

## CHAPTER 5: DISCUSSION

### 5.1 Outdoor Temperature Measurements

The temperature measurements on the outdoor specimen appear to follow a similar trend on both hot and cold days. Initially the ambient temperature is warmer than the top surface, interface and aluminum surface of the beam. As the beam is exposed to direct sunlight, the top surface temperature begins to increase and soon passes the ambient temperature. As the top surface warms, the bottom aluminum surface also begins to warm. As the aluminum and top surface continue to warm, the interface temperature increases. By the warmest part of the day, the interface has the highest temperature. However, the difference in the temperatures between the top surface, the interface, and the aluminum is not significant. At peak temperature they were all within 2 °C [3 °F] of each other. It may be possible that light transmitted through the epoxy caused the higher temperature at the interface. The top surface, interface, and aluminum surface all obtain higher temperatures than the ambient temperature.

As cooling begins, the ambient temperature decreases most rapidly. As the ambient temperature decreases, the top surface begins to cool. The aluminum surface then begins to cool and the interface is the last part to cool in the system. Eventually the aluminum surface and the interface cool to a lower temperature than the top surface.

Overall it appears that the aluminum has the largest effect on the interface temperature. The aluminum achieves both higher and lower temperature extremes than the overlay surface, and the interface temperature is consistently similar to the aluminum temperature.

## 5.2 Control Specimens

As stated in section 4.2, the control specimens were tested in three groups. Control group 3 yielded the least amount of variability; however, it included only 5 data points which is relatively small. A statistical analysis was performed on the three control groups to determine if they could be combined to form one control group. Side one of the specimens from control groups 1 and 2 were tested in the same manner as those in control group 3. That is, they were tested immediately after removing the specimen from the dry ice bath. The problem is that side 2 of the specimens from control groups 1 and 2 were tested without returning them to the dry ice bath.

The first step of the analysis was to separate the results from sides 1 and 2 of the first two control groups and a statistical comparison between sides 1 and 2 of the first two control groups was performed. Comparisons were also conducted between the side 1 results of control groups 1 and 2 and control group 3. The results are presented in Table 9.

**Table 9: Descriptive Statistics for Individual Sides of Control Groups**

<b>Test Group</b>	<b>Number of Tests</b>	<b>Mean [J/m<sup>2</sup>]</b>	<b>Standard Deviation</b>	<b>Coefficient of Variation [%]</b>
<b>Ctrl 1-1</b>	7	139	18.9	13.5
<b>Ctrl 1-2</b>	5	130	13.1	10.0
<b>Ctrl 2-1</b>	8	125	18.6	14.8
<b>Ctrl 2-2</b>	8	124	11.2	9.0
<b>Ctrl 3</b>	5	104	7.7	7.5

Before the comparison tests were conducted, the test groups were tested for normality to see if the data were normally distributed. Three of the five test groups were not normally distributed. This eliminated comparing the test groups using a two-sample T test, which is a test for normally distributed data. A two-sample Wilcoxon rank sum test was used, this is a nonparametric test that does not require that the data be normally distributed<sup>15</sup>. The hypothesis that one test group was equal to another test group was tested against the hypothesis that the two test groups were not equal using a 95% confidence level. P-values were obtained for each comparison. If the p-value was less than 0.05, there was sufficient evidence to suggest that the two groups were statistically equal. Table 10 presents the results of the comparison tests.

**Table 10: Statistical Comparison Results**

<b>Comparison</b>	<b>p-value</b>
Ctrl 1-1 vs Ctrl 1-2	0.1939
Ctrl 1-1 vs Ctrl 2-1	0.1649
Ctrl 1-1 vs Ctrl 2-2	0.0933
Ctrl 1-2 vs Ctrl 2-1	0.7694
Ctrl 1-2 vs Ctrl 2-2	0.5101
Ctrl 2-1 vs Ctrl 2-2	0.8336
Ctrl 1-1 vs Ctrl 3	0.0485
Ctrl 2-1 vs Ctrl 3	0.0638

