DURABILITY EVALUATION OF CONCRETE SEALED WITH POLYUREA POLYASPARTIC COATINGS

By

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Abstract:

For this project, the performance of various polyaspartic coating materials was investigated. Motivation for this study was to assess various options for the containment of concrete within bridge parapet walls to prevent the falling of materials on passing vehicles and pedestrians as the bridge's concrete erodes over time. The purpose of the investigation is to identify several acceptable manufacturers of polyaspartic polyuria coating materials that could be used on a scaled concrete surface to inhibit further surface disintegration such as mortar flaking and scaling. To evaluate durability characteristics of these materials, several test methods were performed. ASTM D7234 and D6677 were used to test the adhesion ability of the various coatings to the concrete substrate. Cyclic freezing/thawing, wetting/drying (Hartell and Zeng), and salt ponding were performed in accordance with ASTM C666 and ASTM D7234 to understand the coatings ability to perform and protect concrete over time due to extreme weather conditions. In order to better aid in the adhesion comparative analysis between different coating types, compression/modulus of elasticity testing (ASTM C39/ASTM469) was performed along with flexural testing (ASTM C78). Results demonstrate that the coating systems retained could be used as part of a repair strategy to remediate deteriorated concrete cover for the prevention of further damage caused by moisture transport and to contain minor scaled concrete fragments.

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CHAPTER 1

INTRODUCTION

Deterioration of bridge parapet walls is a major concern for the Ohio Department of Transportation (DOT) as well as all DOTs that experience freezing and thawing. These walls spall over time, leading to dangerous circumstances for pedestrians and traffic below. Maintenance crews have increased danger as they remove said degraded concrete through lane closures. These closures influence traffic below the bridge as well as subjecting said traffic to falling debris. Once the cracked and deteriorated concrete is removed from the parapet walls, the resulting cross section is thinned and therefore more susceptible to degradation mechanisms such as freezing/thawing. This causes corrosion to the rebar reinforcement as the concrete cover is reduced. In short, a new method of repair is needed not only for the safety of maintenance crews, but also for all traffic on or below bridges in question. A proposed new method of repair involves the use of polyaspartic polyurea coating systems. Polyaspartic polyureas are a concrete sealant that can be applied to a prepared surface using a paint roller or spray applicators. This material not only seals the concrete, but may provide a reinforcing barrier that can retain future loose concrete.

For this project, performance of various polyaspartic coating materials was investigated. The purpose of the investigation is to identify several acceptable manufacturers of polyaspartic polyuria coating materials that could be used on a scaled concrete surface to inhibit further surface disintegration, such as mortar flaking and scaling. Application guidelines from manufacturer recommendations are provided. The coating could be used as part of a repair strategy for the containment of deteriorated concrete, preventing further damage from moisture transport.

Objectives of the study:

1. Identify coating materials from several manufacturers of polyurea polyaspartic;

2. Determine bond performance of coating systems;

3. Determine Modulus of Rupture, a quantification of flexural strength, of coated notched and non-notched concrete beams;

4. Determine ability of coating system to confine surface deterioration;

5. Determine performance of coating system under various weathering conditions.

An experimental research methodology comprising several types of mechanical testing and durability testing was devised to meet these objectives. Following sections include details of the materials studied as well as testing procedures, results, and discussion.

CHAPTER 2

REVIEW OF LITERATURE

Concrete is widely used in the construction field. It is cheap to produce, can be easily formed into various shapes, and can be used for many different applications. However, one of the biggest disadvantages to concrete is that it is indeed a porous material. It is susceptible to various degradation mechanisms involving substance penetration. This can take the form of chloride penetration which can cause rebar corrosion, as well as sulfate penetration which can lead to deterioration of the cementitious matrix. Concrete can be at an even higher risk to items such as corrosion when there are cracks present at the surface. This has been combated in the field by applying various maintenance coatings on the concrete surface. This has been done to hopefully reduce the effect of the environment on the concrete.

Different coating types have been researched in an attempt to help mitigate these risks. Epoxy is widely used in the concrete industry as a way to either coat the rebar being placed in the concrete, or the surface of the concrete itself. However, the main problem with this is that epoxy is extremely susceptible to damage through handling. For example, if there is a small nick in the epoxy coating when the rebar is placed, this area will start to exhibit pitting corrosion at the exposed area. This can drastically reduce the service life of a structure. Therefore, more coating types are being produced and are starting to be implemented in the concrete industry. This paper looks at polyaspartic polyureas as a possible replacement for epoxy concrete surface coatings.

Epoxy coating systems are widely used in the concrete industry because of its properties relating to its high adhesion, flexibility, and chemical/solvent resistance. It is still quite popular in the industry because of the growth of industrialization of the need for new manufacturing facilities. The market for floor coatings (industrial) is controlled by major corporations in the construction paints and coating industry. Through various mergers and acquisitions, the industry is able to further refine existing products and develop new products for more extreme environments (“Industrial floor coating” 2017). However, the main issue still seen with epoxy use is how easily the coating can be affected through handling.

Polyurethanes are used for substance penetration prevention and abrasion resistance and are quite economical while maintaining a decent quality. However, polyurethanes are susceptible to temperature and humidity at the time of application. This causes the coating to actually bubble up under the surface, leading to a loss of adhesion between the coating and the concrete (Cain 2016). Polyurethanes typically provide chemical resistance, abrasion resistance, durability, and UV ray stability. This makes them ideal for industrial and commercial applications. Recent developments have made them a one-part sealer with low odor during application. This gives it an advantage over other coating types as there are fewer fumes and low volatile organic compounds (VOC) (Tator 2015).

Polyaspartic coatings are widely used in the construction industry to help protect concrete from various mechanisms that will contribute to a lower estimated service life of the structure. One of the main advantages of using this type of coating is the fast cure time (Tator 2015). In the construction industry, a lot of the downtime is spent waiting for concrete to cure or the coating to cure. It is important to be able to get these structures open quickly or have quick repairs. This type of coating helps mitigate downtime on the curing of the coating itself. Multiple layers can be applied in a day and cured quickly (Tator 2015). One of the main takeaways from this is that if it is a roadway being repaired, the coating will be cured in less than a day, allowing the road to be open the very next day. Polyaspartic coatings are a two-part system. Typically, a resin mixed with some sort of accelerating agent turning the liquid into a solid after proper curing time. "Polyaspartic coatings are manufactured by carrying out polymeric condensation of ammonia and maleic anhydride in the presence of a polar solvent sans active hydrogen to produce polysuccinimide. The hydrolyzing of polysuccinimide results in polyaspartic coatings ("Polyaspartic Coatings Market" 2017)." They typically exhibit reduced curing time, long shelf life, a thick film, and high compatibility of the surface bond to various materials. They also display good durability with gloss and surface protection and can be applied in multiple layers. Typical uses of a polyaspartic coating include corrosion protection, protection from harsh environments, shop floors, garage floors, and industrial and manufacturing facilities ("Polyaspartic Coatings Market" 2017). They are also used for steel and concrete protection in construction. It has been found that even a single layer of these coating types is sufficient to be able to resist abrasion, mitigate corrosion as well as provide resistance to outside chemical penetration (Tator 2015).

Polyureas find similar use to polyaspartic coatings like protecting concrete against substance penetration and abrasion. This has given further rise to the polyurea industry as spray applications have arisen. This, in fact, helps combat some of the disadvantages of the polyurethane industry. These coatings have an increased resistance to a wider temperature range while maintaining the previously listed advantages. They are even less susceptible to humidity as well (Cain 2016). Polyureas have been commonly used in the construction field for roof repairs, car lots, and bridges. This is useful as the environment during application is variable day-to-day since these areas are exposed to the environment. One of the main issues seen during the application of the polyurea coatings is that the fast cure time does not let the coating sink into the voids and cracks in the surface (Cain 2016). However, this is why the coatings have been developed as a multi-layer system. The primer used in this system helps to eliminate bubbles in the coating as well as keep moisture from traveling to the surface during the curing process, reducing surface voids. In order to further help protect from issues such as this, an aliphatic polyurea coating is often used as the top coat for these types of coating systems as they provide a resistance to UV exposure (Cain 2016).

Another great characteristic of polyureas includes their aging resistance, which is especially important in regard to UV and abrasion exposure. “Polyureas are finding new applications in increasing the survivability of structures under impact loading, including blast and ballistic loading events (Zhang et al. 2017).” Polyureas generally have a faster reaction rate than polyurethanes. Because it has such a quick reaction rate, it is commonly used in spray applications. Spraying equipment is more expensive, however, because the coating sets so quickly, the area needing to be coated can be covered very quickly and the structure can be reopened in a fraction of the time as opposed to other coating types (Zhang et al. 2017). Polyureas are elastic polymers that exhibit almost incompressible behavior in deformations volumetrically. Polyureas are comprised of a soft and hard segment. The separation of the phases is what gives this coating type its many advantageous properties. “In polyurea, the main components are di□ or polyisocyanate molecules exothermically reacting with polyols and forming extended chains and networks bonded by urethane groups. Polyols are switched with amine molecules resulting in polymers with urea bonding (Zhang et al. 2017).”

Polyureas are finding even more application uses in the construction industry, especially in anticorrosion fields. This coating has excellent adhesion to concrete and steel. Polyureas are often used for surface treatments like the lining of a truck bed, pools, boats, and even landfills. It is even starting to be used in sewage facilities since it is highly resistant to chemicals like hydrogen sulfide gas and sulfuric acid (Komurlu and Kesimal 2015). Table 1 below shows a summary of information form the above literature review.

Table 1: Typical use and properties of commonly used protective coating types

Coating Type	Typical Use	Properties
Polyurea	Lining for: truck beds, ships, pools, landfills, sewage facilities Corrosion protection	Strong adhesion Ageing resistance Chemical resistance

	Industrial floor coating Concrete coating Roof repair Bridge coating	Moisture resistance Fast reaction rate Elastic response Corrosion resistance High adhesion UV stability
Polyaspartic	Construction industry Corrosion protection Industrial floor coating Concrete coating	Fast reaction rate Long shelf life High adhesion Chemical resistance Corrosion resistance Durable Great surface protection Abrasion resistance
Polyurethane	Industrial and commercial application	Chemical resistance Abrasion resistance UV stability Slow reaction rate
Epoxy	Industrial floor coating Corrosion protection Rebar coating	Chemical/solvent resistance High adhesion flexibility

Polyaspartic or polyurea based coatings are more versatile than epoxy or polyurethane coating types. Summarized in Table 1, this can be attributed to their various application types such as concrete protection, corrosion protection, truck bed/ship linings, landfills, sewage facilities, industrial floor coatings, and roof repairs. The properties responsible for the several different uses of these coatings are strong adhesion with many different surface types, aging resistance, chemical resistance, moisture resistance, elastic response, UV stability, abrasion resistance, durability, surface protection, a long shelf life, and a fast reaction rate. The main difference between them and polyurethanes is that they cure faster, which is very important in the construction industry. The main thing that sets them apart from epoxy coatings is that they offer better protection, especially if corrosion is a concern. Polyaspartic or polyurea coatings are resistive to physical deformations on the surface, unlike epoxy. As such, these coating types were used and testing in the laboratory; to provide additional or better protection in a wider span of environmental conditions.

CHAPTER 3

EXPERIMENTAL METHODOLOGY

For this research project, various polyaspartic polyurea coating materials were investigated under laboratory conditions. The goal of this investigation is to determine the performance of the coatings applied onto a repaired concrete surface after the specimens were subjected to various mechanical and durability tests commonly performed for concrete materials. The following test methods were carried out:

- ASTM D7234 "Standard Test Method for Pull-Off Adhesion Strength of Coatings on Concrete Using Portable Pull-Off Adhesion Testers",
- ASTM C78 "Standard Test Method for Flexural Strength of Concrete" for crack resistance propagation",
- ASTM C469 "Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression" for confining deterioration,
- ASTM C666 "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing" to replicate freeze-thaw, and;
- A wet-dry test was performed simulating a 30-minute rain event with a recurrence period of 1 in 5 years for Midwestern states (Hartell and Zeng 2020).

This series of tests was selected to determine whether the polyaspartic polyureas are effective at containing degraded concrete and durable to weathering. Since the target application is transportation infrastructure situated in the Midwest of the United States, the performance to the action of freeze-thaw and wet-dry cycling are of interest as well as resistance to salt scaling degradation. In addition, the mechanical response of the composite material (i.e. coated concrete) is of interest to determine its serviceability under load.

Herein, the performance of several products and manufacturers are compared. Each product was applied onto a concrete specimen's surface according to manufacturer application guidelines, which are also provided herein. Since the coating efficiency is being evaluated as a repair strategy for concrete cover remediation, the specimen surfaces were also prepared using a needle scaler to mimic field conditions were damaged concrete would be removed prior to coating application.

An experimental research program that comprised of several types of mechanical testing and durability testing was devised to meet the research objectives. Details of the materials studied and the procedures followed are presented in the following sections.

3.1 Specimen Preparation

3.1.1 Concrete Materials

For this study, a single concrete mixture (0.45 water-to-cement ratio) was used in the preparation of all concrete samples. The concrete mixtures were prepared with #57 crushed Limestone as the coarse aggregate and natural sand for the fine aggregate. A Type-I cement manufactured in Oklahoma was used in the mixture as well. The chemical composition of the cement is given in

Table 2. An air-entraining admixture was also added to the concrete mixture in order to mimic commonly used concrete mixtures for transportation infrastructure. Mixture proportions are presented in Table 3. The air content of the concrete mixtures was 6.0%.

Table 2: Chemical composition of Portland cement

Chemical composition (% by weight)					
MgO	CaO	SO3	SiO2	Al2O3	Fe2O3
1.9	62.9	3.3	19.4	5.1	3.4

Table 3: Mixture design details

Mixture	w/cm	Water (kg/m^3)	Cement (kg/m3)	Coarse Agg. (kg/m3)	Fine Agg. (kg/m3)	Air Ent. (oz)	Paste (%)
1	0.45	163.2	362.5	1088.7	709.0	16.0	29.7

3.1.2 Making of Specimen

Materials were batched and mixed in a temperature-controlled environment and samples were cast respecting standard methods of preparing concrete samples in a laboratory environment (ASTM C 192).

