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Field Implementation of Geopolymer Coatings

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Submitted by
Dr. P. N. Balaguru, Principal Investigator
Mohamed Nazier, Graduate Assistant
Mohamed Arafa, Graduate Assistant

Dept. of Civil & Environmental Engineering
Center for Advanced Infrastructure & Transportation (CAIT)
Rutgers, The State University
Piscataway, NJ 08854-8014

NJDOT Research Project Manager
Mr. Robert Sasor

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16. Abstract

The results presented in this report deal with an evaluation of Geopolymer coatings for durability and field demonstration applications. The primary objectives were to establish a temperature range in which the coating could be applied, establish the surface conditions and requirements, and to demonstrate field applications which were done at Rutgers University campuses and on actual transportation structures.

A brief description of fiber composites is presented in the introduction chapter. The study on the establishment of a temperature range is presented in Chapter 2. The durability test results under wetting and drying conditions and scaling are presented in Chapters 3 and 4, respectively, and the field applications are described in Chapter 5. Conclusions and recommendations are presented in Chapter 6. The recommended application procedure for the geopolymer coatings is presented in Appendix A.

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Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Scope and Objective

In a previous study sponsored by the New Jersey Department of Transportation (NJDOT), a fiber reinforced-inorganic polymer composite was formulated. The composite, known as Geopolymer was evaluated as a protective coating material for transportation infrastructure. The unique features of this composition are as follows:

- The matrix used in the composite is inorganic, and fire and UV resistant.
- The system is water-based and has no toxic substances. No toxins are released during the application or curing.
- The coating can be applied with minimum surface preparation.
- The permeability of the coating material is much less than the permeability of concrete but it allows the release of vapor pressure build-up. Therefore, the coating does not delaminate from the parent surface.
- The matrix is compatible with concrete, bricks, steel and wood.
- The matrix cures to a glassy texture and hence organic paints do not adhere to geopolymer coated surfaces. This aspect can be effectively used to create a graffiti resistant surface, which was one of the primary motivations for this study.

For more information see the following relevant reports: Balaguru, P., Kurtz, S., and Rudolph, J. (1996); Balaguru, P., Slattum, K. (1995); Foden, A., Balaguru, P., and Lyon, R. (1996A).

The previous study established the viability of the Geopolymer product for protective coating applications. The primary objectives of the current study are as follows:

- Establish a temperature range in which the coating can be applied, given the requirement being that the coating should be able to withstand rain after 24 hours of curing.

- Establish the surface condition and requirements. One of the questions was, whether the material can be applied on rough surfaces which have exposed aggregates due to deterioration. In most cases, the surface preparation consists of removing excess dust build-up and pre-wetting.
- Make field demonstration applications at Rutgers University campuses and on actual transportation structures.

The results presented in this report deal with the aforementioned objectives and a summary of durability tests in a parallel study supported by the New England Transportation Consortium (NETC).

A brief description of fiber reinforced composites is presented in the introduction chapter. The study on the establishment of temperature range is presented in Chapter 2. The durability test results under wetting and drying conditions and scaling are presented in Chapters 3 and 4 respectively, and the field applications are described in Chapter 5. Conclusions and recommendations are presented in Chapter 6. The recommended application procedure is presented in Appendix A.

1.2 Background Information on Fiber Composites

Recently, high strength fiber composites, known as Fiber Reinforced Polymers (FRP), have been evaluated for rehabilitation of the transportation infrastructure and have been found to show excellent potential. For example, fiberglass boats have been known to provide excellent service for 50 years with little or no maintenance. Some of these boats are constantly exposed to sea water, and bridge decks and other structural elements are exposed to the same type of aggressive environment. If a protective layer of composite can be placed around super structures, such as exposed piers and pier caps, their service life can be extended.

The first step in the development of these composites is the selection of a matrix. The matrix may be broadly defined as either organic or inorganic. The organic matrices are generally comprised of acrylics, epoxies, latexes or polymers. They are usually single or multi component systems, the latter of which exhibits better mechanical properties. The first part is usually a resin, while the second part is an activator. Once the two parts are mixed, setting time varies between 15 minutes to 2 hours, at which point they can be formulated to adhere to most materials. These organic matrices have been used to improve the performance of concrete for several decades. The strengths of the organic matrices are their very low permeability, dimensional stability, and high elongation before rupture. Although impermeability is strength in many applications of composites, it is a weakness when they are used for concrete protection. Because they are completely impermeable, the matrices are unable to release vapor pressure build-up within the structure of concrete. Vapor pressure build-up is known to cause delamination of the matrix and can be quite damaging to the concrete. (ACI Committee 515, 1986)

In an attempt to improve upon the performance of the organic matrices, a number of inorganic matrices that contain polymer additives have been developed. The matrices have permeability lower than concrete but are not totally impermeable. It is believed that when used as a protective layer, the matrix can slow the ingress of water but at the same time allow the vapor pressure to be released. The most widely used inorganic matrix thus far has been a Portland cement based system. Because of the large grain sizes of the cement, it has been difficult to develop thin and workable matrices. In addition to the Portland cement based system, alumino silicate and phosphate based compounds are used in inorganic matrices. The major advantages of these compounds are stability under UV light, hardness and compatibility with concrete. A potassium alumino silicate, one of a family of Geopolymer materials was used for the current project.

Reinforcing fibers for the composites are available in a wide variety of material compositions and sizes. The common fiber types used in the construction industry are carbon, glass, nylon, polyester and steel. In many applications, steel fibers would be preferred because of their strength, stiffness and durability. In the current study, it is not feasible to use steel fibers because the coatings are expected to be quite thin. Therefore, only fine steel fibers would be acceptable. Micro steel fibers are available, but are quite expensive and would impair the development of a cost effective system. Carbon fibers are more expensive than glass and nylon fibers, but are the most durable. They are inert and can be used with a number of matrices while withstanding temperatures up to 800°F. Glass fibers deteriorate in alkali environments and nylon fibers are quite dense and difficult to impregnate with the matrix. Each of the fibers is available in various forms: micro fibers, discrete fibers 3 to 6 mm in length, tows, and fabrics.

For the current investigation, coatings based on polysilicates developed as a polymer for use in composites were used. This matrix, which is water based, is non toxic, cures at room temperature and was found to be durable under wet-dry and scaling conditions. Various formulations were made using different alumina-silica ratios, micro fibers and short discrete carbon fibers. The matrices were evaluated for working time and curing temperatures ranging from 40°F to 70°F.

Chapter 2

Curing Temperature and Parent Surface Condition

The polymer used in this study is a two component system. The liquid, called Component A, has to be mixed with a powder, called Component B, using a high shear mixer. Typically, industrial strength drills with mixing blades that are used for mixing two component polymers can be used in the field. The feasibility of this procedure was demonstrated in one of the field applications described in Chapter 5. In the laboratory, high shear mixers, known as choppers were used for mixing. Components A and B mix to a thick paint consistency, which can be applied by brush, roller, or sprayer. These application techniques were demonstrated both in the laboratory and in the field. The coating dries in about 2 hours.

Based on the initial tests, it was assumed that if the ambient temperature is more than 40°F, the surface can cure in 24 hours and can withstand rain in about 24 hours. The upper limit is about 90°F. At temperatures higher than 90°F, the matrix looses workability quickly. The working time or pot life at 70°F is about 2 hours. The pot life reduces to about 1 hour at 90°F.

