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ENVIRONMENTAL INFLUENCE ON THE BOND BETWEEN A POLYMER CONCRETE OVERLAY AND AN ALUMINUM SUBSTRATE

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16. Abstract Chloride-ion-induced corrosion of reinforcing steel in concrete bridge decks has become a major problem in the United States. Latex-modified concrete, low-slump dense concrete, and hot-mix asphalt membrane overlays are some of the most used rehabilitation methods. Epoxy-coated reinforcing steel was developed and promoted as a long-term corrosion protection method by the Federal Highway Administration. However, recent evidence has suggested that epoxy-coated reinforcing steel will not provide adequate long-term corrosion protection. The Reynolds Metals Company developed an aluminum bridge deck system as a proposed alternative to conventional reinforced steel bridge deck systems. The deck consists of a polymer concrete overlay and an aluminum substrate. The purpose of this investigation was to evaluate the bond durability between the overlay and the aluminum substrate after specimens were conditioned in various temperature and humidity conditions. The different environmental conditionings all had a significant effect on the bond durability. Specimens conditioned at 30 °C, 45 °C, and 60 °C at 98 percent relative humidity all showed a decrease in interfacial bond strength after conditioning. There was also a decrease in the interfacial bond strength for the specimens conditioned in freezing and thawing cycles and specimens conditioned in a salt water soak. The only exposure condition that increased the bond strength was drying the specimens continuously in an oven at 60 °C.					
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ABSTRACT

Chloride-ion-induced corrosion of reinforcing steel in concrete bridge decks has become a major problem in the United States. Latex-modified concrete, low-slump dense concrete, and hot-mix asphalt membrane overlays are some of the most used rehabilitation methods. Epoxy-coated reinforcing steel was developed and promoted as a long-term corrosion protection method by the Federal Highway Administration. However, recent evidence has suggested that epoxy-coated reinforcing steel will not provide adequate long-term corrosion protection. The Reynolds Metals Company developed an aluminum bridge deck system as a proposed alternative to conventional reinforced steel bridge deck systems. The deck consists of a polymer concrete overlay and an aluminum substrate. The purpose of this investigation was to evaluate the bond durability between the overlay and the aluminum substrate after specimens were conditioned in various temperature and humidity conditions.

The different environmental conditionings all had a significant effect on the bond durability. Specimens conditioned at 30 °C, 45 °C, and 60 °C at 98 percent relative humidity all showed a decrease in interfacial bond strength after conditioning. There was also a decrease in the interfacial bond strength for the specimens conditioned in freezing and thawing cycles and specimens conditioned in a salt water soak. The only exposure condition that increased the bond strength was drying the specimens continuously in an oven at 60 °C.

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INTRODUCTION

Chloride-ion-induced corrosion of reinforcing steel in concrete bridge decks has become a major problem in the United States. Steel will spontaneously corrode in the earth's moist, oxygen-rich environment. However, the high-alkali environment of concrete forms a passive layer around the steel. This, in turn, reduces the spontaneous corrosion activity of the steel to nil. The problem arises from chloride ions that are present in seawater and deicer salts. Chloride ions that reach the concrete-steel surface begin to destroy the passive layer around the steel and allow the corrosion process to begin. These chloride ions reach the concrete-steel surface by diffusing through either the concrete pore water or cracks in the concrete. Once the steel has started corroding, it can cause cracks, spalling, and delaminations on the bridge deck.

Latex-modified concrete, low-slump dense concrete, and hot-mix asphalt membrane overlays are some of the most used rehabilitation methods. One of the limitations of these

systems is that the chloride-contaminated concrete is left in place. The corrosion activity still occurs at a reduced rate. Because the corrosion activity does still occur in these systems, it reduces their service life. The service life of latex-modified concrete and low-slump dense concrete rehabilitation overlays and hot-mix asphalt membrane rehabilitation overlays are 22 to 26 years and 10 to 15 years, respectively.¹ The current design life is for 75 to 100 years, thus making the service life of these rehabilitation overlays unacceptable.

Epoxy-coated reinforcing steel (ECR) was developed and promoted as a long-term corrosion protection method for newly constructed bridge decks by the Federal Highway Administration, who estimated that a coating that did not comply with the specifications would provide 46 years of corrosion-free protection. As a result of this, ECR is the most widely used corrosion protection system today. However, recent evidence has suggested that ECR will not provide adequate long-term corrosion protection. Some service life extension estimates are 5 to 7 years if the coating has not debonded from or is in the process of debonding from the bar when chloride ions arrive at the depth of the steel. In cases where the concrete pore water has debonded the coating from the steel, the service life extension is nil.

To date, extensive efforts have been directed toward improving basic concrete properties and the protection of reinforcing steel for long-term corrosion protection. However, little effort has been directed toward the development and use of corrosion-durable materials such as aluminum or composites.

The Reynolds Metals Company developed an aluminum bridge deck system. This system is proposed as an alternative to conventional reinforced steel bridge deck systems. The system consists of an aluminum substrate with a polymer concrete overlay. The substrate is an aluminum alloy 6063-T6 extruded bar stock. The overlay consists of an epoxy binder and silica sand aggregate. Reynolds conducted research on this system, with the main focus on the bond between the polymer concrete overlay and the aluminum substrate. Specimens were prepared both with and without pretreatment of the aluminum substrate surface prior to the application of the polymer concrete overlay. The pretreatment of the aluminum surface is done in the hope that it will provide for a better bond between the two materials. The pretreatment consists of a buffed finish by mechanical buffers to remove the oxide layer. The panel is then washed with pressurized water to remove surface debris. A chromate pretreatment is then applied and allowed to dry before application of the polymer concrete overlay. Specimens were subjected to various environmental conditionings that included a salt spray exposure, ultraviolet light exposure, and freezing and thawing cycles. Pullout strength tests and fatigue tests were performed on the specimens after environmental aging. Reynolds was able to conclude from its test results that a surface pretreatment is essential to a good bond between the aluminum substrate and the polymer concrete overlay. It was found that if properly prepared, the composite system is durable after environmental exposure and fatigue.²

There are some advantages to using an aluminum bridge deck system as opposed to a conventional reinforced concrete deck system. One is that the aluminum bridge deck systems are a prefabricated modular design. This helps to reduce the time needed to install the system; it also reduces the need for formwork and site concrete. Another advantage is that the aluminum bridge

deck system has a lower dead weight (152 kPa) than the concrete bridge deck system (690 kPa). Last, the aluminum bridge deck system has a potential for a longer service life because of its ability to resist the effects of deicer salts.

