ASSESSMENT OF MOISTURE-TOLERANT COATINGS FOR DECREASING OPEN TOP CONSTRUCTION TIME

By
Christine Keith, Mohammad Amin Dehghani Najvani,
Matthew O'Reilly, Mario Medina, David Darwin,
Ali Natheer Abdul Baki, Luay Ali Nazzal,
Kyoung Ok Lee

A Report on Research Sponsored by

Electric Power Research Institute

Structural Engineering and Engineering Materials
SM Report No. 123
April 2017

THE UNIVERSITY OF KANSAS CENTER FOR RESEARCH, INC.
2385 Irving Hill Road, Lawrence, Kansas 66045-7563

ASSESSMENT OF MOISTURE-TOLERANT COATINGS FOR DECREASING OPEN TOP CONSTRUCTION TIME

By:

Christine Keith

Mohammad Amin Dehghani Najvani

Matthew O'Reilly

Mario Medina

David Darwin

Ali Natheer Abdul Baki

Luay Ali Nazzal

Kyoung Ok Lee

A Report on Research Funded by

THE ELECTRIC POWER RESEARCH INSTITUTE

Structural Engineering and Engineering Materials
SM Report No. 123

THE UNIVERSITY OF KANSAS CENTER FOR RESEARCH, INC.
LAWRENCE, KANSAS
APRIL 2017

ABSTRACT

Open top construction is a practice commonly used in the construction of large structures, such as nuclear power plants, as it allows large equipment to be easily placed by lowering it into position from above. Doing so, however, requires the concrete floor to be finished and coated prior to placement. Current coating manufacturer recommendations state that concrete should be allowed to dry for a minimum of 28 days prior to coating application to avoid compromising the bond between the coating and the concrete or between coating layers that could result from excessive moisture. This requirement delays the construction process, adding significant costs. The ability to apply coatings without damage prior to 28 days would greatly reduce construction time and cost.

Ten coating systems were evaluated in this study. The coatings were applied 7, 14, 21, 28, and 45 days after the end of wet curing. Coating adhesion was evaluated using the Standard Test Method for Pull-Off Strength of Coatings on Concrete Using Portable Adhesion Testers and the Standard Test Method for Evaluating Adhesion by Knife 7, 21, 28, and 56 days after application of the final top layer of the coating systems. Moisture vapor emission rate (MVER) and concrete relative humidity (RH) were monitored throughout the tests. Most but not all of the coatings investigated in this study may be applied to concrete as early as 7 days after completion of wet curing, at MVER values over 10 lb/1000 ft^2/day (565 μg/m^2/s) and internal relative humidity (RH) above 80%, without significant adverse effects on coating adhesion, offering the potential to speed open top construction of nuclear power plants. The thickness of concrete does not affect the value or rate of change in MVER or RH. Thicker coatings exhibit relatively poor performance in the knife test compared to thinner coatings. Coating systems should be evaluated to ensure that they can be successfully applied at early ages. Larger-scale prototype early-age applications should be performed and subjected to the full range of required testing for the appropriate Service Level prior to wide-scale application of these findings.

Keywords

adhesion, coatings, concrete, construction schedule, moisture vapor emission rate, relative humidity

ACKNOWLEDGEMENTS

This report is based on a report presented by Christine Keith in partial fulfillment for the requirements for the M.S. degree from the University of Kansas. Support for the study was provided by the Electric Power Research Institute. Materials were supplied by the Carboline Company, Flowcrete Group Ltd., PPG Industries, Inc., Warren Environmental Inc., and Midwest Concrete Materials. Thanks are due to David Scott who provided project oversight for the Advanced Nuclear Technology Program of the Electric Power Research Institute.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1 INTRODUCTION

1.1 General

The construction of nuclear power plants is a time-consuming and costly process; reducing construction time and expense is of critical importance. As such, the use of open top construction has become common in the construction of nuclear power plants around the world. This type of construction allows large equipment to be placed inside a structure before the next level is built. The equipment is typically placed on concrete slabs after the application of a floor coating. This can result in significant delays during construction, as most floor coatings require a 28 to 60 day waiting period between the end of wet curing of the concrete and the application of the first coating layer (such as a primer or other first layer of a multi-coating system). Alternatives, such as installing the equipment on uncoated slabs with temporary protective barriers or installing the equipment after placement of the overhead slab, pose other difficulties that increase the cost of construction. Significant cost savings can be achieved by applying coatings at earlier ages. There is, however, a concern that a significant amount of moisture from the "green" concrete can rise to the surface and compromise the bond between the coating and the concrete, between layers of coating (such as the primer and the top coat), or both, causing problems such as disbondment, blistering, and/or adhesive breakdown (Craig 2003).

1.2 Background

Coating manufacturers require extended curing times to minimize damage due to an excessive rate at which moisture leaves the surface of the concrete or high relative humidity (RH) within the concrete (Carboline 2005, 2012, 2015a, 2015b, Flowcrete 2012, 2015, PPG 2016a, 2016b, Warren Environmental 2016). Freshly mixed concrete has a relative humidity of 100%; this water is necessary for the concrete to hydrate and gain strength. As the concrete cures and then dries, the relative humidity of the concrete decreases. This decrease occurs more rapidly at the surface of the concrete than in the interior. The rate at which moisture vapor leaves the surface of the concrete is known as the moisture vapor emission rate (MVER).

A high MVER or RH in the concrete can cause problems, such as blistering (Figure 1.1), delamination, adhesion loss (Figure 1.2), or delamination (Figure 1.3), as escaping water becomes trapped under the coating. These problems are well documented for impermeable floor coverings, such as the tile and vinyl coverings pictured in Figures 1.1 through 1.3. Although very little research has addressed the susceptibility of thinner epoxy-based two-part coatings to this type of damage, the well-documented problems with floor coverings have been used to develop guidelines for coating application and are the principal reason for the long concrete drying times used by the industry. Thus, out of an abundance of caution, coating manufacturers have generally adopted MVER and relative humidity guidelines similar to those used by the damage-prone floor coatings, recommending an MVER no higher than 3-5 lb/1000 ft^2/day (170-283 $\mu g/m^2/s$), an internal relative humidity no more than 70 to 90%, or both. This is in spite of the fact that newer coating systems have been developed that should be more adaptable to moisture flow. Based on discussions in preparation for this study, it became clear that coating manufacturers have never evaluated the true capabilities of these new systems.

It can take weeks or months for concrete to reach MVER or relative humidity levels deemed acceptable based on current guidelines, creating potential delays in construction. Furthermore, the time to reach the desired MVER can vary based on the concrete mixture proportions, initial curing method, and long-term environmental exposure conditions. Suprenant (1997) analyzed work by Brewer (1965), investigating concrete with water-cement (*w*/*c*) ratios between 0.4 and 1.0 exposed to varying environmental conditions. It was found that it would take between 46 days and more than 365 days for concrete to reach an MVER of 3 lb/1000 ft^2/day (170 $\mu g/m^2/s$), with higher *w*/*c* ratios and exposure to external moisture extending the time to reach the desired MVER. Subsequent research by Suprenant and Malisch (1998b) found no decrease in drying time for *w*/*c* ratios below 0.40. Suprenant and Malisch (1998a) also examined the effect of slab thickness on drying time and found no significant difference in drying time for slabs ranging in thickness from 2 in. to 8 in. (51 mm to 204 mm). This finding suggests laboratory specimen results may be applied to field findings. Thicker concrete slabs, however, such as are commonly used in nuclear power plant construction, were not investigated.

Figure 1.1: Blistering under a floor covering (ACI 302.2R-06)

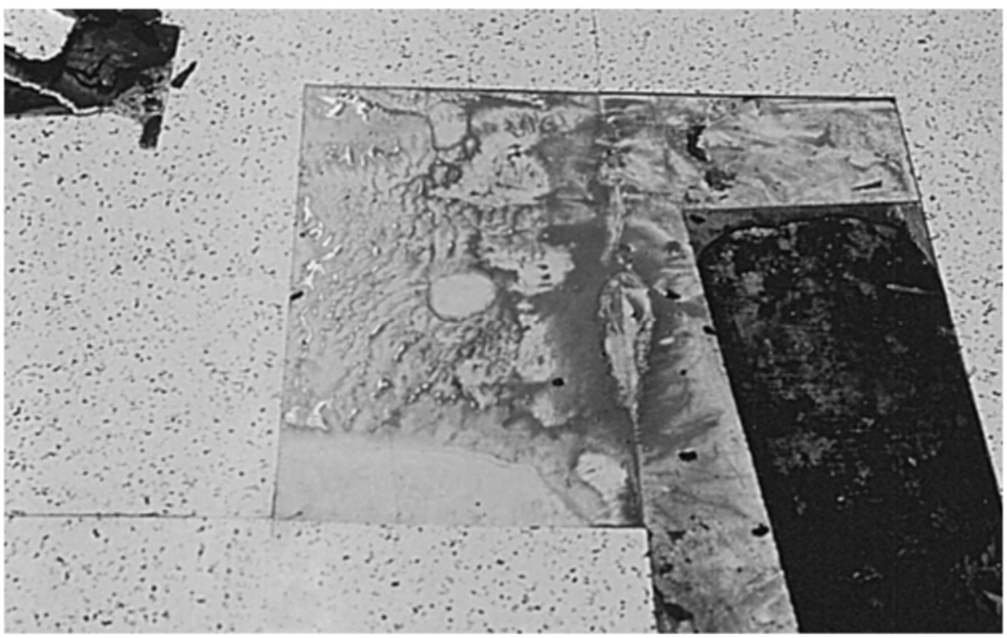

Figure 1.2: Adhesive failure in solid vinyl tile (ACI 302.2R-06)

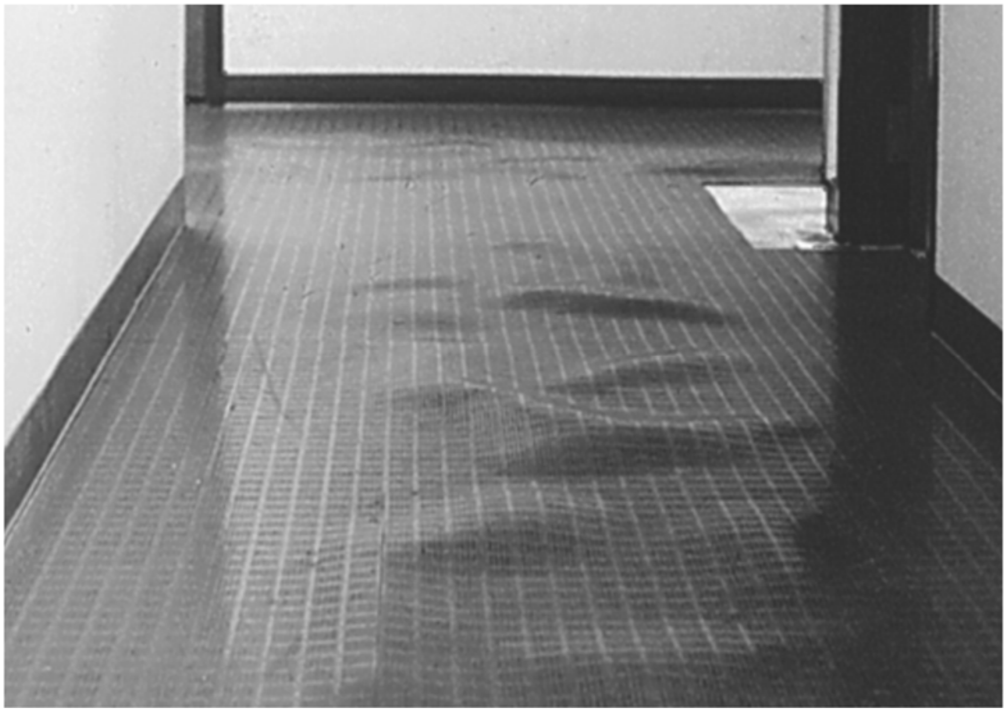

Figure 1.3: Debonding of floor covering (ACI 302.2R-06)

1.3 Objectives and Scope

This study investigated the performance of ten moisture tolerant coatings when applied to concrete at early ages. The current recommendations for moisture vapor emission rate (MVER) and relative humidity (RH) were evaluated to determine if the coatings under study can be applied at higher MVER or relative humidity values without significant reductions in adhesion strength. The results can be used to establish a technical basis for the time of application of moisture tolerant coatings.

In addition, a comparison of MVER and RH over time for concrete specimens with thicknesses of 6 in. and 24 in. (153 mm and 610 mm) was performed to establish if the findings of this and other studies may be applied to thick concrete slabs.

Chapter 2 EXPERIMENTAL WORK

Two types of concrete specimens were used in the study. The first type, referred to as "slab specimens," measured 3 ft × 4 ft × 0.5 ft (910 mm × 1200 mm × 150 mm). These specimens were used to test the performance of moisture tolerant coating systems applied to concrete surfaces after various periods of drying. To this end, coatings were applied 7, 14, 21, 28, and 45 days after the cessation of wet curing. . Wet curing for these specimens consisted of a seven-day period after casting during which the concrete was covered with wet burlap and plastic sheeting. Coating adhesion was evaluated using the Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers (ASTM D7234) and the Standard Test Method for Evaluating Adhesion by Knife (ASTM D6677) 7, 21, 28, and 56 days after application of the final top layer of the coating system. In addition, moisture vapor emission rate (MVER) and internal relative humidity were measured in accordance with the Standard Test Method for Measuring Moisture Vapor Emission Rate of Concrete Subfloor Using Anhydrous Calcium Chloride (ASTM F1869) and the Standard Test Method for Determining Relative Humidity in Concrete Floor Slabs Using in situ Probes (ASTM F2170), respectively. These tests are described later in this chapter. The second type of specimen, referred to as "block specimens," measured 2 ft × 2 ft × 2 ft (610 mm × 610 mm × 610 mm) and was used to investigate the effects of concrete thickness on MVER and internal relative humidity. The specimens were cast and tested in three series.

2.1 Coating Systems

Ten coating systems from four manufacturers, identified as A through D, were tested. The systems were applied in one, two, or three layers, as shown in Table 2.1. Table 2.2 provides a general description of the coating materials. The coating systems are designated both by a number and by the coating materials used in the various layers. For example, coating system 1 (A1/A2) consists of a primer coat, consisting of coating material A1, and a second layer, or top coat, consisting of coating material A2. Coating system 10 (D1) was applied in a single layer.

Table 2.1: Coating Systems and Manufacturer

Coating System	Primer/First Layer	Second Layer	Third Layer	Manufacturer
1 (A1/A2)	A1	A2		A
2 (A1/A4)	A1	A4		A
3 (A3/A4)	A3	A4		A
4 (A3/A4×2)	A3	A4	A4	A
5 (A4/A4)	A4	A4		A
6 (B1×2)	B1	B1		B
7 (B1×2/A4)	B1	B1	A4	B/A
8 (B2×2)	B2	B2		B
9 (C1/C2)	C1	C2		C
10 (D1)	D1			D

Table 2.2: Descriptions of Coating Materials

Product Identifier	Coating Material
A1	Damp-proof epoxy primer
A2	100% solids epoxy self-leveling coating
A3	Polyamidoamine epoxy penetrating primer/sealer
A4	Cycloaliphatic amine self-priming epoxy coating
B1	Solvent and water free epoxy resin
B2	Vapor permeable, water-dispersed epoxy coating
C1	Amidoamine epoxy sealer
C2	Amine self-leveling epoxy coating
D1	Full viscosity base epoxy coating

The coating materials were two-part epoxies. After preparing the concrete surface (Section 2.2.2), the individual coatings were mixed and applied according the manufacturer's specifications. Table 2.3 shows the volume of each part of the coatings, how much was applied to a specimen, and the application tool used to apply the coating. A jiffy mixer was used to mix the two-part epoxies. Two coating materials, A2 and C2, contained visible particles in the coating after mixing. In accordance with the manufacturers' recommendations, these coatings were strained using a 30-mil (0.76 mm) mesh strainer before application. Coating system 7 (B1/B1/A4) (Table 2.1), consisting of coating materials B1 and A4, was the only system evaluated with coatings from two different manufacturers; this combination is a manufacturer-approved system with the potential for early application to concrete.