In order to carry out the testing regimen, approximately 33 cylinders (Ø100 mm x 200 mm), 48 concrete blocks (6 in x 6 in x 6in) and 109 prisms (3 in x 4 in x 12 in) were prepared and demolded after 24 hours.

After demolding, the samples were placed in a moist curing room maintained within ASTM temperature limits for 28 days.

After curing, the samples were placed in a controlled dry room (73 ° F, 50% RH) for a period of 14 days to allow internal moisture to evaporate and achieve field conditions. Meanwhile, the surfaces of the samples were prepared as that described in Section 3.1.3 to obtain the required surface texture and physical characteristics determined prior to product application. After 14-days of air-drying, the coatings were applied onto the surface as explained in Section 3.1.3.1

3.1.3 Concrete Surface Preparation and Coating

The International Concrete Repair Institute (ICRI) guidelines were instrumental in defining adequate surface preparation prior to application of a coating. Hydrodemolition techniques are commonly used in the field for removal of surface concrete. Since hydrodemolition was not possible to conduct on small-scale laboratory samples, a needle-scaler was the chosen surface preparation method since it produces a similar concrete surface profile as that obtained with hydrodemolition (Hughes and Bischof 2013). This required the removal of approximately 1/8" to 1/4" of concrete from the sample's surface exposing the coarse aggregate. The concrete surface profile (CSP) achieved is approximately 6 to 8 CSP in accordance with ICRI recommendations (ICRI 1997).

Prior to application, the surface must be clean, free of dust and debris. (ICRI 1997) According to product manufacturer recommendations, the surface moisture content must be below 4% (concrete scale) prior to application of the primer, which was checked with a concrete surface moisture meter. For this study, a TRAMEX surface moisture meter device was used.

3.1.3.1 Product Application

For preparation, mixing and product application, manufacturer instructions were followed. The following general procedure was used.

1. Accurately measure the required volumes for Part A and Part B in separate containers.
2. Pour both products into a plastic disposal pan (paint tray is recommended for easy rolling/application).

3. Hand mix the product thoroughly for approximately two minutes. Do not use a mechanical mixer. It was found that mechanical mixing generated an excessive number of air bubbles.

4. Apply the product onto the prepared surface using a lint free (low lint) roller. A release or flow control roller is recommended for even application. The nap size will depend on the surface profile of concrete. A 3/8 inch nap was used for this study due to coarse surface profile (CSP ranges from 6 to 8).

5. Allow the product to cure prior to the next application. The surface must be tacky (barely sticky to the touch without any product sticking to the finger) before applying the following coat. The time between coats depends on ambient environmental conditions.

6. Repeat steps 1 through 5 for application of the subsequent top coat layers until the desired thickness is reached.

In laboratory environmental conditions (71°F, 50% RH), the time between each coating layer varied between 45 and 90 minutes. The pot life for each product once mixed varied; however, the products were in a workable state for 30 to 60 minutes. Before disposing of the polyurea / polyaspartic products, the material on the roller and in the pan must harden and dry. They may be temporarily discarded in a bag until the product cures and then the bag may be put in the trash. However, in a wet state, the product is an EPA controlled substance. In the hardened state, the material is not. The rollers, clear plastic measuring cups, and the pan cannot be reused after coming into contact with the material, so it is recommended to use a pan liner or disposable pan during application. It is suggested to keep paper towels and cleaning products onsite in line with the products' Safety Data Sheet (SDS) recommendations.

3.2 Manufacturer and Product Selection

Four manufacturers of polyaspartic polyurea coating systems for concrete were identified. The following tables list the products evaluated along with manufacturer's recommended layer thicknesses and comments for specific products observations Table 3 to

Table 7.

It should be noted that the manufacturers supply the materials by batch, so for field use, it is relatively easy to combine on the container of one part with one of the other part to get the correct proportions. For laboratory scale testing, however, it is more difficult to get the correct proportions with small batches. Although utmost care and precision was taken in the preparation of coating batches, deficiencies were noticed in some instances, which may have affect laboratory results. In such cases, the manipulation error is mentioned in the Results and Discussion Section.

Table 4: VersaFlex product thickness and application information

VersaFlex Product	Mixing Ratio (A: B)	Recommended Layer Thickness	Notes
VF20 (Primer)	1:1	10 mils	The Quick Mender product had a short pot life once mixed (5 to 10 minutes). For this reason, it was not considered for further analysis.
Aliphatic Clear Coat	1:2	10 mils	
Clear Seal	1:1	--	
Quick Mender	1:1	--	

Table 5: Citadel Floor Finishing Systems / Rust-Oleum product thickness and application information

Citadel / Rust-Oleum Product	Mixing Ratio (A: B)	Recommended Layer Thickness	Notes
Polyurea 350 (Primer)	1:2	6-8 mils	--
Polyurea Polyaspartic RG-80X	1:1	4-6 mils	

Table 6: Mirabel Coatings product thickness and application information

Mirabel Coatings Product	Mixing Ratio (A: B)	Recommended Layer Thickness	Notes
Polyaspartic Clear Coat (Fast Curing)	1:1	--	The same product is used for both the primer and top coat. However, the product can be diluted with methyl ethyl ketone (MEK) to reduce the viscosity of the product permitting better absorption by the porous concrete. Part A and Part B contain 84 percent solids. A reduction of up to 60% solids is recommended. Depending on the volume prepared, dilute the product up to 1.4 times the initial volume prepared. Ex: (1) 500 ml of Part A and 500 ml of Part B are mixed for a total of 1000 ml. (2) Dilute the product to 1400 ml (1.4 x 1000). Therefore, 400 ml (1400-
Polyaspartic Clear Coat (Slow Curing)	1:1	--	

			1000) of MEK is added to dilute the product.

Table 7: Creative Material Technologies product thickness and application information

Creative Materials Technologies Product	Mixing Ratio (A: B)	Recommended Layer Thickness	Notes
DYNA Prime N-23 (Primer)	1:1	--	--
DYNA-PUR 7416 Aliphatic Clear Coat (Top Coat)	1:1	--	
DYNA Prime N-23-NT6 (Primer)	1:1	--	
DYNA-PUR 7416-NT6 Aliphatic Polyurea (Top Coat)	1:1	--	

3.3 Exposure Conditions and Testing Methods

3.3.1 Influence of Concrete Moisture Content and Coating Thickness

Two test surfaces were evaluated; a “dry” and a “wet” surface. 24 hours prior to application of the products, the blocks were either kept in a dry environment (50% RH) or placed in a wet environment (immersed in tap water) to simulate different environmental conditions encountered in the field and the influence of moisture intake. Next, the “dry” and “wet” samples were removed from their environment and allowed to dry until they reached a surface reading of 3% to 4% moisture content (concrete scale) measured with a (TRAMEX) moisture meter.

Also, the influence of the layer thickness of the coating material on its bond strength was evaluated. Three thicknesses were evaluated which were prepared by applying 1, 2 and 3 coats of the product. For each specimen type, two test replicates were performed on one block (Figure 1).

3.3.1.1 Pull-off Testing

To assess the bond performance of the products to the surface of concrete, pull-off testing as per ASTM D7234 was performed. 6”x6”x6” block samples were used for that purpose. (Figure 1)

Figure 1: Example of Pull-off Testing

3.3.2 Coating Influence on Concrete Cracking

Assuming adequate bonding of the coating system onto the concrete surface, the influence of the coating material on the mechanical performance of the concrete material was evaluated. Prism specimens were tested under flexural loading conditions and cylindrical specimens were tested under compressive loading conditions. The latter tests were performed to evaluate resistance to cracking and fragment retention.

3.3.2.1 Flexural Testing

Flexural testing as per ASTM C78 was carried-out to determine the performance in resisting crack initiation and propagation under tensile loading (Figure 2). For each coating system evaluated, the sample size consisted of three beam replicates and three notched-beam replicates (3” x 4” x 12”) in accordance with the standard. The beams were cast, conditioned and prepared following the methodology described previously. Only one coating thickness was evaluated, the three-layer system.

Figure 2: Flexural test setup

3.3.2.2 Compression and Modulus of Elasticity Testing

To determine the ability of the coating system to confine surface deterioration. A series of 4 in x 8 in cylinder samples were cast and conditioned as previously described. Nine sample replicates for each coating type were scaled as following that described previously. For each pair of nine cylindrical samples, one, two and three layers of the product were applied on three of the nine replicates. After extended curing time, the samples were subjected to a displacement controlled compression load in accordance with the ASTM C469 standard (Figure 3). The stress-strain behavior of the composite systems was evaluated to determine the efficacy of the coating system to contain fissured concrete and fragments.

Figure 3: Example of a cylindrical sample and Modulus of Elasticity Testing

3.3.3 Influence of Cyclic Freezing and Thawing Exposure

Rapid freeze-thaw testing was conducted to investigate the performance of the coating systems as per the ASTM C666 standard. However, the beam samples were prepared and conditioned as that described previously. Three beam replicates per coating product were prepared. Once the coating was sufficiently cured, the beam samples were vacuum saturated prior to placing in the freeze-thaw chamber (Figure 4).

3.3.3.1 Rapid Freeze-Thaw Testing

The test method followed for assessing the loss in durability due to the action of frost was ASTM C 666 procedure B. At intermittent cycles, the residual dynamic Modulus of Elasticity of each sample was determines by performing a resonant frequency test as per ASTM C215.

3.3.3.2 Visual Condition Characterization

At the end of the exposure period, a visual characterization of the coating material was conducted to evaluate the condition of the coating post temperature cycling.

3.3.3.3 Flexural Testing

After rapid freeze-thaw testing was performed on concrete beams per ASTM standard C666, the beams were then subjected to flexural testing per ASTM standard C78. Here, mechanical testing was performed to further assess the performance of the coated concrete specimens after freezing and thawing exposure.

3.3.3.4 Evaluation of Coating Adhesion by Knife (V-Notch

The bond performance of the coating after the action of frost was evaluated. In accordance with ASTM standard D6677, testing was performed the coated concrete samples in order to further assess the adhesion ability of the coating to the concrete. This method was used since the sample geometry did not permit pull-off testing. After flexural testing, away from the fracture surface, incision (V-notch) were made as per ASTM D6677 on the coating. The coating was attempted to be pulled back using the tip of a knife in order to evaluate the ability of the coating to stay bonded to the surface (**Error! Reference source not found.**).

Figure 4: Freeze-thaw chamber with sample beams

Figure 5: V Notch Testing

3.3.4 Influence of Salt Solution Exposure

In order to assess the influence of longterm salt solution exposure, the ASTM standard C1543 with some modifications was perfromed. This test method is commonly performed to determine the penetration of chloride ions into concrete through ponding. However, the difference between this standard and the method used in the laboratory is that samples were not chemically analyzed over time. Here, salt solution ponding was performed to assess the coatings' resistance to chemical degradation along with bond performance after three months of continuous ponding. The setup is shown in Figure 6.

3.3.4.1 Visual Condition Characterization

At the end of the exposure period, a visual characterization of the coating material was conducted to evaluate the condition of the coating. The intent was to assess the impact of the salts on the bond between the coating and concrete specimen as well as see if there are any visible distress features on the specimen after the ponding period.

3.3.4.2 Pull-off Testing

As per described previously, the pull-off test method (ASTM D7234) was performed. This was done to demonstrate the impact of deicing salts on concrete covered with a polyaspartic/polyurea coating system. Two test replicates per sample surface were performed (Figure 5).

Figure 6: Pull-off testing of salt ponding samples

3.3.5 Influence of Cyclic Wetting and Drying Exposure

After undergoing the flexure test, the scaled standard beams (no notch) were further investigated under wet-dry conditions (Figure 7). The procedure followed that of Hartell and Zeng where significant damage to concrete after the weathering exposure occurred (Hartell & Zeng, 2020). The beams were exposed to simulated rain exposure for an hour every day for 100 days or 100 wet-dry cycles. The precipitation event was determined by finding the average rainfall data for a northern region in the Midwest, which was found to be approximately an inch in a 30 minute event. Subsequently, the samples were allowed to dry in laboratory conditions for a period of 24 hours. To avoid water ponding, the samples were elevated above the bottom of the tank.

3.3.5.1 Visual Condition Characterization

At the end of the exposure period, a visual characterization of the coating material was conducted to evaluate the condition of the coating.

3.3.5.2 Evaluation of Coating Adhesion by Knife (V-Notch)

Again, the V-notch bond performance test was performed after the exposure period to determine how wetting and drying-cycles affected the bond performance of the coating types.

Figure 7: Cyclic wet-dry exposure setup (rain precipitation simulation)

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Influence of Concrete Moisture Content and Coating Thickness

Here, the influence of layer thickness and moisture of the concrete at the time of application on bond performance was evaluated. It has been reported that the presence of moisture within the substrate may affect the bond performance. The types of coatings evaluated generally do not exhibit disbonding and are good systems to use because of their resistance to moisture. However, they can experience poor substrate adherence if exposed to water and moisture in the air during the coating process. (Tator 2015) Primer coats are essential in order to ensure higher bond strength and reduce the risk of disbondment. (Ha 2013) Still, post-application moisture transport and vapor transport may also affect bond performance by the creation of surface blisters. (Zhang 2012) (Ha 2013) The experimental regimen devised evaluated these principles.

4.1.1 Pull-off Testing

The pull-off test (ASTM D7234) was performed to assess the bond performance of each coating systems. Bond strength of a particular coating can be variable. The failure type can indicate the bond. For this testing regimen, there were four different failure modes (Figure 9).

1. The first failure type is between the adhesive and the coating. This failure type is due to improper curing of the adhesive.

2. The second type is the failure of just the coating.

3. The third is the failure of the concrete substrate.

4. The last failure type is a combination of failure due to the coating and the substrate.

The average bond strength results and corresponding coefficients of variation obtained for each specimen type are presented in the following tables along with a bar type graph demonstrating two standard deviations (2s) from the mean to aid in the comparative analysis. Result are presented per product manufacturer in the following sections.

