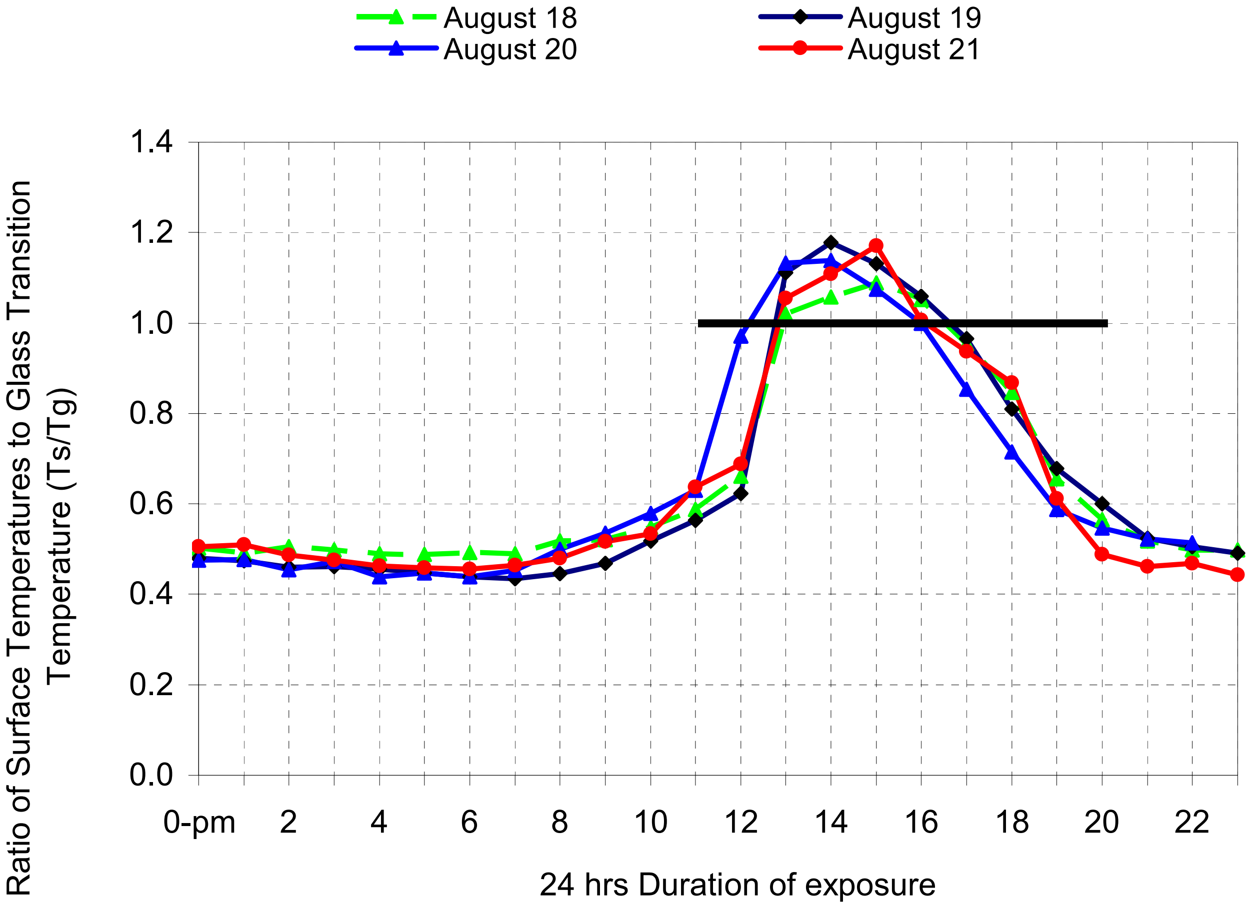


Figure 4-5: Ratio of Deck Surface Temperatures to Glass Transition Temperature.

Maximum ambient temperatures throughout the year are available as part of national meteorological data. As was observed from the measured sunlight exposure data in August 2006, when the maximum ambient temperatures were high the corresponding deck surface temperatures were also high. Thus, annual high ambient temperatures can be used to estimate the frequency at which the deck system will be exposed to temperatures above glass transition temperatures of the E-Bond system.