Table 2.3: Coating Volumes and Application Tools

Product	Part	Volume Proportions	Actual Mixing Volume oz (ml)	Volume Applied to 1 ft^2* oz (ml)	Application Tool
A1	A	2	1.0 (30)	0.68 (20)	Brush
	B	1	0.51 (15)		
A2	A	2.2	2.2 (66)	2.4 (71)	Notched squeegee and back rolled with a spiked roller
	B	1	1.0 (30)		
A3	A	1	0.34 (10)	0.17 (5)	Brush
	B	1	0.34 (10)		
A4	A	1	0.68 (20)	0.74 (22)	Brush
	B	1	0.68 (20)		
B1	A	2	1.4 (40)	0.64 (19)	Roller
	B	1	0.68 (20)		
B2	A	1	0.68 (20)	0.57 (17)	Roller
	B	4	2.7 (80)		
C1	A	1.5	0.51 (15)	0.29 (8.7)	Brush
	B	1	0.34 (10)		
C2	A	2.1	5.4 (160)	3.2 (95)	Notched squeegee and back rolled with a spiked roller
	B	1	2.5 (75)		
D1	A	1	1.0 (30)	1.6 (47)	Roller
	B	2	2.0 (60)		

*1 ft^2 = 0.0929 m^2

2.1.1 Coating Thickness

Dry film thickness was measured after the coating systems had cured for 28 days using Procedure C of Standard Practices for Measurement of Dry Film Thickness of Protective Coating Systems by Destructive, Cross-Sectioning Means (ASTM D4138). In accordance with the procedure, a drill bit with a 45-degree angle on the tip was used to create a hole through the coating. The horizontal projection of each layer in a coating system equaled the thickness of the layer. Measurements (four per sample) were made using a magnifying crack comparator. Table 2.4 shows the recommended dry film thicknesses provided in the manufacturers’ literature along with measured dry film thicknesses. In most cases, the coating thicknesses were within the manufacturer's recommended range, except for coating material B1. The thickness of coating material B1 was less than one-third of the manufacturer-recommended thickness. Coating materials A2 and C2 were significantly thicker than the others with thicknesses between 20 and 35 mils (510 and 890 μm) and 35 and 50 mils (890 and 1270 μm), respectively. No other coating material exceeded 15 mils (380 μm) in thickness. The manufacturer of coating material D1 did not provide a specific value for coating thickness.

Table 2.4: Coating Thickness

Coating Material	**Recommended Dry Film Thickness, mil (μm)***	**Average Measured Dry Film Thickness, mil (μm)**	**Measured Dry Film Thickness Range, mil (μm)**
A1	5-8 (185-205)	4 (102)	3-5 (75-125)
A2	30 (760)	29 (737)	20-35 (510-890)
A3	1-2 (25-50)	3 (76)	2-3 (50-75)
A4	5-7 (125-180)	7 (178)	5-9 (127-230)
B1	16-20 (405-510)	5 (127)	4-6 (100-150)
B2	6-8 (150-205)	9 (229)	8-11 (205-280)
C1	2-4 (50-100)	4 (102)	3-5 (75-125)
C2	35-45 (785-1145)	41 (1041)	35-50 (890-1270)
D1	-**	6 (152)	3-15 (75-380)

*According to Manufacturer
** Information not provided by manufacturer

2.1.2 Series 1 and Series 2 Test Slabs

Series 1 and Series 2 each had five slabs cast in a single concrete placement; each slab received a single coating system applied at five different ages–7, 14, 21, 28, and 45 days after the end of a 7-day wet curing period. Series 1 slabs were used to test coating systems 1 through 5. Series 2 slabs were used to test coating systems 6 through 10. The systems were tested at 7, 21, 28, and 56 days after the last coat for each system was applied to the slab. A schematic of the slab indicating the application schedule and the five test locations, referred to as squares, is shown in Figure 2.1. Square 6 was reserved for measuring MVER throughout the test period.

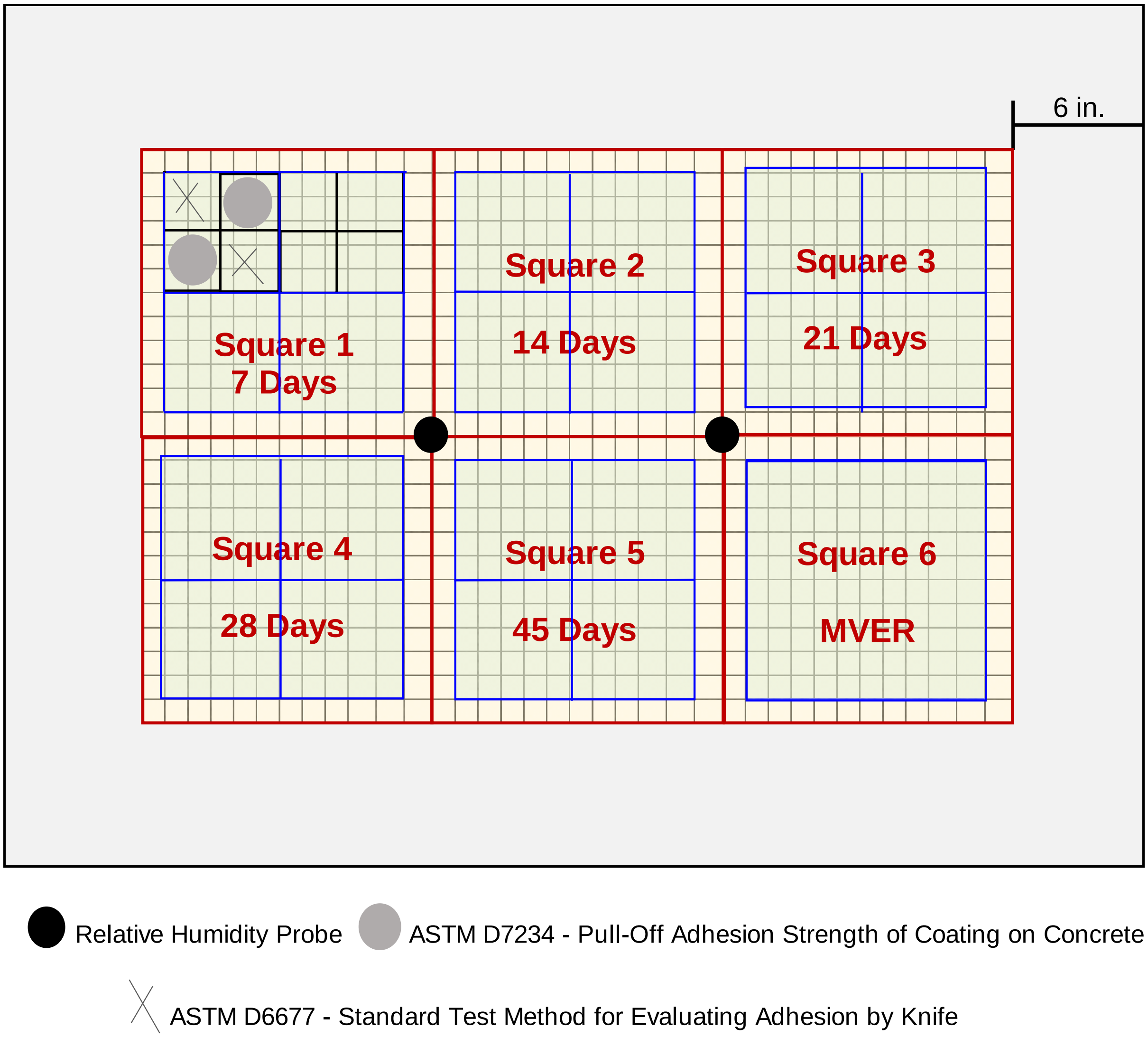

Figure 2.1: Schematic of slab showing application schedule (days after end of wet-curing) and test locations for Series 1 and 2

2.1.3 Series 3 Test Slabs

Series 3 had four slabs cast in a single concrete placement. Coatings were applied seven days after completion of wet-curing on two slabs and 14 days after completion of wet-curing on the other two. Unlike Series 1 and 2, in which one slab served as a test specimen for a single coating system applied at five different ages, each slab in Series 3 had five different coating systems applied at a single age. Having two slabs for each application age allowed all ten coating systems to be reevaluated when applied 7 and 14 days after wet-curing. The change in test protocol was used to determine if covering a greater percentage of the surface area of the slab at an early age would alter the coating performance. Surface preparation, coating application procedures, and testing procedures remained the same as for Series 1 and 2 slabs.

2.2 Slab and Block Specimens

Slabs measured 3 ft × 4 ft × 0.5 ft (910 mm × 1200 mm × 150 mm). Two No. 5 (No. 16) reinforcing bars were cast into the slab at mid-depth; these bars extended beyond the sides of the slab to aid in lifting and moving the specimens. Within a 6-inch (150-mm) uncoated border around the periphery of the slab, the upper surface was subdivided into six 1-ft (305-mm) squares, as shown in Figures 2.1 and 2.2. Five of the six squares were used to test the coating systems; the sixth was left uncoated and was used to monitor MVER. Relative humidity was measured at two points located 18 in. (457 mm) from the long and short edge of the slab. A slab specimen after application and evaluation of a coating system is shown in Figure 2.2.

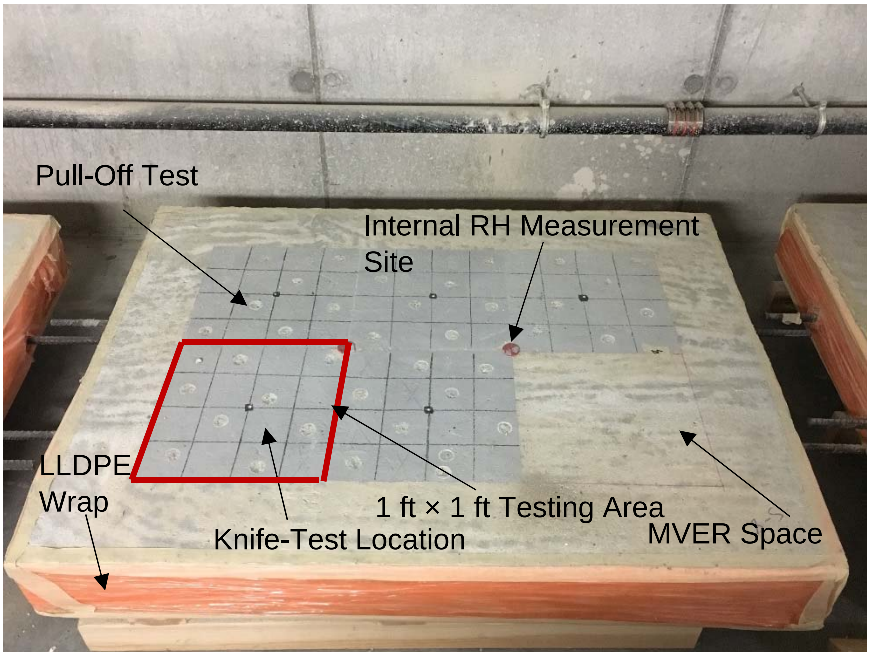

Figure 2.2: Slab specimen showing testing subdivisions and test locations

Blocks (Figure 2.3) were cast to compare MVER and relative humidity readings to those of the slabs to determine the effect of concrete thickness. The blocks were 2-ft (610-mm) cubes and were left uncoated. Both slab and block specimens were placed on top of 2 × 4 (38 × 89 mm) dimension lumber to allow the free flow of air to, and moisture loss from, the bottom of the specimens. Both slabs and blocks were wrapped on the sides with lineal low density polyethylene (LLDPE), held in place by masking tape, to prevent moisture loss from the sides of the specimens and reduce the likelihood of lateral transmission of vapor.

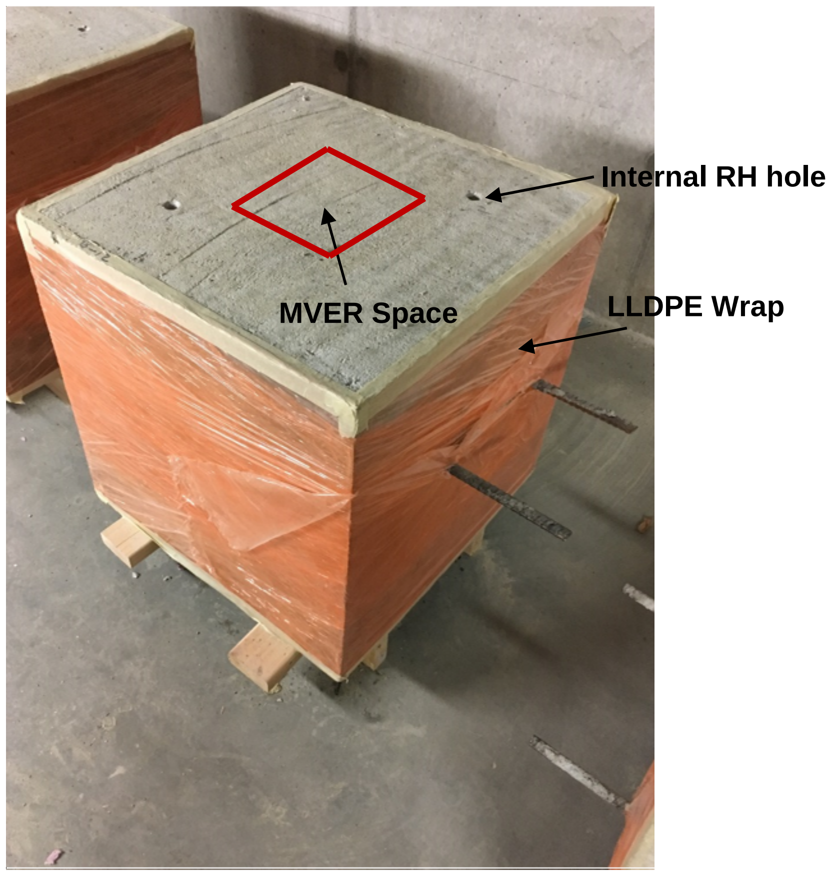

Figure 2.3: Block specimen showing test locations

2.2.1 Casting and Wet Curing

Non-air-entrained ready-mixed concrete with a water-cement (*w*/*c*) ratio of 0.45 was used for all specimens. Four batches of concrete were placed; the first placement consisted of the blocks in Series 1, the second placement consisted of the slabs in Series 1, the third placement consisted of the blocks and slabs in Series 2, and the fourth placement consisted of the blocks and slabs in Series 3. The mixture proportions are shown in Table 2.5. The plastic concrete properties are shown in Table 2.6.

Table 2.5: Concrete Mixture Proportions

Material	Description	Quantity, lb/yd^3 (kg/m^3)
Cement	Type I/II	564 (335)
Water	-	254 (151)
Coarse Aggregate	Crushed Limestone	1256 (745)
Fine Aggregate	Kansas River Sand	1884 (1118)
Admixture	Mid-Range Water Reducer	48 oz/yd^3 (1.86 L/m^3)

Table 2.6: Plastic Concrete Properties

Specimens	Date	Slump	Temperature	Unit Weight
		in (mm)	°F (°C)	lb/ft^3 (kg/m^3)
Series 1 blocks	4/4/2016	1.75 (45)	60 (15.6)	152.1 (2436)
Series 1 slabs	4/14/2016	2.5 (65)	52 (11.1)	150.1 (2404)
Series 2 slabs and blocks	5/17/2016	8 (205)	46 (7.8)	146.4 (2345)
Series 3 slabs and blocks	7/26/2016	3.5 (90)	82 (27.8)	143.6 (2300)

Forms for the specimens consisted of 2 × 4 (38 × 89 mm) dimension lumber and ¾-in. (19-mm) plywood. The forms for the slabs and blocks are shown in Figures 2.4 and 2.5, respectively.

Figure 2.4: *Slab specimen formwork*

Figure 2.5: Block specimen formwork

The interior of the forms was coated with mineral oil prior to casting. Concrete was placed in the forms in two layers and consolidated using a spud vibrator. The slabs and blocks were screeded, bull floated, and then hand floated. This was the only surface finish used in all specimens and blocks. The specimen surfaces were further prepared to Concrete Surface Profile 3 (CSP 3) The concrete was covered with wet burlap and plastic sheeting for seven days for wet curing, as shown in Figure 2.6. The burlap was rewetted daily. After seven days, the burlap was removed, the specimens were demolded, and placed in controlled environmental chambers. The chambers were designed to maintain an air temperature of 73±3°F (22.8±1.7°C) and an air relative humidity of 50±5%.

Figure 2.6: Wet curing of specimens

2.2.2 Surface Preparation

Prior to the application of the coatings, the surfaces of the concrete slabs were prepared to Concrete Surface Profile 3 (CSP-3), which is described as open pores throughout the surface and a sandpaper-like texture. CSP 3 is recommended when the primer thickness range is between 4-10 mils (ICRI 2013). Surfaces were prepared using recycled glass abrasive material with an approximate diameter of 2 mils (0.05 mm) and an abrasive blaster [rated for 10 CFM (17 m^3/hr) at 90 psi (620 kPa)] one day before the application of the first coat. The surface was then cleaned of any debris by using a wet/dry shop vacuum prior to application of the coating. A prepared surface, ready for coating application, is shown in Figure 2.7.