(a) (b)

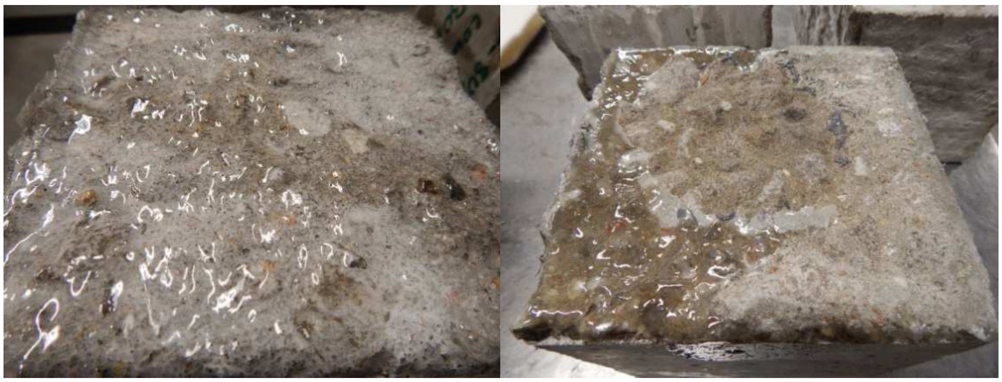
(c) (d)

Figure 8: failure types consisted of: (a) adhesive failure, (b) coating failure, (c) substrate failure, and (d) a combination of coating and substrate failure

4.1.1.1 VersaFlex Aliphatic Clear Coat and Clear Seal

The samples prepared with the Aliphatic Clear Coat did not achieve proper hardening. After an extended period of curing, the applied product was still tacky to the touch. No thickness measurements were taken for these samples. This problem may be attributable to the inaccurate measuring of each part and the mixing of the product. This resulted in a low pull load and failure in the coating and bond interface.

Moreover, a few of the samples prepared with the Clear Seal coating system demonstrated disbondment from the concrete surface which resulted in low bond-strength and high variability in the measurements. There were signs of coating flaking for all samples post-testing after an extended period of time (Figure 9). Pull-off test results are presented in Table 8.



(a) (b)

Figure 9: (a) Rustoleum RG-80X disbondment prior to testing flaking and (b) VersaFlex Clear Seal flaking from the surface

Table 8: Results of the pull-off test for VersaFlex products

	Concrete Moisture Conditioning	Number of Coats	Coating Thickness (mils, ± 0.4)	Average Pull-load (psi)	Coefficient of Variation (%)
VersaFlex					
Aliphatic Clear Coat	Dry	One	10.7	232.2	32.9
	Wet		N/A	85.9	73.3
	Dry	Two	11.9	170.1	17.2
	Wet		N/A	182.9	38.1
	Dry	Three	N/A	22.3	40.4
	Wet		N/A	17.5	12.9
Clear Seal	Dry	One	10.6	298.9	48.1
	Wet		10.6	302.1	35.7
	Dry	Two	11.5	483.4	5.6
	Wet		11.4	168.6	98.7
	Dry	Three	14.1	556.5	4.9
	Wet		11.9	338.7	57.8

Observing the results for samples prepared with the Aliphatic Clear Coat presented in Figure 10, there are no observable trends as failure types varied due to improper hardening of the coating. It would seem that the application of several coats during early-age curing may have further affected the curing mechanism of the coating. As seen in Figure 11 and Figure 12, failures mainly occurred within the coating material or at the bond interface between the epoxied pull-disc and the coating interface. The highest average pull-load recorded is for the one-layer coating system applied on the dry sample. Fracture types for both replicates are observable in Figure 8. The fracture occurred at the bond interface between the concrete and coating.

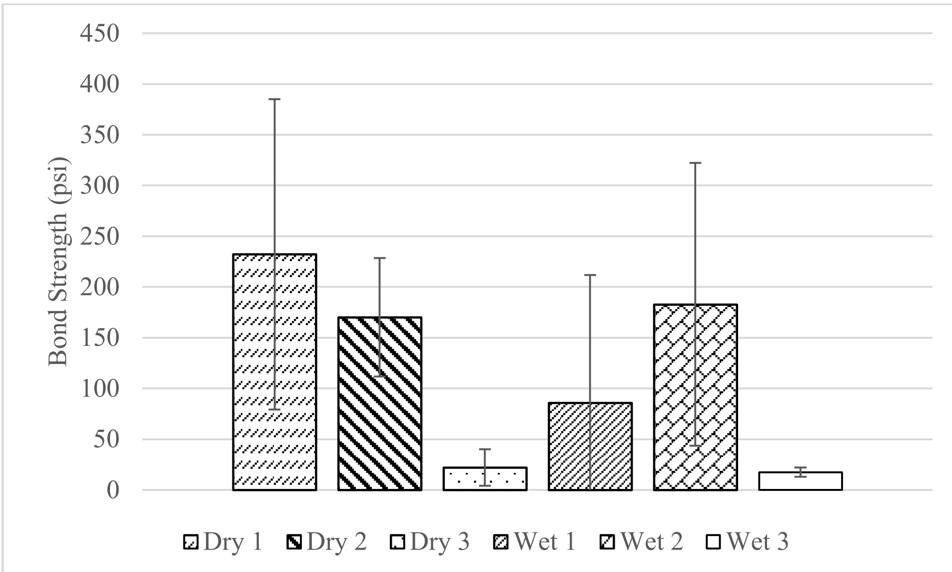


Figure 10: VersaFlex - Aliphatic Clear Coat: Pull-off test result comparison between dry and wet samples and coating thicknesses

(a) (b) (c)

Figure 11: VersaFlex Aliphatic Clear Coat failure type for wet samples with (a) one layer, (b) two layers and (c) three layers of product

(a) (b)

Figure 12: VersaFlex Aliphatic Clear Coat failure type for dry samples with one layer of product: (a) replicate A and (b) replicate B.

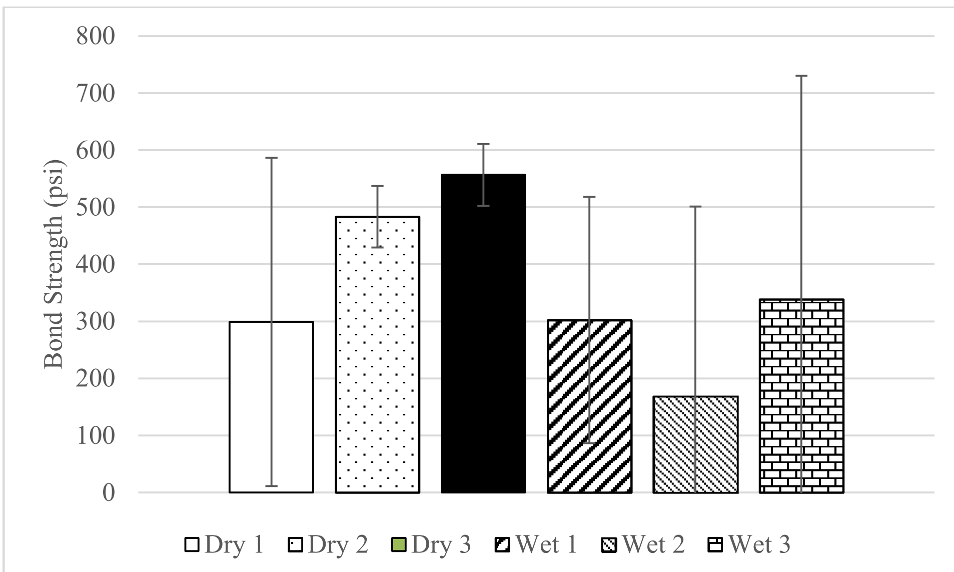


Figure 13: VersaFlex Clear Seal: Pull-off test result comparison between dry and wet samples and coating thicknesses

Results for the Clear Seal coating product are presented in Figure 13. It would seem that there is a slight gain in performance for the coatings applied on dry samples in comparison to that of the wet samples. However, the high variability in results obtained for the wet replicates cannot validate this statement. As seen in Figure 14 illustrating fracture types for dry and wet replicates with a 3 layers coating system, the dry replicates both exhibited partial failure within the concrete; however, one of the wet replicates exhibited failure in the concrete while the other failed at the bond interface. The latter resulting in a low recorded average and a high coefficient of variation. Similar fracture patterns also occurred for the 1- and 2-layer coating systems which contributed to the high variability in measurements. As previously discussed, this may be caused by the observed disintegration of the coating with time combined with the influence of moisture transport post-application.

(a) (b)

(c) (d)

Figure 14: VersaFlex Clear Seal Coating failure type for samples with 3 layers of product: (a)&(b) dry replicates and (c)&(d) wet replicates

4.1.1.2 Rustoleum (Citadel) Polyurea Polyaspartic RG-80X

Overall, bond test strength results for the RG-80X product were inconclusive as the coating experienced disbonding from the concrete substrate over time. The results seen in Table 9 are very low in comparison to that of the other products. As previously stated, it would seem that the coating disbonded with curing time which resulted in coating bond failures for all of the samples (Figure 16 and Figure 17). There are no distinguishable trends for the effects of moisture nor layer thickness on bond strength (Figure 15).

Table 9: Results of the pull-off test for Rustoleum products

	Concrete Moisture Conditioning	Number of Coats	Coating Thickness (mils, ± 0.4)	Average Strength (psi)	Coefficient of Variation (%)
Rustoleum (Citadel)					
Polyurea Polyaspartic RG-80X	Dry	One	8.28	146.3	12.3
	Wet		8.14	81.1	2.8
	Dry	Two	8.92	68.4	49.3
	Wet		8.2	182.9	72.6
	Dry	Three	11.46	112.9	21.9
	Wet		10.68	23.9	28.3

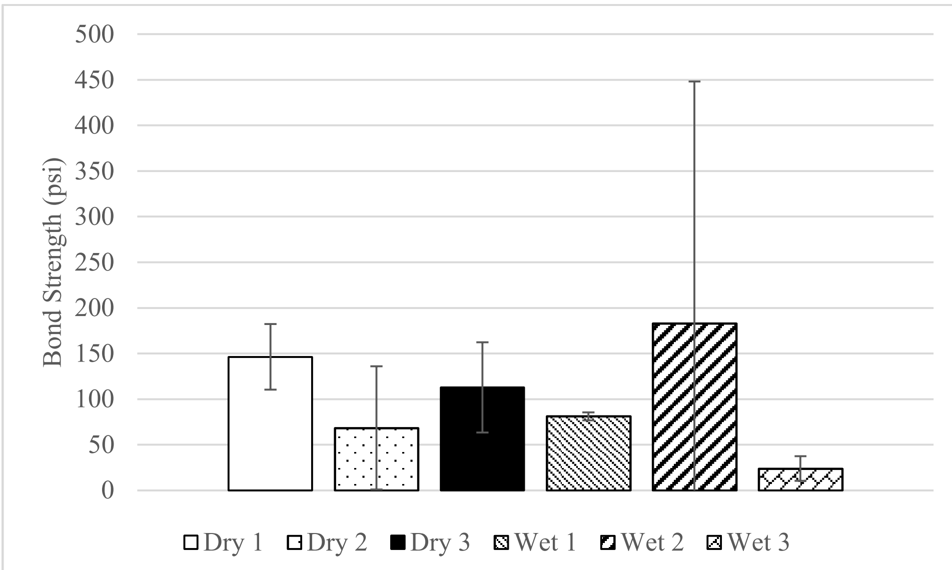


Figure 15: Polyurea Polyaspartic RG-80X- Pull-off test result comparison between dry and wet samples and coating thicknesses

(a) (b) (c)

Figure 16: Rustoleum RG-80X failure type for dry samples with (a) one layer, (b) two layers and (c) three layers of product

(a) (b) (c)

Figure 17: Rustoleum RG-80X failure type for wet samples with (a) one layer, (b) two layers and (c) three layers of product