2.1 Test Setup for Establishing Curing Temperature Range

Running water was used to simulate rain. Concrete prisms with dimensions of 2x2x13 inches were used for parent surfaces. Photographs of the concrete prisms are shown in Figures 2.1(a) and 2.1(b). One surface of the prism was coated with the polymer and allowed to dry for 24 hours at temperatures ranging from 40 to 70°F. Initially, it was assumed that some of the formulations may not cure in one day, especially at 40°F. Therefore, the samples were cured at 40, 50, 60 and 70°F and exposed to running water after 24 hours. Exposing the samples to running water was continued for 5 days. Most of the initial formulations cured hard enough to resist running water in 24 hours, even at 40°F ambient temperature. Therefore, some of the later formulations were evaluated only at 40 and 50°F.

Figure 2.1(a) Concrete Prisms Coated with Geopolymer and Exposed to Running Water

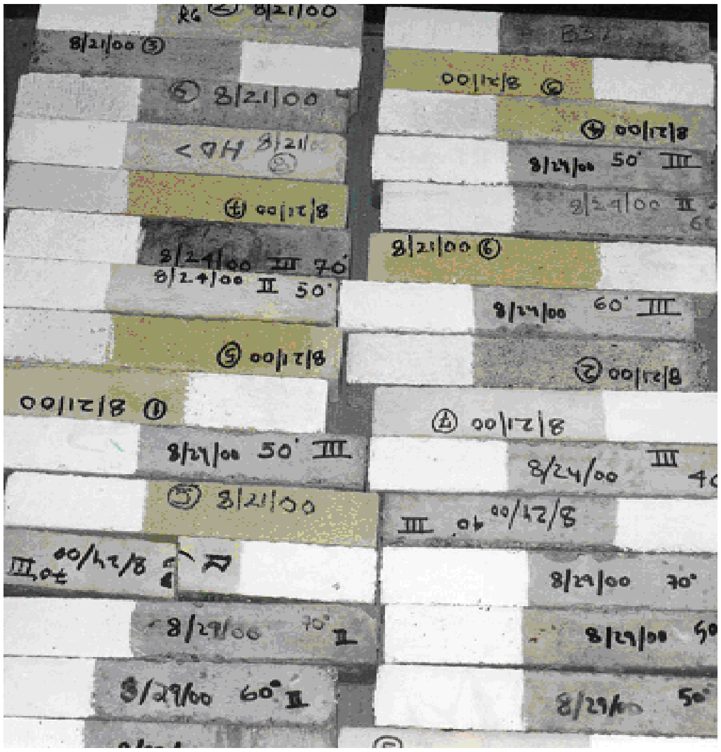

Figure 2.1(b) Concrete Prisms Coated with Geopolymer and Exposed to Running Water

The major variables were: filler material type, filler volume fraction, fiber type and fiber volume fraction. The filler materials were either ground zirconium sand or titanium oxide powder. The fiber types were: micro fibers that were micrometers long (called Woolastocote), carbon micro fibers that were less than 1mm long, 3mm long carbon fibers, and 6mm long nylon fibers. The fiber volume fraction ranged from: 10 to 15 percent for micro fibers, 0.2 percent for nylon fibers, and up to 15 percent for carbon fibers.

The various mixture combinations are presented in Table 2.1. In Table 2.1, White SiO_2 and $AlSiO_2$ refer to two types of Component B (powder). White SiO_2 consists of only silica fume where as $AlSiO_2$ contains both alumina and silica. MK is processed Kaolin clay which is commercially available. The carbon powder refers to micro carbon fibers that are less than 1mm long. The diameter of the 3 mm long carbon fibers is about 7 micrometers.

Other than erosion and cracks, the other response variables were reduction in working time and consistency.

Table 2.1: Details of Matrix for Various Mixtures

Mix Number	Composition
Mix 1	50g Liquid, 60g $AlSiO_2$, 25g Woolastocote, 25g $ZrSiO_4$ and 0.2g nylon fibers
Mix 2	50g liquid, 67.5g White SiO_2, 5g MK, 15g Woolastocote, 12g TiO_2 liquid and 0.2g nylon fibers
Mix 3	50 g liquid,60g $AlSiO_2$, 15g Woolastocote, 10g TiO_2 powder and 0.2g nylon fibers
Mix 4	50g liquid, 60g White SiO_2, 5g MK, 15g Woolastocote, 10g TiO_2 powder and 0.2g nylon fibers
Mix 5	50g liquid, 60g White SiO_2, 5g MK, 15g Woolastocote, 5g TiO_2 powder, 5g TiO_2 liquid and 0.2g nylon fibers
Mix 6	150g liquid, 180 $AlSiO_2$, 60g Woolastocote, 60g $ZrSiO_4$ and 0.6g nylon fibers

Mix 7	100g liquid, 120g $AlSiO_2$, 50g Woolastocote, 50g $ZrSiO_4$
Mix 8	100g liquid, 120g $AlSiO_2$, 50g Woolastocote, 20g TiO_2 liquid, and 0.4g nylon fibers
Mix 9	100g liquid, 120g $AlSiO_2$, 50g Woolastocote and 20g TiO_2 liquid
Mix 10	100g liquid, 145g White SiO_2, 10g MK and 30g Woolastocote
Mix 11	100g liquid, 145g White Sio_2, 10g MK, 30g Woolastocote and 3g Carbon fibers
Mix 12	100g liquid, 145g White Sio_2, 10g MK, 30g Woolastocote, 14g Carbon Powder and 3g Carbon fibers
Mix 13	100g liquid, 145g White Sio_2, 10g MK, 30g Woolastocote, 28g Carbon Powder and 3g Carbon fibers
Mix 14	100g liquid, 145g White Sio_2, 10g MK, 30g Woolastocote, 15g $ZrSiO_4$, 28g Carbon Powder and 3g Carbon fibers
Mix 15	100g liquid, 127.1g White SiO_2, 10g MK, 30g $ZrSiO_4$ and 10g Carbon Powder
Mix 16	100g liquid, 132.2g White SiO_2, 10g MK, 25g $ZrSiO_4$ and 15g Carbon Powder
Mix 17	50g liquid, 69.6g White SiO_2, 5g MK, 15g $ZrSiO_4$, 1g Turmeric powder and 2.5g Carbon Powder
Mix 18	50g liquid, 69.6g White SiO_2, 5g MK, 15g $ZrSiO_4$, 2g Turmeric powder and 2.5g Carbon Powder
Mix 19	50g liquid, 69.6g White SiO_2, 5g MK, 15g Woolastocote, 15g $ZrSiO_4$ and 2.5g Carbon Powder
Mix 20	50g liquid, 69.6g White SiO_2, 5g MK, 15g Woolastocote, 15g $ZrSiO_4$, 2g Turmeric powder and 2.5g Carbon Powder
Mix 21	50g liquid, 69.6g White SiO_2, 5g MK, 15g Woolastocote, 15g $ZrSiO_4$, and 2.5g Carbon Powder

Mix 22	50 g Liquid, 25g Geopolymer, 55g W210, 15g $ZrSiO_4$ and 2.5g Carbon Powder
Mix 23	50 g Liquid, 35.5g Geopolymer, 55g W210, 15g $ZrSiO_4$ and 2.5g Carbon Powder

2.2 Test Results and Discussion

The results are presented in Table 2.2 on Page 10. It can be seen that most formulations withstand running water after 24 hours of curing. The mixes that had a working time of less than 2 hours are identified in the table.