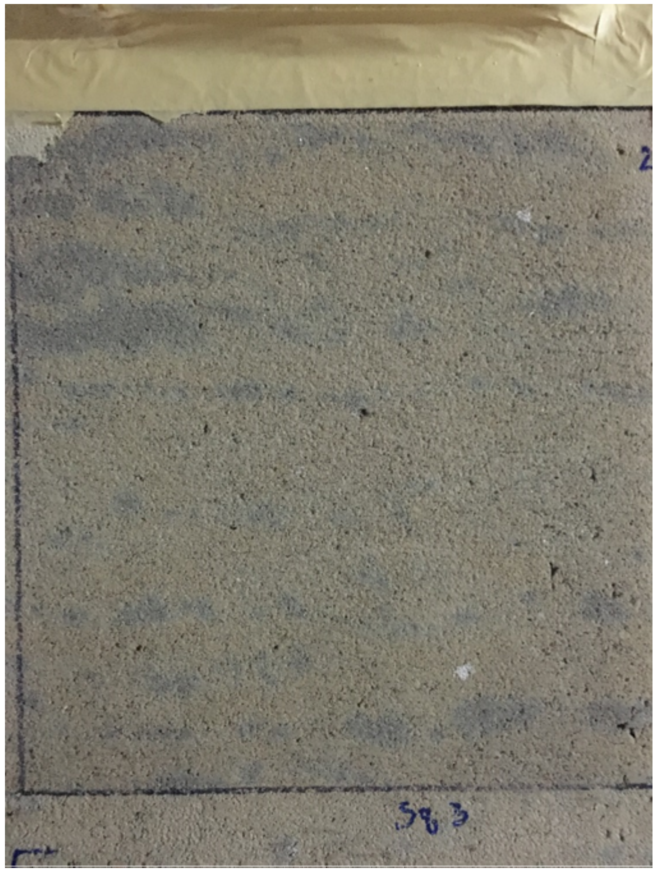

Figure 2.7: Concrete surface prepared to Concrete Surface Profile 3 (CSP-3)

2.2.3 Environmental Chambers

Two environmental chambers were constructed to control the exposure conditions for the specimens throughout testing. The target air temperature and humidity ranges were 73°F±3°F (22.8±1.7°C) and 50%±5%, respectively. Heat lamps, air conditioner units, humidifiers, and dehumidifiers controlled the environment inside the environmental chambers. Environmental Chamber 1 is shown in Figure 2.8.

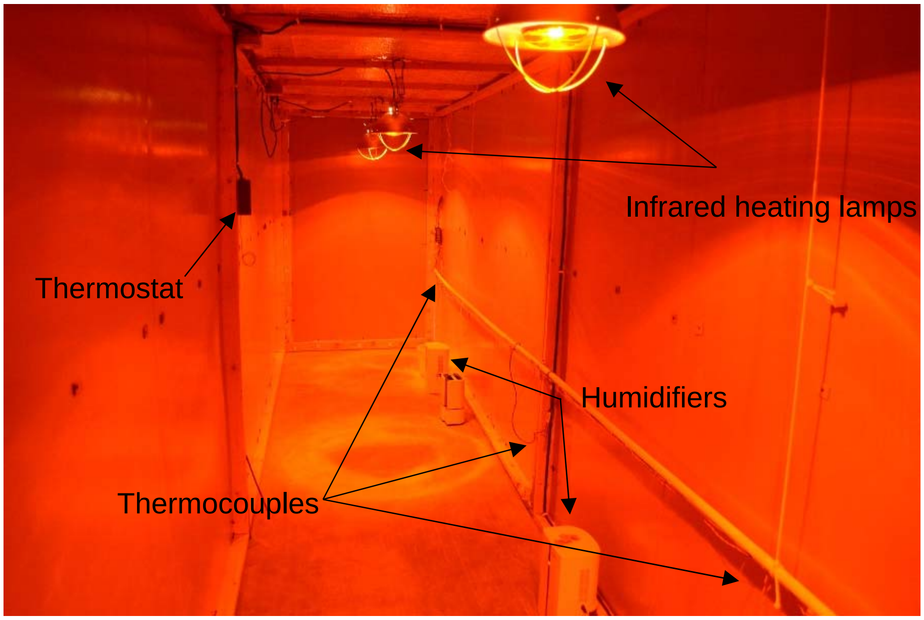

Figure 2.8: Interior of Environmental Chamber 1 in space heating mode

Sensors were installed in the environmental chambers to continuously monitor air temperature and relative humidity. Air temperature and relative humidity readings were taken every 10 seconds, which were then averaged over 1-hour periods. Environmental controls were adjusted based on the readings.

2.2.3.1 Environmental Testing Conditions

Environmental Chamber 1

Environmental Chamber 1 contained the Series 1 and Series 3 slabs and blocks and the Series 2 blocks. During the testing period, from April 11 to October 13, 2016, the mean values of air temperature and humidity were 73.5°F (23.1°C) and 50.4%, respectively. The average air temperature and relative humidity readings are shown in Appendix A.

Environmental Chamber 2

Environmental Chamber 2 contained the Series 2 slabs. During the testing period, from May 24 to September 4, 2016, the mean air temperature and humidity were of 74.9°F (23.8°C) and 49.9%, respectively. The average air temperature and relative humidity readings are shown in Appendix A.

2.3 Moisture Testing

2.3.1 Moisture Vapor Emission Rate Test (ASTM F1869)

The amount of water emitted from the surface of the concrete (the moisture vapor emission rate or MVER) was continuously monitored throughout the duration of testing for both slab and block specimens in accordance with ASTM F1869. The MVER is measured by exposing a highly absorptive material (anhydrous calcium chloride) to a known surface area of concrete in an otherwise sealed environment for 60 to 72 hours. Any moisture leaving the surface of the concrete during this period is absorbed by the calcium chloride, allowing the MVER to be calculated based on the change in weight of the anhydrous calcium chloride. This test requires that a portion of the concrete be covered with a plastic cover and sealed. The change in weight is recorded and the MVER for the specimen is calculated using Eq. (1).

$$MVER = \frac{52.91 \times \Delta M}{A \times T} \tag{1}$$

where:

ΔM = change in mass (weight gain) of anhydrous $CaCl_2$ (g);

A = area under the cover minus the area under the $CaCl_2$ container (ft^2);

T = exposure time (hours).

The MVER value is reported as the weight of moisture per 1000 square feet per day or per square meter per second. Current recommendations from coating manufacturers state that the MVER value should be below 3-5 lb/1000 ft^2/day (170-283 µg/m^2/s) before the coatings are applied to the concrete (Suprenant and Malisch, 1998a).

2.3.2 Internal Relative Humidity Test (ASTM F2170)

The internal relative humidity test was performed in accordance with the provisions of the Standard Test Method for Determining Relative Humidity in Concrete Floor Slabs Using in situ Probes (ASTM F2170). In this test, a 1.2-in. (30.5-mm) deep by ¾-in. (19.1-mm) diameter hole is drilled into the top of the specimen to place an in-situ probe at 20% of the depth of the slab. After drilling, the hole is cleaned to remove any dust or debris that could affect the test results. The holes in the blocks were also drilled to a depth of 1.2 in. (30.5 mm) to provide near-surface readings that would allow the effect of concrete depth on relative humidity to be determined. Once a hole is drilled, a base, sleeve, and cap are installed in the hole to seal it and to allow for the subsequent insertion of a RH-measuring sensor. The holes are left untouched for three days to allow the interior environment to stabilize. To take a relative humidity reading, the cap and sleeve are removed and a sensor is placed inside the hole. Each sensor is left in the hole for at least 45 minutes to allow the reading to stabilize before recording the value.

2.3.3 pH Test (ASTM F710)

For Series 3 slabs, the pH of the concrete surface was measured just prior to coating application in accordance with Section 5.2 of the Standard Practice for Preparing Concrete Floors to Receive Resilient Flooring (ASTM F710). The results of these measurements are presented in Appendix B.

2.4 Adhesion Testing

Two pull-off tests (ASTM D7234) and two knife tests (ASTM D6677) were performed on each specimen 7, 21, 28, and 56 days after application of the final layer of a coating system. These tests are described below.

2.4.1 Pull-Off Test (ASTM D7234)

A pull-off test was performed to test the adhesion of the coating layers to each other and of the coating system to the concrete. This test was performed in accordance with the Standard Test Method for Pull-Off Strength of Coatings on Concrete Using Portable Adhesion Testers (ASTM D7234). The test uses 0.79-in (20-mm) diameter dollies. Before applying the dolly, the surfaces of the dolly and the coating are roughened using an abrasive pad. Then the dolly and coating are cleaned using isopropyl alcohol to remove any oil or debris. Next, an adhesive is applied to the dolly. The dolly is firmly pressed onto the coated surface and secured in place with masking tape. After a minimum of 24 hours, the coating around the dolly is scored with a hole saw and the dolly is pulled off at a loading rate of 30 psi/s (200 kPa/s) to failure.

For each dolly, the stress at failure is recorded, as well as the type of failure or failures, when multiple failure modes are observed. Three failure types are possible: 1) concrete failure (substrate failure) (Figure 2.9), 2) coating failure (either separation between layers of the coating system or separation between the coating system and the concrete) (Figure 2.10) and 3) glue failure

(Figure 2.11). When multiple failure modes occurred on a single dolly (Figure 2.12), the failures were categorized based on the approximate surface area of the dolly represented by each failure mode. Tests with up to 20% glue failure are considered valid (ASTM D7234). Any test with over 20% glue failure are considered invalid, and the test must be repeated.

Figure 2.9: Pull-off test exhibiting concrete (substrate) failure

Figure 2.10: Pull-off test exhibiting coating and partial coating failures

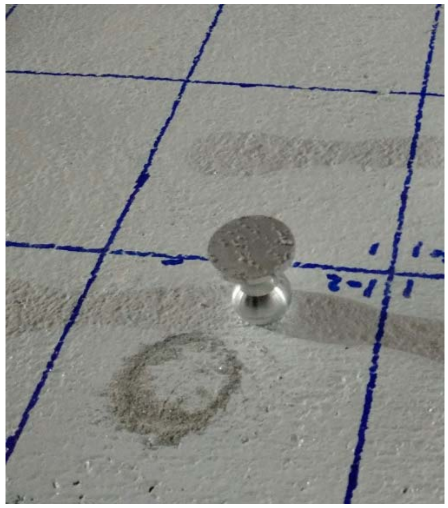

Figure 2.11: Pull-off test exhibiting glue failure

Figure 2.12: Pull-off test exhibiting 60% concrete substrate failure and 40% glue failure

2.4.2 Knife Test (ASTM D6677)

In addition to the pull-off test, a knife test was performed to test the adhesion of the coating layers to the concrete. To perform the knife test, a retractable utility knife and a metal straight edge are used in accordance with the Standard Test Method for Evaluating Adhesion by Knife (ASTM D6677) to cut an X into the coating and attempt to lift the coating from the concrete surface. The straight edge is placed on the area being tested, and a straight line at least 3 in. (75 mm) in length is cut into the coating. The straight edge is then turned to an angle of 30 to 45° to cut the second leg of the "X". After the "X" is made, the tip of the knife is used to try to lift the coating at the acute angle at the intersection of the lines. The results are rated using the chart shown in Figure 2.13. A higher rating corresponds to better performance in the knife test; a rating of 10 indicates a minimal amount of coating was able to be removed with great difficulty (Figure 2.14), while progressively lower numbers indicate a larger area was able to be removed with less effort (Figure 2.15).

Rating	Description
10	Coating is extremely difficult to remove; fragments no larger than approximately 0.8 by 0.8 mm (1⁄32 in. by 1⁄32 in.) removed with great difficulty.
8	Coating is difficult to remove; chips ranging from approximately 1.6 by 1.6 mm (1⁄16 by 1⁄16 in.) to 3.2 by 3.2 mm (1⁄8 by 1⁄8 in.) can be removed with difficulty.
6	Coating is somewhat difficult to remove; chips ranging from approximately 3.2 by 3.2 mm (1⁄8 by 1⁄8 in.) to 6.3 by 6.3 mm (1⁄4 by 1⁄4 in.) can be removed with slight difficulty.
4	Coating is somewhat difficult to remove; chips in excess of 6.3 by 6.3 mm (1⁄4 by 1⁄4 in.) can be removed by exerting light pressure with the knife blade.
2	Coating is easily removed; once started with the knife blade, the coating can be grasped with ones fingers and easily peeled to a length of at least 6.3 mm (1⁄4 in.).
0	Coating can be easily peeled from the substrate to a length greater than 6.3 mm (1⁄4 in.).

Figure 2.13: Knife test rating (ASTM D6677)

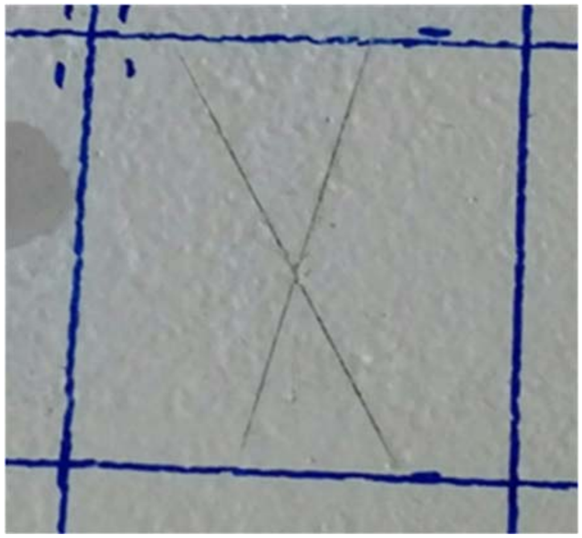

Figure 2.14: Knife test rating 10

Figure 2.15: Knife test rating 4

Chapter 3 TEST RESULTS

3.1 Moisture Tests

3.1.1 Moisture Vapor Emission Rate

The average moisture vapor emission rate (MVER) results for the slabs and blocks in Series 1, 2, and 3 are shown, respectively, in Figures 3.1, 3.2, and 3.3. Each data point represents the average of the results from five slabs in Series 1 and 2, four slabs in Series 3, and four blocks in each series. The MVER results for the individual specimens are shown in Figures C.1 through C.6 in Appendix C. As shown in Figures 3.1, 3.2, and 3.3, the MVER values for the slabs and blocks were similar throughout the testing. The difference in average MVER values between the slabs and the blocks in Series 1 and 2 was small, and for readings taken after seven days, less than 1 lb/1000 ft^2/day (57 $\mu g/m^2/s$).

The MVER values obtained when using the slabs and blocks in Series 3 were nearly identical throughout the test period. The values for Series 3 were about 3 lb/1000 ft^2/day (170 $\mu g/m^2/s$) higher than the values for Series 1 and about 2 lb/1000 ft^2/day (113 $\mu g/m^2/s$) higher than the values for Series 2 at the beginning of testing; however, the values for the three series approached each other over time. At 71 days, the slabs and blocks in all series exhibited MVER values of close to 5 lb/1000 ft^2/day (283 $\mu g/m^2/s$). None of the slabs and blocks in any series reached MVER values near the lower end of range of recommended by the manufacturers, 3 lb/1000 ft^2/day (170 $\mu g/m^2/s$). In fact, all coatings were applied to the concrete when the MVER values were above the upper limit of the recommended range, 5 lb/1000 ft^2/day (283 $\mu g/m^2/s$). Overall, the results agree with the findings of Suprenant and Malisch (1998a), who showed that slab depth does not have a significant impact on the moisture vapor emission rate.