Presented in Figure 4.6 are the maximum ambient temperature measured 2.5 ft above the ground, in the open, at a meteorological station in Fort Lauderdale, Florida in 2004 and 2005

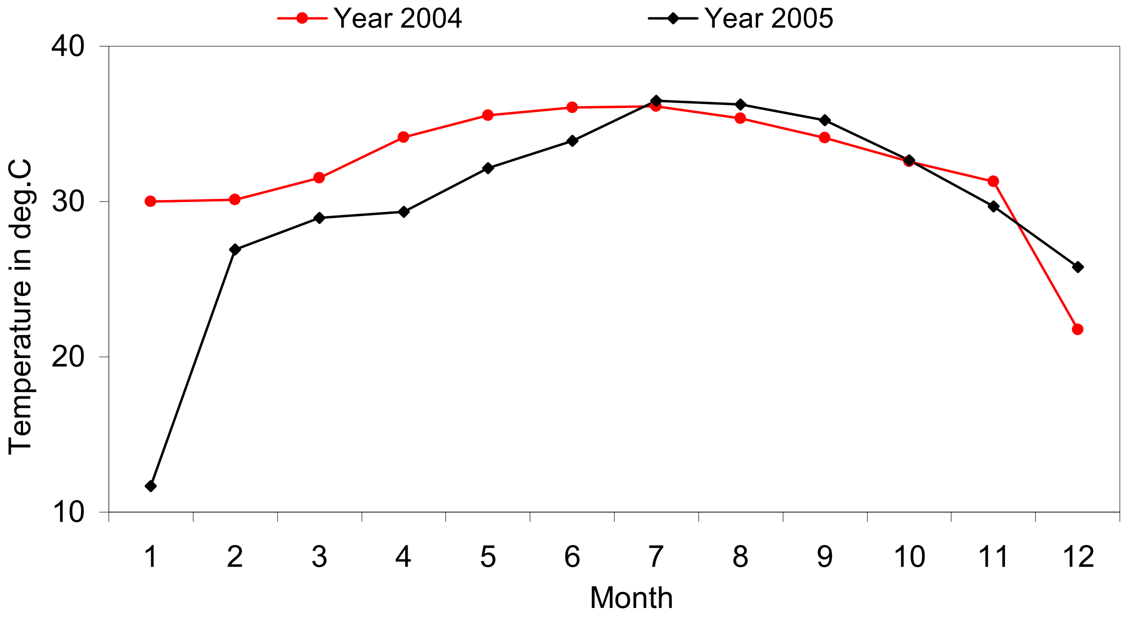


Figure 4-6: Ambient Temperatures 2.5 ft from Direct Sunlight-Fort-Lauderdale Station.

. Unless there are situations such as high convection winds it is most likely that days with high ambient temperatures will lead to corresponding high deck surface temperature. Thus it is reasonable to extend the four day observation we had in Tallahassee to the annual data presented in Figure 4.6 and conclude that decks in this location will be subjected to temperatures exceeding glass transition temperatures for over half of the year. This was the justification of the cyclic thermal loading adopted in this study.

As presented in chapter 3, sensors to measure temperature and strain caused by the expansion of the epoxy inside the cell were installed (Figure 3.5). One set of the sensors (a thermocouple and stain measurement clip) were installed 6-mm (1.4-in) from the top surface, hereby referred to as the "top sensor" and another set was installed 6-mm (1/4-in) from the bottom surface of the epoxy, hereby referred to as the "bottom sensors".

Presented in Figures 4-7 is the temperature and clip strain variation of the top sensor-set relative to specimen environmental exposure time.