One of the major issues associated with the use of an aluminum bridge deck system is the ability of the polymer concrete overlay to provide an acceptable skid and wear resistance on the riding surface. Skid resistance is a measure of frictional characteristics of a surface (ACI 116R); wear is the deterioration of a surface attributable to traffic use and/or the environment.³ Another major issue of concern is the life of the bond between the polymer concrete overlay and the aluminum substrate when it is subjected to environmental factors and the fatigue effects of passing traffic. This can lead to major problems if the overlay becomes debonded from the aluminum. If this occurs, the traffic surface becomes the aluminum, which offers little to no skid resistance.

PURPOSE AND SCOPE

The purpose of this investigation was to evaluate the bond durability between the polymer concrete overlay and the aluminum substrate. The scope of this investigation is limited to the following environmental exposure conditions:

1. 30 °C, 98 percent relative humidity
2. 45 °C, 98 percent relative humidity
3. 60 °C, 98 percent relative humidity
4. Freezing and Thawing: 60 °C, 100 percent relative humidity, for 20 hours, -25 °C for 4 hours
5. Salt Water Soak: 6 percent NaCl (by weight) solution
6. Dry at 60 °C.

The temperature ranges were determined from field measurements taken at the bridge site. A small section of the polymer concrete overlay and aluminum substrate, instrumented with a thermocouple, was placed at the bridge site and monitored. The temperature range for the freezing and thawing tests was chosen for extreme conditions that the overlay may be subjected to in Virginia's climate. The 6 percent NaCl solution comes from the accepted test parameters for chloride penetration determination in concrete.

METHODS AND MATERIALS

Specimen Preparation

Conditioning Specimens

Eight beams were received from Reynolds in March 1997. The beam dimensions were 305 mm in width, 1.8 m in length, and 305 mm in height. The beams consisted of an aluminum top and bottom flange with webbing and a polymer concrete overlay on the top flange. Test specimens were cut from seven of the eight beams received from Reynolds. The specimen plan dimensions were 51 mm x 305 mm. The specimens consisted of the polymer concrete overlay and the aluminum substrate from the top flange of the beam. Figure 1 shows the specimen plan dimensions. Specimens were cut from the beams using a commercial water jet cutter; an abrasive was used in the water to cut through the polymer concrete overlay and the aluminum. This cutting process produced a smooth cut that appeared well suited for this material. Twenty-four specimens were obtained from each beam for a total of 168 specimens. All of the specimens were numbered in accordance with their location on the original beams. The numbers were etched on the aluminum surface of each specimen. A 3-mm notch was then cut at the center of each specimen through the polymer concrete overlay to the aluminum surface across the center of the specimen width. The notch was cut using an abrasive wheel. This was done to create a specimen that is suitable for the modified mixed mode flexure (MMF) test being used in this investigation. After the specimens were numbered and notched, they were post-cured in an oven at 60 °C for 24 hours.

Outdoor Temperature Specimen

The remaining beam was used for an outdoor temperature experiment. Copper/constantine thermocouples were attached at various locations on the beam. At each location, thermocouples were attached at the top surface of the overlay, at the interface between the overlay and the aluminum substrate, and at the bottom of the aluminum surface of the top flange. A 5-mm hole was drilled through the aluminum to the interface. The thermocouples were attached using an epoxy. The sides of the beam were covered with Styrofoam sheeting 25 mm thick to simulate in-service boundary conditions. The beam was then placed outside on concrete blocks to elevate it off the ground about 1.2 m. The thermocouple wires were run to the data acquisition device through a PVC pipe so that they would remain protected from direct sunlight, which could influence the temperature readings. The data acquisition device was set to take temperature readings every 30 minutes. The purpose of this experiment is to determine the maximum and minimum field temperatures that the polymer concrete and aluminum will achieve when exposed to typical Virginia weather conditions.

Test Method

Modified Mixed Mode Flexure Test

The test procedure is a modified version of the MMF test. In a standard MMF test procedure, the specimen is loaded at the center between the two supports. The specimens used for this experiment were loaded at the quarter point as shown in Figure 2. The modification allows for the specimen to have a longer debond length and for each side of the specimen to be tested separately. This test is conducted to determine the critical strain energy release rate, G_{cr} , which is a measure of the fracture toughness of the material. Each specimen will yield two test results, one result from each side of the notch.

Test Specimen Preparation

Prior to MMF testing, an 11-mm aluminum plate was bonded to the polymer concrete surface of each conditioned specimen. Figure 3 presents the bonded aluminum plate geometry. This procedure became necessary because the polymer concrete overlay was too thin to store enough energy to debond. Bonding the aluminum plate to the overlay increases the thickness, thus storing enough energy to debond the overlay from the original aluminum substrate. The aluminum plates were cut from sections of the aluminum beams used to fabricate the MMF test specimens. Any loose aggregate was removed from the specimens before the aluminum plate was bonded to the polymer concrete overlay surface. The plates were bonded to the overlay surface using Tamms Flexolith 216R epoxy. To improve the bond, the aluminum plate surface was sanded using sand paper until the surface was clean. The specimens were then post cured for 24 hours in an oven at 60 °C. Post curing was done to ensure that the specimens were more stable over time. After post curing, a notch was cut through the bonded plate over the original notch in the polymer concrete overlay as the final specimen preparation step.