Mixes 6, 7 and 10 developed hair line cracks. Mixes 6 and 7 had larger volume fractions of fibers and micro fibers, and Mix 10 had no fillers and a very low volume fraction of micro fibers. These mixes were helpful to identify the minimum and maximum amount of fibers and fillers that can be incorporated in the mix without affecting the performance.

The mixes with lower workable time can be used in cold weather if accelerated curing is needed.

Based on the results presented in Table 2.2 and observations made during mixing and application of coatings, the following observations can be made.

- The two successful mixture combinations for Component B are as follows:
    1. 100g liquid, 135g White silica fume and 10g kaolin clay.
    2. 100g liquid, 110g Alumino Silicate.

For both formulations, 30g micro fibers and 30g of fillers can be added. These additives provide both shrinkage reduction, and reduction in overall cost. Filler materials are less expensive than the polymer.

- Carbon fibers can be added to increase the toughness (resistance to abrasion and flying objects). However, addition of these fibers changes the color to light gray.
- Nylon fibers also provide increased toughness. Since the density is low and they mat easily, only about 0.2 volume percent is needed.
- Even though a number of formulations have been evaluated, the authors recommend only the two aforementioned formulations. This will reduce the variability and possible mistakes in the field.

- If the ambient temperature is more than 70°F, pot life can be extended by storing the mixed polymer in a bed of ice. Typically, the bucket containing the polymer can be placed in a large vessel that has ice cubes.

Table 2.2: Results of Tests (After 24 Hours of Curing) on Various Types of Coatings and Different Curing Temperatures

Mix Number	Number of Samples	Curing temperatures	Results
Mix 1	8	40, 50, 60, 70°F	• No erosion and no cracks
Mix 2	8	40, 50, 60, 70°F	• No erosion and no cracks
Mix 3	4	40, 50, 60, 70°F	• No erosion and no cracks
Mix 4	4	40, 50, 60, 70°F	• No erosion and no cracks
Mix 5	4	40, 50, 60, 70°F	• No erosion and no cracks
Mix 6	4	40, 50, 60, 70°F	• Hairline cracks seen after three days
Mix 7	4	40, 50, 60, 70°F	• Hairline cracks seen after three days • Good consistency and workability compared to others • Early setting compared to others

Mix 8	4	40, 50°F	• Good workability and no cracks seen
Mix 9	4	40, 50°F	• Good workability and no cracks seen
Mix 10	4	40, 50°F	• Cracks appeared after two days
Mix 11	4	40, 50°F	• No cracks • Color lightened after three days
Mix 12	4	40, 50°F	• No cracks
Mix 13	4	40, 50°F	• No cracks • Darker color then Mix 12
Mix 14	4	40, 50°F	• No cracks • Difficult to work with
Mix 15	4	40, 50°F	• Workability time more than 45 minutes at 70°F • No cracks
Mix 16	4	40, 50°F	• 30 minutes workability time • No Cracks
Mix 17	4	40, 50°F	• 40 minutes workability time at 70°F • No Cracks • Looks like concrete

Mix 18	4	40, 50°F	• 40 minutes workability time at 70°F • No Cracks • Looks like concrete
Mix 19	4	40, 50°F	• Workable • No cracks
Mix 20	4	40, 50°F	• Workable • No cracks • More workable than Mix 19
Mix 21	4	40, 50°F	• Workable • No cracks
Mix 22	4	40, 50°F	• No Cracks
Mix 23	4	40, 50°F	• No Cracks

- Mixes 15, 17, 18, 20, 21-23 had a different hardener
- Mk - Processed kaolin clay
- TiO_2 – Titanium dioxide

2.3 Parent Surface Types and Preparation

Different types of parent surfaces were evaluated using structures at the Rutgers University, Livingston Campus. These were:

i. Smooth finish; top surface of a new high strength concrete slab with sheen (almost polished surface) still present. Figure 2.2, below.

ii. Smooth finish of mortar on a relatively new wall (about 5-year old surface), Figure 2.3, next page.

iii. Rough surface of an aged mortar wall (back of the Livingston Campus lab, about 15-year old surface), Figure 2.4, next page.

iv. Rough surface with spalled areas (about 15 to 20 years old), Figure 2.5, Page 15.

v. Very rough surface with exposed aggregated. In one surface more than 95% of the aggregated were exposed, Figure 2.6, Page 15.

All the surfaces were cleaned using low pressure water to remove excess dirt build up. This was the only preparation. In all cases, the application was successful.

Figure 2.2 Application on a Smooth Surface

Figure 2.3 Application on a Vertical Wall, Relatively New Smooth Surface

Figure 2.4 Application on a 15 Year Old Aged Surface

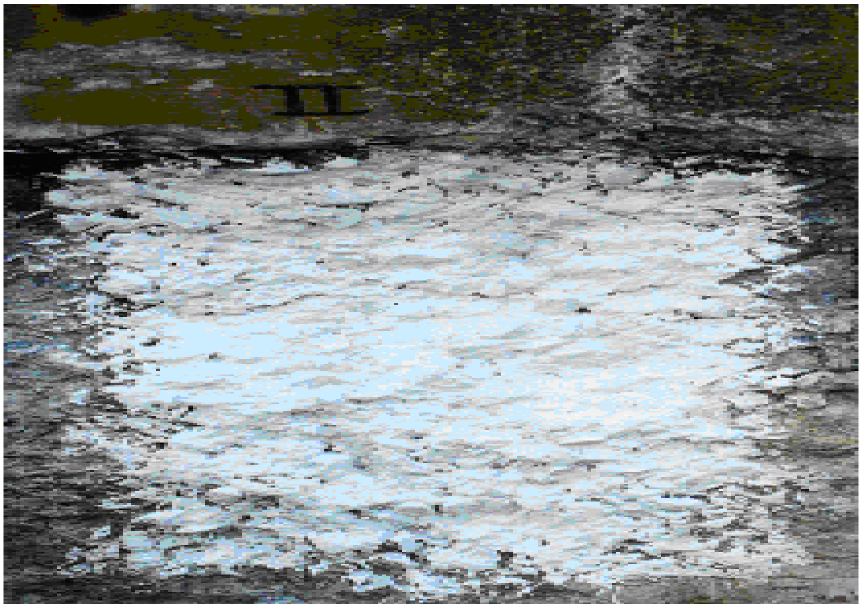

Figure 2.5 Application on Rough Surface with Spalled Areas

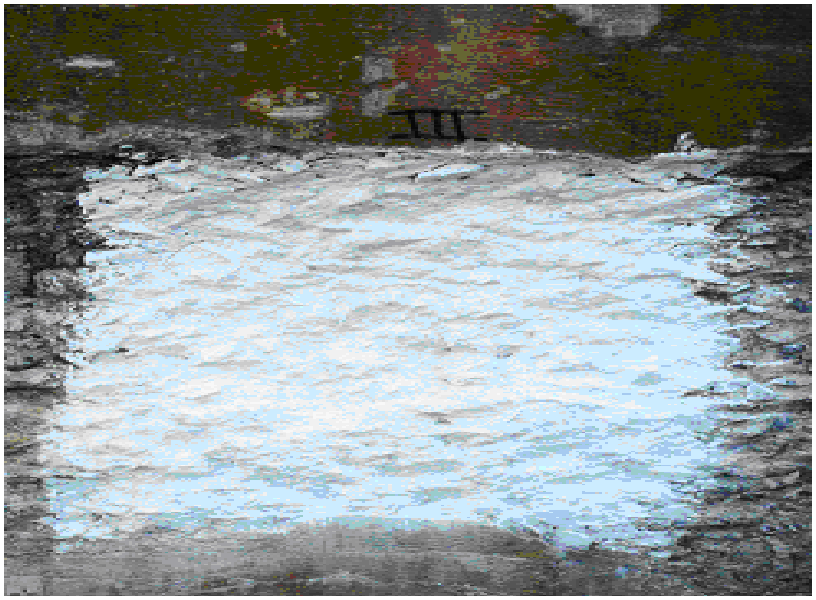

Figure 2.6 Application on Very Rough Surface with 95% of the Aggregates Exposed

2.4 Method of Application

Most of the applications were done by using paint brushes. In addition two types of sprayers, one a common commercial low cost sprayer and a custom made sprayer, were also used. Since both sprayers were effective, the authors recommend the low cost commercial unit for application. Based on the consistency and the flow through the various nozzles used in this study, the authors expect that any sprayer used for epoxies can be used for a Geopolymer matrix.