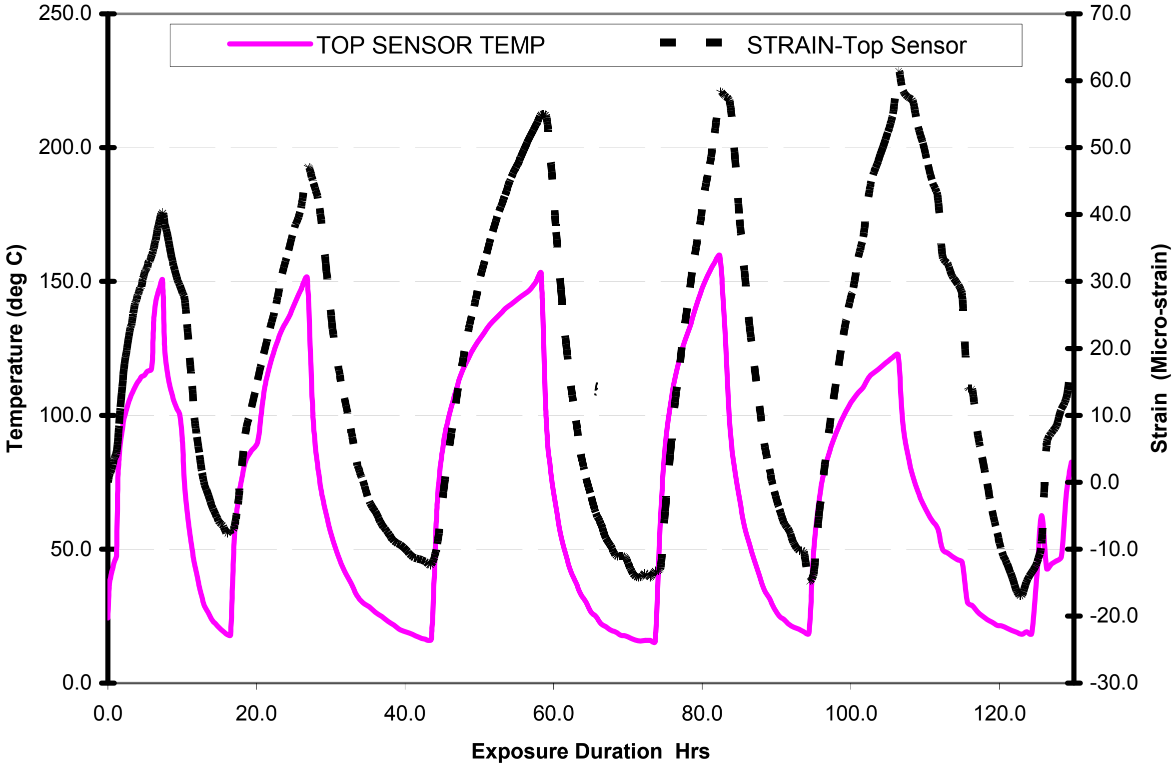


Figure 4-7: Temperature and Strain Variation at TOP Sensor

As it can be observed from Figure 4.7, the peaks of the clip strains have a very good correspondence to the peak temperatures at the same location. It may be recalled that the clip strains are caused by the expansion of the epoxy relative to the steel surface. This is due to the fact that the clip is of an L-shape with one leg fixed to the steel surface and one leg suspended (embedded) in the epoxy. The strain gages are installed on the suspended leg thus recording the strain as the leg is flexed by the expanding epoxy.

Presented in Figure 4.8 are the variations of the upper and lower picks of the top-clip strains. Also presented in Figure 4.8 are the trend lines for these peak strains.