Test Procedure

As stated previously, the modified MMF test is conducted to determine the critical strain energy release rate, G_{cr} , which is a measure of the fracture toughness of the material. The first part of the test involves placing the specimen in a dry ice bath to obtain a temperature of -33 °C to reduce viscoelastic influences. After the temperature is reached, the specimen is placed in a three-point bend test to initiate a precrack at the polymer concrete and aluminum substrate interface. The precrack length is measured on each side of the notch in the specimen. The specimen is then placed back in the dry ice bath to ensure that the test specimen temperature remains at -33 °C. The specimen is removed from the dry ice bath, and the MMF test is conducted on one side of the specimen. The specimen is then returned to the dry ice bath, and the second side of the specimen is then tested at the test temperature. Figure 3 presents the modified MMF test geometry.

Environmental Exposure Conditioning

Humidity Chamber Conditioning

The humidity chamber conditioning involves three temperatures at 98 percent relative humidity: 30 °C, 45 °C, and 60 °C. Deionized water was put into each of the three humidity chambers to a level of approximately 51 mm. A support made of chlorinated polyvinylchloride pipe was placed into each chamber; the supports were approximately 76 mm in height. The purpose of the supports was to keep the specimens above the water level and in the 98 percent relative humidity condition. Two aluminum strips were placed across each support to add extra support for the weight of the specimens. The specimens were stacked directly on the supports in layers. Each layer consisted of four specimens. Between each layer, two Plexiglas strips were placed to prevent the specimen layers from touching. This also allowed moisture to enter the overlay surface of the specimens. The specimen layers were rotated weekly to allow for uniform conditioning of all specimens. A total of 20 specimens were conditioned in each chamber.

Freezing and Thawing

Specimens for freezing and thawing conditioning were conditioned according to the following cycle: 60 °C, 100 percent relative humidity for 20 hours, -25 °C for 4 hours. The specimens were placed in a polypropylene container. The container was filled with deionized water until the specimens were submerged. The container was then covered and placed in an oven at 60 °C for 20 hours. After 20 hours, the specimens were removed from the container and placed directly on 4-mil sheet plastic on the freezer plate. The specimens were then covered with sheet plastic to keep them moist. The specimens were allowed to cool for 4 hours. After 4 hours of cooling, the specimens were placed back into the polypropylene container, covered, and placed back into the oven. This completed one cycle. The specimens were moved between the oven and freezer each day, with one cycle taking 1 day to complete. A total of 20 specimens were conditioned.

Salt Water Soak

The specimens were conditioned in a 6 percent NaCl (by weight) solution. The specimens were placed in a polypropylene container. The container was then filled with a 6 percent NaCl solution until the specimens were submerged. The container was then covered and placed in an oven at 60 °C. An air pump was attached to the container to aerate the salt solution. The specimens were removed from the container once per week and hand dried. The hand dried specimens were then placed in a clean, dry polypropylene container and placed back into the oven at 60 °C for 24 hours. After 24 hours of drying, the specimens were placed back into the container filled with the 6 percent NaCl solution, covered, and placed back into the oven. The specimens were dried on Tuesday of each week. Potential measurements, as follows, of the NaCl solution were taken every 2 or 3 days to ensure that the actual solution remained at about 6 percent. Six beakers containing 0, 4, 5, 6, 7, and 8 percent NaCl (by weight) solution were prepared. Each solution was tested using a specific ion chloride electrode, and the resulting

potential was recorded. A solution concentration curve was developed for each weekly assessment of the concentration of the conditioning salt solution. The potential measurements were then taken on the actual solution and the corresponding concentration was calculated from the concentration curve. A total of 20 specimens were conditioned.

Dry Conditioning

A total of 20 specimens were dry conditioned. This procedure involved placing the specimens directly into an oven at 60 °C and allowing them to dry continuously. The humidity chamber, salt water soak, and dry test specimens were conditioned for 1 year. The freezing and thawing specimens were conditioned for 300 cycles. Table 1 presents the test matrix for the conditioned specimens and the control specimens.

Materials

Aluminum

The aluminum being used for this system is an aluminum alloy 6063-T6 extruded bar stock. The aluminum alloy makes up the top and bottom flange and the webbing of the beam. This material generally has the following mechanical properties:

- Modulus of Elasticity, 70 GPa
- Tensile Strength, 260 MPa
- Coefficient of Thermal Expansion: 24×10^{-6} mm/mm/°C.

Polymer Concrete

The overlay for this system is an epoxy-based polymer concrete. The epoxy is Tamms Flexolith 216 R. This is a two-component epoxy compound. Part A is the base, and Part B is the hardener. Part A contains ethylhexyl glycidyl ether, and part B contains diethylene triamine.⁴ The two parts are combined 1:1 by volume and thoroughly mixed at a slow mix speed. The mixed binder is then applied to the pretreated top surface of the aluminum beam. After the epoxy binder is spread, silica sand aggregate is broadcast over the wetted surface and the sand is fully saturated with epoxy. The aggregate to epoxy binder ratio is 3:1. The procedure can be repeated to obtain the desired overlay thickness. The technical data sheet from Tamms for Flexolith 216R lists the following mechanical properties for the material:

- Modulus of Elasticity, 900 MPa
- Tensile Strength, 19 MPa
- Coefficient of Thermal Expansion, 9×10^{-5} mm/mm/°C.

RESULTS

Outdoor Temperature Measurements

Temperature measurements were conducted on the outdoor temperature specimen from July 1997 to May 1998. As stated previously, the purpose of this experiment was to determine the maximum and minimum field temperatures that the polymer concrete and aluminum achieve when exposed to typical Virginia weather conditions. Temperature readings were taken from three locations on the beam. At each location, readings were taken at the top surface of the overlay, at the interface between the overlay and the aluminum, and at the bottom of the aluminum surface of the top flange. Ambient temperature readings were also taken at approximately 51 mm above the center of the beam.