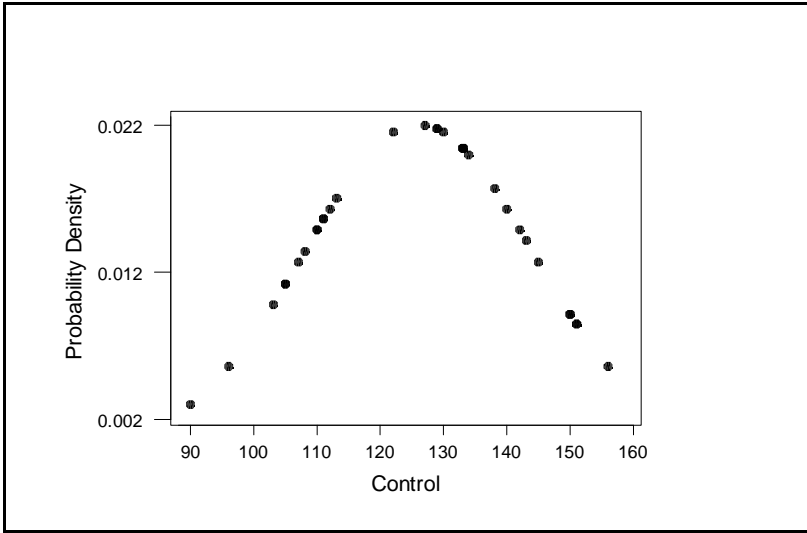
As presented in Table 10, the only comparison that demonstrates that there was a significant difference between groups was between Ctrl 1-1 and Ctrl 3. The p-value was 0.0485 which is slightly less than 0.05. All of the other comparisons indicated that there were no

significant differences between the test group results. Based on these results, the individual control groups may be combined to form one sample group. Table 11 presents the descriptive statistics of the combined control group.

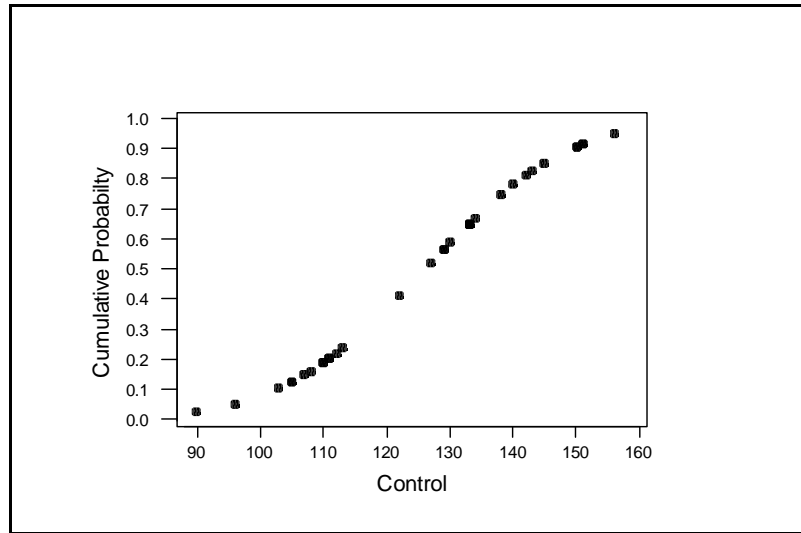
**Table 11: Descriptive Statistics for Combined Control Group**

	<b>Number of Tests</b>	<b>Mean [J/m<sup>2</sup>]</b>	<b>Standard Deviation</b>	<b>Coefficient of Variation [%]</b>
<b>Control</b>	33	126	18.1	14.4

A normality test was conducted on the combined specimen data and yielded a p-value of 0.079, this suggests that the data were normally distributed. Figures 13 and 14 present the Probability Density and Cumulative Probability of the control data. Both figures demonstrate that the data possesses normal distribution characteristics.



**Figure 13: Probability Density of Control Group**



**Figure 14:** Cumulative Probability of Control Group

### 5.3 Humidity Chamber Specimens

The specimens conditioned at 30 °C [86 °F] and 45 °C [113 °F] performed better than the specimens conditioned at 60 °C [140 °F]. The polymer concrete overlay on the specimens conditioned at 60 °C [140 °F] was much darker than the specimens conditioned at the lower temperatures. It appears that overlay was weakened as specimens routinely failed in the overlay instead of at the interface between the overlay and the aluminum substrate. The specimens that did fail at the interface between the original aluminum substrate and the polymer concrete overlay had a much lower  $G_{cr}$  value than those of the specimens conditioned at 30 °C [86 °F] and 45 °C [113 °F].

A statistical analysis was conducted on the 30 °C [86 °F] and 45 °C [113 °F] test results to determine if the average  $G_{cr}$  values were significantly different from those of the control specimens. Normality tests were conducted all of the test groups and all were found to be normally distributed. Therefore, two sample T tests were conducted on the test groups. Table 12 presents the results of the T tests.