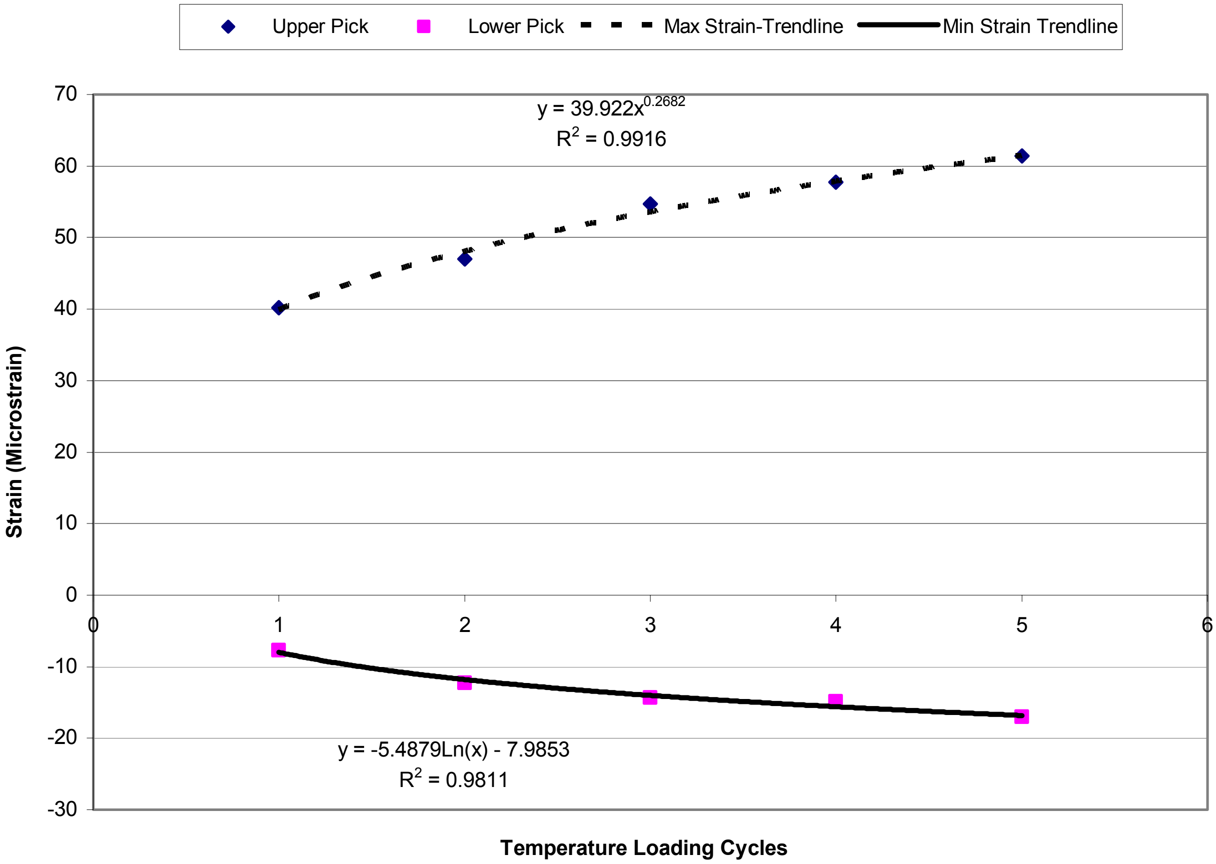


Figure 4-8: Strain Rate of Change at the BOTTOM Sensor

From this plot it is evident that as the number of cycles increases the peak strain increases.

Presented in Figures 4-9 is the temperature and clip strain variation of the bottom sensor-set relative to specimen environmental exposure time.