Chapter 3

Durability: Wet-Dry Conditions

3.1 Introduction

Continuous exposure to wet-dry conditions is detrimental to concrete used in construction. The degradation is more rapid for structures located in marine environments due to the presence of salt. Elements exposed to such environments are gradually weakened and will eventually have to be replaced or repaired. Typically, concrete on the exposed surface is weakened more rapidly than concrete within the structure. During placement, the presence of water near the formwork makes the surface concrete weaker because of an increase in the water-cement ratio resulting in faster degradation. Epoxy coatings have been used to increase the durability of exposed surfaces. High strength fibers made of aramid, glass or carbons have been used in conjunction with epoxies when strengthening is required.

Epoxies and other organic matrices have been utilized as a protective coating for several decades because they seal the surface of the concrete. Their main drawback is their inability to release vapor pressure buildup that causes damage in the concrete and delamination of the dried epoxy (ACI Committee 503, 1989). The results presented in this chapter focus on the inorganic matrices that comprise the next generation of barrier and strengthening systems. They are less permeable than concrete, thus slowing the flow of water through the weakened exterior surfaces. Vapor pressure is released because the matrices are not totally impermeable. In strengthening applications, the matrices form a strong bond between the surface of the concrete and the fiber reinforcement.

The objective of this part of the investigation was to evaluate the effect of wet-dry cycles found in marine environments. In barrier applications, the objective was to evaluate the coatings and the durability of coated concrete. In strengthening applications, the effectiveness of the matrices used in conjunction with carbon reinforcement was studied.

3.2 Experimental Evaluation

The Geopolymer matrix was used to bond continuous carbon fibers in the form of tows or fabrics. The reinforcement consisted of one, two or three tows, or one or two layers of unidirectional fabric. The area of one carbon tow was 0.00286 in^2 and the carbon fabric had an area of 0.0115 in^2. In addition, samples were strengthened with a discrete fiber reinforced mix. The Geopolymer matrix was comprised of a potassium alumino silicate solution and silica fume with no carbon contamination. The pure silica fume was needed to obtain a matrix that could be used to wet the carbon fibers. The standard formulation was as follows.

Liquid: 100g
Silica fume: 125g
Wetting Agent: 1g

3.2.1 Preparation of Concrete Prisms

Two mix proportions were used to prepare the concrete prisms. The dimensions of the prisms were 2 X 2 X 13 inches. <u>For the first concrete mix,</u> the cement : fine aggregate : course aggregate ratio was 1: 2.14 : 1.79. The maximum size of the course aggregate was 0.375 in. The water/cement ratio was 0.5. This concrete was designated as high strength concrete. <u>For the second concrete mix</u>, the cement: fine aggregate: course aggregate ratio was 1 : 2.95 : 2.04. Again, the maximum size of the course aggregate was 0.375 in. and the water/cement ratio was 0.6. This mix was designated as the low strength mix. The prisms were cast using 2 X 2 X 13 in. steel molds, covered with polyethylene sheets and kept for 24 hours at room temperature and humidity. At the end of 24 hours, the samples were removed from the molds and cured for 28 days in a room maintained at 100% relative humidity.

3.2.2 Application of Strengthening Systems

[The following procedure is similar to the procedure used for field applications as recommended by ACI Committee 515]. The concrete prisms were sand blasted and cleaned with a wire brush. Sand blasting was performed using silica quartz sand at a pressure of 80 psi. Once the surface was cleaned, a thin layer of the inorganic matrix was applied to fill the small air voids and to create a smooth surface. Pre-cut carbon tows and sheets were impregnated with the matrix and placed on the prepared concrete surface and bonded using grooved rollers. A second layer of the matrix was applied as a protective coating. The samples were cured for 24 hours at room temperature, followed by 24 hours at 80°C (176°F). The elevated temperature was used to ensure adequate curing in a two day period. The accelerated curing was used to save time. The high strength concrete prisms were used for the tests.

3.2.3 Test Procedure

Exposure to wetting and drying were the two major steps involved in testing the samples. . A special set-up was built for exposing the samples to wetting and drying. The samples were tested under flexure using a third point loading. The following sections provide the pertinent details.

Wet-Dry Chamber

A special set-up was built for exposing the samples to wetting and drying. A 53 X 27 X 24 inch stainless steel basin containing the specimens was elevated to a height of 4 feet. A reservoir containing 25 gallons of a 3% saline solution was installed beneath the basin. In an attempt to more closely duplicate marine environments, a commercial product named Instant Ocean™ was used to prepare the 3% saline solution. A heater and a temperature gage were attached to the salt water reservoir to insure that the water remained at a constant temperature of 100°F. Elevated temperature was used to further accelerate the deterioration process. The salt water was pumped from the reservoir to the basin containing the samples by a pump installed outside the reservoir. A timing valve attached to the drain of the basin controlled the flow of the water back into the reservoir. An 18 inch fan was installed 2 feet above the basin to help circulate air during dry cycles.

After the test specimens were placed in the stainless steel basin, the timer was set to allow for three hour wet and three hour dry cycles. At the beginning of each wet cycle, the pump filled the basin to a level that totally submerged the samples with salt water from the reservoir. After three hours, the basin’s drain valve opened allowing water from the basin to drain back into the reservoir and the fan began to circulate air above the basin. At the conclusion of the three hour dry cycle, the wet portion of the next cycle began. Visual inspection confirmed the complete drying of the samples.

Flexure Test

Samples strengthened with carbon reinforcement were tested in flexure using a three point bending test. The simply supported clear span was 12 inches. The load was applied using an MTS testing machine with a 10,000 lb. capacity. The mid-span deflection was measured using an LVDT. Both load and deflection were recorded by a computer.

3.3 Test Variables and Results

The test samples consisted of the following:

- Two control samples
- Two samples strengthened with two or four percent (by weight) discrete carbon fibers
- Two samples strengthened with one, two or three carbon tows
- Two samples strengthened with one or two layers of carbon fabric

For each variable, two samples were tested at 0, 50, and 100 cycles of exposure. The objective was to determine whether discrete fibers would add strength and toughness to plain concrete and whether it is possible to add continuous reinforcement (tows and fabric) to plain concrete. In both cases, the wet-dry cycling provided the information on durability. Note that the carbon fibers do not corrode and therefore the failure can only occur because of the deterioration of the matrix or the interface.