**Table 12: Two Sample T Test Results for Humidity Chamber Test Groups**

Comparison	p-value
Control vs 30 °C [86 °F] 6 months	0.0039
Control vs 30 °C [86 °F] 9 months	0
Control vs 30 °C [86 °F] 12 months	0
Control vs 45 °C [113 °F] 6 months	0.0002
Control vs 45 °C [113 °F] 9 months	0.0001
Control vs 45 °C [113 °F] 12 months	0.0001
30 °C 6 months vs 30 °C 9 months	0
30 °C 9 months vs 30 °C 12 months	0.11
45 °C 6 months vs 45 °C 9 months	0.0016
45 °C 9 months vs 45 °C 12 months	0.31

For the specimens conditioned at 30 °C [86 °F] the average  $G_{cr}$  decreased from 115 J/m<sup>2</sup> after 6 months of conditioning to 76 J/m<sup>2</sup> after 9 months of conditioning. The p-value for the control versus the 30 °C [86 °F] 6 months conditioning was 0.0039 which is less than 0.05. This suggest that statistically there are significant differences between the average  $G_{cr}$  values for the control and 30 °C [86 °F] test groups. When comparing the 30 °C [86 °F] test groups of 6 and 9 months to each other, the p-value was 0.0000, this suggests that there are significant differences

between the two test groups. The average  $G_{cr}$  decreased slightly from  $76 \text{ J/m}^2$  for specimens conditioned for 9 months to  $68 \text{ J/m}^2$  for specimens conditioned for 12 months. The  $45 \text{ }^\circ\text{C}$  [ $113 \text{ }^\circ\text{F}$ ] test groups had similar T test results. The average  $G_{cr}$  values were significantly different from the control specimens, as well as, significant differences between the specimens tested after 6 and 9 months of conditioning. However, there wasn't a significant difference between the 9 and 12 month test results.

The results demonstrate that 6 months of conditioning specimens at  $30 \text{ }^\circ\text{C}$  [ $86 \text{ }^\circ\text{F}$ ] and  $45 \text{ }^\circ\text{C}$  [ $113 \text{ }^\circ\text{F}$ ] in humidity chambers has a significant effect on the interfacial strength between the polymer concrete overlay and the aluminum substrate. The results also show that continued conditioning of the specimens at the above temperatures further decreases the interfacial strength.

#### **5.4 Freezing and Thawing Specimens**

Freezing and Thawing specimens were tested after 70, 182 and 300 cycles. The critical strain energy release rate values for the specimens tested after 70 cycles were somewhat more variable than those tested after 182 and 300 cycles. Two sample T tests were conducted comparing the F&T test groups to the control test group, as well as to each other. Table 13 presents these results.

**Table 13: Two Sample T Test Results for Freezing and Thawing Test Groups**

<b>Comparison</b>	<b>p-value</b>
Control vs F&T 70 Cycles	0.3
Control vs F&T 182 Cycles	0.0002
Control vs F&T 300 Cycles	0
F&T 70 Cycles vs F&T 182 Cycles	0.032
F&T 182 Cycles vs F&T 300 Cycles	0.0002

The average  $G_{cr}$  value for the specimens tested after 70 cycles was  $112 \text{ J/m}^2$ . The comparison to the control group produced a p-value of 0.30, this suggests that there is insufficient evidence to conclude that there are significant differences between the average  $G_{cr}$  values for the two groups. The specimens tested after 182 cycles had an average  $G_{cr}$  value of  $75 \text{ J/m}^2$ . When compared to the control group, a p-value of 0.0002 was obtained. This suggests that there are significant differences between the groups. A p-value of 0.0320 was obtained when comparing the average  $G_{cr}$  values for the test groups tested after 70 and 182 cycles. This suggests that there are significant differences between the groups. The average  $G_{cr}$  value for specimens tested after 300 cycles was  $57 \text{ J/m}^2$ . A comparison between the specimens conditioned for 182 cycles versus 300 cycles yielded a p-value of 0.0002, this also suggests that there is a significant difference between the results of the specimens tested after 182 and 300 cycles.

The results demonstrate that after 70 cycles of freezing and thawing, the interfacial strength of the specimens are not significantly effected. However, after 182 cycles of freezing and thawing, the interfacial strength of the specimens are significantly effected. A possible reason for this may be that as conditioning progressed, moisture was able to diffuse to the interface between the polymer concrete overlay and the aluminum substrate. Once the moisture is in place, the freezing cycle of the freezing and thawing conditioning causes the water to freeze and expand, thus with increased water at the interface, there's a potential for increased expansion and damage.

## 5.5 Salt Water Soak Specimens

The average  $G_{cr}$  values for the salt water soak specimens remained similar after 2 and 6 months of conditioning. The average values were 102 and 100 J/m<sup>2</sup> after 2 and 6 months of conditioning respectively. Table 14 presents the results of the T tests conducted on the salt water soak test groups.

**Table 14: Two Sample T Test Results for Salt Water Soak Test Groups**

Comparison	p-value
Control vs SWS 2 months	0.0024
Control vs SWS 6 months	0.0004
SWS 2 months vs SWS 6 months	0.84

The results show that there are significant differences between the average  $G_{cr}$  values of the control group and both of the salt water soak test groups. The interfacial strength of the specimens is significantly affected by salt water soak conditioning after only 2 months. However, continued conditioning does not appear to reduce significantly the interfacial strength of the specimen.