4.1.1.3 Mirabel Coating – Slow and Fast

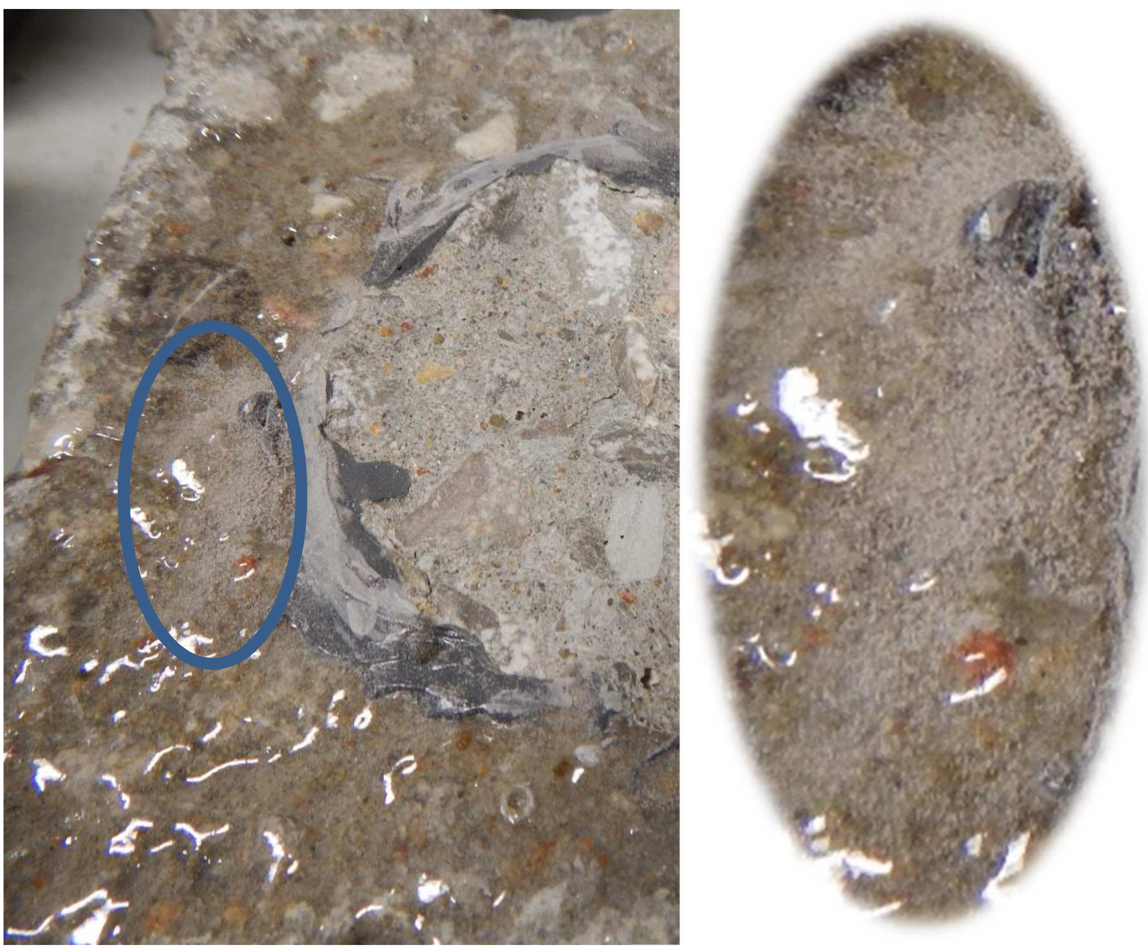


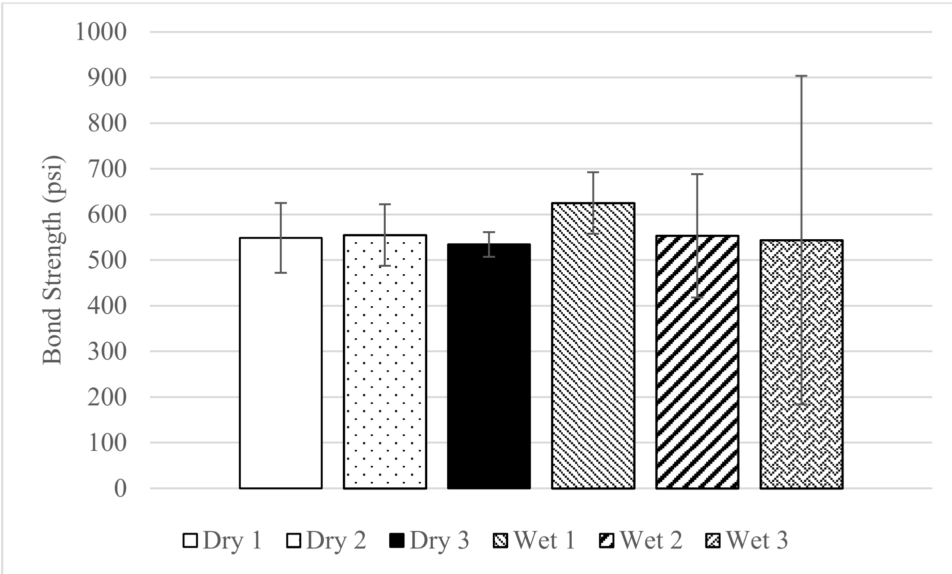
Figure 18: Excessive entrapped bubbles seen within the coating

First, a few noteworthy observations about product performance during the experimental investigation. Thickness readings were not achievable for either of the Mirabel products. This was due to the presence of excessive bubbles entrapped in the coating. There was such a large presence of bubbles that the only consistent measurement reading was an error display. These bubbles appeared during curing of the coating and not at the time of application (Figure 18). The presence of such voids could diminish the effective performance of the coating; however, this was not observable while performing the bond-test. On average, the bond-strength for both the slow and fast curing products seemed adequate (Table 10) as the majority of the failures occurred in the concrete material. Here, consistency in fracture types resulted in lower recorded variability in comparison to that of the other two products discussed previously.

Here, coefficients of variation vary between 2.5% and 33.1% (average of 12.1%) (Table 10). This may be due to the scaled uneven profile of cube surfaces which may have caused loading eccentricities. Moreover, the scaling process to remove the concrete layer may have caused micro-fissures at the surface of the concrete which weakens the bond interface as well. In general, fracture occurred within the concrete material and not at the bond interface (Figure 20 and Figure 21). This demonstrates that the bond strength is superior to the tensile strength of the concrete. Similarities in measurements are due to this principle; they reflect the tensile strength properties of the concrete material at its surface.

Table 10: Results of the pull-off test for Mirabel Coating products

	Concrete Moisture Conditioning	Number of Coats	Coating Thickness (mils, ± 0.4)	Average Strength (psi)	Coefficient of Variation (%)
Mirabel Coating					
Mirabel Fast	Dry	One	N/A	548.6	6.6
	Wet		N/A	624.9	5.4
	Dry	Two	N/A	555.0	6.1
	Wet		N/A	553.4	12.2
	Dry	Three	N/A	534.3	2.5
	Wet		N/A	543.8	33.1
Mirabel Slow	Dry	One	N/A	721.9	16.8
	Wet		N/A	577.2	17.5
	Dry	Two	N/A	707.6	5.4
	Wet		N/A	723.5	10.3
	Dry	Three	N/A	624.9	17.6
	Wet		N/A	454.8	11.9



Seen in

Figure 19 for the Fast curing product, there are no distinguishable trends for values obtained for both the dry and wet samples types as well as for the number of coating layers. The results are relatively consistent for all measurements which are attributable to the failure type (Figure 20 and Figure 21). Therefore, the actual bond performance between the different sample types cannot be determined because of the concrete failure in tension.

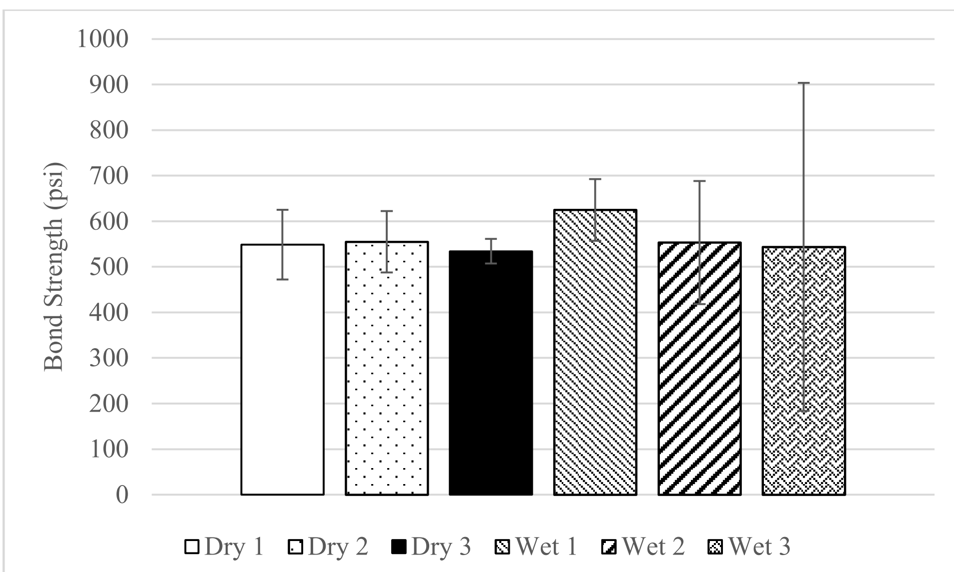


Figure 19: Mirabel Fast: Pull-off test result comparison between dry and wet samples and coating thicknesses

(a) (b) (c)

Figure 20: Mirabel Fast failure type for dry samples with (a) one layer, (b) two layers and (c) three layers of product

(a) (b) (c)

Figure 21: Mirabel Fast failure type for wet samples with (a) one layer, (b) two layers and (c) three layers of product

As for the results obtained for the Slow curing Mirabel product (Figure 22), there seems to be a slight increase in bond-strength in comparison to that of the Fast curing product; however, this difference of 22.5%, 24.1% and 15.9% for the dry samples with 1, 2 and 3 layers respectively is not significant. On the other hand, there is a variable influence for the wet samples with a percent difference of -7.9%, 18.7% and -17.8% for the 1, 2 and 3 layers respectively. As seen in Figure 23 and Figure 24, failure types are similar for all samples as that seen for the Fast product.

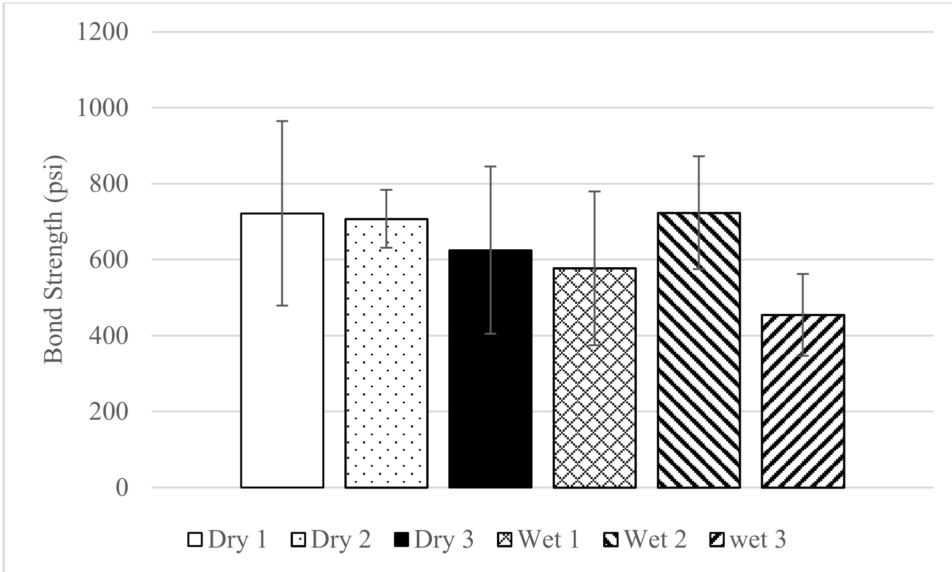


Figure 22: Mirabel Slow: Pull-off test result comparison between dry and wet samples and coating thicknesses

(a) (b) (c)

Figure 23: Mirabel Slow failure type for dry samples with (a) one layer, (b) two layers and (c) three layers of product

(a) (b) (c)

Figure 24: Mirabel Slow failure type for wet samples with (a) one layer, (b) two layers and (c) three layers of product

4.1.1.4 Creative Materials Technologies DYNA-PUR7416 and DYNA-PUR7416 NT6

The last two products evaluated are manufactured by Creative Materials Technologies: *DYNA-PUR7416 and DYNA-PUR7416 NT6.* Both products did not demonstrate any surface features of concern. Moreover, they both performed well for the pull-off testing regimens. Similarly, to the Mirabel products, there no significant differences in performance between the dry and wet sample types. Also, there are no noticeable trends between pull-load and layer thickness. Again, the low coefficients in variation calculated are due to the failure type being in the concrete layer. They vary between 2.9% and 46.8% (average of 14.3%) (Table 11).

The pull-load values obtained for the regular DYNA-PUR7416 product are among the highest recorded for this study. With respect to their counterpart DYNA-PUR7416 NT6, the percent differences are 20.1%, 16.2% and 14.9% for the dry samples with 1, 2 and 3 layers respectively and 53.6%, 25.1% and -11.0% for the wet samples with 1, 2 and 3 layers respectively. Again these differences are not significant due to the inherent variability of the test method and fracture type (Figure 25 to Figure 30).

Table 11: Results of the pull-off test for Creative Materials Technologies products

	Concrete Moisture Conditioning	**Number of Coats**	**Coating Thickness (mils, ± 0.4)**	**Average Strength (psi)**	**Coefficient of Variation (%)**
Mirabel Coating					
Creative Material Technologies					
DYNA-PUR7416	Dry	One	11.74	710.8	2.9
	Wet		12.14	721.9	7.5
	Dry	Two	13.24	636.1	16.3
	Wet		12.66	526.3	28.6
	Dry	Three	14.08	707.6	4.8
	Wet		13.42	435.7	17.6
DYNA-PUR7416-NT6	Dry	One	11.88	580.4	15.1
	Wet		12.32	416.6	13.0
	Dry	Two	11.82	539.1	3.8
	Wet		14.36	408.7	46.8
	Dry	Three	14.76	610.6	3.0
	Wet		15.56	486.6	18.5

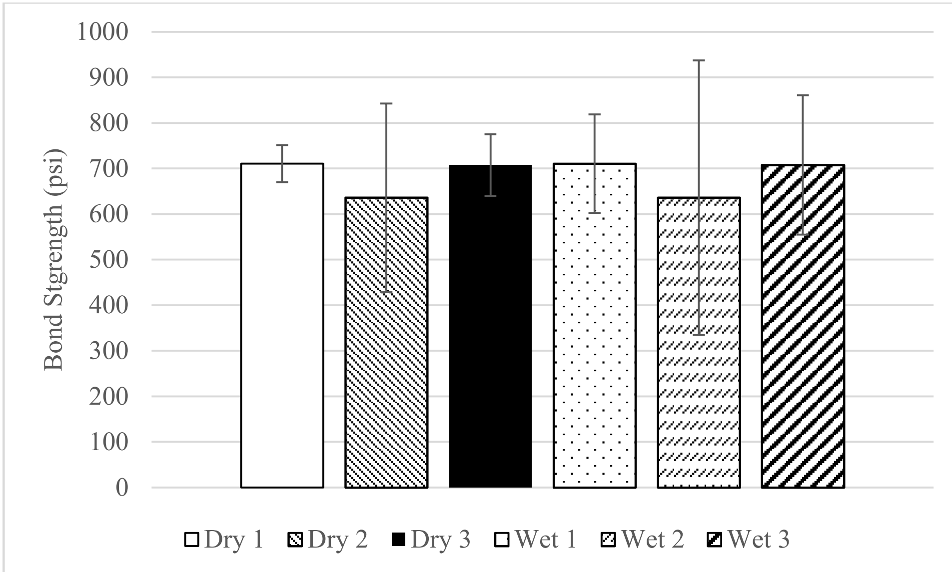


Figure 25: DYNA-PUR7416: Pull-off test result comparison between dry and wet samples and coating thicknesses

(a) (b) (c)

Figure 26: DYNA-PUR7416 failure type for dry samples with (a) one layer, (b) two layers and (c) three layers of product

(a) (b) (c)

Figure 27: DYNA-PUR7416 failure type for wet samples with (a) one layer, (b) two layers and (c) three layers of product