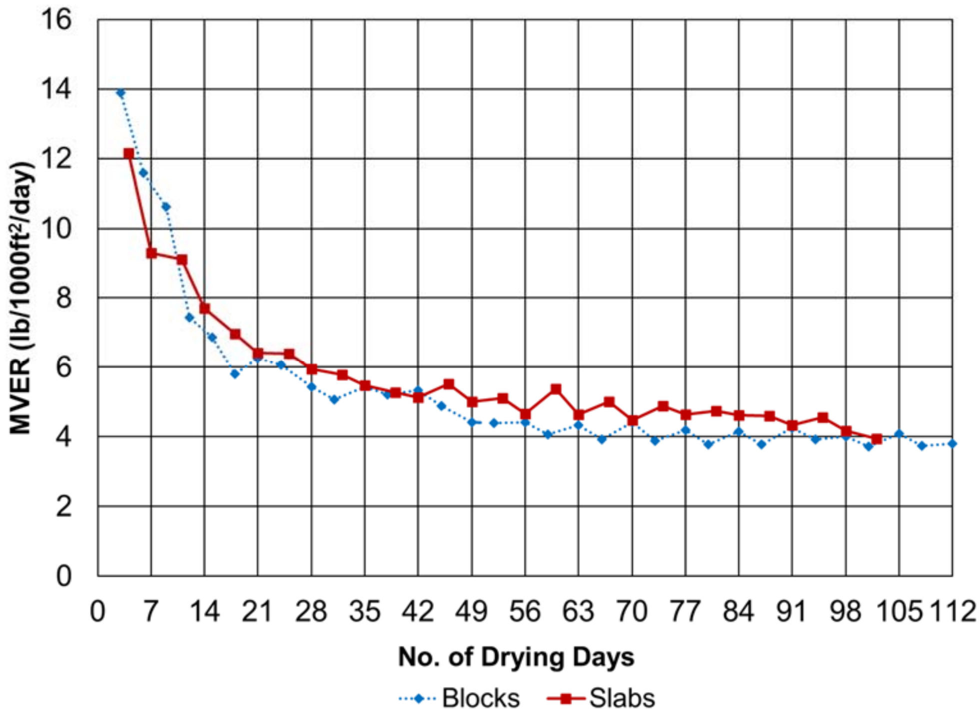

Figure 3.1: MVER averages for slabs and blocks in Series 1 (Note: 1 lb/1000 ft^2/day = 57 µg/m^2/s)

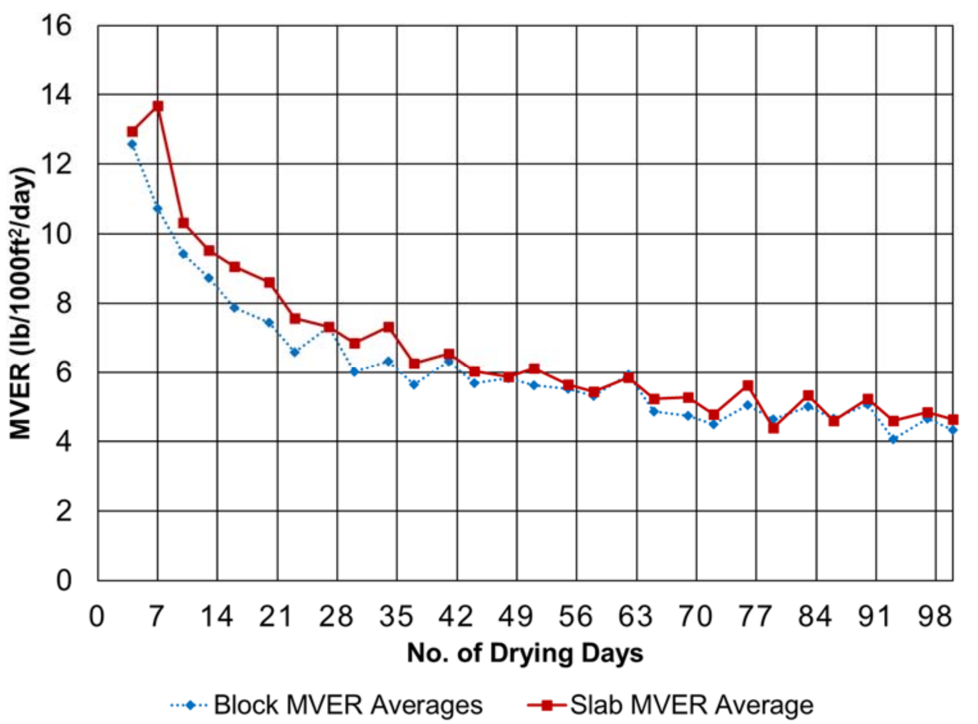

Figure 3.2: MVER averages for slabs and blocks in Series 2 (Note: 1 lb/1000 ft^2/day = 57 µg/m^2/s)

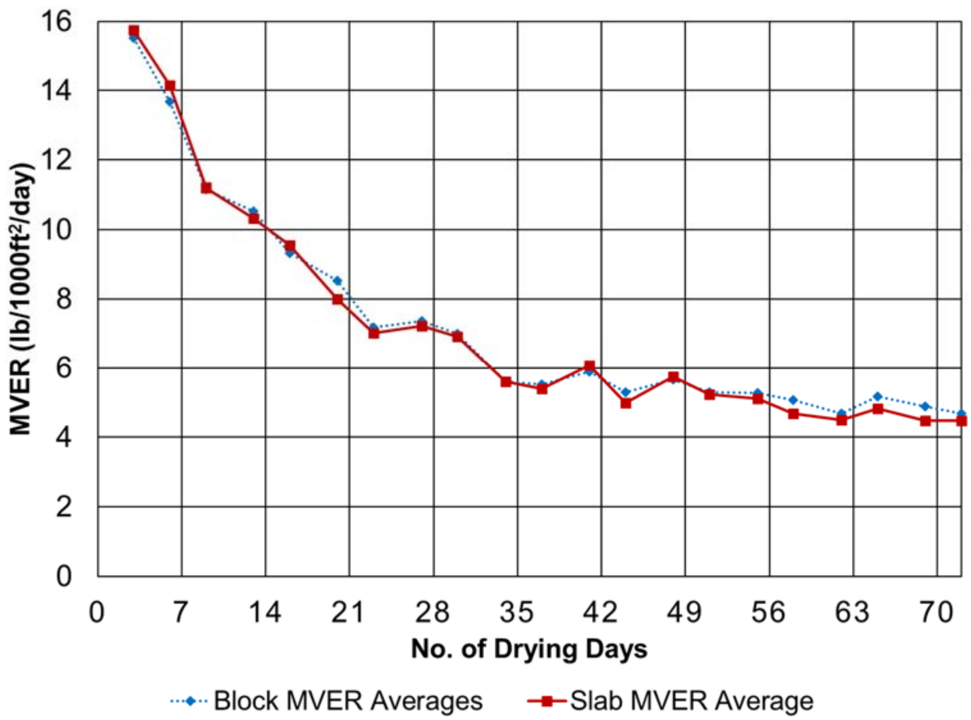

Figure 3.3: MVER averages for slabs and blocks in Series 3 (Note: 1 lb/1000 ft^2/day = 57 $\mu g/m^2/s$)

3.1.2 Internal Relative Humidity

The average internal concrete relative humidity values for the slabs and blocks in Series 1, 2, and 3 are shown in Figures 3.4, 3.5 and 3.6, respectively. Each data point represents the average of readings from two sampling points on five slabs in Series 1 and 2, four slabs in Series 3, and four blocks in each series. Results for the individual slabs and blocks are presented in Figures D.1 through D.6 in Appendix D. As for the MVER results, concrete relative humidity decreased over time and exhibited similar values for the slabs and the blocks. Concrete relative humidity in the slabs and blocks in Series 1 exhibited more variability relative to each other and in total than the other series. The relative variability may be a result of casting the blocks ten days before the slabs, resulting in exposure to somewhat different environmental conditions, although the time between castings did not appear to have affected the MVER results.

The concrete relative humidity at coating application ranged from 76% to 90%. Coating manufacturer A specified that coatings A3 and A4 should be applied when the internal concrete relative humidity was below 90%. This requirement was met, except for the application seven days after the end of wet-curing in Series 3, when the concrete relative humidity was exactly 90%. Manufacturers B, C, and D did not specify a value of concrete relative humidity at the time of application. ASTM F710, which applies to resilient (vinyl) flooring, not coatings, states that floor coverings should be applied when the concrete relative humidity is below 75%. None of the coatings in this study were applied at a relative humidity below 75%.

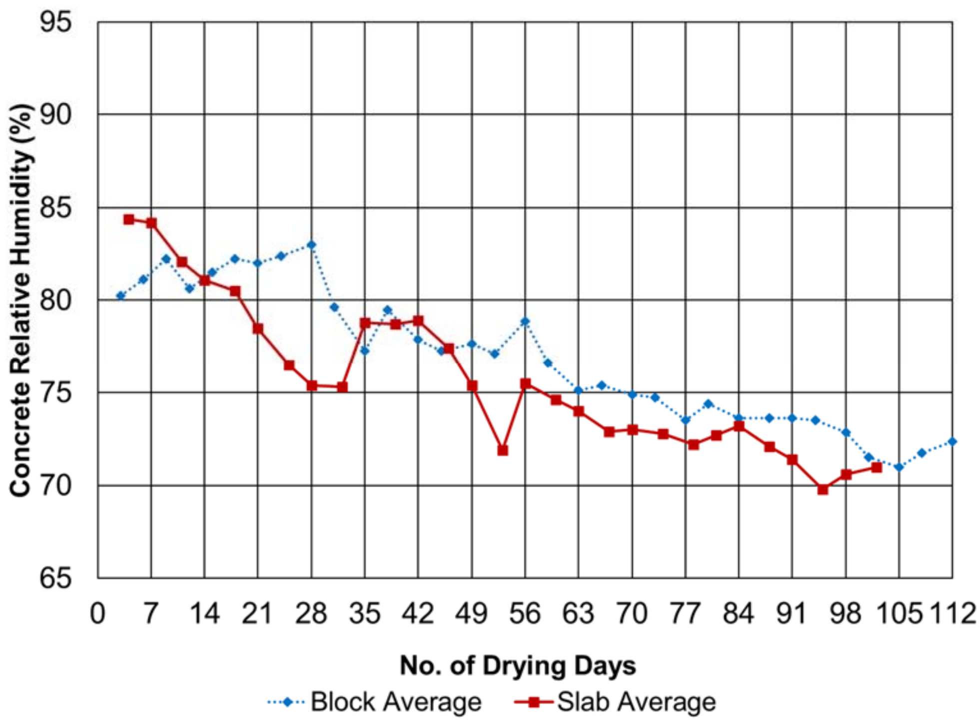

Figure 3.4: Average concrete relative humidity for Series 1 Slabs and Blocks

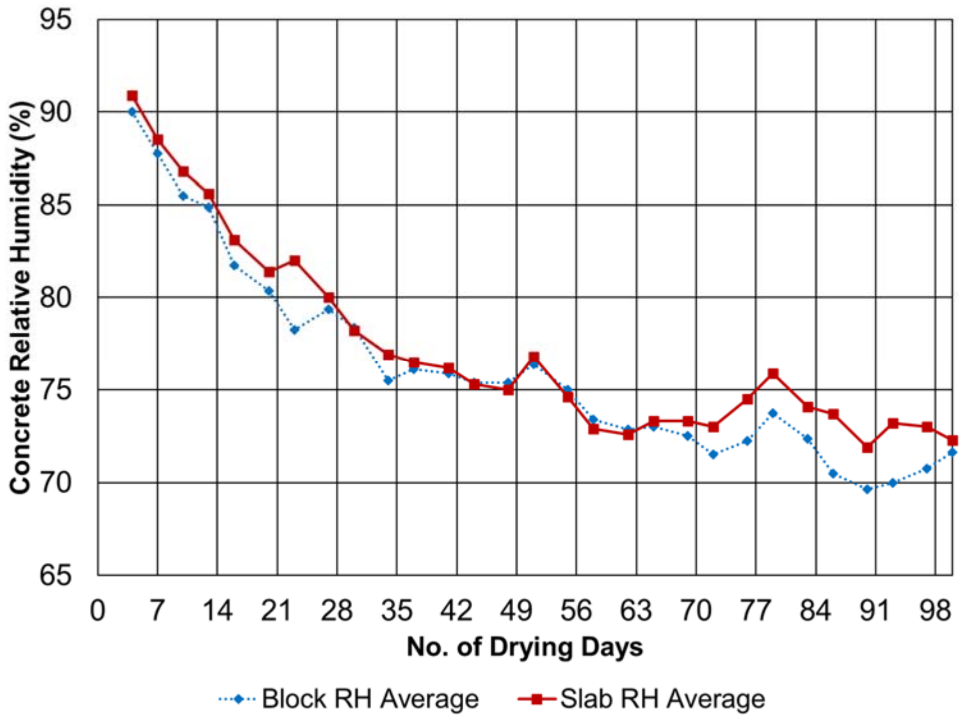

Figure 3.5: Average concrete relative humidity for Series 2 Slabs and Blocks

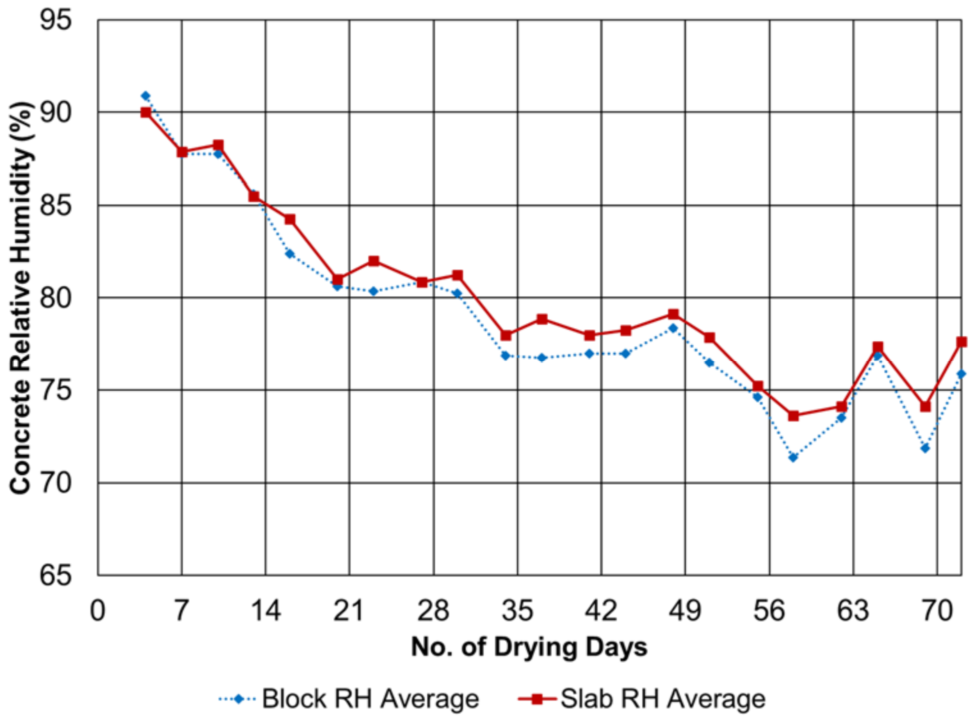

Figure 3.6: Average concrete relative humidity for Series 3 Slabs and Blocks

3.2 Adhesion Tests

Sections 3.2.1 and 3.2.2 present the results from the pull-off and knife tests, respectively. For each test, results are presented for the coatings applied 7, 14, and 45 days after the end of wet-curing. Results for coatings applied 21 and 28 days after wet curing are similar and presented in Appendices C and D for pull-off and knife tests, respectively.

3.2.1 Pull-Off Test

ASTM D5144 requires a minimum pull-off stress at failure of 200 psi (1386 kPa) for Service Level I coatings. Although the location of failure is not specified, a failure occurring entirely in the concrete is considered desirable. (In this section, "failure" indicates the point at which the test specimen lost adhesion or pulled out the concrete substrate, and does not indicate unacceptable performance). All coating systems performed comparably well in the pull-off tests, with the exception of system 8 (B2×2), which exhibited occasional coating failures at reduced stresses at all test ages (although still above the 200 psi minimum specified in ASTM D5144). Considering all ages, the coatings exhibited pull-off stresses at failure in valid tests (not more than 20% glue failure) between 350 and 1090 psi (2413 and 7515 kPa). The vast majority of the failures occurred in the concrete.

Table 3.1 shows the pull-off test results for all coating systems applied seven days after the end of wet curing. In all tables, coating failure refers to a failure between the coating and concrete unless noted otherwise. Coating system 9 (C1/C2), consisting of one layer each of products C1 and C2, exhibited partial coating failures when first tested in Series 2; even with the partial coating failures, the coating system exhibited pull-off stresses between 480 and 710 psi (3310 and 4895 kPa). When this system was retested in Series 3, no coating failures were observed; the range of pull-off stresses at failure [490 to 770 psi (3380 to 5310 kPa)] was similar to those observed in the tests with partial coating failures, suggesting that the coating exhibited adequate strength even with partial coating failures. Coating systems 5 (A4×2), 7 (B1×2/A4), 8 (B2×2), and 10 (D1) also exhibited a partial coating failure in at least one test. With the exception of coating system 8 (B2×2), the pull-off stresses at failure for these tests were similar in magnitude to the pull-off stresses obtained at failure for tests with 100% concrete failures on the same coating system, indicating no reduction in stress due to the partial coating failure. Coating system 8 (B2×2) exhibited reductions in pull-off stress correlating with the coating failures, with stresses of 350 to 650 psi (2413 to 4482 kPa) for tests with partial or complete coating failures and stresses from 570 to 800 psi (3930 to 5520 kPa) for tests with concrete failures. Coating failures were observed when coating system 8 (B2×2) was applied as late as 45 days after the end of wet-curing. No coating system exhibited any correlation between coating age at testing and the tendency for a partial coating failure.

In addition to replicating the evaluations of the coating systems when applied 7 and 14 days after the end of wet curing, Series 3 was used to determine if covering a greater percentage of the surface area of the slab at an early age would alter coating performance. In Series 1 and 2, a single coating system was applied to small sections on the surface of each test slab 7 to 45 days after the end of wet curing, while in Series 3, five tests square were covered at either 7 or 14 days. In Series 1 and 2, the pull-off stresses at failure ranged from 410 to 970 psi (2825 to 6690 kPa). In Series 3, the pull-off stresses at failure ranged from 350 to 870 psi (2415 to 6000 kPa). The lowest and highest stresses for the Series 1 and 2 tests were slightly higher than those for the Series 3 tests. In spite of the slightly lower pull-off stresses, failure was more consistently in the concrete than in the coating in Series 3 than in Series 1 and 2, leading to the conclusion that coating performance was not affected by the percentage of the slab surface covered and that the results in the three series are equally valid.