The response variables were maximum strength, flexural stiffness and toughness. All of these parameters were obtained from the load deflection response. Only the strength results are presented in this report. The performance was similar for toughness and flexural stiffness.

A comparison of the failure loads is shown in Figures 3.1 to 3.3, Pages 21 & 22. For each case, these figures show the average result for the two tested samples. The failure loads are presented as a factor of the failure load of the unexposed control sample. Flexural strength of the control samples improved after exposure to wet-dry conditions.

In some cases, after 100 cycles of wet-dry, the failure load of the control samples had increased by approximately 50 percent. This increase occurred because of continued curing since the testing of the exposed samples was done at a later date.

In all cases, the strengthened samples were durable up to 100 cycles of wetting and drying. The strength and ductility of the concrete samples was increased by the application of the carbon composite system. Peak load and toughness factor values increased as the area of the carbon reinforcement was increased. Effectiveness of the strengthening system was not diminished by exposure to wet-dry conditions.

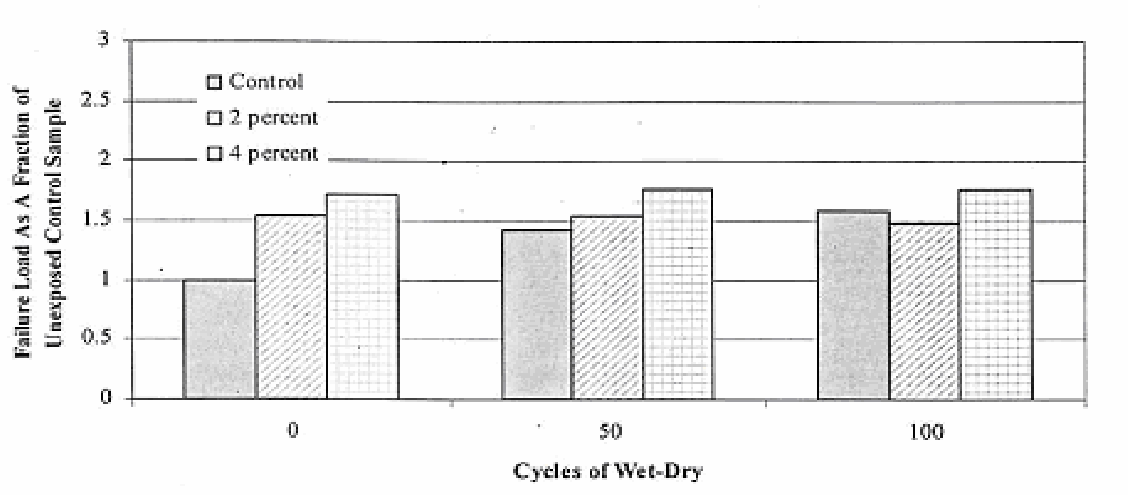

Figure 3.1 Comparison of Failure Loads: Control, 2 Percent and 4 Percent Discrete Carbon Fibers

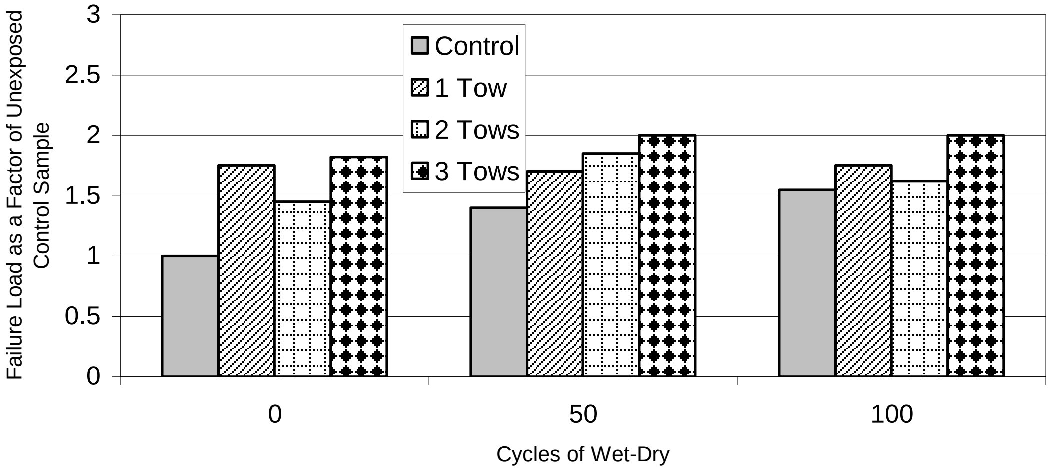

Figure 3.2 Comparison of Failure Loads: Control, 1, 2 and 3 Carbon Tows

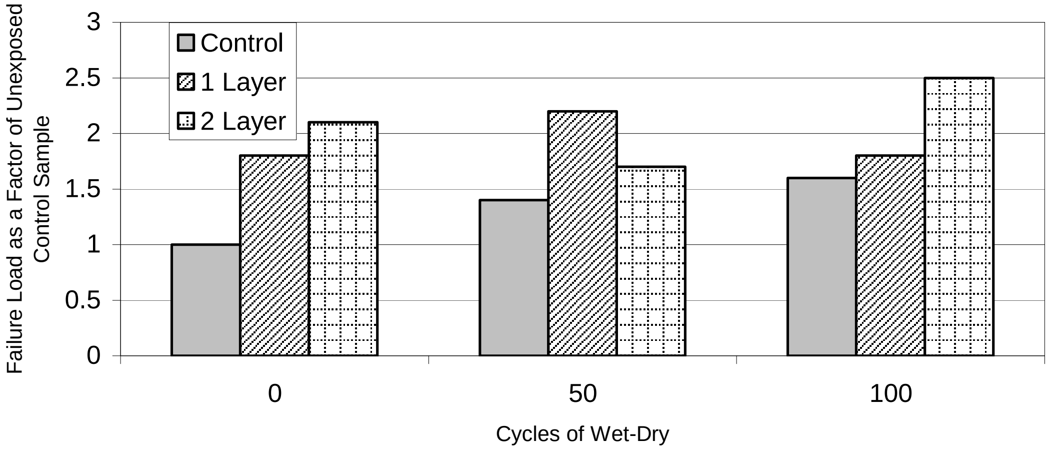

Figure 3.3 Comparison of Failure Loads: Control, 1 and 2 Carbon Fabric Layers

Chapter 4

Durability: Scaling Conditions

4.1 Introduction

The presence of stagnant or ponded water in cold weather environments will lead to the eventual decay of concrete surfaces. Scaling is one of the results of repeated cycles of freezing and thawing in hardened concrete. When the concrete is permeable, moisture flows through the surface of the concrete into any existing voids. When the temperature drops below 0°C, the absorbed water freezes and expands. This expansion causes stress build up that leads to cracking and spalling of the concrete surface. Scaling occurs when the expansion pressure of the ice exceeds the tensile strength of the concrete causing localized fracture at the surface.

One possible solution to the problem of scaling in concrete is to apply a protective coating that will cover existing micro-cracks. The coating should have a lower permeability than the concrete. If the flow rate of water into the structure of concrete is decreased, the damage caused by the freezing cycle can be slowed or prevented. The inorganic matrices evaluated in Chapter 3 have excellent potential in such an application. These matrices can also be used to bond glass or carbon reinforcement to structural elements that need strengthening. Scaling of the surface of the concrete reduces the effectiveness of the repaired structural elements. Deterioration weakens the bond between the surface of the concrete and the carbon reinforcement and may result in delamination and subsequent failure of the repair.