## 5.6 Dry Conditioning Specimens

The average  $G_{cr}$  value for the dry specimens after 6 months of conditioning was 202 J/m<sup>2</sup>. The specimens were placed in an oven and continuously dried at 60 °C [140 °F]. Evidently, this has significantly increased the interfacial strength of the specimens. There was no color change in the overlay. The continuous drying of the specimens may have helped to increase the amount of crosslinking in the polymer, which in turn may have aided in increasing the strength of the overlay and its bond to the aluminum substrate. It appears that both studies involving conditioning at 60 °C [140 °F], dry and at 98% relative humidity, have extreme effects on the overlay. Obviously, moisture at this temperature has an adverse effect on the overlay as well as the interfacial strength. When no moisture is present, it appears to increase the strength of the overlay as well as the interfacial strength.

## 5.7 Reynolds Study

As stated previously in Chapter two, Reynolds Metals Company conducted tests on this system. The type of test conducted by Reynolds on their specimens was a direct tensile pulloff test<sup>4</sup>. The test determines the direct tensile force needed to produce an adhesive or cohesive failure. An adhesive failure occurs at the interface between the overlay and the substrate, a cohesive failure occurs within the overlay or within the substrate. Reynolds conditioned their specimens in three environments and the specimens were tested after being conditioned for 336, 1000 and 2000 hours. The three environmental conditionings included a salt water spray, an ultraviolet light test, and thermocycling. The thermocycling was performed in an environmental chamber with the following being one cycle:

One hour hold at 70 °F  
Two hour ramp to -20 °F  
One hour hold at -20 °F  
Two hour ramp to 70 °F  
One hour hold at 70 °F  
Two hour ramp to 160 °F  
One hour hold at 160 °F  
Two hour ramp to 70 °F

The test results were compared to control specimens tested without conditioning. The testing also involved the effects of different types of pretreatment of the aluminum surface before applying the overlay. The three types of pretreatment were a cleaned only surface with no chemical pretreatment, a chromium based pretreatment, and a non-chromium based pretreatment. The non-chromium based pretreatment was used on the samples that were obtained from Reynolds for this investigation.

The testing method for this investigation was a modified mixed mode flexure (MMF) bending test. This incorporates a tensile and shear force. This test method and Reynolds test method are not directly related; however, similarities do exist in the sense that a tensile force is experienced by the test specimen.

For their salt spray conditioning, they experienced a slight downward trend over time. A salt water soak was performed and test results showed an initial drop in the interfacial bond strength. As conditioning progressed, a slight decrease in the interfacial bond strength was observed. As for thermocycling, Reynolds did not experience a significant drop in pulloff strengths over the 2000 hours of conditioning. In this investigation a thermocycling test was conducted, the cycle was 4 hours at -13 °F and then 20 hours at 140 °F . No significant drop in interfacial bond strength was noted after 70 cycles (about 1700 hours). However, after 182 cycles there was a significant decrease in the interfacial bond strength, this strength continued to

significantly decrease as conditioning progressed. The test results of this investigation appear to follow the trends experienced by Reynolds.

## **5.8 General Discussion**

The test approach in this investigation was designed to analyze and assess the interfacial bond strength between the polymer concrete overlay and the aluminum substrate. Although quantitative values were obtained, the results do not provide an actual numerical value which would indicate if the interfacial bond strength is sufficient or in excess of field performance requirements. However, they provide a specification preparation starting point for a prescription based specification. Should the present constructed deck perform satisfactorily in the field, then future materials that meet these prescription specifications should perform satisfactorily. The prescription specification would suffice until a performance based specification is developed. The development of a performance based test specification would evaluate the system and thus determine the minimum required mechanical properties of the system. Performance tests would also be conducted on the system to measure such performance based tests as skid and wear resistance of the overlay in addition to adhesion requirements. Performance based testing gives a better indication of how the system performs during its service life.

The three other overlay systems cited in Chapter two were latex modified concrete (LMC), low slump dense concrete (LSDC), and hot mix asphalt membrane (HMAM) overlays. The service life estimates for these systems are 22-26 years for LMC and LSDC overlays, and 10-15 years for HMAM overlays. Polymer concrete overlays on portland cement concrete (PCC) decks are used to slow the ingress of chloride ions into the PCC, thus extending the time to damage from corrosion of the reinforcing steel. Polymer concrete overlays on PCC decks vary in service lives relative to polymer type, permeability, and traffic.

The aluminum/polymer concrete system used for this research is the same system that is used on PCC decks in Virginia. These PCC decks with the overlay have a projected minimum service life of 25 years for an average daily traffic (ADT) load of 5000 vehicles per day<sup>1</sup>. Thus for the aluminum deck system this may be considered the minimum performance requirement.