Table 3.1: Pull-Off Test Results for Coatings Applied 7 Days after End of Wet Curing

		Series 1 Slabs				Series 3 Slabs		
Coating System	**Test Age (Days°)**	**Pull-off Stress at Failure (psi) [kPa]**	**Failure Type***	**Failure Type***		**Pull-off Stress at Failure (psi) [kPa]**	**Failure Type***	**Failure Type***
1 (A1/A2)	7	810 [5580]	100% Concrete			630 [4340]	100% Concrete	
	21	590 [4070]	100% Concrete			460 [3170]	100% Concrete	
	28	710 [4890]	100% Concrete			670 [4620]	100% Concrete	
	56	720 [4960]	100% Concrete			690 [4760]	100% Concrete	
2 (A1/A4)	7	250 [1720]	20% Concrete	80% Glue		750 [5170]	100% Concrete	
	21	680 [4690]	100% Concrete			640 [4410]	100% Concrete	
	28	600 [4130]	100% Concrete			630 [4340]	100% Concrete	
	56	790 [5440]	100% Concrete			820 [5650]	100% Concrete	
3 (A3/A4)	7	0 [0]	100% Glue			640 [4410]	100% Concrete	
	21	900 [6200]	100% Concrete			670 [4620]	100% Concrete	
	28	410 [2820]	90% Concrete	10% Glue		560 [3860]	100% Concrete	
	56	770 [5310]	100% Concrete			400 [2760]	100% Concrete	
4 (A3/A4×2)	7	550 [3790]	100% Concrete			870 [6000]	100% Concrete	
	21	680 [4690]	100% Concrete			720 [4960]	100% Concrete	
	28	880 [6060]	100% Concrete			580 [4000]	95% Concrete	5% Glue
	56	760 [5240]	100% Concrete			630 [4340]	100% Concrete	
5 (A4×2)	7	610 [4200]	100% Concrete			570 [3930]	100% Concrete	
	21	500 [3450]	50% Concrete	50% Coating		690 [4750]	100% Concrete	
	28	540 [3720]	90% Concrete	10% Glue		690 [4750]	100% Concrete	
	56	800 [5510]	100% Concrete			450 [3100]	100% Concrete	

°Days after end of wet curing
*For coating failures, failure occurred between coating and concrete unless noted otherwise

Table 3.1 Cont.: Pull-Off Test Results for Coatings Applied 7 Days after End of Wet Curing

		Series 2 Slabs				Series 3 Slabs		
Coating System	**Test Age (Daysº)**	**Pull-off Stress at Failure (psi) [kPa]**	**Failure Type***	**Failure Type***		**Pull-off Stress at Failure (psi) [kPa]**	**Failure Type***	**Failure Type***
6 (B1×2)	7	780 [5370]	100% Concrete			670 [4620]	100% Concrete	
	21	750 [5170]	100% Concrete			540 [3720]	100% Concrete	
	28	750 [5170]	100% Concrete			690 [4750]	100% Concrete	
	56	820 [5650]	100% Concrete			700 [4820]	100% Concrete	
7 (B1×2/A4)	7	480 [3310]	100% Coating			570 [3930]	50% Concrete	50% Coating
	21	630 [4340]	50% Concrete	50% Coating**		450 [3100]	100% Concrete	
	28	750 [5170]	100% Concrete			530 [3650]	100% Concrete	
	56	970 [6690]	100% Concrete			620 [4270]	100% Concrete	
8 (B2×2)	7	650 [4480]	85% Concrete	15% Coating		450 [3100]	100% Coating	
	21	650 [4480]	100% Concrete			350 [2410]	90% Concrete	10% Coating
	28	570 [3930]	100% Concrete			450 [3100]	100% Coating	
	56	800 [5510]	100% Concrete			500 [3450]	40% Concrete	60% Coating
9 (C1/C2)	7	710 [4890]	95% Concrete	5% Coating		580 [4000]	100% Concrete	
	21	480 [3310]	85% Concrete	15% Coating		550 [3790]	100% Concrete	
	28	760 [5240]	50% Concrete	50% Coating		490 [3380]	100% Concrete	
	56	710 [4890]	50% Concrete	50% Coating		770 [5310]	100% Concrete	
10 (D1)	7	730 [5030]	100% Concrete			700 [4820]	100% Concrete	
	21	590 [4070]	100% Concrete			620 [4270]	50% Concrete	50% Coating
	28	630 [4340]	100% Concrete			590 [4070]	100% Concrete	
	56	680 [4690]	95% Concrete	5% Coating		870 [5990]	100% Concrete	

ºDays after end of wet curing
*For coating failures, failure occurred between coating and concrete unless noted otherwise
**Failure occurred between coating layers

Table 3.2 shows the pull-off test results for coatings applied 14 days after the end of wet curing. Pull-off stresses at failure ranged from 390 to 1090 psi (2690 to 7515 kPa) for this age of application. The results are consistent with those for the coatings applied seven days after the end of wet-curing. Similar to the 7-day application, coating system 7 (B1×2/A4) exhibited one coating failure between the coating layers. This occurred when the coating system was tested 56 days after application; this did not occur when the system was tested in Series 3. Coating system 2 (A1/A4) had partial glue failures when tested 7 and 14 days after application; in Series 3, the failure was in the concrete. When glue failure was observed in coating system 2 (A1/A4) for the 14-day coating application of both series, the pull-off stress at failure was approximately the same as when concrete failure occurred. The value presented is, therefore, a lower bound for the actual strength of the coating, which is in line with values obtained with "normal" failures at other ages. Coating system 8 (B2×2) had partial coating failures at 7 and 56 days in Series 2 and at 7, 21, and 28 days in Series 3, and a complete coating failure at 56 days in Series 3. In the two cases when a 100% concrete failure was observed in coating system 8 (B2×2), the pull-off stresses were 810 and 880 psi (3930 and 6065 kPa). When a partial or complete coating failure was observed in the same coating system, the pull-off stress ranged from 390 to 670 psi (2690 to 4620 kPa). As was the case for coatings applied seven days after wet-curing, coating system 8 (B2×2) was the only one to exhibit coating failures coupled with a reduction in pull-off stresses.

In Series 1 and 2, the pull-off stress at failure ranged from 390 to 1090 psi (2690 to 7515 kPa), while in Series 3 the values ranged from 410 to 850 psi (2825 to 5860 kPa). Although the upper end of the stresses was lower for Series 3 than for Series 1 and 2, as for the systems applied at seven days, failure occurred in the concrete more consistently in Series 3 than in Series 1 and 2, again leading to the conclusion that coating performance was not affected by the percentage of the slab surface covered and that the test results obtained in all three series are applicable.

Table 3.2: Pull-Off Test Results for Coatings Applied 14 Days after End of Wet Curing

		Series 1 Slabs			Series 3 Slabs		
Coating System	**Test Age (Daysº)**	**Pull-off Stress at Failure (psi) [kPa]**	**Failure Type***	**Failure Type***	**Pull-off Stress at Failure (psi) [kPa]**	**Failure Type***	**Failure Type***
1 (A1/A2)	7	730 [5030]	100% Concrete		660 [4550]	100% Concrete	
	21	820 [5650]	100% Concrete		640 [4410]	100% Concrete	
	28	710 [4890]	100% Concrete		620 [4270]	100% Concrete	
	56	730 [5030]	100% Concrete		610 [4200]	100% Concrete	
2 (A1/A4)	7	600 [4130]	90% Concrete	10% Glue	720 [4960]	100% Concrete	
	21	540 [3720]	80% Concrete	20% Glue	680 [4690]	100% Concrete	
	28	780 [5370]	100% Concrete		590 [4070]	100% Concrete	
	56	770 [5310]	100% Concrete		760 [5240]	100% Concrete	
3 (A3/A4)	7	510 [3510]	60% Concrete	40% Glue	660 [4550]	100% Concrete	
	21	570 [3930]	100% Concrete		560 [3860]	100% Concrete	
	28	790 [5440]	100% Concrete		730 [5030]	100% Concrete	
	56	910 [6270]	100% Concrete		800 [5510]	100% Concrete	
4 (A3/A4×2)	7	840 [5790]	100% Concrete		800 [5510]	100% Concrete	
	21	570 [3930]	100% Concrete		600 [4130]	100% Concrete	
	28	800 [5510]	100% Concrete		850 [5860]	100% Concrete	
	56	820 [5650]	100% Concrete		710 [4890]	100% Concrete	
5 A4×2	7	680 [4690]	100% Concrete		780 [5370]	100% Concrete	
	21	520 [3580]	100% Concrete		590 [4070]	100% Concrete	
	28	750 [5170]	100% Concrete		840 [5790]	100% Concrete	
	56	740 [5100]	100% Concrete		760 [5240]	100% Concrete	

ºDays after end of wet curing
*For coating failures, failure occurred between coating and concrete unless noted otherwise

Table 3.2 Cont.: Pull-Off Test Results for Coatings Applied 14 Days after End of Wet Curing

		Series 2 Slabs				Series 3 Slabs		
Coating System	**Test Age (Days°)**	**Pull-off Stress at Failure (psi) [kPa]**	**Failure Type***	**Failure Type***		**Pull-off Stress at Failure (psi) [kPa]**	**Failure Type***	**Failure Type***
6 (B1×2)	7	760 [5240]	95% Concrete	5% Coating		710 [4890]	100% Concrete	
	21	850 [5860]	100% Concrete			560 [3860]	100% Concrete	
	28	1090 [7510]	100% Concrete			730 [5030]	100% Concrete	
	56	1000 [6890]	100% Concrete			670 [4620]	100% Concrete	
7 (B1×2/A4)	7	630 [4340]	100% Coating			740 [5100]	100% Concrete	
	21	810 [5580]	100% Concrete			690 [4750]	100% Concrete	
	28	780 [5370]	100% Concrete			730 [5030]	100% Concrete	
	56	840 [5790]	95% Concrete	5% Coating**		710 [4890]	100% Concrete	
8 (B2×2)	7	390 [2690]	25% Concrete	75% Coating		550 [3790]	80% Concrete	20% Coating
	21	810 [5580]	100% Concrete			530 [3650]	50% Concrete	50% Coating
	28	880 [6060]	100% Concrete			610 [4200]	50% Concrete	50% Coating
	56	670 [4620]	5% Concrete	95% Coating		570 [3930]	100% Coating	
9 (C1/C2)	7	740 [5100]	100% Concrete			650 [4450]	100% Concrete	
	21	730 [5030]	100% Concrete			410 [2820]	100% Concrete	
	28	820 [5650]	100% Concrete			590 [4070]	100% Concrete	
	56	750 [5170]	95% Concrete	5% Coating		620 [4270]	100% Concrete	
10 (D1)	7	680 [4690]	100% Concrete			530 [3650]	100% Concrete	
	21	880 [6060]	100% Concrete			650 [4480]	100% Concrete	
	28	820 [5650]	100% Concrete			810 [5580]	100% Concrete	
	56	680 [4690]	100% Concrete			550 [3790]	100% Concrete	

°Days after end of wet curing
*For coating failures, failure occurred between coating and concrete unless noted otherwise
** Coating failure between layers of coating system

For the systems applied 45 days after the end of wet-curing (Table 3.3), failure occurred most often in concrete. The pull-off stresses ranged from 540 psi to 1010 psi (3725 kPa to 6965 kPa). Coating system 7 (B1×2/A4) had two partial coating failures (between the coating and the concrete), with a 5% coating/95% concrete failure in the 7 day and 56 day tests. In these cases, the pull-off stresses at failure were 1010 psi and 750 psi (6965 and 5170 kPa) compared to pull-off stresses at failure of 740 psi and 770 psi (5100 kPa and 5305 kPa) for 100% concrete failures, indicating no loss in adhesion. As observed in tests at earlier application ages, coating system 8 (B2×2) exhibited a partial coating failure between the coating and the concrete, in this case, 56 days after application; the pull-off stress at failure was 550 psi (3790 kPa). The 100% concrete failures for coating system 8 (B2×2) had pull-off stresses ranging from 740 psi to 800 psi (5100 kPa to 5520 kPa) 7 to 28 days after application. A review of the failure types for coating system 8 (B2×2) when applied 21 and 28 days after the end of wet curing (Tables E.1 and E.2 in Appendix E) shows a progressive increase in concrete failures and decrease in coating failures as the age at application increased, suggesting that coating system 8 (B2×2) is one that *does* benefit from increased drying prior to application. The other systems do not appear to require the extra concrete drying.

Table 3.3: Pull-Off Test Results for Coatings Applied 45 Days after End of Wet Curing

Coating System	Test Age (Days°)	Pull-off Stress at Failure (psi) [kPa]	Failure Type*	Failure Type*
1 (A1/A2)	7	600 [4130]	100% Concrete	
	21	780 [5370]	95% Concrete	5% Glue
	28	720 [4960]	95% Concrete	5% Glue
	56	880 [6060]	100% Concrete	
2 (A1/A4)	7	960 [6610]	100% Concrete	
	21	860 [5930]	100% Concrete	
	28	850 [5860]	100% Concrete	
	56	990 [6820]	100% Concrete	
3 (A3/A4)	7	810 [5580]	100% Concrete	
	21	850 [5860]	100% Concrete	
	28	890 [6130]	100% Concrete	
	56	780 [5370]	100% Concrete	
4 (A3/A4×2)	7	850 [5860]	100% Concrete	
	21	1010 [6960]	100% Concrete	
	28	860 [5930]	100% Concrete	
	56	540 [3720]	100% Concrete	
5 (A4×2)	7	830 [5720]	100% Concrete	
	21	860 [5930]	100% Concrete	
	28	870 [5990]	100% Concrete	
	56	900 [6200]	100% Concrete	
6 (B1×2)	7	890 [6130]	100% Concrete	
	21	670 [4620]	100% Concrete	
	28	890 [6130]	100% Concrete	
	56	910 [6270]	100% Concrete	
7 (B1×2/A4)	7	1010 [6960]	95% Concrete	5% Coating
	21	740 [5100]	100% Concrete	
	28	770 [5310]	100% Concrete	
	56	750 [5170]	95% Concrete	5% Coating
8 (B2×2)	7	800 [5510]	100% Concrete	
	21	800 [5510]	100% Concrete	
	28	740 [5100]	100% Concrete	
	56	550 [3790]	50% Concrete	50% Coating
9 (C1/C2)	7	790 [5440]	100% Concrete	
	21	750 [5170]	100% Concrete	
	28	690 [4750]	100% Concrete	
	56	750 [5170]	100% Concrete	
10 (D1)	7	740 [5100]	100% Concrete	
	21	820 [5650]	100% Concrete	
	28	900 [6200]	100% Concrete	
	56	830 [5720]	100% Concrete	

°Days after end of wet curing
*For coating failures, failure occurred between coating and concrete unless noted otherwise

3.2.2 Knife-Test

Tables 3.4 shows the results for the knife tests for all coating systems applied 7, 14, and 45 days after the end of wet-curing. Results for the systems applied at 21 and 28 days are presented in Table F.1 in Appendix F. No pass/fail criteria exist for the knife test. The results, however, can be used to compare the performance of a coating applied at early ages to the same coating applied at later ages to determine if the early application had a detrimental effect. In this test, a higher rating indicates better performance. The performance of the coating systems was not sensitive to either the age at application or the age at test.

All coating systems except 1 (A1/A2) and 9 (C1/C2) exhibited excellent performance regardless of the number of days between the end of wet-curing and coating application. Excluding 1 (A1/A2) and 9 (C1/C2), the coating systems exhibited an average knife test rating of 9 or better, with no decrease in rating, even when the coating systems were applied seven days after wet-curing. Coating systems 1 (A1/A2) and 9 (C1/C2), the thickest in the study, exhibited a much lower rating (that is, the coating was more easily removed) than other systems. When applied seven days after the end of wet curing, system 1 (A1/A2) had knife test ratings between 4 and 6 with an average of 4.5 in Series 1 and similar results in Series 3. At the same age, system 9 (C1/C2) had ratings between 4 and 5 with an average of 4.25 in Series 2 and worse performance (ratings between 0 and 2) in Series 3. When applied 45 days after the end of wet curing, system 1 (A1/A2) exhibited ratings between 4 and 6 with an average of 5.25, comparable to the performance observed after seven days of wet-curing. System 9 (C1/C2) exhibited worse performance when the concrete was allowed to dry for 45 days prior to application with ratings between 1 and 2 and an average of 1.25. It is likely that this lower rating resulted from the high relative thickness of coating materials A2 and C2, the top coats in systems 1 (A1/A2) and 9 (C1/C2). The measured dry film thickness ranged from 20 to 35 mils (0.51 to 0.89 mm) for coating A2 and from 35 to 50 mils (0.890 to 1.27 mm) for coating C2, compared to the other systems with average dry film thicknesses that ranged from 2 and 11 mils (0.050 mm and 0.28 mm). As a result, the knife was easily able to penetrate and lift the coatings, creating a lower rating on the knife test. Despite the low rating in the knife test, systems 1 (A1/A2) and 9 (C1/C2) exhibited good performance in the pull-off test and showed no signs of blistering or other distress. The test does, however, appear to provide a good measure of how easily a coating system can be damaged by gouging. The excellent performance of the other eight coating systems in the knife test, for all ages of application and testing, indicates no problems from early application based on this measure of adhesion.

Nine of the ten coating systems had similar results in Series 1 and 2 and in Series 3. Coating System 9 (C1/C2) exhibited poor performance in all cases, although the performance was poorer in Series 3 than in Series 2, and in neither case would be considered acceptable. Overall, covering more of the concrete at the time of coating application, as done in Series 3 compared to Series 1 and 2, does not appear to have affected the performance of the coating systems as measured by the knife-test. Coupled with the similar insensitivity to the area covered by coatings observed in the pull-off tests, the findings in this study indicate that tests that involve the application of coatings on small regions are valid for measuring coating the same properties at full scale.