The maximum temperatures were obtained on July 28, 1997. The maximum temperature at the top surface of the overlay was 51 °C. The bottom surface of the aluminum of the top flange achieved a maximum temperature of 52 °C. The interface between the overlay and the aluminum had the highest maximum temperature at 53 °C. All of these temperatures were obtained at 4 P.M. The maximum ambient temperature measured was 42 °C. The actual maximum air temperature on that day was 36 °C. Figure 4 presents the temperature measurements for July 18, 1997.

The minimum temperatures were obtained on March 12, 1998. The same minimum temperature of -17 °C was obtained for the overlay surface, interface, and aluminum. This temperature was achieved at 6:30 A.M. with a minimum ambient temperature measured at -15 °C. Figure 5 presents the temperature measurements for March 12, 1998.

Control Specimens

In October 1997, testing of the control specimens was initiated. The specimens were tested in three groups. Control group 1 was precracked at room temperature, and plastic deformation of the aluminum occurred during the precracking of the polymer concrete/aluminum substrate bond. The specimens were then placed in a dry ice bath for 6 hours before MMF testing. Each specimen was removed from the dry ice bath, and side 1 was tested. The specimen was then flipped, and side 2 was tested. A total of 12 measurements were recorded from the possible 16 measurements. The individual measurements were variable. The second control group specimens were placed in a dry ice bath before precracking. Each specimen was removed from the dry ice bath and precracked; the aluminum had not plastically deformed. Before MMF testing, the specimens were placed back in the dry ice bath. The specimens were then tested in the same manner as control group 1. A total of 16 measurements were recorded for the second control group, and the variability was slightly less. The third control group specimens were precracked and tested in the same manner as control group 2. However, after side 1 of the specimen was tested, it was returned to the dry ice bath to return the specimen to the dry ice

temperature. After the specimen returned to the initial test temperature of $-33\text{ }^{\circ}\text{C}$, side 2 was tested. Five measurements were obtained from this test group with less variability than the first two test groups. All subsequent testing was conducted using the procedure used for the third control group. Table 2 presents the descriptive statistics for the three control groups. The means represent the critical strain energy release rate, G_{cr} , (J/m^2).

Humidity Chamber Specimens

As stated previously, specimens were conditioned in three humidity chambers at three temperatures: $30\text{ }^{\circ}\text{C}$, $45\text{ }^{\circ}\text{C}$, and $60\text{ }^{\circ}\text{C}$. Each humidity chamber was at 98 percent relative humidity.

A total of 33 measurements were recorded as an acceptable failure mode for the $30\text{ }^{\circ}\text{C}$ humidity chamber specimens. Most of the test specimens failed at the proper interface, with the proper interface being the interface between the original aluminum substrate and the polymer concrete overlay; others failed within the polymer concrete overlay. The average critical strain energy release rate, G_{cr} , for the specimens tested after 6 months of conditioning was $115\text{ J}/\text{m}^2$. The average G_{cr} for the specimens tested after 9 months of conditioning was $76\text{ J}/\text{m}^2$, and the average G_{cr} for the specimens tested after 12 months of conditioning was $68\text{ J}/\text{m}^2$. Table 3 presents the descriptive statistics for the $30\text{ }^{\circ}\text{C}$ humidity chamber specimens.

The $45\text{ }^{\circ}\text{C}$ humidity chamber specimens yielded 27 measurements from the possible 40 measurements. The specimens tested after 6 months of conditioning all failed at the proper interface. However, 13 of the measurements from the specimens tested after 9 and 12 months of conditioning failed at the interface between the overlay and the top aluminum plate rather than the bond being evaluated, or they failed within the polymer concrete overlay. Thus, only 13 of the possible 26 measurements were recorded as an acceptable failure mode. The average G_{cr} value was 91, 73, and $66\text{ J}/\text{m}^2$ for the specimens tested after 6, 9, and 12 months of conditioning respectively. Table 4 presents the descriptive statistics for the $45\text{ }^{\circ}\text{C}$ humidity chamber specimens.

Many problems were encountered with the $60\text{ }^{\circ}\text{C}$ humidity chamber specimens. Only 5 of the possible 14 measurements were recorded as an acceptable failure mode for the specimens tested after 6 months of conditioning. None of the measurements of the specimens tested after 9 and 12 months of conditioning was recorded as an acceptable failure mode. Failure of most of these specimens occurred within the polymer concrete overlay and not at the interface. Table 5 presents the descriptive statistics for the 6-month, $60\text{ }^{\circ}\text{C}$ humidity chamber specimens.

Freezing and Thawing Specimens

In November of 1997, five freezing and thawing conditioned specimens were tested; the specimens had been exposed to 70 freezing and thawing cycles prior to testing. Difficulties occurred in the testing of these specimens when some of them failed at the interface between the

polymer concrete overlay and the aluminum plate bonded to the top of the overlay. Only 5 of the possible 12 measurements were recorded as an acceptable failure mode. The average G_{cr} value was 112 J/m^2 . In March 1998, seven specimens were tested after being exposed to 182 cycles. Of the possible 14 measurements, 13 were recorded as an acceptable failure mode. The average G_{cr} value was 75 J/m^2 . After 300 cycles of conditioning, 13 of a possible 14 measurements were recorded as an acceptable failure mode. The average G_{cr} was 57 J/m^2 . Table 6 presents the descriptive statistics for the specimens.

Salt Water Soak Specimens

Salt water soak specimens were tested in December 1997 and March 1998 after 2 and 6 months conditioning, respectively. Only 6 of the possible 10 measurements were recorded as an acceptable failure mode for the specimens tested after 2 months of conditioning. The failure again occurred at the top aluminum plate/polymer concrete interface. The average G_{cr} value was 102 J/m^2 . All 14 measurements of the specimens tested after 6 months of conditioning were recorded as an acceptable failure mode. The average G_{cr} value was 100 J/m^2 . All 14 measurements of the specimens tested after 12 months of conditioning were unacceptable failure modes. All of the failures occurred within the polymer concrete overlay. Table 7 presents the descriptive statistics for the specimens.