This chapter presents the results of the scaling resistance study, which is conducted using inorganic matrices and carbon fibers. The system can be used for both coating and strengthening.

4.2 Experimental Investigation

The effectiveness of the inorganic geopolymer matrix (described in Section 3.2) as a surface protector for concrete was evaluated. The matrices were applied to both a high and low strength mortar and subjected to scaling conditions. The matrices used as a surface protector were evaluated using an ASTM rating system throughout the series of scaling cycles (American Society for Testing and Materials, 1996).

Additionally, the effectiveness of a strengthening system consisting of an inorganic matrix used in conjunction with several commercially available forms of carbon (discrete fibers, continuous fiber tows, and fabrics) was studied. In strengthening applications, the effectiveness of the matrix was studied using flexure tests after exposure to scaling conditions. The strength tests were done for high strength concrete samples.

4.2.1 Sample Preparation

Preparation of the samples was done using the procedure described in Chapter 3. First, 2 X 2 X 13 inch prisms were cast and cured. These prisms were coated with the various matrices or strengthened with carbon reinforcement.

4.2.2 Scaling Test Set-Up

A special set-up was built for exposing the test samples to scaling conditions. Rectangular dams were built to fit atop the coated surface of the specimens. The height of the dams was one inch. The dams were attached to the coated surface of the samples with a bead of water proof caulk. Saline solution was contained in the dams atop the samples to a depth of one-fourth of an inch. A mixture of various form of salt, commercially known as Instant Ocean™, was used in the saline solution to duplicate marine environments. A schematic of the scaling test set-up is shown in Figure 4.1.

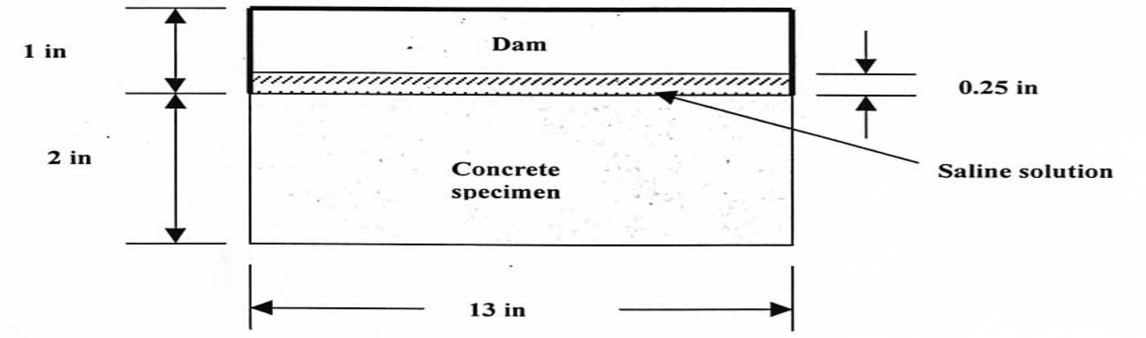

Figure 4.1 Schematic of Scaling Test Specimen

The scaling test described in ASTM C672 was designed to allow the completion of one scaling cycle in a 24-hour period (American Society for Testing and Materials, 1993). The samples with the dams containing the saline solution were placed in a freezing chamber maintained at 0°F. At the end of this freezing cycle, which lasted for 8 hours, the samples were removed from the freezing chamber and kept at room temperature for 16 hours. Therefore, one scaling cycle (freezing and thawing) took one day. At the completion of five scaling cycles, the surfaces of the samples were rinsed and the saline solution was replaced. The samples were exposed to a total of fifty scaling cycles. In certain instances, the testing was discontinued prematurely because the deterioration of the sample prevented containment of the saline solution.

4.2.3 Evaluation Procedure: Surface Condition

The barrier coatings were applied to protect the surface of the samples from the damaging effects of repeated scaling cycles. Deterioration is confined to the surface of the specimens, unlike in the wet-dry cycles where the concrete was weakened internally. A visual evaluation of the samples was sufficient to determine the effectiveness of the barrier coatings. The rating system described in ASTM C672 was used to evaluate the specimens in this chapter. Scaling of the samples was quantified using the system shown below.

(0): Little or no scaling
(1): very slight scaling (2): slight to moderate scaling
(3): moderate scaling
(4): moderate to severe scaling
(5): severe scaling

The samples were evaluated and photographed before exposure to scaling conditions. Additional evaluations were made at the completion of every fifth scaling cycle.

4.3 Test Results: Surface Condition

The data obtained from the durability testing of concrete samples under scaling conditions, evaluated with the rating system introduced in ASTM procedure C672, is presented in Figures 4.2 and 4.3, next page. Performance of the low strength concrete control samples (no coating) is presented in Figure 4.2. The first sample degraded to Level 5 in 15 cycles and broke into pieces. The second sample degraded to Level 5 in 15 cycles and broke into pieces at 25 cycles. The performance of the coated samples for low strength concrete is shown in Figure 4.3. One specimen did not develop any damage and the second one reached moderate scaling at 30 cycles.

High strength concrete samples, with and without coating, did not develop any surface or other damage after 50 cycles of scaling. Since this test method is very subjective, strength tests were performed and the results are presented in the next section.

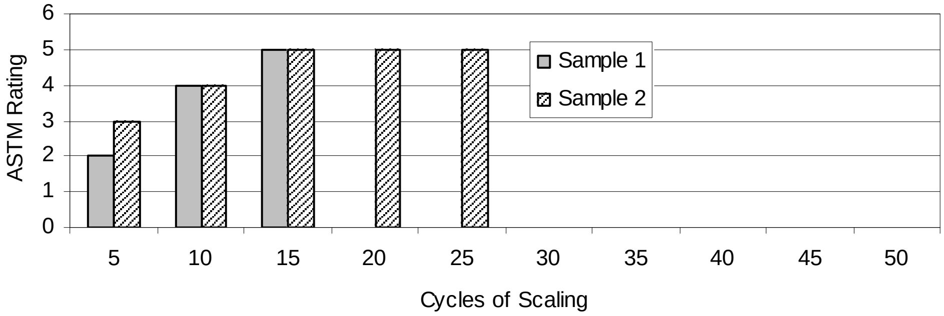

Figure 4.2 Surface Condition of Samples Subjected to Scaling Conditions, Low Strength Concrete and Control

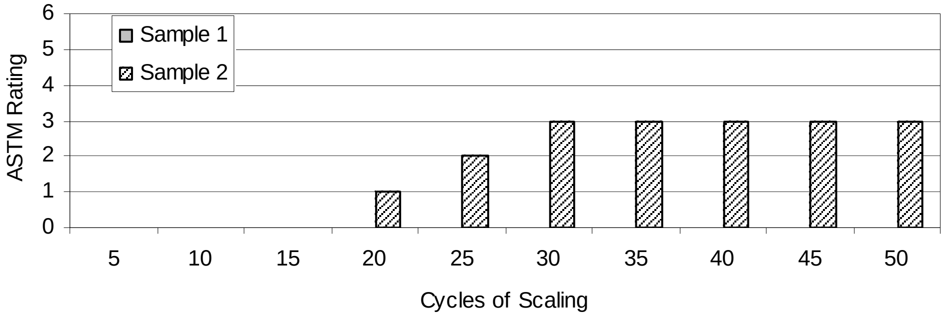

Figure 4.3 Surface Condition of Coated Samples Subjected to Scaling Cycles, Low Strength Concrete

4.4 Test Results and Discussion: Strength Tests

Flexure testing was used to evaluate the strengthened samples exposed to scaling conditions. The test procedure and set-up are described in Chapter 3, Section 3.2.3, of this report. Evaluation was made at the completion of fifty scaling cycles. The data obtained from the flexure testing of samples strengthened with carbon reinforcement is shown in Figures 4.4 to 4.6, below and next page. Included in these figures are the results obtained from the control samples and samples reinforced with chopped carbon fibers, carbon tows and layers of carbon fabric. For each test variable, two samples were tested. Figures 4.4 to 4.6 show the average result for the two tested samples. Unexposed samples and samples exposed to fifty cycles of scaling were evaluated. The increase in strength shown in these figures for the control samples at 50 cycles occurred because of continued curing, since the testing of the exposed control samples was done at a later date.