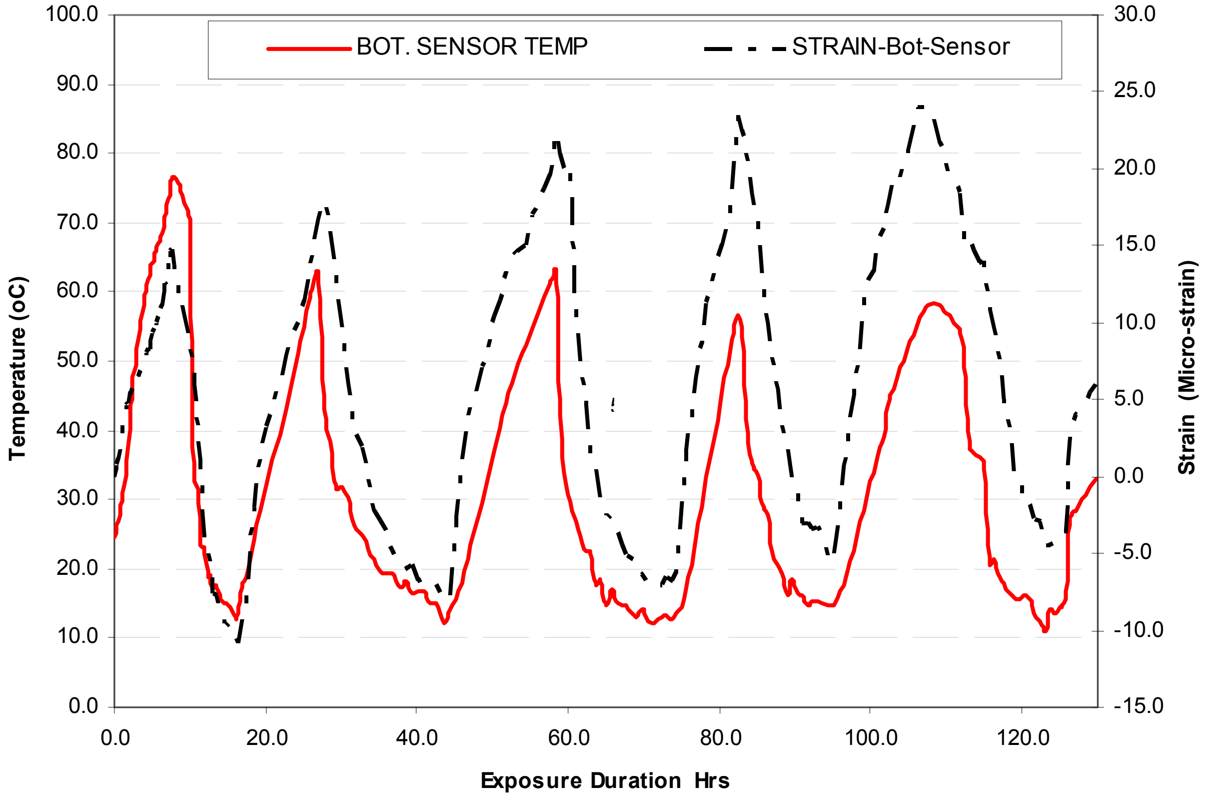


Figure 4-9: Temperature and Strain Variation at BOTTOM Sensor

Just as was observed for the top sensor-set (Figure 4.7) the plots of Figure 4.8 shows that the peaks of the clip strains have a very good correspondence to the peak temperatures at the same location. What is different between the readings of top sensor-set and those of the bottom sensor-set are the recorded magnitudes. The highest peak temperature for the top-sensor is 230^{o}C while the highest peak for the bottom sensor is 78^{o}C, while the peak strains are 60-με and 24-με respectively.

Presented in Figure 4.10 are the variations of the upper and lower peaks of the bottom-clip strains. Also presented in Figure 4.8 are the trend lines for these peak strains.