Dry Conditioning Specimens

In March 1998, eight specimens that had been dried at $60 \text{ }^\circ\text{C}$ for 6 months were tested. All of the 16 measurements recorded were acceptable failure modes. The average G_{cr} value was 202 J/m^2 . Table 8 presents the descriptive statistics for the specimens.

Aluminum

The modulus of elasticity of the aluminum was determined on specimens cut from the bottom flange of the beams. Three specimens were tested with all three test results yielding a modulus of elasticity of 70 GPa .

Polymer Concrete

The modulus of elasticity was determined from polymer concrete specimens prepared by Reynolds. The specimens were tested at room temperature and also at $-33 \text{ }^\circ\text{C}$. The latter temperature is the test temperature of the specimens being tested in the modified MMF test. The modulus of elasticity was 5.1 GPa at room temperature and 9.2 GPa at $-33 \text{ }^\circ\text{C}$.

DISCUSSION

Outdoor Temperature Measurements

The temperature measurements on the outdoor specimen appear to follow a similar trend on 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. Because the aluminum conducts heat so well, the aluminum is soon warmer than the top surface. 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. This probably occurs because of the combined heat of the top surface and the bottom aluminum surface. The top surface, interface, and aluminum surface all obtain higher temperatures than the ambient temperature.

As cooling begins, the ambient temperature decreases the quickest. 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 affect 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.

Control Specimens

As stated previously, the control specimens were tested in three groups. Control group 3 yielded the least amount of variability, but it included only five 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 1 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 the specimen was removed 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.

Before the comparison tests were conducted, the test groups were tested for normality to determine 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.⁵ 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 percent 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 significantly different. Table 10 presents the results of the comparison tests.

Of all the tests conducted on the individual control groups to determine if there was a significant difference between the groups, only one test result showed a significant difference. Statistically, at the 0.05 level, Ctrl 3 is significantly different from Ctrl 1-1. However, since the probability of accepting the null hypothesis is very small (0.05 versus 0.0485), it was decided to include these values in the control sample. The results of all other statistical tests are not affected by this decision because the resultant is to lower the average control group value. Table 11 presents the descriptive statistics of the combined control group.

A normality test was conducted on the combined specimen data and yielded a p value of 0.079; this suggests that the data are normally distributed. Figures 6 and 7 present the probability density and cumulative probability of the control data. Both figures demonstrate that the data have normal distribution characteristics.

Humidity Chamber Specimens

The specimens conditioned at 30 °C and 45 °C performed better than the specimens conditioned at 60 °C. The polymer concrete overlay on the specimens conditioned at 60 °C was much darker than the specimens conditioned at the lower temperatures. It appears that hydrolysis occurred within the polymer concrete overlay of these specimens. This would account for the darkening of the overlay. It also appears that the 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 and 45 °C.

A statistical analysis was conducted on the 30 °C, 45 °C, and 60°C test results to determine if the average G_{cr} values were significantly different from those of the control specimens. Normality tests were conducted on 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.

For the specimens conditioned at 30 °C, the average G_{cr} decreased from 115 J/m² after 6 months of conditioning to 76 J/m² after 9 months of conditioning. The p value for the control versus the 30 °C 6-month conditioning was 0.0039, which is less than 0.05. This suggests that statistically there are significant differences between the average G_{cr} values for the control and 30 °C test groups. When comparing the 30 °C test groups of 6 and 9 months, 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 J/m² for specimens conditioned for 9 months to 68 J/m² for specimens conditioned for 12 months. The 45 °C test groups had similar t test results. The

average G_{cr} values were significantly different from the control specimens, there were also significant differences between the specimens tested after 6 and 9 months of conditioning. However, there was not a significant difference between the 9- and 12-month test results. The 60°C specimens tested after 6 months of conditioning had an average G_{cr} value of 76 J/m². The p value for the control group versus the 60°C 6-month conditioning group was 0.0000. This suggests that statistically there are significant differences between the average G_{cr} values for the control and 60°C test groups.

The results demonstrate that 6 months of conditioning specimens at 30 °C, 45 °C, and 60°C in humidity chambers have 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 these temperatures further decreases the interfacial strength.

Freezing and Thawing Specimens

Freezing and thawing specimens were tested after 70, 182, and 300 cycles. The specimens tested after 70 cycles were more variable than those tested after 182 and 300 cycles. Normality tests were conducted on all of the test groups, and all were found to be normally distributed. Two sample t tests were conducted comparing the test groups to the control test group, as well as to each other. Table 13 presents these results. The average G_{cr} value for the specimens tested after 70 cycles was 112 J/m². 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 J/m². 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 J/m². 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 affected. However, after 182 cycles of freezing and thawing, the interfacial strength of the specimens is significantly affected.

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/m² after 2 and 6 months of conditioning, respectively. Normality tests were conducted on all of the test groups, and all were found to be normally distributed. Table 14 presents the results of the t tests conducted on the salt water soak test groups. 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.

Dry Conditioning Specimens

The average G_{cr} value for the dry specimens after 6 months of conditioning was 202 J/m². The specimens were placed in an oven and continuously dried at 60 °C. Evidently, this significantly increased the interfacial strength of the specimens. The overlay appeared to be more brittle than the original specimens. There was no color change in the overlay. The continuous drying of the specimens may have helped to increase the amount of cross linking 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 conditioning at 60 °C dry and at 98 percent 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, the strength of the overlay as well as the interfacial strength appears to increase.

Aluminum

As stated previously, the modulus tests were conducted on tensile specimens fabricated in accordance with ASTM B557. The calculated modulus of elasticity was 70 GPa, which is consistent with the published value of 70 GPa for 6063-T6 aluminum⁶.