Insignificant changes in the flexural strength of the strengthened samples were noted after exposure to the scaling conditions. Exposed strengthened samples maintained at least 97 percent of their unexposed flexural strength.

The strengthening system comprised of layered carbon and the inorganic matrix was proven to be durable in scaling environments. The carbon maintained a strong bond with the concrete and delamination did not occur. The flexural properties of the exposed samples were comparable to those of the unexposed samples.

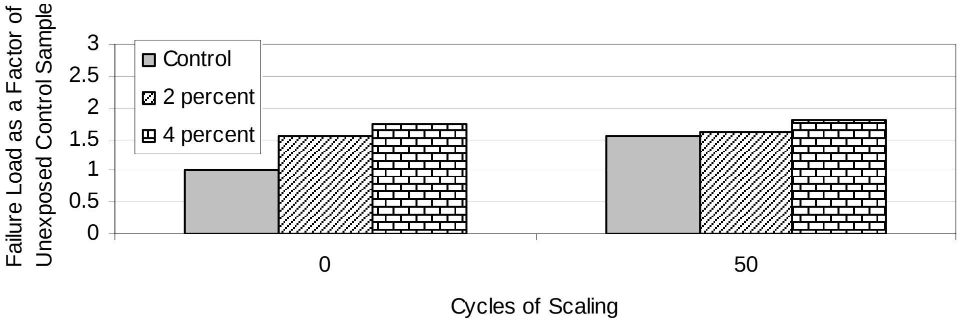

Figure 4.4 Comparison of Failure Loads: Control, 2 and 4 Percent Discrete Carbon Fibers

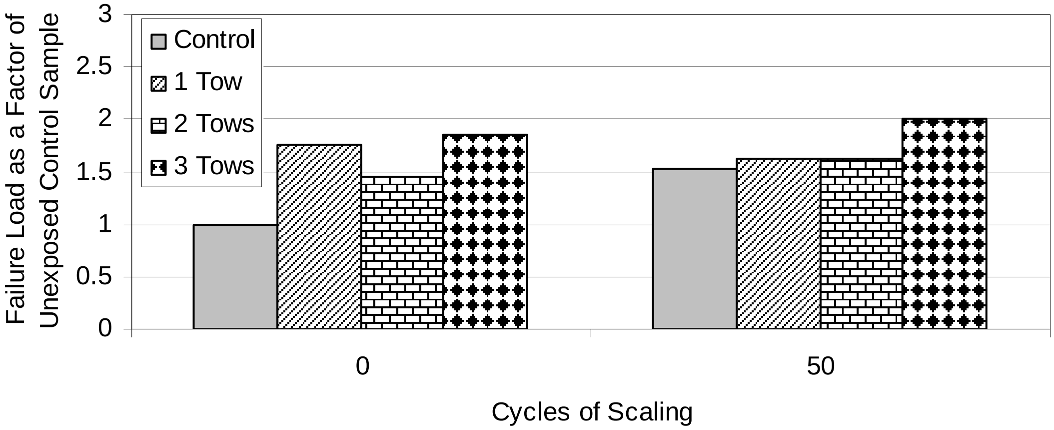

Figure 4.5 Comparison of Failure Loads: Control, 1, 2, and 3 Carbon Tows

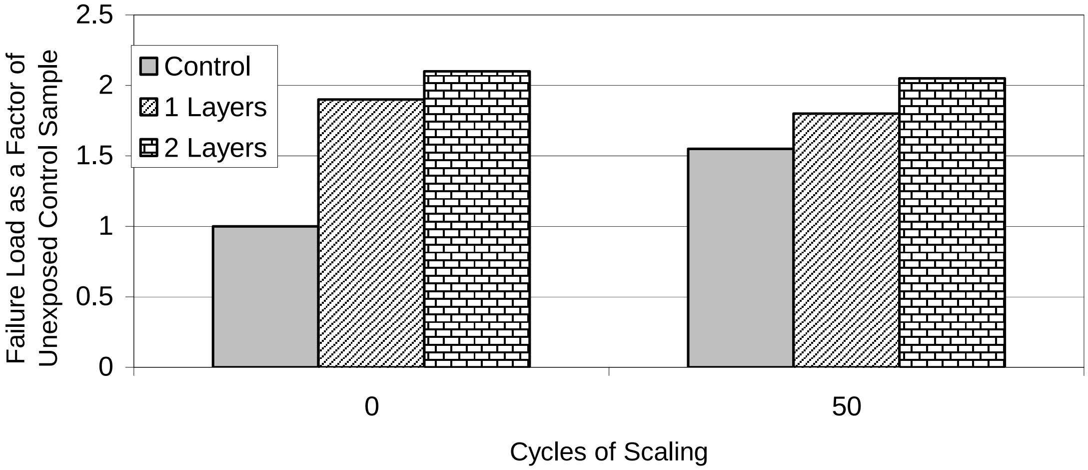

Figure 4.6 Comparison of Failure Loads: Control, 1 and 2 Carbon Fabric Layers

4.5 Summary

Exposure of scaling environments is detrimental to the surface of concrete elements used in construction. In this chapter, the ability to prevent such degradation by the application of a protective coating was studied. Because structural concrete of various strengths is used in practice, high and low strength concrete mixes were used in this investigation. The high strength concrete used in this investigation was able to resist scaling without the application of a barrier coating. The low strength samples were susceptible to surface damage when exposed to the scaling conditions. The destruction of the surface of the low strength samples was significantly slowed or prevented by the application of the Geopolymer coating.

The effectiveness of strengthening applications using high strength fibers can be hampered by exposure to scaling environments. The system studied in this chapter was comprised of inorganic matrix and various forms of carbon. The results obtained from the flexure testing of these samples indicate that the system is resistant to scaling conditions. The flexural strength and ductility of the specimens were determined before and after exposure to the scaling conditions. Comparable results were observed regardless of the type of carbon reinforcement used.

Chapter 5

Field Durability Study and Demonstration Applications

5.1 Field Durability Study

Durability under field (outside exposure) conditions was evaluated using two locations at the Rutgers University Campus in New Brunswick, New Jersey. The first location, at the Livingston Campus also served as a test bed for application of the geopolymer coating to surfaces with different levels of deterioration. A total of 18 test applications were made. Most of the surfaces were on vertical walls and some of them were on a relatively smooth concrete surface, Figures 2.2 - 2.6, Pages 13 -15. In the case of vertical walls, the surface deterioration varied from a weathered but good concrete surface to completely spalled (with exposed aggregate) surface, Figure 2.6, Page 15.