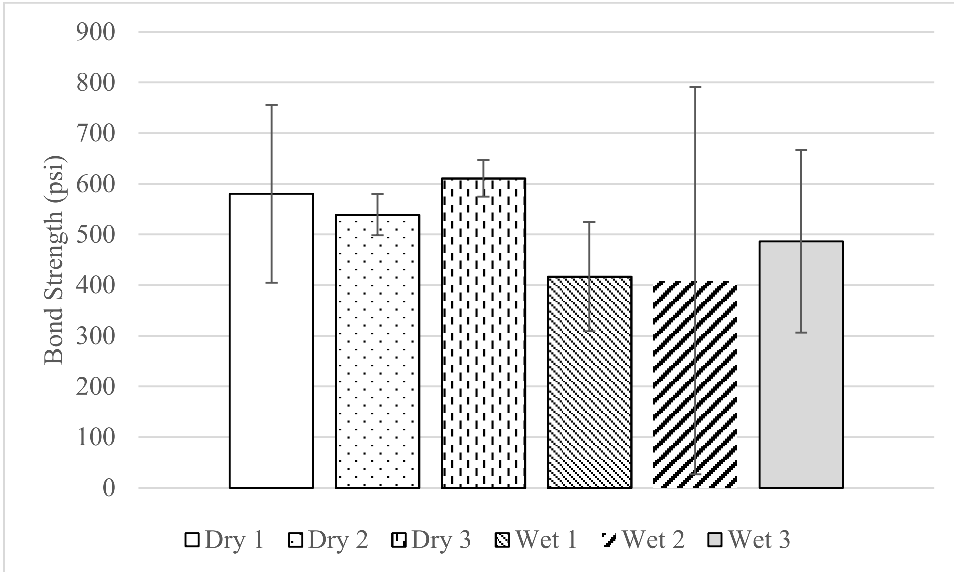


Figure 28: DYNA-PUR7416 NT6: Pull-off test result comparison between dry and wet samples and coating thicknesses

(a) (b) (c)

Figure 29: DYNA-PUR7416 NT6 failure type for dry samples with (a) one layer, (b) two layers and (c) three layers of product

(a) (b) (c)

Figure 30: DYNA-PUR7416 NT6 failure type for wet samples with (a) one layer, (b) two layers and (c) three layers of product

4.1.1.5 Overall pull-off test performance

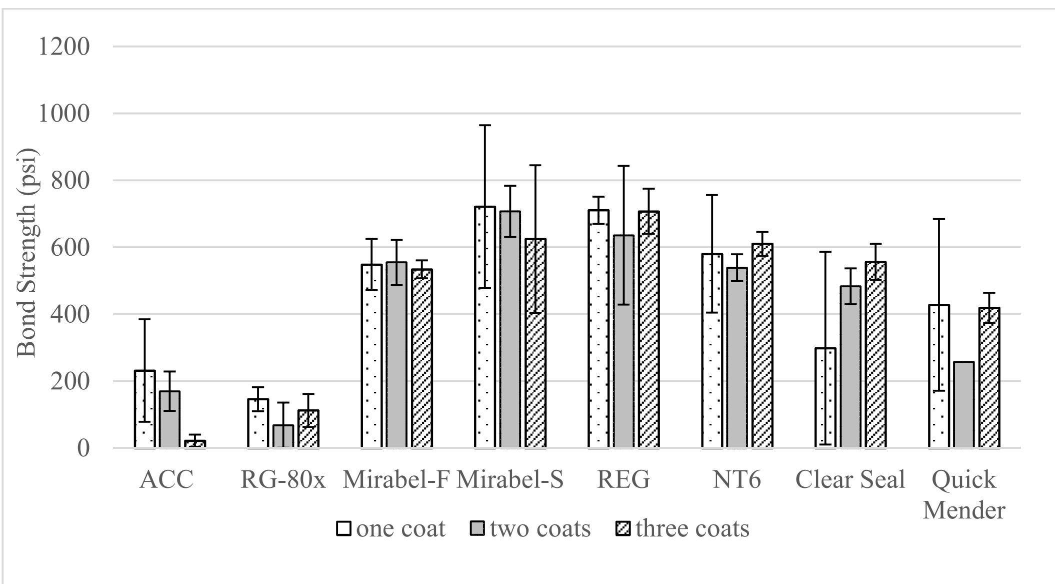


Figure 31: Pull-off test results comparison for all products, dry samples

As seen in Figure 31, the materials with the highest pull load are the Mirabel Slow and the DYNA-PUR7416 (REG) followed by DYNA-PUR7416 NT6 and the Mirabel Fast. The latter having the lowest recorded coefficients of variation. The variability in the fracture types and coating condition resulted in lower pull-loads for the VersaFlex Clear Seal and Aliphatic Clear Coat. The lowest results recorded are for the Rustoleum Polyurea Polyaspartic RG-80X.

However, RG-80X was not eliminated and its performance was still evaluated for the other test regimens. As an outcome of this first experimental task, the noticed potential in disbonding and flaking arising in time lead to an increase in the time period between coating and testing. A period of at least 3 weeks was planned for the other test regimens to allow sufficient hardening of the coating system and to provide a sufficient amount of time for problems to occur if they were to occur. Also, quality control on the preparation of the products was increased. Better care was taken in the precision of the measuring and mixing time of Parts A and B to ensure reproducibility of the coatings. The latter helped eliminate some of the noticed problems for the Rustoleum RG-80X and the VersaFlex Aliphatic Clear Coat.

4.2 Coating Influence on Concrete Cracking

4.2.1 Flexural Testing

A series of tests were carried out on a scaled standard beam and scaled notched beam specimens coated on a single face. The beams were tested in such a manner that the coated face would be under tensile stress while loading. Therefore, an increase in Modulus of Rupture (MOR) could be due to the composite effect of both the coating and concrete materials' properties. A summary of the results obtained for the flexural test regimen is presented in the following sections. Table 12 to Table 13 provide the average coating thicknesses, average Modulus of ruptures, coefficients of variation along with the results of an ANOVA hypothesis test; followed by a comparative graph depicting the average values obtained for each sample type with two standard deviations from the average (Figure 32 to Figure 33).

4.2.1.1 Standard Beams – All Products

As seen in Table 12 and Figure 32, all beam samples outperformed the control sample except for the samples prepared with the VersaFlex Aliphatic Clear Coat and the Mirabel Fast curing product. Two of the products demonstrated superior properties: Creative Material Technologies DYNA-PUR7416 and Polyurea Polyaspartic RG-80X. Although disbondment was noticeable for the Aliphatic Clear Coat and RG-80X cube samples, the beam samples did not show any signs of disbondment. The increase in modulus of Rupture could be due to the composite effect of the coating providing additional resistance to tensile crack initiation.

However, the results of an ANOVA test, where the null hypothesis is that the mean modulus of Rupture for all groups is the same, demonstrate that the null hypothesis is supported. The returned p-value (0.22) is superior to a generally accepted confidence level of 0.05 for concrete testing. Moreover, looking at the potential range in mean values represented by the 95% confidence range (2s) for all products with respect to that of the control value, it can be seen that the results are similar (Figure 32). However, the slightly higher (but still acceptable) coefficients of variation obtained for the coated samples may have influenced this hypothesis outcome.

Table 12: Results of flexural testing for scaled standard beams, all products

Name	Coating Thickness (mils, ± 0.4)	Modulus of Rupture (psi)	COV (%)
Control	N/A	556.0	5.1
VersaFlex			
Aliphatic Clear Coat	15.8	513.5	2.5
Clear Seal	12.3	572.1	12.7
Rustoleum (Citadel)			
Polyurea Polyaspartic RG-80X	11.5	670.9	11.2
Mirabel			
Fast	N/A	525.6	16.5
Slow	N/A	592.0	1.5
Creative Material Technologies			
DYNA-PUR7416	12.3	630.9	9.2
DYNA-PUR7416-NT6	13.6	613.1	8.2
ANOVA TEST for Modulus of Rupture			
F value	1.5	p-value	0.22

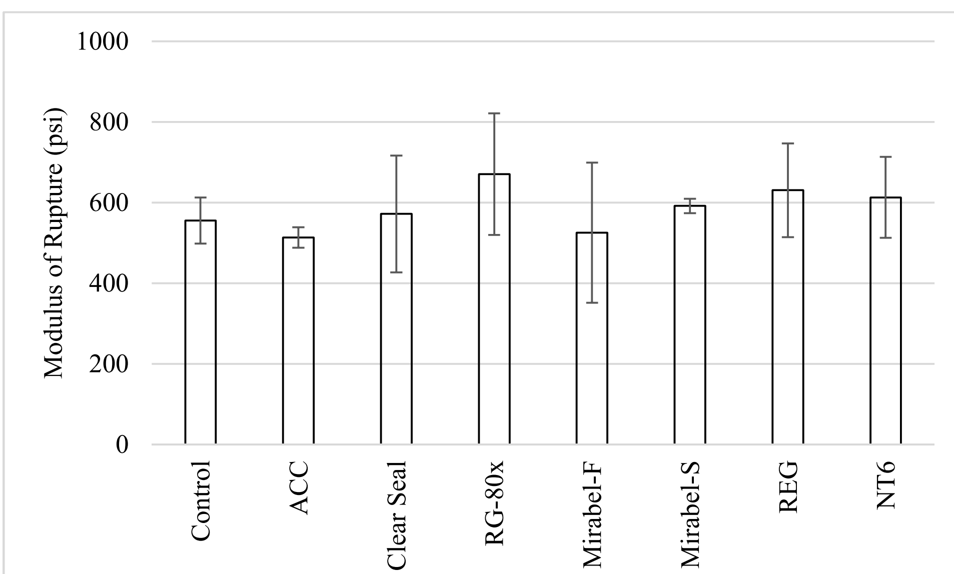


Figure 32: Flexural test results comparison for scaled standard beams, all products

As previously mentioned in the experimental procedure section, the uneven scaled surface of the test face may have contributed to the variance in results. Since the uneven surface may have been a potential source of error, a new test regimen without scaled surfaces was carried out for four of the evaluated products. The results of the comparative analysis are shown in Figure 33 and Table 13. These samples have a higher standard deviation but also have a much higher modulus of rupture compared to that of the scaled samples. The Mirabel Fast product recorded the highest strength; although, the Fast product specimen recorded the second lowest strength for its scaled counterpart. Looking at the trend, there are no discernable differences between coating products as that seen for the scaled standard beams.

Table 13: Results of flexural testing for standard beams, all products

Name	Coating Thickness (mils, ± 0.4)	Modulus of Rupture (psi)	COV (%)
VersaFlex			
Aliphatic Clear Coat		832.2	4.0
Rustoleum (Citadel)			
Polyurea Polyaspartic RG-80X		821.1	9.4
Mirabel			
Fast	N/A	1095.1	4.4
Creative Material Technologies			
DYNA-PUR7416		910.9	7.3
ANOVA TEST for Modulus of Rupture			
F value	4.07	p-value	0.002

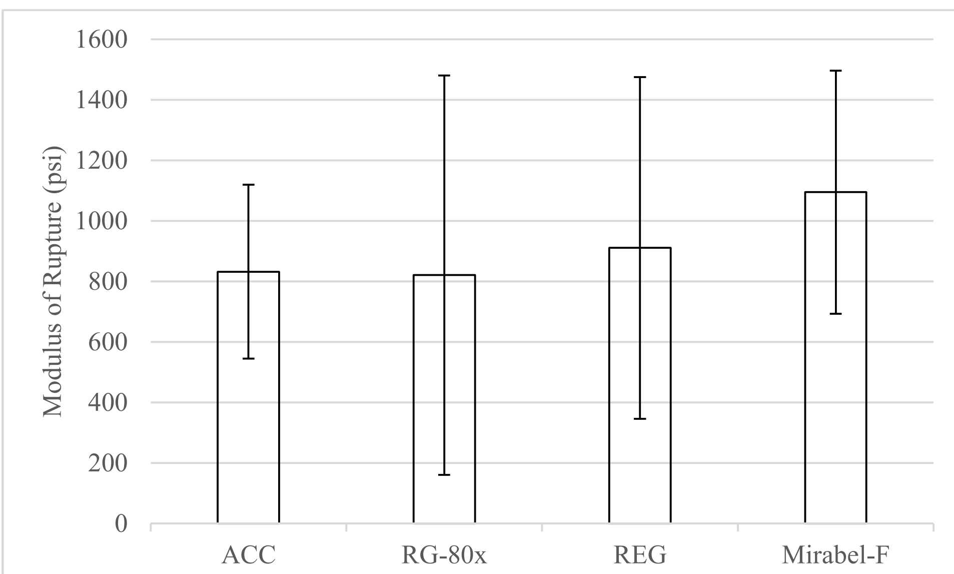


Figure 33: Flexural test results comparison for standard beams, all products

4.2.1.2 Notched Beams – All Products

First, it needs to be mentioned that the results presented in Table 14 and Figure 34 are a second trial. The results for the first set of beams were unusually low with higher than acceptable coefficients of variation. As such the test regimen was restarted. The second set of data was more acceptable; but, high variability and low results were still obtained for the Aliphatic Clear Coat and Mirabel Fast curing products respectively. On average, all but the Mirabel products surpassed the control value. As previously stated, the increase in modulus of Rupture could be due attributed to the composite effect of the coating.

For this sample set, the null hypothesis (the mean modulus of Rupture for all groups are the same) is rejected. The returned p-value (1.9 E-4) is inferior to the confidence level of 0.05. However, the high F value demonstrates a high variance for the data set. Thus, a subsequent analysis was conducted removing the results obtained for the samples coated with the Mirabel products. In this case, the returned F and p-value are 0.78 and 0.58 respectively. In this case, the null hypothesis would be supported with an acceptable variance. This can be seen in Figure 34 where the mean values within the range in standard deviations (2s) are all within that of the control and each other except for the Mirabel Products.