Polymer Concrete

Modulus test results showed that the modulus of elasticity for specimens tested at both room temperature and -33 °C were within the range of 6 to 10 GPa for typical polymer concretes.⁷

Field Performance

The test series demonstrate that the time of field installation would have a significant effect on the interfacial bond strength between the polymer concrete overlay and the aluminum substrate. For installations placed during the summer months, post-curing at or above 60°C would take place. A higher bond strength would be developed than with those placed in the fall prior to being exposed to a wet, cold environment. The higher bond strengths during summer placement are illustrated by the higher strain energy release rates for the 60°C dried specimens where post-curing took place. A recommendation of placing these systems in the summer months is warranted, and post-curing these systems should they be installed in the fall months is justified.

All of the exposure conditions used in this study (humidity, freezing and thawing, and salt water) resulted in a decrease of the interfacial bond strength between the polymer concrete overlay and the aluminum substrate. Of these exposure conditions, freezing and thawing appears to be the most detrimental. The reduction in interfacial bond strength caused by freezing and thawing is most likely related to the stresses induced by the mismatch in coefficients of thermal expansion between the polymer concrete and the aluminum. However, the mismatch between polymer concrete and aluminum is less than that between polymer concrete and portland cement concrete. Thus, it is expected that the polymer concrete/aluminum system will have a service life at least equal to that of a polymer concrete/portland cement concrete system. This would also be true relative to failure conditions caused by the moisture degradation of the bond between the aggregate and the polymer concrete. This bond loss would influence the wear rate of the polymer concrete and thus is not related to the interfacial characteristics between the polymer concrete overlay and the aluminum substrate.

As more experience is gained in the field performance of these polymer concrete/aluminum systems, the results of these environmental exposure tests will become more meaningful as performance acceptance criteria.

CONCLUSIONS

- Conditioning specimens in humidity chambers at 30 °C, 45 °C, and 60 °C had an affect in the interfacial bond strength between the polymer concrete overlay and the aluminum substrate.
- Specimens conditioned in the 30 °C and 45 °C humidity chambers showed a significant decrease in the average critical strain energy release rate, G_{cr} over time. The specimens in the 60 °C humidity chamber did show a significant decrease in average G_{cr} after 6 months of conditioning. However, continued conditioning after 6 months caused failure within the polymer concrete overlay.
- Conditioning specimens in freezing and thawing cycles caused a significant decrease in the interfacial bond strength as conditioning progressed.
- Salt water soak conditioning of the specimens significantly decreased the interfacial bond strength over the first 6 months of conditioning. Specimens tested after 12 months of conditioning failed within the polymer concrete overlay.
- Conditioning the specimens in an oven at 60 °C helped to increase the interfacial bond strength over time.

RECOMMENDATIONS

1. Investigate the bond between the aggregate and the polymer.
2. Investigate the wearing resistance of the polymer concrete overlay under different environmental exposure conditions.

ACKNOWLEDGMENTS

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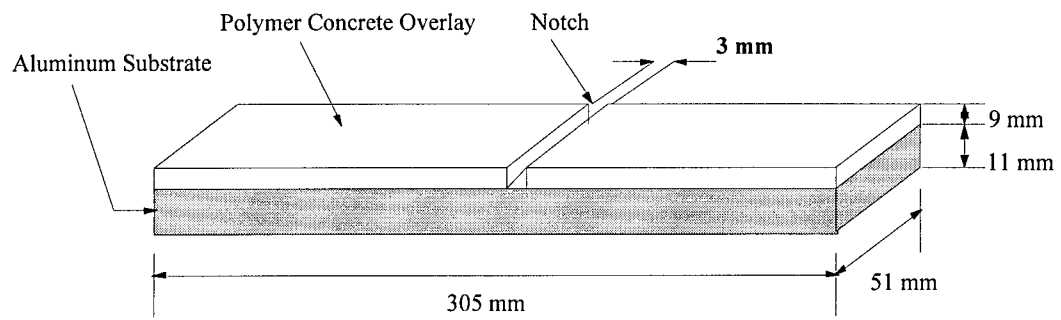