Table 3.4: Knife-Test Results for Coatings Applied 7, 14, and 45 Days after End of Wet Curing

Coating System	Test Age (Days°)	Applied 7 days after wet curing		Applied 14 days after wet curing		Applied 45 days after wet curing
		Series 1 and 2	Series 3	Series 1 and 2	Series 3	Series 1 and 2
		Rating	Rating	Rating	Rating	Rating
1 (A1/A2)	7	6	4	5	3	6
	21	4	6	6	2	6
	28	4	3	4	7	5
	56	4	7	4	7	4
2 (A1/A4)	7	8	10	10	8	10
	21	10	10	10	10	10
	28	10	10	10	10	10
	56	10	10	10	10	10
3 (A3/A4)	7	10	10	10	10	10
	21	10	10	10	10	10
	28	10	10	10	10	10
	56	10	10	10	10	10
4 (A3/A4×2)	7	10	8	10	9	10
	21	10	10	10	10	10
	28	10	10	10	9	10
	56	10	10	10	10	10
5 (A4×2)	7	10	10	10	10	10
	21	10	10	10	10	10
	28	10	10	10	9	10
	56	10	10	10	10	9
6 (B1×2)	7	10	10	10	10	10
	21	10	10	10	10	10
	28	10	10	10	10	10
	56	10	10	10	10	10
7 (B1×2/A4)	7	10	10	10	10	10
	21	10	10	8	10	8
	28	8	10	10	10	10
	56	8	10	10	10	10
8 (B2×2)	7	10	10	7	8	10
	21	7	9	10	10	10
	28	10	8	10	10	10
	56	10	9	10	10	10
9 (C1/C2)	7	4	0	4	0	1
	21	4	0	5	1	2
	28	4	2	4	0	1
	56	5	1	8	2	1
10 (D1)	7	8	10	10	10	10
	21	8	10	10	10	10
	28	8	10	10	10	10
	56	10	10	10	10	10

°Days after end of wet curing

3.3 Discussion

The performance of the coating systems evaluated in this study based on the pull-off and knife tests indicate that coatings may be applied at ages as early as seven days after the end of wet-curing without detrimental effect. At this age, the concrete in this study exhibited moisture vapor emission rates (MVER) greater than 10 lb/1000 ft^2/day (565 $\mu g/m^2/s$) and internal concrete relative humidity (RH) measurements over 80%. These observations demonstrate that current manufacturer guidelines (which are based largely on guidelines for impermeable floor coverings) are overly conservative for many products. Comparisons between the 6-in. (150-mm) thick slab specimens and 24-in. (610-mm) thick block specimens show no significant differences in the value or rate of change in MVER or RH, indicating that the results obtained in this study are applicable to coatings applied to thick concrete placements. This observation matches the results of similar a comparison made by Suprenant and Malisch (1998a). The similarity of the test results in Series 1 and 2 with those in Series 3 indicate that coating performance was not affected by the percentage of the slab surface covered and that tests that involve the application of coatings to small regions are valid for measuring the same properties at full scale.

The research performed for this study only examined coating adhesion. Other requirements for Service Level I coatings, such as abrasion resistance, chemical resistance, fire resistance, and radiation tolerance, should be investigated prior to widespread use of these coatings at early ages.

Chapter 4 SUMMARY AND CONCLUSIONS

4.1 SUMMARY

Current construction practices require long drying times between the end of concrete curing and the application of coatings, often 28 days or longer. These practices are based on findings and experience with relatively impermeable floor coverings, which are prone to blistering, buckling, and/or adhesion failure when moisture becomes trapped under the covering. Little research has been performed on the performance of coating systems when applied at early ages. Manufacturers, therefore, follow the long drying-time recommendations used for floor coverings. Reducing drying time could result in significant savings during construction. These savings are of significant interest in the construction of nuclear power plants and other structures, particularly those that utilize open top construction. Ten coatings from four manufacturers were applied to concrete 7, 14, 21, 28, and 45 days after the end of wet curing. Coating adhesion was tested using the pull-off (ASTM D7234) and knife (ASTM D6677) tests. The coatings were applied to concrete with moisture vapor emission rates (MVER) and internal relative humidity (RH) greater than the limits currently recommended by manufacturers.

4.2 CONCLUSIONS

Based on the results presented in this report, the following conclusions can be drawn:

1. Coatings are available for which adhesion is not affected by early-age application to concrete with moisture vapor emission rates (MVER) above 10 lb/1000 ft^2/day (565 $\mu g/m^2/s$) and internal relative humidity (RH) above 80% when tested within 56 days of application. This observation offers the potential to speed open top construction of nuclear power plants.
2. The thickness of concrete does not affect the value or rate of change in MVER or RH. A key implication is that the results of this study can be applied to deep concrete members.
3. Thicker coatings are more readily removed in the knife test compared to thinner coatings. In this study, this performance did not correlate with signs of visual damage or poor

performance in the pull-off tests, but may be a measure of the ability of coatings to resist gouging.

4. Coating performance is not affected by the percentage of the slab surface covered and tests that involve the application of coatings to small regions are valid for measuring the same properties at full scale.

4.3 RECOMMENDATIONS

1. One of the coatings evaluated in this study proved to be sensitive to high MVER, high RH, or both. Its performance, as measured by the pull-off test, improved as the concrete dried, indicating that coating systems should be evaluated individually to ensure that they can be successfully applied at early ages.

2. This study was conducted in a controlled environment. Prior to wide-scale application of these findings, manufacturers would be wise to conduct wider-scale trial applications correlated with performance in a controlled environment to determine the suitability of their coating systems for early-age application under more varied environmental conditions.

3. This study was limited to adhesion strength and was conducted over a relatively short time scale–the last pull-off and knife tests were performed 56 days after application of the final layer of the coating. Additional research should be performed on prototype large scale applications and include additional tests for Service Level I coatings, such as abrasion resistance, chemical resistance, fire resistance, and radiation tolerance prior to widespread use of these coatings at early ages.

REFERENCES

ACI Committee 302, 2006, *Guide for Concrete Slabs that Receive Moisture-Sensitive Flooring Materials* (302R-06), American concrete Institute, Farmington Hills, MI, 42 pp.

ASTM D4138, 2013, "*Standard Practices for Measurement of Dry Film Thickness of Protective Coating Systems by Destructive, Cross-Sectioning Means*," ASTM International, West Conshohocken, PA, 6 pp.

ASTM D6677, 2012, "*Standard Test Method for Evaluating Adhesion by Knife*," ASTM International, West Conshohocken, PA, 2 pp.

ASTM D7234, 2012, "*Standard Test Method for Pull-Off Adhesion Strength of Coatings on Concrete Using Portable Pull-Off Adhesion Testers*," ASTM International, West Conshohocken, PA, 9 pp.

ASTM F1869, 2011, "*Standard Test Method for Measuring Moisture Vapor Emission Rate of Concrete Subfloor Using Anhydrous Calcium Chloride*," ASTM International, West Conshohocken, PA, 4 pp.

ASTM F2170, 2011, "*Standard Test Method for Determining Relative Humidity in Concrete Floor Slabs Using in situ Probes*," ASTM International, West Conshohocken, PA, 5 pp.

ASTM F710, 2011: "*Standard Practice for Preparing Concrete Floors to Receive Resilient Flooring.*" ASTM International, West Conshohocken, PA, 8 pp.

Brewer, H. W., 1965, "Moisture Migration—Concrete Slab-on-Ground Construction," *Bulletin* D89, Portland Cement Association, Skokie, IL, May 1965, 17 pp.

Carboline, 2005, *SEMSTONE 110/110 EP product data*, The Carboline Company, St, Louis, MO, 2 pp.

Carboline, 2012, *Carboguard 1340N product data*, The Carboline Company, St. Louis, MO, 2 pp.

Carboline, 2015a, *Sanitile 945 SL product data*, The Carboline Company, St. Louis, MO, 3 pp. (www.carboline.com)

Carboline, 2015b, *Carboguard 890N product data*, The Carboline Company, St. Louis, MO, 3 pp.

Craig, P., 2003, "Moisture Mitigation," *Concrete International*, Vol. 25, No. 8, pp. 23-27.

Flowcrete North America, Inc., 2012, *Hydraseal DPM*, Conroe, Texas. (www.flowcrete.us), 2 pp.

Flowcrete Americas, 2015, *Flowseal EPW*, Spring, Texas. (www.flowcreteamericas.com), 2 pp.

ICRI, 2013. “Selecting and Specifying Concrete Surface Preparation for Sealers, Coatings, and Polymer Overlays, and Concrete Repair,” *Technical Guideline* No. 310.2R. International Concrete Repair Institute, St. Paul, MN, 54 pp.

PPG Protective & Marine Coatings, 2016a, *Product data sheet KL5500/KL5500B,* 5 pp.

PPG Protective & Marine Coatings, 2016b, *Product data sheet KL5129/KL5129B,* 4 pp.

Suprenant, B., 1997, “Moisture Movement Through Concrete Slabs,” *Concrete Construction*, Vol. 42, No. 11, pp. 879-885.

Suprenant, B. A. and Malisch, W. R., 1998a “Quick-Dry Concrete: A New Market for Ready-Mix Producers,” *The Concrete Producer,* May, pp. 330-333.

Suprenant, B. A. and Malisch, W. R., 1998b, “Are your slabs dry enough for floor coverings?” *Concrete Construction,* Vol. 43, No. 8, Aug., pp. 671-674.

Warren Environmental Inc., 2016, *Hand Application Instructions,* Warren Environmental Systems, 2 pp.

APPENDIX A ENVIRONMENTAL CHAMBER RESULTS

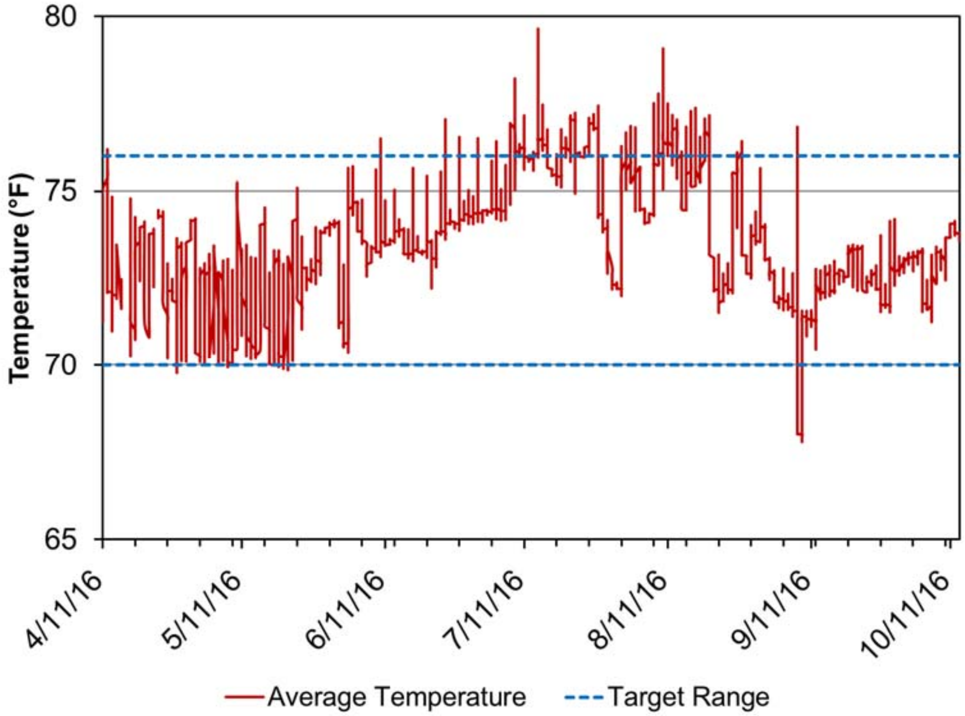

Figure A.1: Environmental Chamber 1 Average Air Temperature

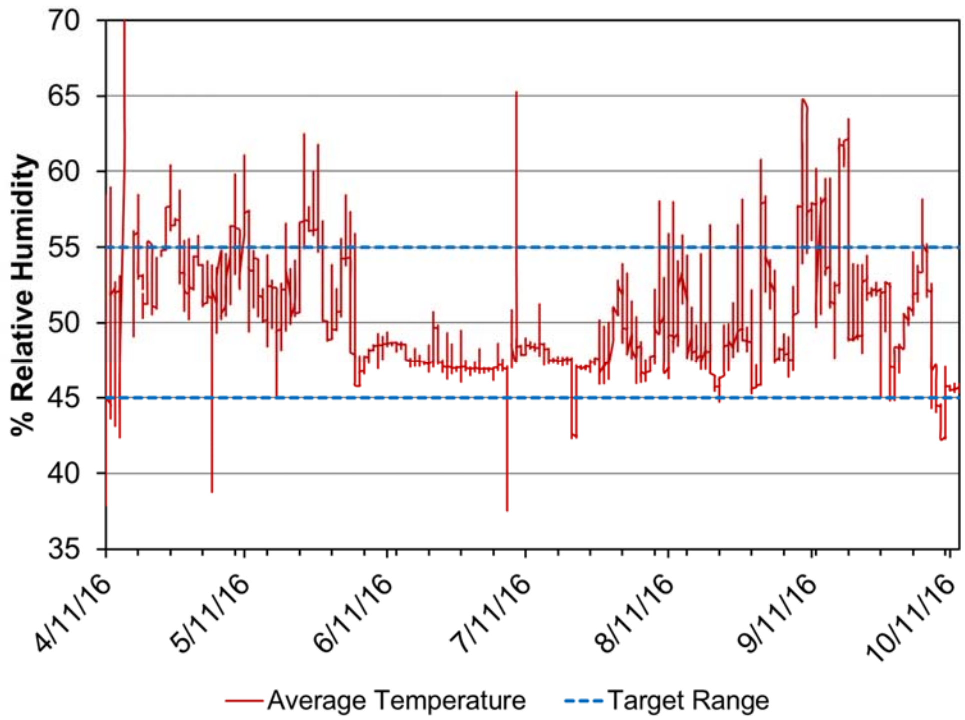

Figure A.2: Environmental Chamber 1 Average Air Relative Humidity

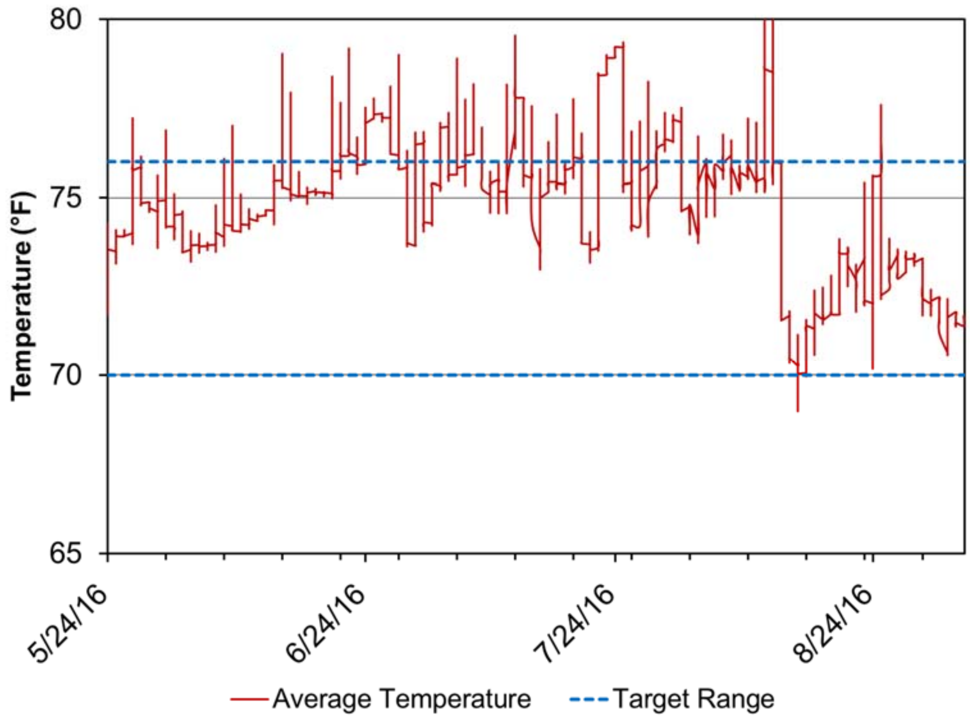

Figure A.3: Environmental Chamber 2 Average Air Temperature

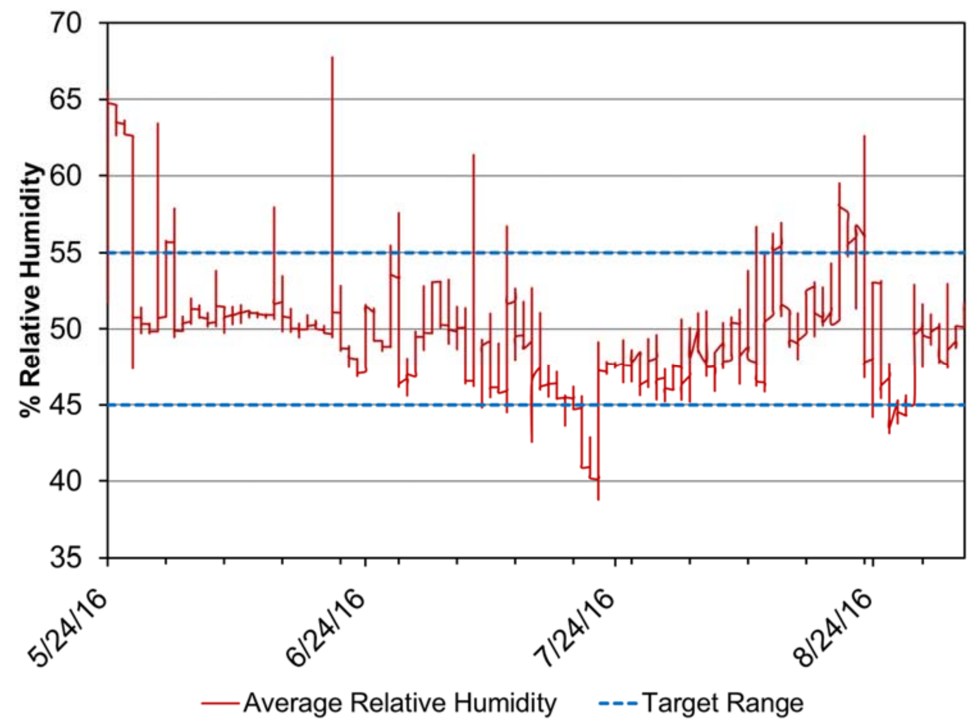

Figure A.4: Environmental Chamber 2 Average Air Relative Humidity

APPENDIX B PH RESULTS

Table B.1: pH test results for Series 3 Slabs

Test	pH				Average
Slab 11	11	11	11	11	11
Slab 12	10	11	<10	11	<10.5
Slab 13	10.5	11	11	11	10.9
Slab 14	10	10.5	11	11	10.6