Table 14: Results of flexural testing for scaled notched beams, all products

Name	Coating Thickness (mils, ± 0.4)	Modulus of Rupture (psi)	COV (%)
Control	N/A	438.1	4.9
VersaFlex			
Aliphatic Clear Coat	14.8	527.5	22.7
Clear Seal	13.3	511.8	5.5
Rustoleum (Citadel)			
Polyurea Polyaspartic RG-80X	12.5	503.8	10.3
Mirabel			
Fast	N/A	564.79	11.64
Slow	N/A	325.0	11.5
Creative Material Technologies			
DYNA-PUR7416	12.9	489.7	10.0
DYNA-PUR7416-NT6	13.6	486.8	6.4
ANOVA TEST for Modulus of Rupture			
F value	4.3	p-value	0.007

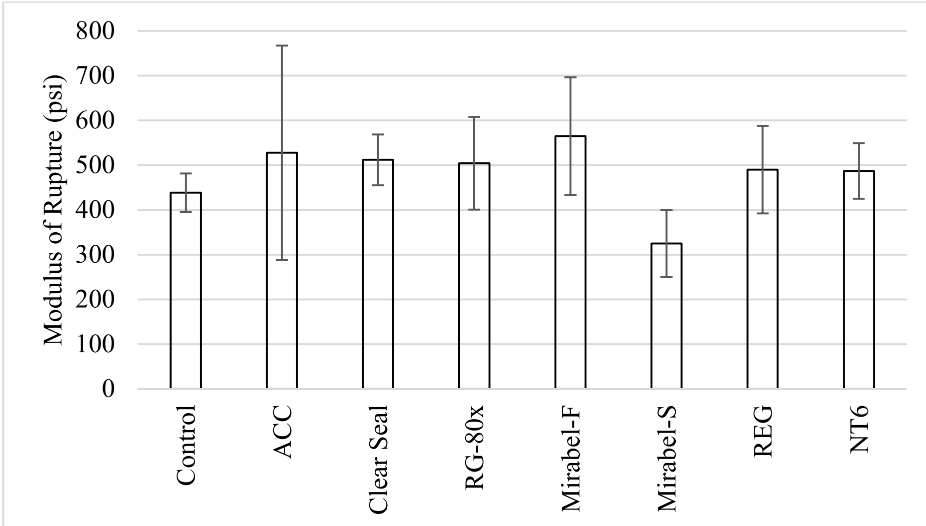


Figure 34: Flexural test results comparison for scaled notched beams, all products

Again, the uneven scaled surface of the test face may have contributed to the variance in results. Since the uneven surface may have been a potential source of error, a new test regimen was completed by testing notched beams without scaling them. The results are shown in Table 15 and Figure 35. The results demonstrate that although the average values are slightly lower than that reported for the scaled notched-beams, there are still within the 95% confidence interval. Again, the statistical variance implies that the average means recorded are similar for all products.

Table 15: Results of flexural testing for notched beams, all products

Name	Coating Thickness (mils, ± 0.4)	Modulus of Rupture (psi)	COV (%)
VersaFlex			
Aliphatic Clear Coat		486.3	6.1
Clear Seal		525.4	8.0
Rustoleum (Citadel)			
Polyurea Polyaspartic RG-80X		445.9	8.8
Creative Material Technologies			
DYNA-PUR7416-NT6		448.0	1.5
ANOVA TEST for Modulus of Rupture			
F value	3.78	p-value	0.059

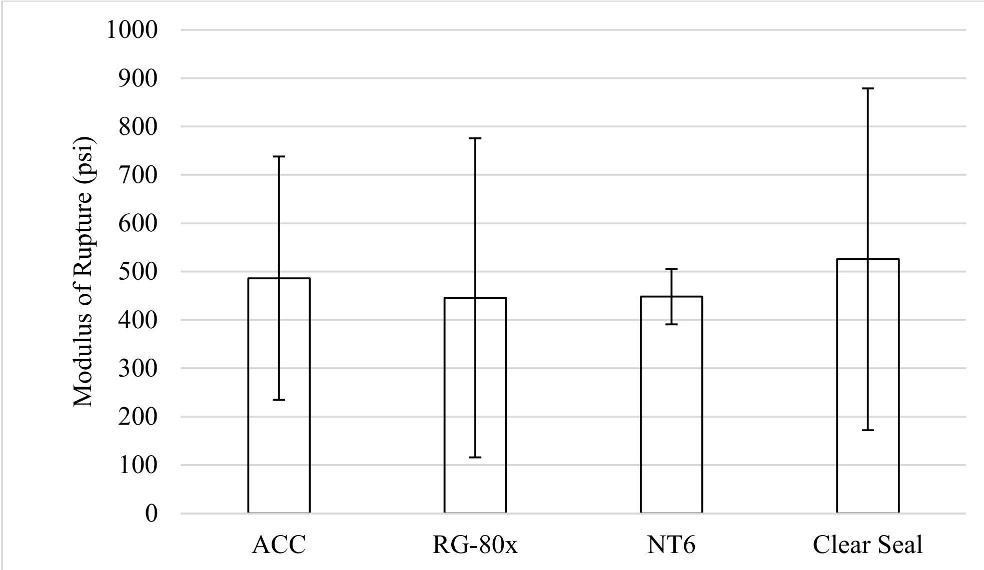


Figure 35: Flexural test results comparison for notched beams

4.2.2 Compression Testing

A series of tests were performed on cylindrical samples coated with the products investigated. Prior to coating, the sample surfaces were scaled exposing the coarse aggregate has that described for the previous sample types. After a prolonged curing time of the coating systems, the static modulus of elasticity test (ASTM C469) and the compressive strength test (ASTM C39) were performed to assess the ability of the coatings to aid the composite material in resisting deformation under load and contain fractured concrete. Here, the influence of layer thickness was evaluated. The average results and corresponding coefficients of variation obtained for each specimen type are presented in the following tables (Table 16 to Table 19) along with the obtained stress-strain behaviors during compression loading (**Error! Reference source not found.** to **Error! Reference source not found.**) for the one-layer coating systems. In addition to this, Figure 36 to a) b) c)

Figure 41 depict the failures types obtained for one representative cylinder for each coating thickness and product type.

First, the application of a polyaspartic polyuria coating on the concrete samples seems to have a beneficial effect on increasing the compressive strength of the cylindrical concrete sample. On average, there is a noticeable increase of approximately 10%. The coating may have provided a confining type effect to the cylinder under compression load by providing transverse resistance to the developed tensile stress. This can be seen by the failure types demonstrated in Figure 36 to a) b)

c)

Figure 41. For all products and number of coatings, the coating material held the fractured concrete sample together. Although small fissures propagated through the surface of the coating, no concrete fragments were loss and the cylinder shape was still somewhat intact. Therefore, the coatings were able to contain the concrete fragments from scaling and/or spalling in comparison to the uncoated samples.

However, signs of coating disbondment were visually noticeable post-testing. All samples except for the Creative Material Technologies' products exhibited coating disbondment. For these samples, the measured compressive strengths were slightly lower which may be attributed to the lost in composite effect during loading. This may also explain the slightly higher coefficients of variation obtained for samples showing disbonded coating. This behavior was independent of coating thickness.

The effects of coating thickness were evaluated within the product type. An analysis of variance was conducted to determine whether increasing the number of coats would increase the compressive strength of the concrete composite. In Table 16 to Table 19, the results of the ANOVA demonstrate that there is no statistical difference between the compressive strengths obtained. Therefore, the small differences in strength seen between coating thickness are negligible. However, there is a noticeable trend where the single coat systems outperformed their counterparts, except for the RG-80X and Clear Seal products.

Table 16: Results of the compression test for VersaFlex Coating products

	Concrete Moisture Conditioning	**Number of Coats**	**Coating Thickness (mils, ± 0.4)**	**Average Strength (psi)**	**Coefficient of Variation (%)**	**ANOVA F-Value/ p-value**
Mirabel						
Aliphatic Clear Coat	Dry	One	10.8	3729	7.5	6.410/0.083
	Dry	Two	11.5	3668	8.1	
	Dry	Three	13.0	3611	7.6	
Clear Seal	Dry	One	8.4	3881	4.6	0.138/0.879
	Dry	Two	9.7	3460	5.8	
	Dry	Three	10.7	4056	7.0	

a) b) c)

Figure 36: VersaFlex Aliphatic Clear Coat failure type with a) one coat, b) two coats, and c) three coats

a) b) c)

Figure 37: VersaFlex Clear Seal failure type with a) one coat, b) two coats, and c) three coats

Table 17: Results of the compression test for Rustoleum Coating products

	Concrete Moisture Conditioning	Number of Coats	Coating Thickness (mils, ± 0.4)	Average Strength (psi)	Coefficient of Variation (%)	ANOVA F-Value/ p-value
Mirabel						
RG-80X	Dry	One	9.2	3252	10.5	0.483/0.658
	Dry	Two	10.0	3526	8.8	
	Dry	Three	11.4	3509	3.9	

a) b) c)

Figure 38: Polyurea Polyaspartic RG-80X failure type with a) one coat, b) two coats, and c) three coats

Table 18: Results of the compression test for Mirabel Coating products

	Concrete Moisture Conditioning	Number of Coats	Coating Thickness (mils, ± 0.4)	Average Strength (psi)	Coefficient of Variation (%)	ANOVA F-Value/ p-value
Mirabel						
Fast	Dry	One	N/A	2887	9.0	55.115/0.018
	Dry	Two	N/A	3685	3.9	
	Dry	Three	N/A	3844	4.1	

a) b) c)

Figure 39: Mirabel Fast failure type with a) one coat, b) two coats, and c) three coats

Table 19: Results of the compression test for Creative Materials Technologies products

	Concrete Moisture Conditioning	Number of Coats	Coating Thickness (mils, ± 0.4)	Average Strength (psi)	Coefficient of Variation (%)	ANOVA F-Value/ p-value
Creative Material Technologies						
DYNA-PUR7416	Dry	One	7.4	3983	3.8	3.978/0.201
	Dry	Two	9.8	3878	5.6	
	Dry	Three	11.9	3936	3.1	
DYNA-PUR7416 -NT6	Dry	One	12.2	4113	6.7	0.483/0.658
	Dry	Two	12.9	1741	6.5	
	Dry	Three	14.2	3979	6.1	

a) b) c)

Figure 40: DYNA-PUR7416 (REG) failure type with a) one coat, b) two coats, and c) three coats

a) b) c)

Figure 41: DYNA-PUR7416 NT6 failure type with a) one coat, b) two coats, c) three coats

4.2.2.1 Overall Compression Test Performance

The two-layer coating for the DYNA-PUR7416-NT6 was the lowest ultimate compressive strength at 1741 psi. The rest of the coatings, even the one and three layer thicknesses of the NT6 have ultimate compressive strengths that are all above 2600 psi. Another observation about the coatings is that all of the coatings managed to hold together the cylinders during the compression test, preventing the cylinder from exploding, even though the cylinders did fail within the coatings. However, the VersaFlex, Rustoleum (Citadel), and the Mirabel products all experienced disbonding as shown in the cylinder pictures. In Figure 42 below, the coatings with the highest consistent compressive strength are the VersaFlex Aliphatic Clear Coat and the Creative Material Technologies DYNA-PUR7416. However, as seen in the cylinder failure pictures, the Aliphatic Clear Coat held the cylinders together more.

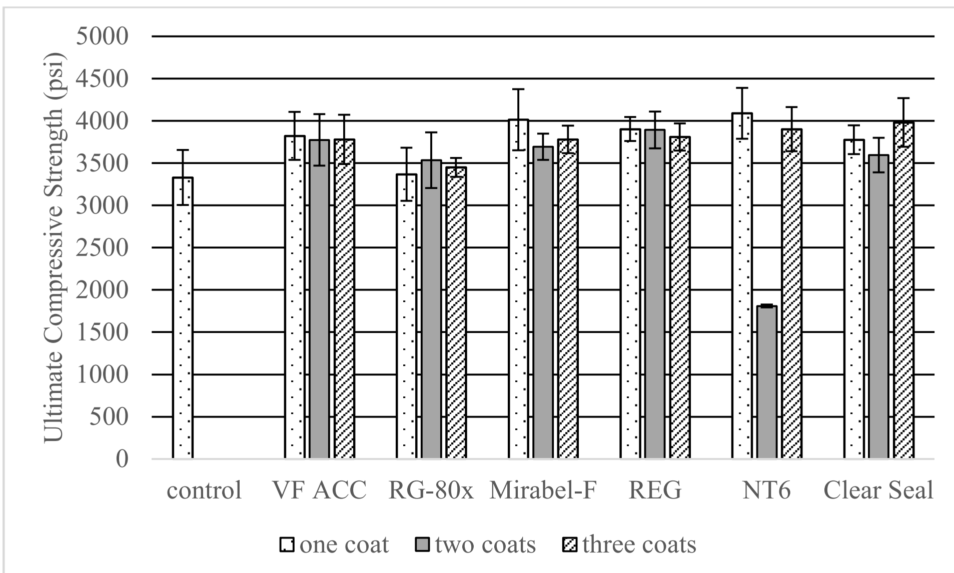


Figure 42: Compression test results, all samples

4.2.3 Modulus of Elasticity Testing

The stress-strain behavior for each sample type was recorded while conducting the load test. The calculated chord modulus of Elasticity, following the procedure stated in ASTM C469, is shown in Table 20. For a few samples, due to equipment failure, it was not possible to record the strain response for both sample replicates. In the case of the Aliphatic Clear Coat and DYNA-PUR7416-NT6 products, no strain results were obtained for either sample replicates. With available results, there is no statistical difference between the product types based on the returned p-value from an ANOVA test. Results obtained for the 1, 2 and 3 coats systems were statistically insignificant where analysis of Variance was possible to conduct. However, results demonstrate an increase in stiffness properties of the composite system in comparison to that of the control sample. There is an average percent increase in modulus of Elasticity of 61% for coated samples.