Figure 1: Specimen Dimensions

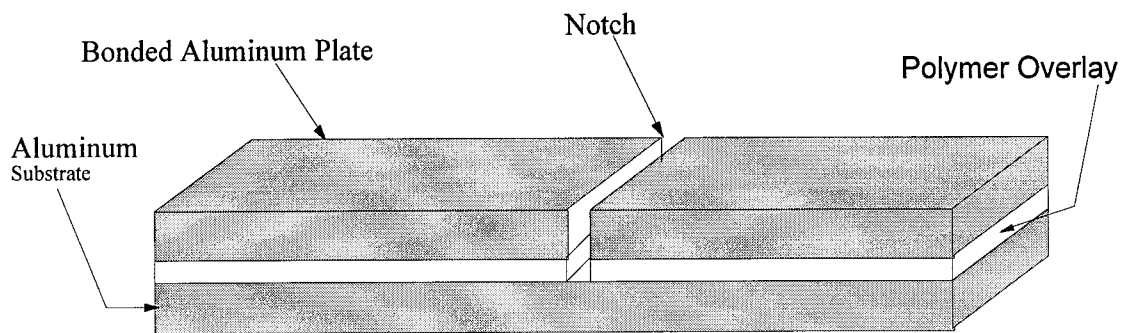


Figure 2: Test Specimen Geometry

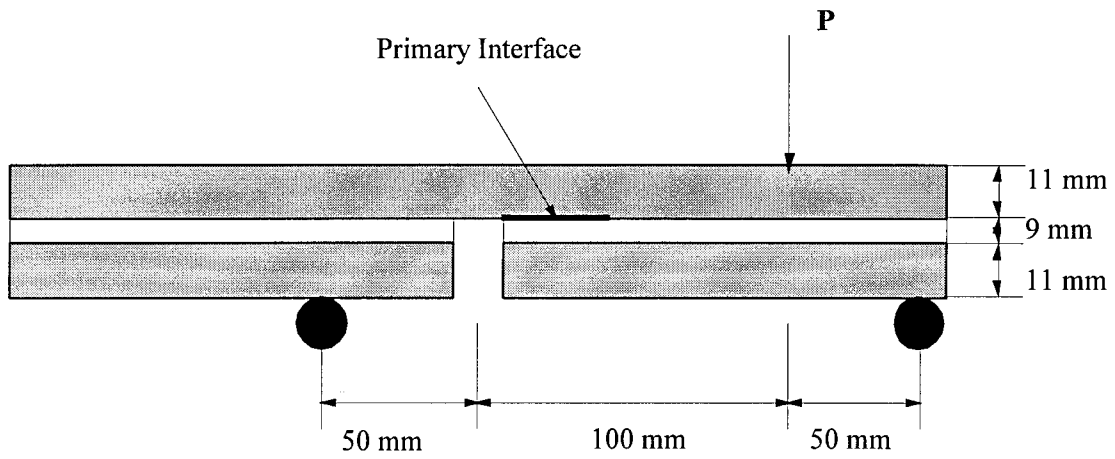


Figure 3: Modified Mixed Mode Flexure Test Geometry

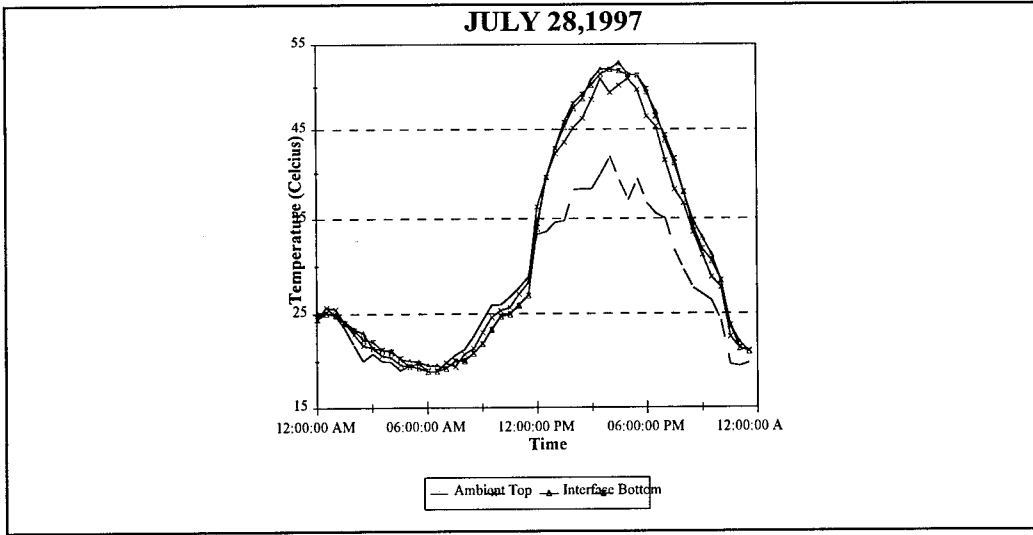


Figure 4: Maximum Temperature of Outdoor Specimen

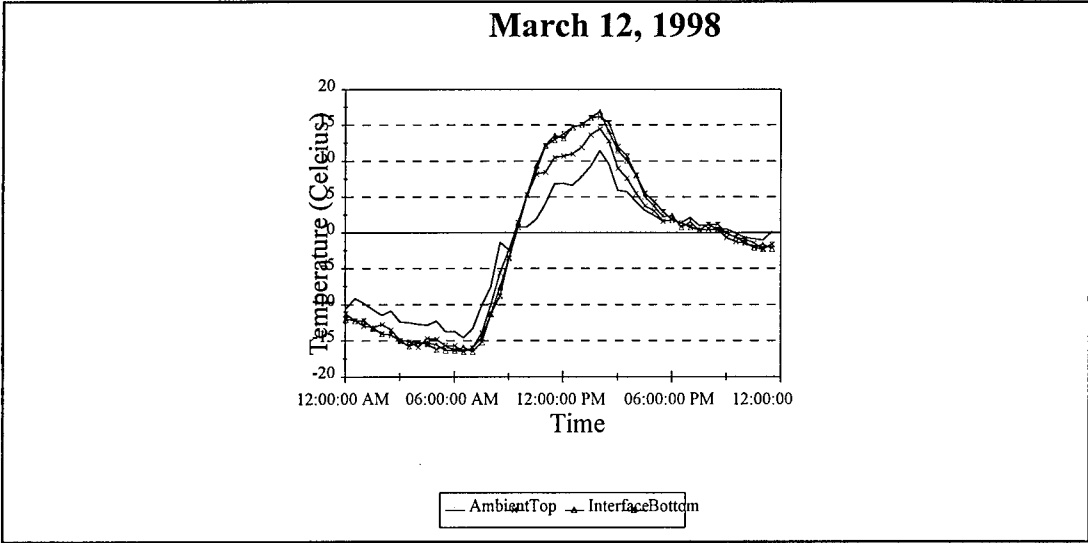


Figure 5: Minimum Temperature of Outdoor Specimen

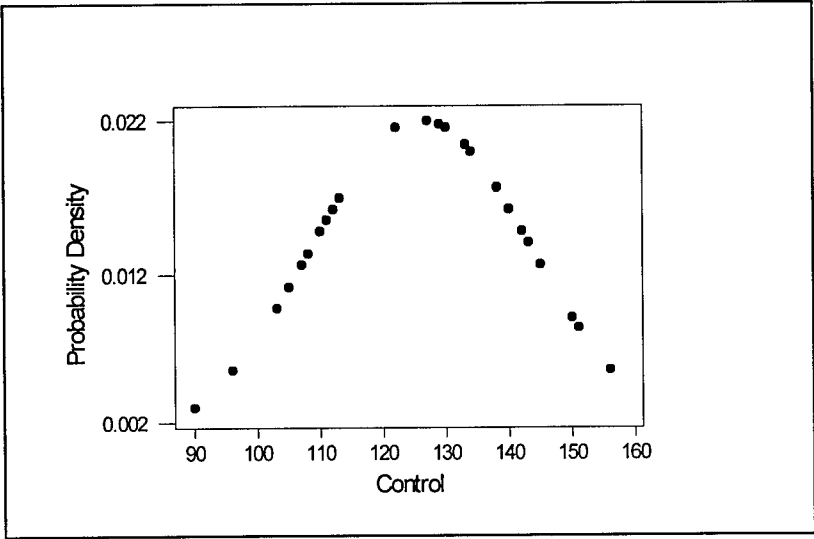


Figure 6: Probability Density of Control Group

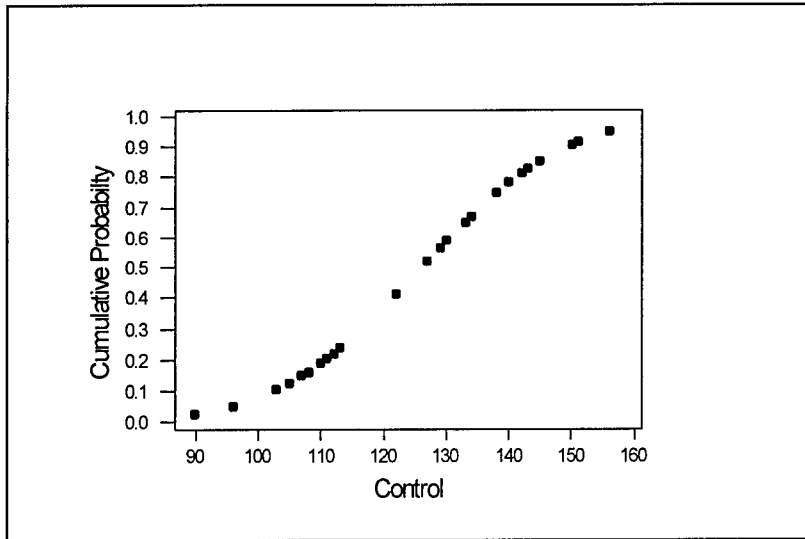


Figure 7: Cumulative Probability of Control Group

Table 1: Study Test Matrix

	30°C 98% RH	45°C 98% RH	60°C 98% RH	Freezing & Thawing	Salt Water Soak	Dry
Baseline (Control)	25					
Static Bond Toughness						
Test at 2 Months				6	6	
Test at 6 Months	7	7	7	7	7	8
Test at 9 Months	7	7	7			
Test at 12 Months	6	6	6	7	7	12

NOTE: The Control specimens were post-cured for 24 hours at 60°C [140°] before testing. All other specimens were post-cured in the same manner before conditioning.

Table 2: Descriptive Statistics for Control Groups

Test Group	Sample Size	Mean [J/m²]	Standard Deviation	Coefficient of Variation [%]
Control Group 1	12	136	16.9	12.4
Control Group 2	16	125	14.8	11.8
Control Group 3	5	104	7.7	7.5

Table 3: Descriptive Statistics for Humidity Chamber Specimens at 30 C

Conditioning Time	Sample Size	Mean [J/m²]	Standard Deviation	Coefficient of Variation [%]
6 Months	14	115	14.8	12.9
9 Months	12	76	11	14.5
12 Months	7	68	8.6	12.7

Table 4: Descriptive Statistics for Humidity Chamber Specimens at 45 C

Conditioning Time	Sample Size	Mean [J/m²]	Standard Deviation	Coefficient of Variation [%]
6 Months	14	91	17.5	19.2
9 Months	7	73	12.9	17.7