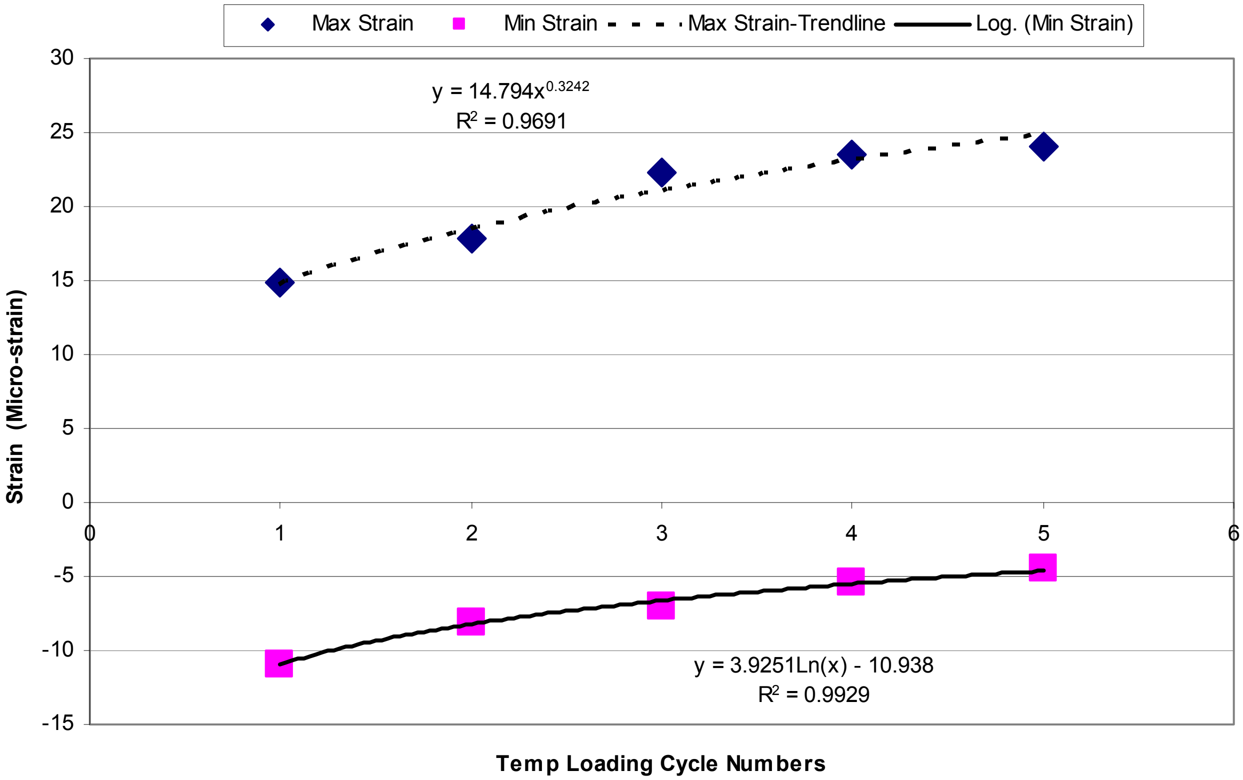


Figure 4-10: Strain Rate of Change at the BOTTOM Sensor

In addition to the temperature and strain variations presented above the following were observed

a) bleeding of the epoxy on the side exposed to elevated temperatures,

b) softening (as evidenced by the ability to penetrate a screw driver into the epoxy fill).

These observations can be explained by the fact that as the temperatures increase to values close to or greater than the glass transition point the epoxy looses its stiffness and starts to flow, thus leading to softness and bleeding.

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

Groups of epoxy cylinders were exposed to various levels of cyclic temperature exposure. Each group consisted of a total of three (3) cylinders of 100-mm (4-in) diameter and 200-mm (8-in) high. Some groups had the cyclic temperature exposure conducted with the peak temperature above the glass transition point of the epoxy. These “high temperature cycles” had temperatures varying from 17.4°C(63.3°F) to 75.6° C (168°F). Other cylinder groups were subjected to temperature cycles with the peak temperature below the glass transition point (Tg) of the epoxy. These “low temperature cycles” had temperatures varying from 6.6°C (43.9°F) to 44.3°C (112°F). A set of three cylinders were not subjected to any cyclic temperature variation. This was the control group. The sequencing of the tests is as presented in the first and last columns of Table 4-3. This translates to about 1-cycle a day plus a few hours. In each case one of the set was treated at “high temperature cycles” and the other at “low temperature cycles”.

Presented in Table 4.3 is the strength of the cylinders subjected to the treatment described above. As it can be observed from these results there is drastic loss of strength relative to the control specimen. The higher the number of cycles the higher the loss, though it tends to stabilize at about 50%. This implies that as the epoxy experiences some elevated temperatures it undergoes changes that end up affecting its strength.

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

Temperature Cycles	"Low-Temperature Cycle" Exposure			"High Temperature Cycles" Exposure			Total Duration Cyclic Temp. Testing (Days)
	Load (lb)	Strength* (psi)	Loss** (%)	Load (lb)	Strength* (psi)	Loss** (%)	
Control (0 cycles)	12990	1190	0	12990	1190	0	0
7	11115	845	-29	10471	834	-30	10
14	8392	668	-44	7935	632	-47	22
28	7373	587	-51	5710	510	-57	30
35	6892	549	-54	6490	517	-57	40

* Cylinder cross-sectional Area = 12.6 square inches

** Loss as compared to the control set, i.e. no cyclic temperature exposure.

These observations are in line with what has been reported in the literature. For example Sprinkel (1993) suggested that temperatures above the glass transition temperature affect the physical and mechanical properties of polymer materials. Another possible explanation found in the literature is that at elevated temperatures the free water molecules in the epoxy are allowed to escape leading to changes in phase morphology of the cured epoxy matrix , thus resulting in changes of its mechanical characteristics.