Table 20: Results of Modulus of Elasticity (E) testing, all products

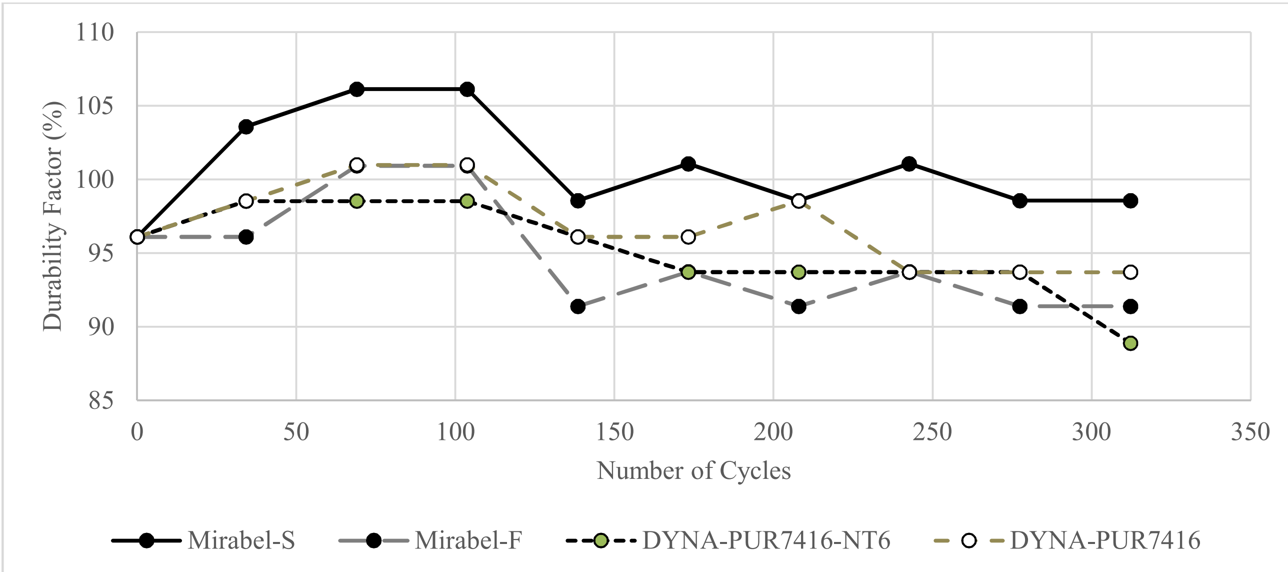
Name	One Coat E (ksi)	Two Coats E (ksi)	Three Coats E (ksi)
Control	1665.26		
VersaFlex			
Aliphatic Clear Coat		2663.18	2675.33
Clear Seal	3071.93	3937.88	1881.36
Rustoleum (Citadel)			
Polyurea Polyaspartic RG-80X	2663.22	2237.60	2567.65
Mirabel			
Mirabel Fast	2746.06	2596.17	2617.61
Creative Material Technologies			
DYNA-PUR7416	2734.04	2590.66	2582.18
DYNA-PUR7416-NT6	-	2680.59	2565.78
ANOVA for Modulus of Elasticity, one coat			
F-value	0.530	p-value	0.749
ANOVA for Modulus of Elasticity, two coats			
F-value	0.604	p-value	0.706
ANOVA for Modulus of Elasticity, three coats			
F-value	0.762	p-value	0.614

In addition to the Table 21, ANOVA analysis was performed on the three different coating thicknesses within each coating type. The only one that showed a significant difference between layer thicknesses was the Mirabel Fact coating with a p-value of 0.018 and an F-value of 55.12. The rest of the coatings had an alpha value higher than 0.05, showing no significant difference.

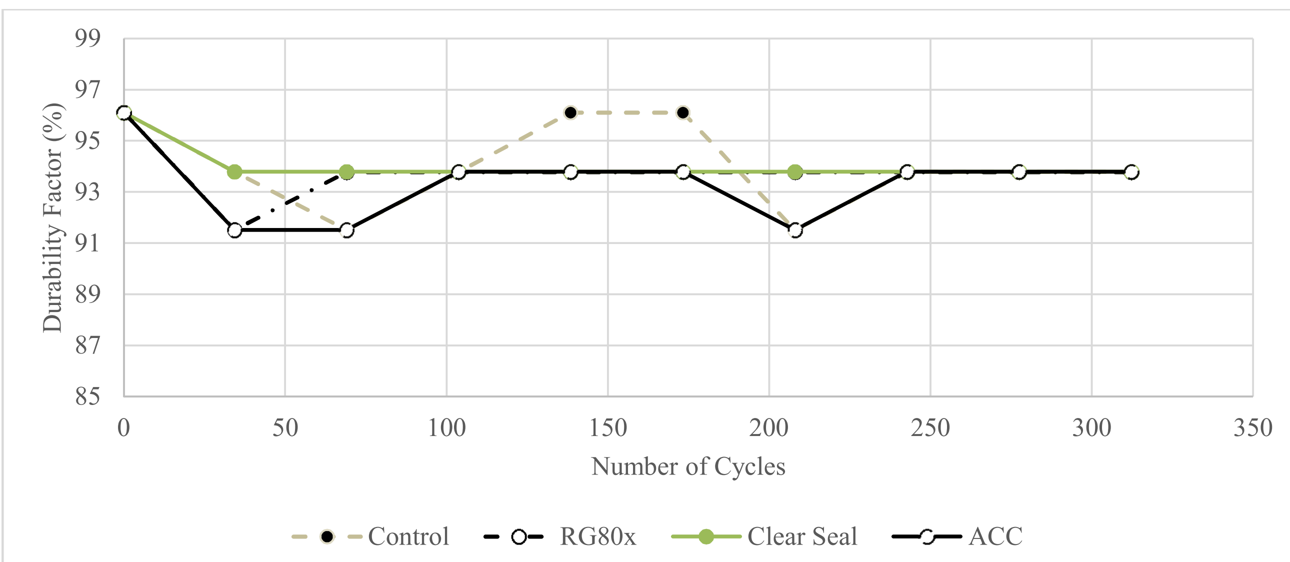
In the context of field exposure and resistance to durability mechanisms such as freezing and thawing of concrete, an increase in mechanical properties of the concrete cover, due to the composite effect provided by the coating, may give additional resistance to stress-strain related surface damage. In this case, the small increase in measured coating thicknesses between 1, 2 and 3 coats are not sufficient to significantly change the results. But it is recommended to apply more than one coat to ensure adequate and even coverage of the entire area and prevent small areas susceptible to water infiltration. (Tator 2015) Also, the product types evaluated have been reported to be sensitive to erosion-abrasion type deterioration (Tator 2015) so a slight increase in the initial thickness could increase the service life of the coating. This principle is of interest in the rapid freeze-thaw durability test conducted on prismatic samples.

4.3 Influence of Cyclic Freezing and Thawing Exposure

4.3.1 Rapid Freeze-Thaw Testing



a)



b)

Figure 43: Cyclic freeze-thaw test result comparison between product types: a) Creative Material Technologies and Mirabel products, b) Rustoleum and Versaflex products

A series of rapid freeze-thaw cycling was performed to determine the performance of the coating on a scaled surface. The test regimen was performed as per ASTM C666 except for sample conditioning as mentioned in the experimental procedure section. As per ASTM C666 criteria, all coated concrete products performed well and are considered acceptable (Figure 43). The Durability Factor maintained above 90% for the duration of the test. This is as expected since the concrete mixture is the same for all products and air entrainment provided acceptable resistance to damage. However, a visual characterization of the samples' surfaces demonstrated signs of deterioration due to freeze-thaw exposure. This will be further expanded on in the V-Notch Testing Results.

4.3.2 Flexural Testing

As seen in Table 21 and Figure 44, half of the beam samples outperformed the control sample. Two of the products demonstrated superior properties, VersaFlex Clear Seal and Polyurea Polyaspartic RG-80X. The DYNA-PUR7416/DYNA-PUR7416-NT6 and the Mirabel Slow/Fast curing products recorded lower strength than that of the control's. The increase in modulus of Rupture could be due to the composite effect of the coating providing additional resistance to tensile crack initiation.

Table 21: Results of flexural testing for freeze-thaw beams, all products

Name	Coating Thickness (mils, ± 0.4)	Modulus of Rupture (psi)	COV (%)
Control	N/A	702.6	4.5
VersaFlex			
Aliphatic Clear Coat		705.1	15.6
Clear Seal		739.5	0.6
Rustoleum (Citadel)			
Polyurea Polyaspartic RG-80X		764.8	13.4
Mirabel			
Fast	N/A	696.5	8.1
Slow	N/A	556.2	18.6
Creative Material Technologies			
DYNA-PUR7416		584.5	5.4
DYNA-PUR7416-NT6		517.4	13.8
ANOVA TEST for Modulus of Rupture			
F value	2.45	p-value	0.116

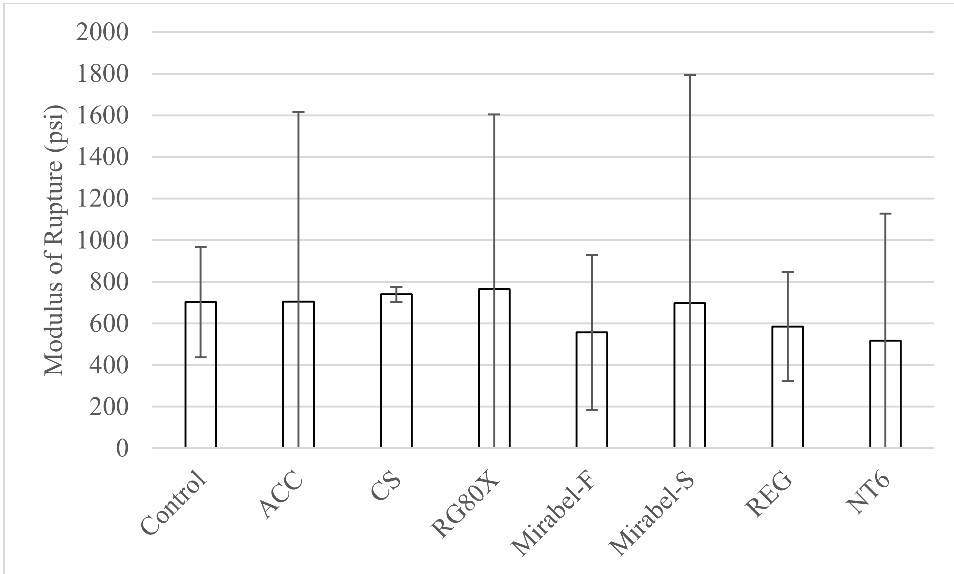


Figure 44: Flexural test results comparison for freeze-thaw beams

However, the results of an ANOVA test, where the null hypothesis is that the mean modulus of Rupture for all groups is the same, demonstrate that the null hypothesis is supported. The returned p-value (0.12) is superior to a generally accepted confidence level of 0.05 for concrete testing. Moreover, looking at the potential range in mean values represented by the 95% confidence range (2s) for all products with respect to that of the control value, it can be seen that the results are similar (Figure 44). However, the slightly high (but still acceptable, except for the Mirabel Slow product) coefficients of variation obtained for the coated samples may have influenced this hypothesis outcome. The accepted coefficient of variation for this test is 16%.

As previously mentioned in the experimental procedure section, the uneven scaled surface of the test face may have contributed to the variance in results. The Polyaspartic Polyurea RG80X product recorded the highest strength. Looking at the trend, there are no discernable differences between coating products for the scaled standard freeze-thaw beams. However, the decrease in performance for the materials studied may have been caused by a degradation of the coating itself during low temperature cycling.

4.3.3 Visual Condition Characterization

Pictures of distress features seen for specimens are provided in

Table 22 to

Table 28. The main visible surface features seen for all sample types are:

- mortar flaking,
- edge deterioration and scaling,
- aggregate exposure from loss of coating,
- erosion of coating across the sample surface.

Surface disintegration is noticeable for uncoated concrete surfaces and at its edges. In some instances, the coating prevented the loss in material as seen in Figure 45 where a scaled piece was retained by the coating. However, loss in the coating was noticeable across the sample surfaces. At various degrees, all samples exhibited erosion of the coating. Tator (2015) reported that one of the biggest drawbacks of a polyaspartic coating is its low abrasion resistance. Here the repeated action of ice nucleation at the sample surface led to abrasion-erosion type damage. This should be considered when evaluating appropriate coating thicknesses as they may degrade with time (

Table 22 to

Table 28). Still, the coating was considered performant in inhibiting surface deterioration of the concrete itself assuming good bond performance in time.

Figure 45: Mirabel Fast Freeze-Thaw Test Surface Results

4.3.4 Evaluation of Coating Adhesion by Knife (V-Notch)

The bond performance of the coating was assessed by carrying-out the V-notched test on sample surfaces. An example of the surface test for each sample type can be seen in

Table 22 to

Table 28. For both Mirabel products, the coating remained intact. Seen in Figure 45, the concrete had failed and cracked, but the coating still held the small piece of the concrete to the beam until it was forcibly removed. However, both products from Creative Material Technologies exhibited areas of poor bond performance. When performing the V-notched test, the coatings easily peeled off the surface.

Table 22: Mirabel-Fast Visual Characterization and V-Notch Test Results

	Distress Features • Mortar Flaking • Deterioration of Edges • Abrasion on the coating surface exposing the aggregate • Thinner coating than first applied
	Results • Could not peel back coating • Coating disintegrated

Table 23: Mirabel-Slow V-Notch Test Results

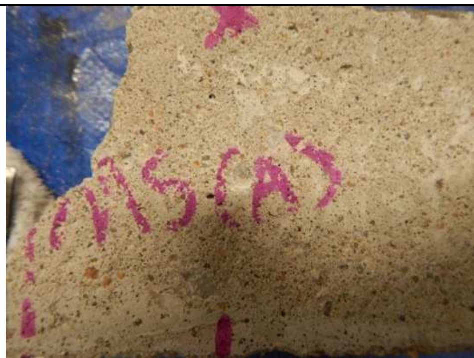
	Distress Features • Mortar Flaking • Deterioration of Edges • Abrasion on the coating surface exposing the aggregate • Thinner coating than first applied
	Results • Could not peel back coating • Coating disintegrated

Table 24: DYNA-PUR7416-NT6 V-Notch Test Results

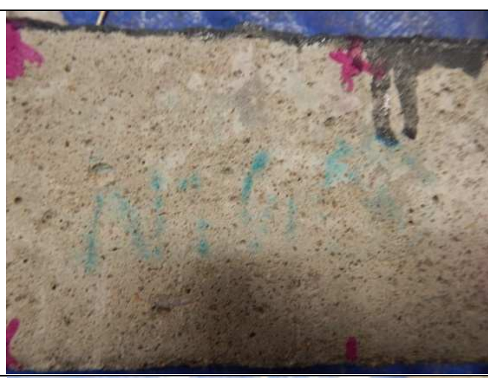
	Distress Features • Mortar Flaking • Deterioration of Edges • Abrasion on the coating surface exposing the aggregate • Thinner coating than first applied
	Results • Coating peeled very easily in strips

Table 25: DYNA-PUR7416 V-Notch Test Results

	Distress Features • Mortar Flaking • Deterioration of Edges • Abrasion on the coating surface exposing the aggregate • Thinner coating than first applied
	Results • Coating peeled very easily in strips

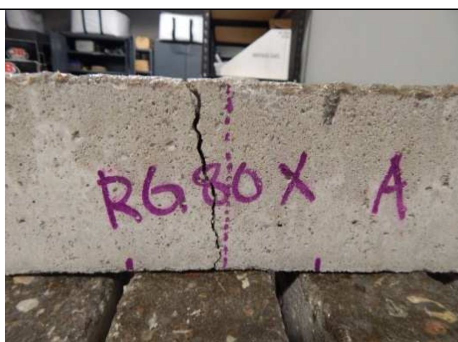
Table 26: Aliphatic Clear Coat V-Notch Test Results

	Distress Features • Mortar Flaking • Deterioration of Edges • Abrasion on the coating surface exposing the aggregate • Thinner coating than first applied
	Results • Could not peel back coating • Coating disintegrated

Table 27: Clear Seal V-Notch Test Results

	Distress Features • Mortar Flaking • Deterioration of Edges • Abrasion on the coating surface exposing the aggregate • Thinner coating than first applied
	Results • Could not peel back coating • Coating disintegrated

Table 28: Polyurea Polyaspartic RG-80X V-Notch Test Results

	Distress Features • Mortar Flaking • Deterioration of Edges • Abrasion on the coating surface exposing the aggregate • Thinner coating than first applied
	Results • Could not peel back coating • Coating disintegrated

4.4 Influence of Salt Solution Exposure

4.4.1 Pull-off Testing

All slab samples after having undergone a salt ponding exposure were evaluated to determine its effect on bond performance and coating resistance to prolonged salt solution exposure. The bond test (ASTM D7234) was performed. Only a one-coat layer system was trialed. The results of the pull-off test are shown in Figure 46 and Table 23. For a given sample where two test replicates were performed, it can be seen that the results exhibited a high variability for all coating types, Table 23. The RG-80X coating had the least variability.