12 Months	6	66	11.5	17.4

Table 5: Descriptive Statistics for Humidity Chamber Specimens at 60 C

Conditioning Time	Sample Size	Mean [J/m²]	Standard Deviation	Coefficient of Variation [%]
6 Months	5	76	17.9	23.6

Table 6: Descriptive Statistics for Freezing and Thawing Specimens

Conditioning Time	Sample Size	Mean [J/m²]	Standard Deviation	Coefficient of Variation [%]
70 Cycles	5	112	24.3	21.7
182 Cycles	13	75	12.6	16.8
300 Cycles	13	57	6.2	10.9

Table 7: Descriptive Statistics for Salt Water Soak Specimens

Conditioning Time	Sample Size	Mean [J/m²]	Standard Deviation	Coefficient of Variation [%]
2 Months	6	102	11.9	11.7
6 Months	14	100	19.9	19.9

Table 8: Descriptive Statistics for Dry Specimens

Conditioning Time	Sample Size	Mean [J/m²]	Standard Deviation	Coefficient of Variation [%]
6 Months	16	202	35.2	17.4

Table 9: Descriptive Statistics for Individual Sides of Control Groups

Test Group	Sample Size	Mean [J/m²]	Standard Deviation	Coefficient of Variation [%]
Ctrl 1-1	7	139	18.9	13.5
Ctrl 1-2	5	130	13.1	10
Ctrl 2-1	8	125	18.6	14.8
Ctrl 2-2	8	124	11.2	9
Ctrl 3	5	104	7.7	7.5

NOTE: Ctrl 1-1 = Control Group 1 - Side 1, Ctrl 1-2 = Control Group1 - Side 2, etc.

Table 10 Statistical Comparison Results

Comparison	P-Value
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

Table 11: Descriptive Statistics for Combined Control Group

	Sample Size	Mean [J/m²]	Standard Deviation	Coefficient of Variation [%]
Control	33	126	18.1	14.4

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

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

Comparison	P-Value
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

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