In materials science, failure is defined as the loss of load carrying capacity of a material unit. This definition *per se* introduces the fact that material failure can be examined at different scales, from microscopic, mesoscale to macroscopic. In structural problems, where the structural response should be determined beyond the initiation of nonlinear material behavior, material failure is of profound importance for the determination of the integrity of the structure. On the other hand, due to the lack of globally accepted fracture criteria, the determination of the structure's damage, due to material failure, is still under intensive research. Material failure can be distinguished in two broader categories depending on the scale in which the material is examined:

Microscopic failure

Microscopic material failure is defined in terms of crack propagation and initiation. Such methodologies are useful for gaining insight in the cracking of specimens and simple structures under well defined global load distributions. Microscopic failure considers the initiation and propagation of a crack. Failure criteria in this case are related to microscopic fracture. Some of the most popular failure models in this area are the micromechanical failure models, which combine the advantages of continuum mechanics and classical fracture mechanics . Such models are based on the concept that during plastic deformation, microvoids nucleate and grow until a local plastic neck or fracture of the intervoid matrix occurs, which causes the coalescence of neighbouring voids.

Macroscopic failure

Macroscopic material failure is defined in terms of load carrying capacity or energy storage capacity, equivalently. Macroscopic failure criteria can be classified in four categories:

Stress or strain failure
Energy type failure
Damage failure
Empirical failure.

Five general levels are considered, at which the meaning of deformation and failure is interpreted differently: the structural element scale, the macroscopic scale where macroscopic stress and strain are defined, the mesoscale which is represented by a typical void, the microscale and the atomic scale. The material behaviour at one level is considered as a collective of its behaviour at a sublevel. An efficient deformation and failure model should be consistent at every level.

Structural failure refers to loss of the load-carrying capacity of a component or member within a structure or of the structure itself. Structural failure is initiated when the material is stressed to its strength limit, thus causing fracture or excessive deformations. The ultimate failure strength of the material, component or system is its maximum load-bearing capacity. When this limit is reached, damage to the material has been done, and its load-bearing capacity is reduced permanently, significantly and quickly. In a well-designed system, a localized failure should not cause immediate or even progressive collapse of the entire structure. Ultimate failure strength is one of the limit states that must be accounted for in structural engineering and structural design.

According to the above defined failure criteria the epoxy filled deck shows a number of characteristics that may be construed as failure. These are:

a) Bleeding of the epoxy as the temperatures were elevated
b) Softening of the epoxy, to the extent that a sharp object such as a screwdriver could easily penetrate the material.
c) Loss of carrying capacity, as determined by the cylinder test, as the temperatures were elevated.

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 broadcast aggregates. 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 temperatures on compressive strength, the performance of the filled deck systems under cyclic temperatures, and the effect of combined temperature on the filled deck systems.

Conclusions

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

1. There is a significant loss of strength as the epoxy material is subjected to a series of temperature cycles. This conclusion is in line with what has been reported in the literature (Sprinkel (1993)).
2. At elevated temperature there is bleeding of the epoxy. This is likely to lead to durability problems and potential safety hazard since the bleeding may prevent adequate adhesion of the skid resistance sand layer broadcasted on the filled deck.
3. At elevated temperatures there was softening of the epoxy, to the extent that a sharp object such as a screwdriver could easily penetrate the material

4. Thermal analysis results showed that the E-bond 526 lightweight materials had a glass transition temperature of about 52^{o}C.(126^{o}F) 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 62^{o}C (144^{o}F) and could become higher during the summer season; this also affects the performance of the deck system..
5. The strains measured suggest that there is a significant relative strain between the steel plates and the filled epoxy. This relative strain is likely to cause adhesion problems as the system undergoes thermal cyclic loading.
6. The low glass transition temperature of the epoxy is a significant problem. Under normal applications the bridge running surface temperature exceeds the glass transition temperature of the epoxy.

In summary it can be concluded that the dissimilar materials will lead to durability concerns. This accelerated testing was limited, with temperatures raised to levels that may occur on the epoxy filled bridge deck at a limited frequency.

Recommendations

There is a need to find and/or develop epoxies with higher glass transition temperatures, such that they will be able to withstand the high bridge surface temperatures without impaired mechanical characteristics. Epoxies with these low T_g should not be used as fill materials in high temperature zones such as Florida.

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