In addition to surface deterioration, a second major variable was fiber type and fiber volume content. Both micro and discrete fibers were evaluated at volume fractions ranging from 0.5 to 20%. These applications also served as demonstration projects confirming that very little surface preparation is needed. All these surfaces were cleaned with low pressure water and allowed to dry to saturated surface dry conditions before applying the coating. All but two coatings were applied using paint brushes. One coating was applied using a custom made sprayer and another coating was applied using an inexpensive sprayer. The coatings were applied between March and November to evaluate the influence of temperature range.

The second set of coatings was applied on the curbs of a parking lot on Busch Campus, Figures 5.1(a), 5.1(b) and 5.1(c), next page and Page 32. These curbs had a good surface except in one case; part of the curb was broken. The surfaces were simply wetted before the application of the coating. In these applications, the coatings were subjected to snow exposure and abrasion of snow removal equipment. There was also abrasion due to sand or dust particles blown by the wind.

Experience gained during these applications was used to formulate the recommended application procedure presented in Appendix A. These applications confirmed the earlier findings, that the coating can be applied on a pre-wetted surface at ambient temperatures between 40° and 90° F. After mixing, the geopolymer matrix can be stored in cold temperatures to increase the pot life. The coated surface becomes dry after 4 hours and can resist a moist environment, including fog and drizzle. In one case, it rained 2 hours after the application but the coating was not affected.

Figure 5.1(a) Coating on Concrete Curb on Busch Campus

Figure 5.1(b) Coating on Concrete Curb on Busch Campus, the Second Set

Figure 5.1(c) Coating on Concrete Curb on Busch Campus, a Close Up View

5.2 Field Applications on Transportation Structures

Field applications consisted of: (1) Coating a New Jersey Barrier in Trenton, N.J., (2) Coating a guide rail near Trenton, (3) coating a retaining wall on Route 18 in New Brunswick, (4) Coating a New Jersey Barrier near an ocean front in Rhode Island, and (5) Coating of curbs and a retaining wall on Route 1 and Route 295 near Providence, Rhode Island.

The coating application on Route 1, Trenton was carried out with the cooperation of NJDOT engineers and field personnel, see Figure 5.2, next page. The NJDOT provided traffic control and pre-wetting. Graduate students and NJDOT field personnel applied the coating with paint brushes.

The retaining wall coating on Route 18 was applied in November 2000 and covered about 10 square feet. This coating contained only micro fibers and was applied using paint brushes on the pre-wetted surface.

The coatings in Rhode Island were applied in October 1998 and April 1999 (see curb, Figure 5.3, next page). Coatings on NJ barriers and curbs were applied using paint brushes and the coating on the retaining wall was applied using a power sprayer. The retaining wall on which the coating was power sprayed covered several hundred square feet.

All the applications on the concrete surfaces are performing well. The first application is about 8 (in 2008) years old. The coating application to the guide rail in Trenton, N.J. was not successful.

These projects demonstrated the viability of field application using paint brushes and a power sprayer.

Figure 5.2 Coating on Route 1 South, Close-Up View

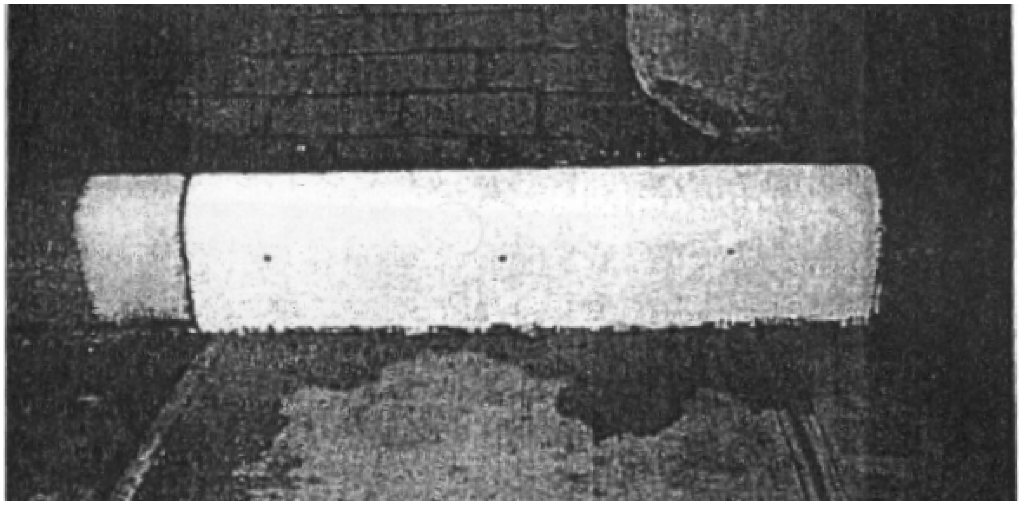

Figure 5.3 Application of Coating on Curb in Rhode Island

Chapter 6

Conclusions

This report focus on the development of an inorganic geopolymer matrix that can be used both as a protective coating and also as a strengthening coating with the addition of micro, discrete, and continuous carbon fibers and carbon fabrics. Durability studies led to the following conclusions.

- The geopolymer coating is durable in wetting and drying conditions. Concrete samples coated with carbon reinforced geopolymer did not degrade after 100 cycles of wetting and drying.
- Under scaling conditions, the geopolymer coating slowed or prevented damage to the surface of the coated concrete samples.

Evaluation of plain concrete strengthened with an inorganic geopolymer coating and subjected to wetting & drying and scaling conditions led to the following conclusions.

- The inorganic matrix in combination with carbon tows and carbon fabrics can be used to strengthen plain concrete members.
- Wetting and drying conditions (100 cycles) do not decrease the strength of samples coated with carbon reinforced geopolymer.
- Strengthened samples exposed to scaling conditions had a small (about 3%) decrease in strength from their unexposed strength.

Evaluation of the geopolymer matrix for field applications, which is the main focus of this study, led to the following conclusions:

- The geopolymer coating can be applied in the ambient temperature range of 40 to 90° F. At temperatures higher than 80°F, the pot life might be less than 2 hours.

- The coated surface should be protected from direct rain or running water for the first 24 hours.
- The coating should not be subjected to freezing in the first 24 hours.
- The geopolymer coating can be applied to new or weathered concrete surfaces that have exposed aggregates.
- The surface should be pre-wetted. Loose and oily materials should be removed. Light dust will not reduce the adherence of the geopolymer coating material.
- The geopolymer coatings are durable in field conditions. The oldest application, under saltwater exposure conditions in Rhode Island, is 9 (in 2008) years old.

Appendix A

Guidelines for Application of Inorganic Geopolymer Coating

Surface Preparation

The coating can be applied on both good and weathered surfaces. Loose dirt and oily build-ups should be removed. The surface should be pre-wetted to saturated surface dry condition.

Material and Equipment Needed

The Geopolymer matrix is supplied as a two component system. The liquid Part A should be mixed with powder Part B using a high shear mixer or mixing blades attached to industrial strength drills used for mixing paints or polymers. Fibers can be added during the mixing.

Mixing Procedure

Part A, Part B and any additives, such as fibers, should be mixed to a uniform paint like consistency.

Application Procedure

The coating can be applied using a brush, roller, or sprayer. Inexpensive slurry systems used for spraying stucco or cement slurry can be used.

Protection for the First 24 Hours

The coated surface should be protected against heavy rain, running water, and freezing for the first 24 hours. The coating will cure to a hard surface in dry or foggy conditions.

Temperature range for application is 40° F to 90° F.

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