APPENDIX C MVER INDIVIDUAL RESULTS

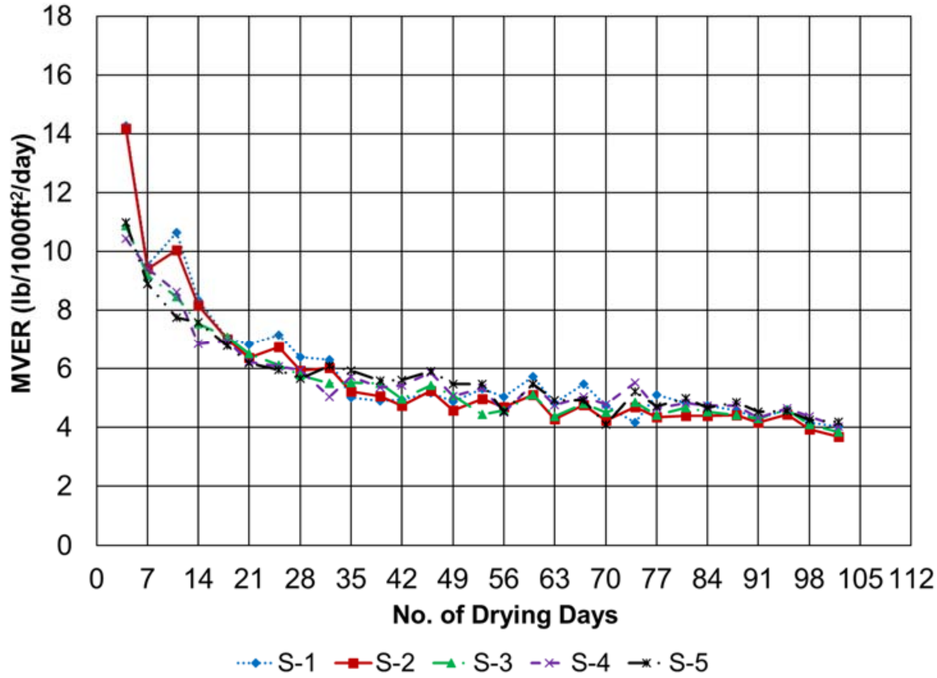

Figure C.1: Individual MVER results for slabs in Series 1 (Note: 1 lb/1000 ft^2/day = 57 μg/m^2/s)

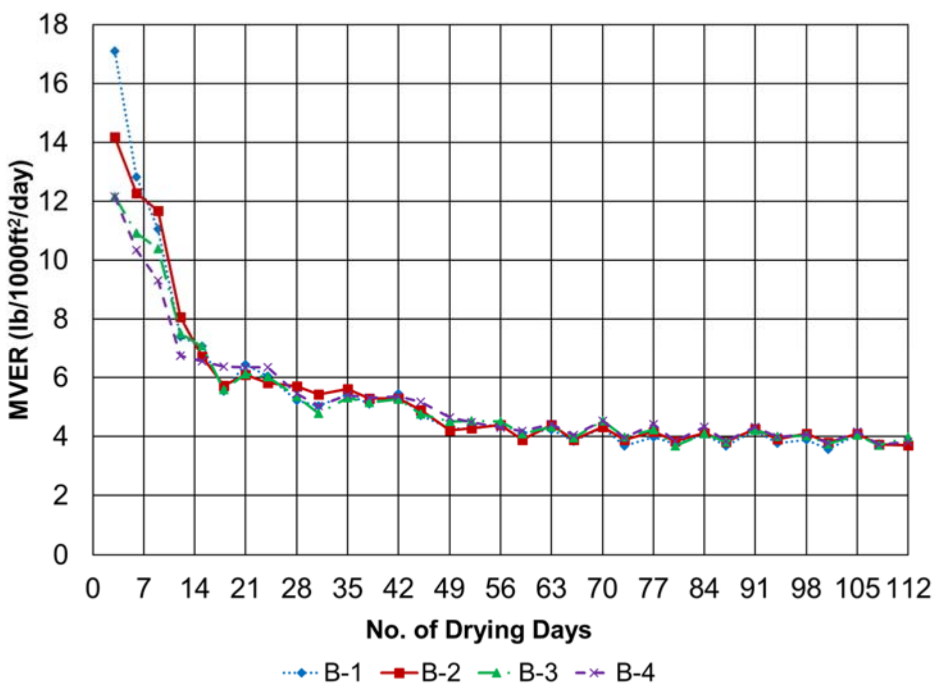

Figure C.2: Individual MVER results for blocks in Series 1 (Note: 1 lb/1000 ft^2/day = 57 μg/m^2/s)

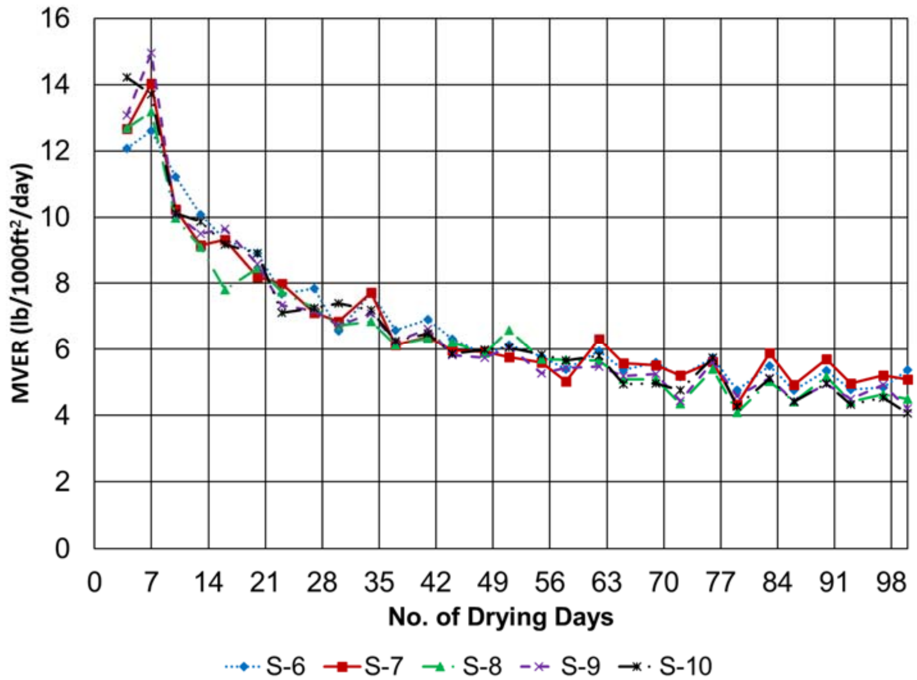

Figure C.3: Individual MVER results for slabs in Series 2 (Note: 1 lb/1000 ft^2/day = 57 $\mu g/m^2/s$)

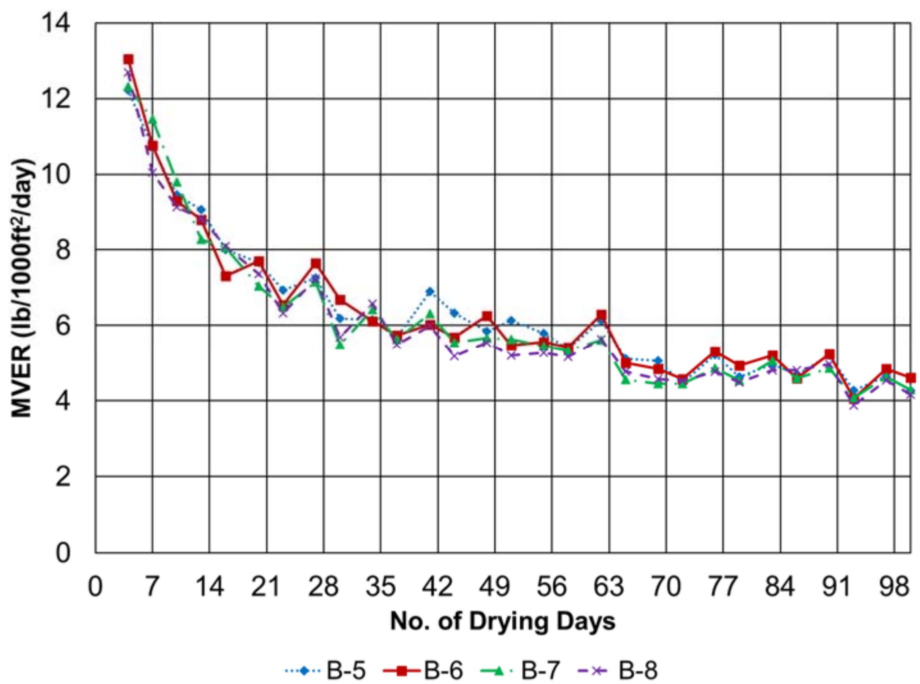

Figure C.4: Individual MVER results for blocks in Series 2 (Note: 1 lb/1000 ft^2/day = 57 $\mu g/m^2/s$)

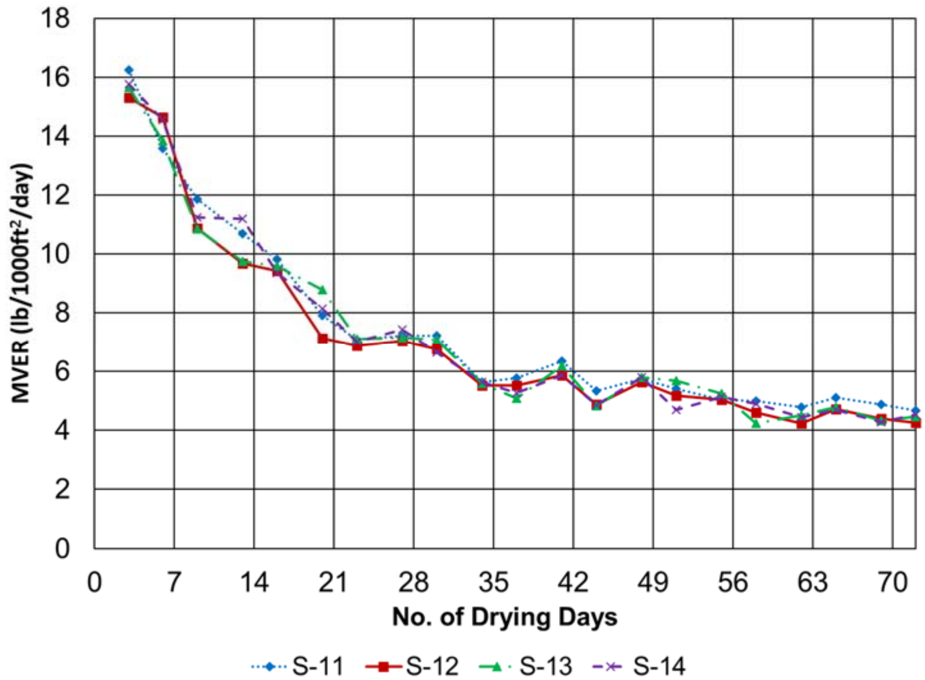

Figure C.5: Individual MVER results for slabs in Series 3 (Note: 1 lb/1000 ft^2/day = 57 μg/m^2/s)

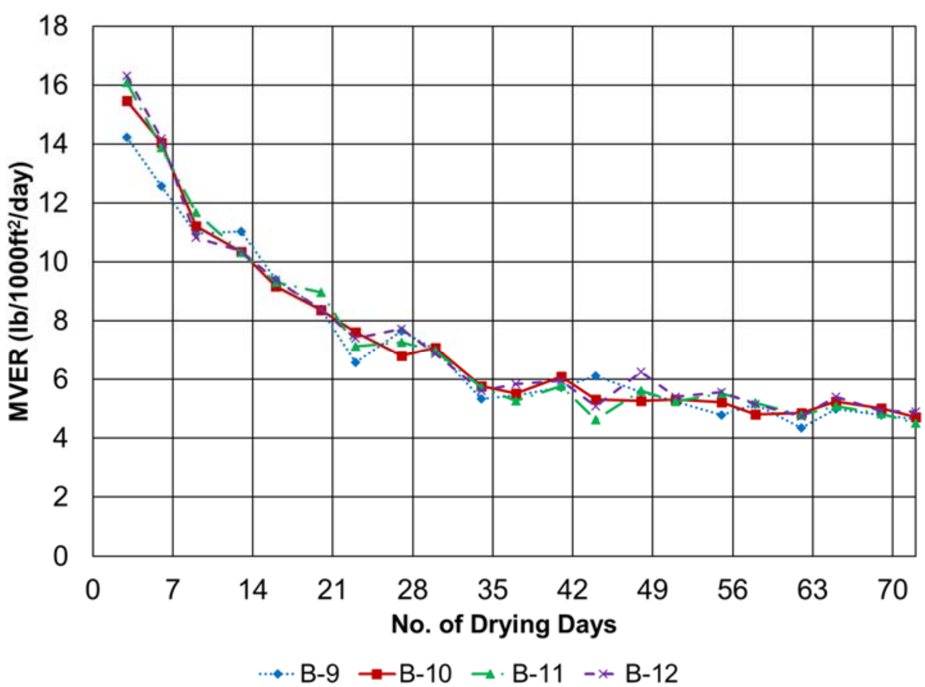

Figure C.6: Individual MVER results for blocks in Series 3 (Note: 1 lb/1000 ft^2/day = 57 μg/m^2/s)