Since all sample replicates only have one layer of the coating, the high coefficients of variation can be attributed to the uneven scaled surface as mentioned before. However, since the uneven distribution of the concrete slabs did not provide coefficients of variations this high for the un-weathered samples discussed in section 4.1, the performance of the coating may have been causal to the noticeable trend. Moreover, the recorded bond strengths are lower than that obtained for the cube samples. As such, salt solution exposure may have a negative effect on the coating systems evaluated. However, looking at the results, there are no real discernable differences between coating types as they are all within the two standard deviations of each other (Figure 50).

Table 29: Pull-off Testing Results after for Salt Ponding Exposure – All Samples

	Sample	**Average Pull-load (psi)**	**Coefficient of Variation (%)**
Aliphatic Clear Coat	One	394.4	95.8
	Two	502.5	43.0
	Three	313.3	56.0
Polyurea Polyaspartic RG-80X	One	364.1	1.2
	Two	271.9	28.1
	Three	327.6	11.0
Mirabel Fast	One	378.5	N/A
	Two	607.4	7.4
	Three	N/A	N/A
DYNA-PUR7416	One	621.7	15.2
	Two	626.5	N/A
	Three	475.5	53.9
DYNA-PUR7416-NT6	One	359.4	25.0
	Two	343.5	2.6
	Three	318.0	99.0
Clear Seal	One	567.7	5.5
	Two	375.3	43.1
	Three	612.2	0.7

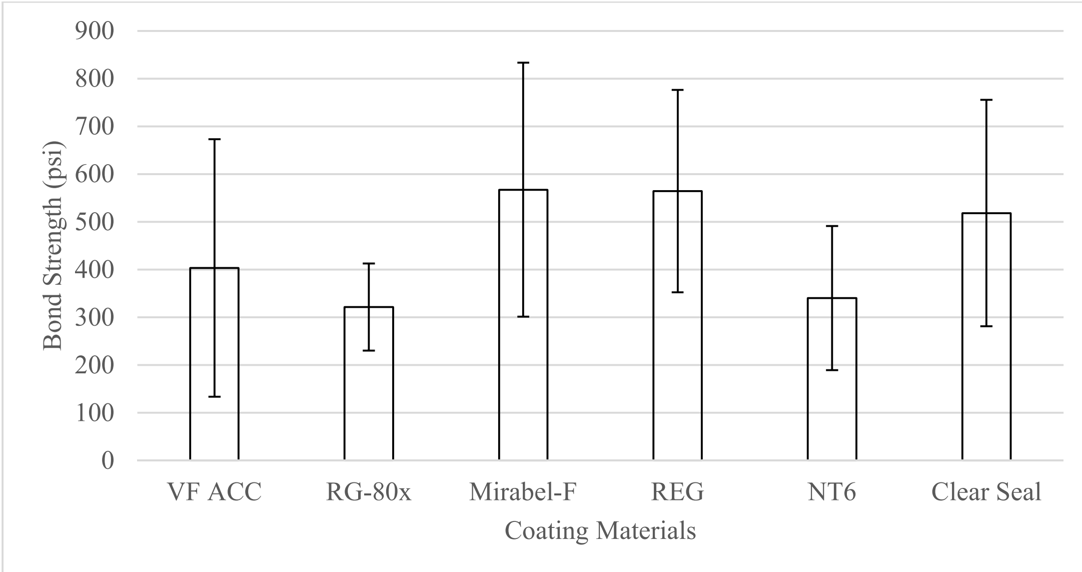


Figure 46: Pull-off test results comparison for all products, salt ponding exposure

4.4.2 Visual Condition Characterization

In addition to a higher variability, the test samples exhibited signs of deterioration similar to that seen for the freeze-thaw samples. Mainly a loss of coating thickness was clearly visible on the sample surfaces, but accurate measurements of the thickness lost were unattainable due to the surface conditions post salt ponding. Further visual characterization of samples surfaces per coating manufacturer is provided in tables 24 to 29.

Table 30: VersaFlex Aliphatic Clear Coat Visual Characterization after Salt Ponding Exposure

	Distress Features • Thinner coating than first applied • Few partial failures of combined coating and adhesive • Most failures in the concrete substrate

Table 31: Rustoleum Polyurea Polyaspartic RG-80X Visual Characterization after Salt Ponding Exposure

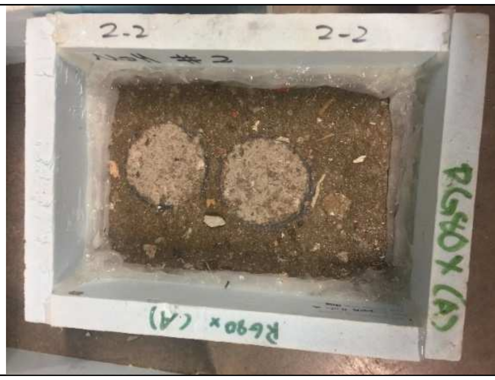
	Distress Features • Thinner coating than first applied • Few partial failures of combined coating and adhesive • Most failures in the concrete substrate

Table 32: Mirabel-Fast Visual Characterization after Salt Ponding Exposure

	Distress Features • Thinner coating than first applied • Few partial failures of combined coating and adhesive • Few failures of the coating bond

Table 33: DYNA-PUR7416 Visual Characterization after Salt Ponding Exposure

	Distress Features • Thinner coating than first applied • Few partial failures of combined coating and adhesive • Few failures of adhesive itself • Few failures of the coating bond

Table 34: DYNA-PUR7416 NT6 Visual Characterization after Salt Ponding Exposure

	Distress Features • Thinner coating than first applied • Few partial failures of combined coating and adhesive • Few failures of adhesive itself

Table 35: Clear Seal Visual Characterization after Salt Ponding Exposure

	Distress Features • Thinner coating than first applied • Few partial failures of combined coating and adhesive • Most failures in the concrete substrate

4.5 Influence of Cyclic Wetting and Drying Exposure

4.5.1 Visual Condition Characterization and Evaluation of Coating Adhesion by Knife (V-Notch)

Similar to the other two durability exposure types, the main visual effects seen after 100 cycles of a simulated rainfall event are a loss of thickness, mortar flaking, exposed aggregates, and deterioration of the coating. Further characterization per coating type is described in Tables 31 to 37. As for the residual bond performance, some coatings like the Clear Seal still exhibited a strong adhesion to the concrete substrate, and could not be pulled back when performing the V-notched test. However, the same can not be said of other coating types such as the DYNA-PUR7416 which could be very easily removed and actually peeled in large flakes. The extreme result seen from this exposure regimen was that for the Mirabel coatings which actually started to disintegrate when the V-Notch test was performed. Here, the loss in coating thickness may have contributed to the inability to perform the test.

Table 36: Mirabel-Fast Visual Characterization and V-Notch Test Results after Wet-Dry Exposure

	Distress Features • Mortar Flaking • Deterioration of Edges • Abrasion on the coating surface exposing the aggregate • Thinner coating than first applied
	Results • Could not peel back coating • Coating disintegrated

Table 37: Mirabel-Slow Visual Characterization and V-Notch Test Results after Wet-Dry Exposure

	Distress Features • Mortar Flaking • Deterioration of Edges • Abrasion on the coating surface exposing the aggregate • Thinner coating than first applied
	Results • Could not peel back coating • Coating disintegrated

Table 38: DYNA-PUR7416-NT6 Visual Characterization and V-Notch Test Results after Wet-Dry Exposure

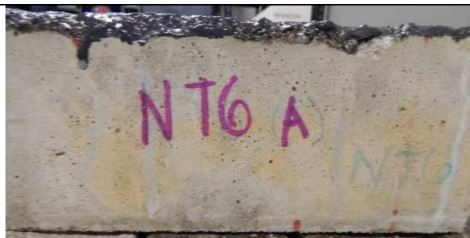
	Distress Features • Mortar Flaking • Deterioration of Edges • Thinner coating than first applied
	Results • Coating peeled very easily in strips

Table 39: DYNA-PUR7416 Visual Characterization and V-Notch Test Results

	Distress Features • Mortar Flaking • Deterioration of Edges • Thinner coating than first applied
	Results • Coating peeled very easily in strips

Table 40: Aliphatic Clear Coat Visual Characterization and V-Notch Test Results after Wet-Dry Exposure

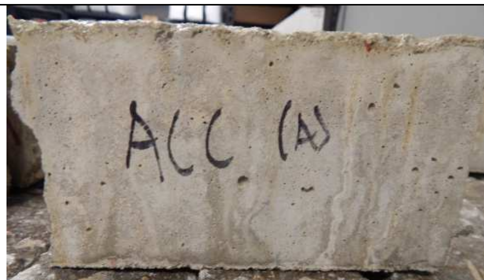
	Distress Features • Mortar Flaking • Thinner coating than first applied
	Results • Could not peel back coating • Coating disintegrated

Table 41: Clear Seal Visual Characterization and V-Notch Test Results

	Distress Features • Mortar Flaking • Deterioration of Edges • Abrasion on the coating surface exposing the aggregate • Thinner coating than first applied
	Results • Could not peel back coating • Coating disintegrated

Table 42: Polyurea Polyaspartic RG-80X V-Notch Test Results after Wet-Dry Exposure

	Distress Features • Mortar Flaking • Deterioration of Edges • Abrasion on the coating surface exposing the aggregate • Thinner coating than first applied
	Results • Could not peel back coating • Coating disintegrated

CHAPTER 5

CONCLUSION

The purpose of the investigation was to identify several acceptable manufacturers of polyaspartic polyuria coating materials that could be used on a scaled concrete surface to inhibit further surface disintegration. In order to achieve the latter, an adequate bond-strength between the coating and the substrate must be achieved. As such, this was evaluated by performing the pull-off test and the V-notched test. Results demonstrated that bond performance was acceptable but variable throughout the study for all tested products. Here, adequate surface preparation (dry, clean and free of loose debris) along with adequate product batching, mixing and application will favor bond performance.

As for the mechanical performance of the products, the presence of a thin coat of product did not significantly add to the performance of the concrete samples under flexural nor compression loading. The performance of the products is considered to be similar for all. There are no additional benefits in terms of mechanical performance to adding 2 or 3 coats of product. However, due to the uneven surface profile of scaled concrete, it is still recommended to apply more than one coat to ensure adequate coverage of all affected area. Water infiltration through discontinuous areas could lead to a loss in bond performance. In the end, all products met the study objective of containing failed concrete fragments. For the compression test in accordance with ASTM C39, the applied products aided in restraining the failed concrete cylinder also giving a slight increase in strength and stiffness properties.

Moreover, the susceptibility of the polyaspartic polyurea products to erosion-abrasion resistance may factor into selecting the number of desired coats. At the end of durability exposures simulating weathering, all products showed visible signs of surface degradation which may have contributed to disbondment at various degrees. Here, further testing would be required to determine the deterioration mechanisms and potentially a time-to-deterioration for these products. Still, 300 cycles of freezing and thawing were sufficient to visually reduce the surface layer and expose small areas to water infiltration. To a lesser extent, similar distress features are also noticeable for cyclic wetting and drying and salt solution exposures.

Both Creative Material Technologies'and Mirabel's products performed adequately in the laboratory. However, it was observed that the bond performance may be affected by weathering exposures. For freeze-thaw exposure, Creative Material Technologies and Mirabel products demonstrated signs of bond degradation. On-the-other-hand, the products initially failing the bond-test (Rustoleum and VersaFlex), performed adequately for all other tests including freeze-thaw testing. In the case of the Rustoleum RG-80X, the disbondment issue initially seen was not observed for the remainder of the study.

It is recommended that further durability testing be performed to confirm findings and better understand causal factors. Here, loss in coating thickness should be monitored and performed on even surface profiles to overcome encountered challenges for coating thickness measurements.

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VITA

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Candidate for the Degree of

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Thesis: DURABILITY EVALUATION OF CONCRETE SEALED WITH POLYUREA POLYASPARTIC COATINGS

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Education:

Completed the requirements for the Master of Science in Civil Engineering at Oklahoma State University, Stillwater, Oklahoma in May, 2020.

Completed the requirements for the Bachelor of Science in Civil Engineering at Oklahoma State University, Stillwater, Oklahoma in May, 2018.

Experience:

Graduate Research Assistant May 2018 –Present

- Lead coordinator of various testing methods for polyaspartic polyureas, commissioned and governed by the Ohio DOT to improve durability of bridge parapet walls
- Implemented multiple bridge load testing hardware and software systems to evaluate necessary repair to the I-235 bridge, commissioned and governed by the Oklahoma DOT

Graduate Teaching Assistant: Engineering Materials Lab May 2018 – Present

- In-depth knowledge of chemical structure, strengths, weaknesses, and mechanical properties of steel, timber, and concrete
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- Interacting one on one with students

Professional Memberships:

Chi Epsilon, Civil Engineering Honor Society Fall 2018 – Present
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