APPENDIX D INDIVIDUAL INTERNAL RELATIVE HUMIDITY RESULTS

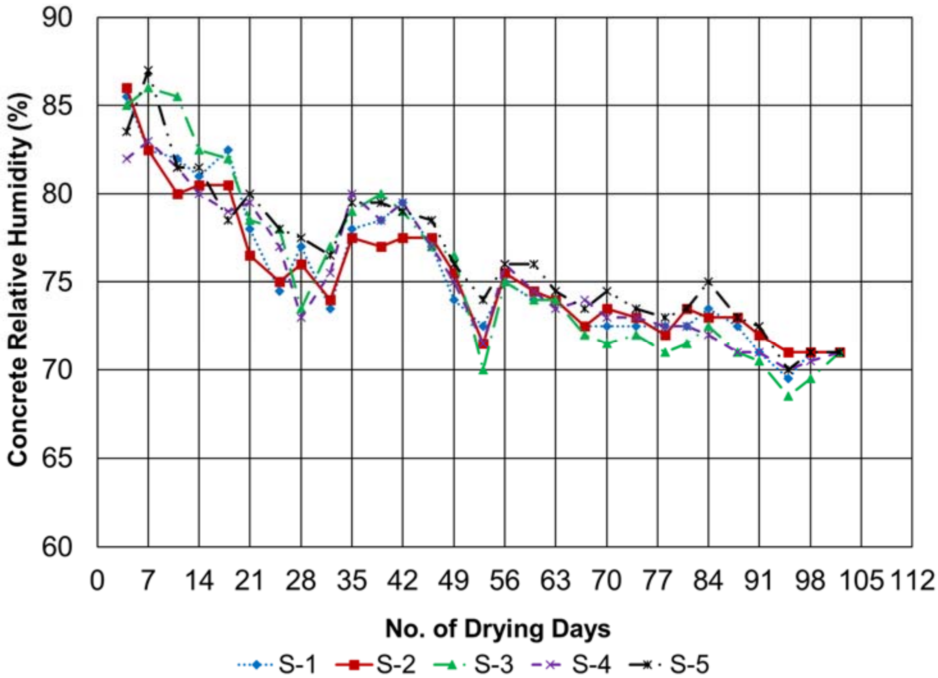

Figure D.1: Individual concrete relative humidity results for Series 1 slabs

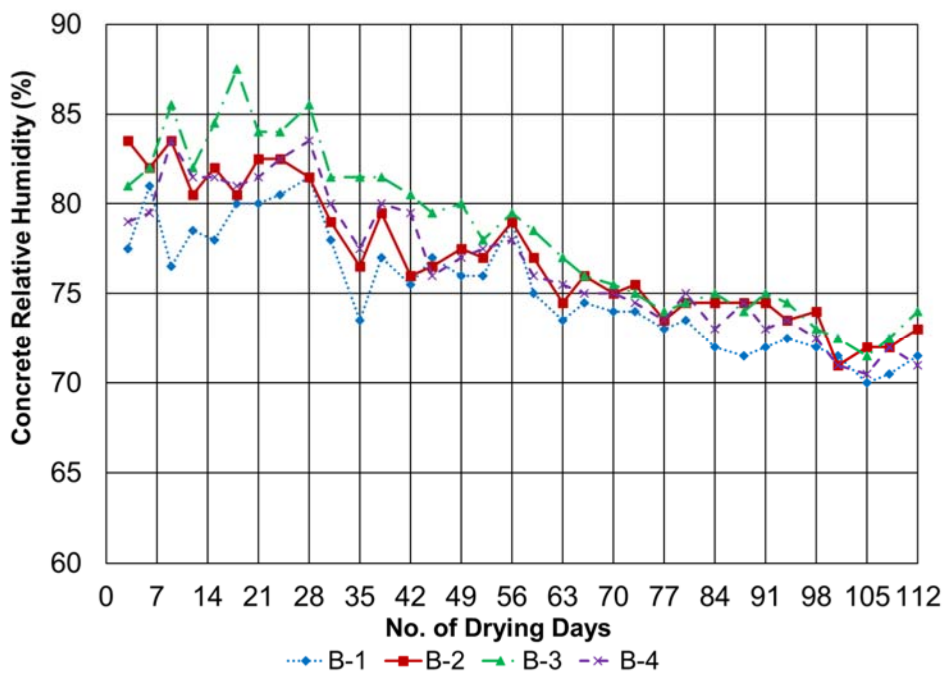

Figure D.2: Individual concrete relative humidity results for Series 1 blocks

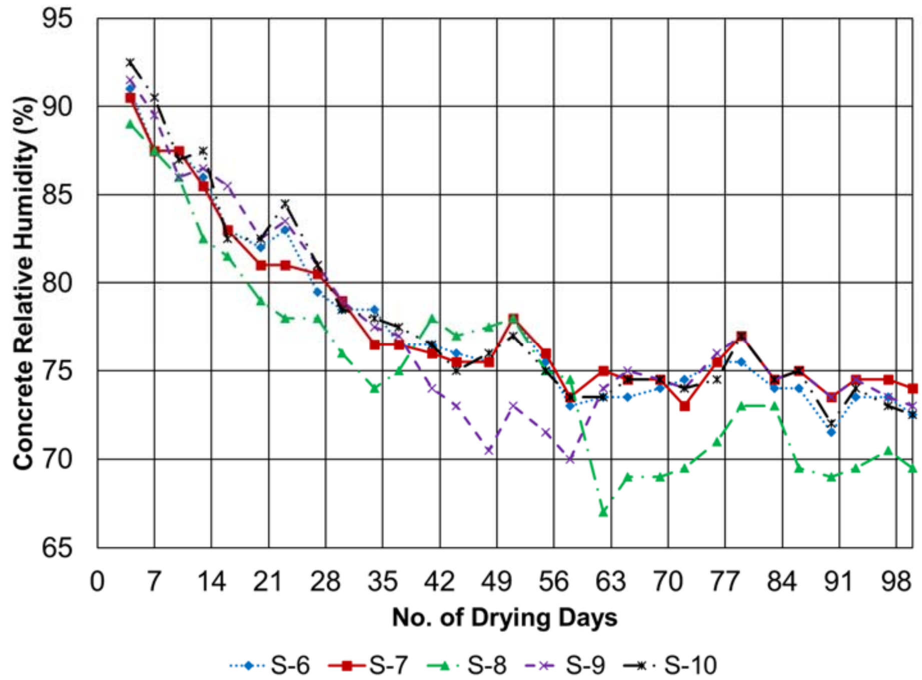

Figure D.3: Individual concrete relative humidity results for Series 2 slabs

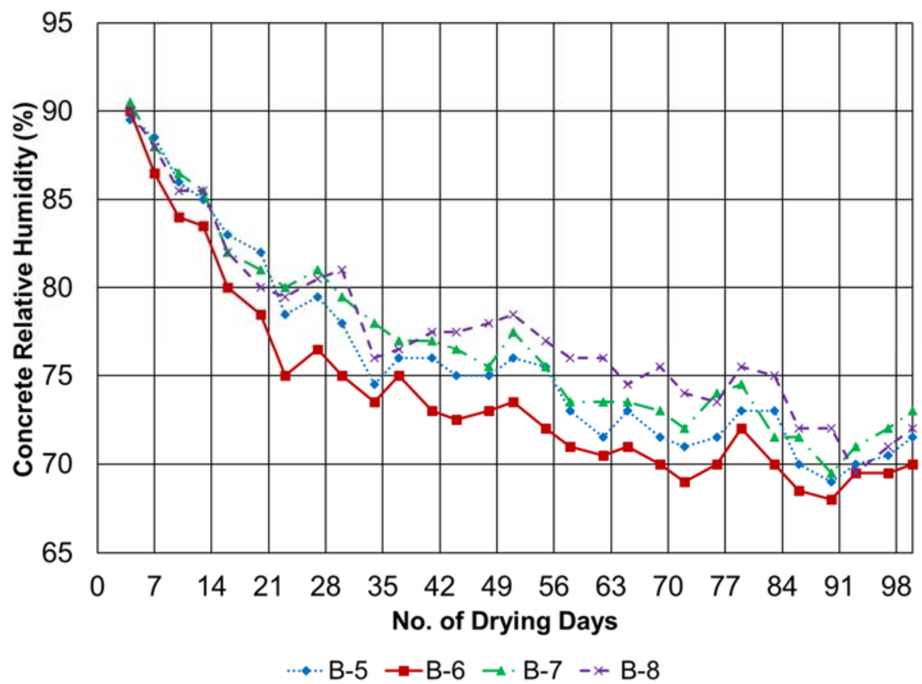

Figure D.4: Individual concrete relative humidity results for Series 2 blocks

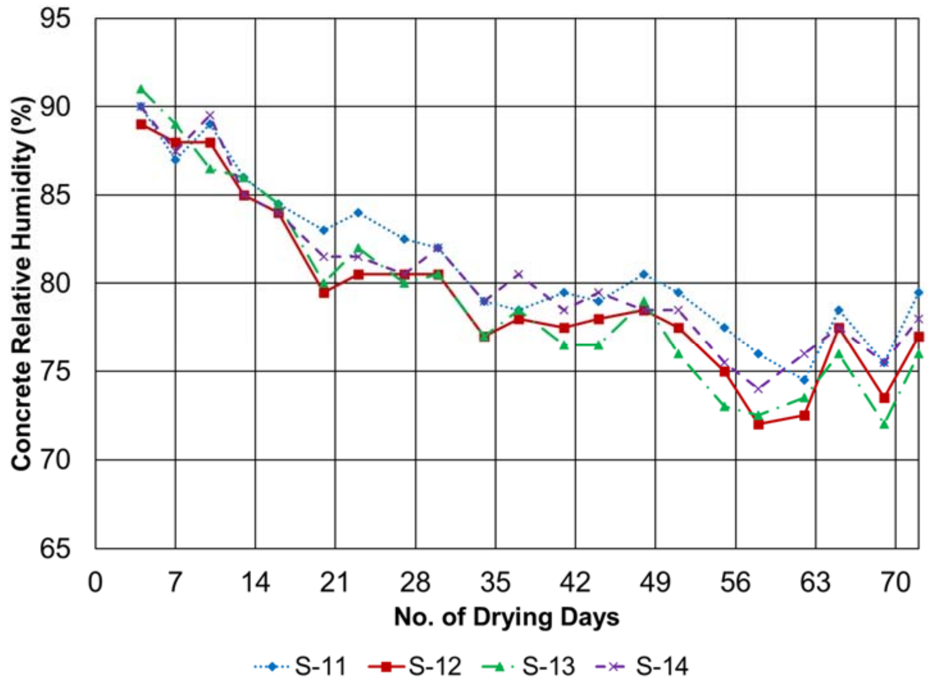

Figure D.5: Individual concrete relative humidity results for Series 3 slabs

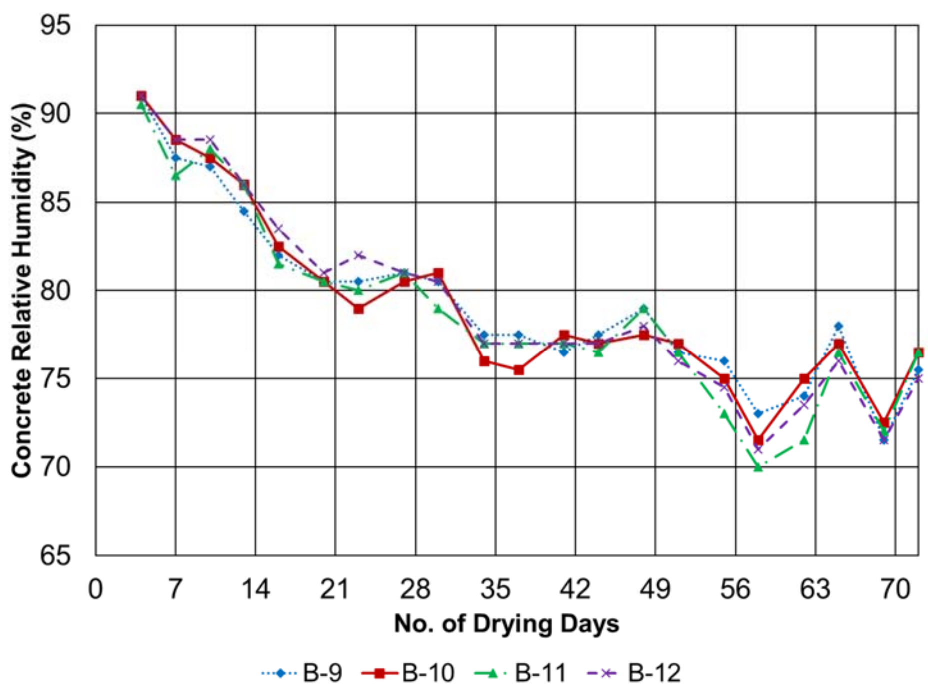

Figure D.6: Individual concrete relative humidity results for Series 3 blocks

APPENDIX E PULL-OFF TEST RESULTS

Table E.1: Pull-Off Test Results for Coatings Applied 21 Days after End of Wet Curing

Coating System	Test Age (Days°)	Pull-off Stress at Failure (psi) [kPa]	Failure Type*	Failure Type*
1 (A1/A2)	7	720 [4960]	100% Concrete	
	21	780 [5370]	100% Concrete	
	28	680 [4690]	100% Concrete	
	56	800 [5510]	100% Concrete	
2 (A1/A4)	7	770 [5310]	100% Concrete	
	21	780 [5370]	100% Concrete	
	28	780 [5370]	100% Concrete	
	56	960 [6610]	100% Concrete	
3 (A3/A4)	7	740 [5100]	100% Concrete	
	21	960 [6610]	100% Concrete	
	28	710 [4890]	100% Concrete	
	56	910 [6270]	100% Concrete	
4 (A3/A4×2)	7	740 [5100]	100% Glue	
	21	880 [6060]	100% Concrete	
	28	740 [5100]	100% Concrete	
	56	960 [6610]	100% Concrete	
5 (A4×2)	7	780 [5370]	100% Concrete	
	21	820 [5650]	100% Concrete	
	28	740 [5100]	100% Concrete	
	56	830 [5720]	100% Concrete	
6 (B1×2)	7	730 [5030]	100% Concrete	
	21	950 [6550]	100% Concrete	
	28	1040 [7170]	100% Concrete	
	56	640 [4410]	95% Concrete	5% Glue
7 (B1×2A4)	7	730 [5030]	100% Concrete	
	21	990 [6820]	100% Concrete	
	28	890 [6130]	100% Concrete	
	56	800 [5510]	100% Concrete	
8 (B2×2)	7	660 [4550]	85% Concrete	15% Coating
	21	790 [5440]	100% Concrete	
	28	630 [4340]	80% Concrete	20% Coating
	56	750 [5170]	90% Concrete	10% Coating
9 (C1/C2)	7	Tests not performed due to coating application error		
	21			
	28			
	56			
10 (D1)	7	700 [4820]	100% Concrete	
	21	840 [5790]	100% Concrete	
	28	770 [5310]	100% Concrete	
	56	980 [6750]	95% Concrete	5% Glue

°Days after end of wet curing
*For coating failures, failure occurred between coating and concrete unless noted otherwise

Table E.2: Pull-Off Test Results for Coatings Applied 28 Days after End of Wet Curing

Coating System	Test Age (Days°)	Pull-off Stress at Failure (psi) [kPa]	Failure Type*	Failure Type*
1 (A1/A2)	7	790 [5440]	100% Concrete	
	21	700 [4820]	100% Concrete	
	28	750 [5170]	100% Concrete	
	56	730 [5030]	100% Concrete	
2 (A1/A4)	7	680 [4690]	100% Concrete	
	21	830 [5720]	100% Concrete	
	28	770 [5310]	100% Concrete	
	56	830 [5720]	100% Concrete	
3 (A3/A4)	7	590 [4070]	100% Concrete	
	21	820 [5650]	100% Concrete	
	28	880 [6060]	100% Concrete	
	56	760 [5240]	100% Concrete	
4 (A3/A4×2)	7	710 [4890]	100% Concrete	
	21	670 [4620]	100% Concrete	
	28	640 [4410]	100% Concrete	
	56	830 [5720]	100% Concrete	
5 (A4×2)	7	490 [3380]	90% Concrete	10% Glue
	21	710 [4890]	100% Concrete	
	28	750 [5170]	100% Concrete	
	56	860 [5930]	100% Concrete	
6 (B1×2)	7	890 [6130]	100% Concrete	
	21	880 [6060]	100% Concrete	
	28	920 [6340]	100% Concrete	
	56	990 [6820]	100% Concrete	
7 (B1×2/A4)	7	950 [6550]	100% Concrete	
	21	890 [6130]	100% Concrete	
	28	470 [3240]	95% Concrete	5% Coating
	56	960 [6610]	100% Concrete	
8 (B2×2)	7	680 [4690]	100% Concrete	
	21	850 [5860]	100% Concrete	
	28	520 [3580]	90% Concrete	10% Coating
	56	810 [5580]	100% Concrete	
9 (C1/C2)	7	770 [5310]	100% Concrete	
	21	750 [5170]	100% Concrete	
	28	680 [4690]	100% Concrete	
	56	680 [4690]	100% Concrete	
10 (D1)	7	920 [6340]	100% Concrete	
	21	860 [5930]	100% Concrete	
	28	780 [5370]	100% Concrete	
	56	820 [5650]	100% Concrete	

°Days after end of wet curing
*For coating failures, failure occurred between coating and concrete unless noted otherwise

APPENDIX F KNIFE TEST RESULTS

Table F.1: Knife-Test Results for Coatings Applied 21 and 28 Days after End of Wet Curing

Coating System	Applied 21 days after wet curing		Applied 28 days after wet curing	
	Test Age (Days°)	Rating	Test Age (Days°)	Rating
1 (A1/A2)	7	5	7	6
	21	5	21	6
	28	5	28	4
	56	4	56	5
2 (A1/A4)	7	10	7	10
	21	10	21	10
	28	10	28	9
	56	10	56	10
3 (A3/A4)	7	10	7	10
	21	10	21	10
	28	10	28	10
	56	10	56	10
4 (A3/A4×2)	7	10	7	10
	21	10	21	10
	28	10	28	10
	56	10	56	10
5 (A4×2)	7	10	7	10
	21	10	21	10
	28	10	28	10
	56	10	56	10
6 (B1/B1)	7	10	7	10
	21	10	21	10
	28	10	28	10
	56	10	56	10
7 (B1×2/A4)	7	10	7	8
	21	10	21	8
	28	8	28	10
	56	10	56	10
8 (B2×2)	7	8	7	10
	21	10	21	10
	28	10	28	10
	56	10	56	10
9 (C1/C2)	Did not perform		7	3
			21	3
			28	2
			56	1
10 (D1)	7	10	7	10
	21	10	21	10
	28	10	28	10
	56	10	56	10

°Days after end of wet curing