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Evaluate Performance of Sealers and Coatings Applied to TxDOT Bridge Substructures

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16. Abstract

Protecting concrete bridge substructures against deterioration over time is an important aspect of bridge preservation, and it is routinely conducted by state departments of transportation. The application of coatings and sealers to protect bridge substructure concrete from corrosion is a common practice. However, a laboratory-based performance evaluation of potential sealers and coatings on a representative concrete substrate is crucial for selecting suitable coating/sealer products that meet project requirements. In the present research project, a systematic laboratory-based performance evaluation test protocol was developed to evaluate the effectiveness of representative coating/sealer products (three water-based coatings, three solvent-based coatings, and two sealers) on resisting moisture and chloride ingress through substructure concrete and achieving adequate adhesion performance (for coatings) under both normal and accelerated weathering conditions. Water absorption (ASTM D6489) and sorptivity (ASTM C1585) tests were conducted to evaluate moisture resistance, and rapid chloride permeability (ASTM C1202), chloride ponding (ASTM C1556), and innovative direct corrosion measuring tests (steady-state and accelerated methods) were conducted to evaluate chloride-induced corrosion resistance of the tested sealers and coatings. Monitoring through the measurement of dry film thickness for coating and depth of penetration for sealers was found to be effective in confirming a proper application. The solvent-based coating and sealers better resisted moisture and chloride ingress into the concrete substrate than the water-based coatings. Similarly, the solvent-based coatings showed higher pull-off adhesion strength than the water-based coatings. Ranking through comparative assessment of the tested products based on their performance in the selected tests under both normal and weathered conditions was considered a measure of corrosion protection effectiveness and useful to select suitable products for field applications.

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Concrete Bridge Substructure, Surface Preparation, Coating and Sealer Materials, Pull-Off Adhesion Test, Depth of Penetration, Rapid Chloride Ion Penetration, Chloride Ponding, Concrete Durability, Sorptivity

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DISCLAIMER

This research was sponsored by the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of FHWA or TxDOT. This report does not constitute a standard, specification, or regulation.

This report is not intended for construction, bidding, or permit purposes. The researcher in charge of the project was Dr. Anol K. Mukhopadhyay.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: RESEARCH OVERVIEW

1.1 Overview of the Problem and Research Significance

Concrete bridge substructures undergo deterioration for several reasons, including but not limited to corrosion of reinforcement, attacks due to environmental conditions, weathering, etc. (*1*–*3*). To prolong the service life of such bridge substructures, regular monitoring/inspection is a common practice. Condition assessment of bridge substructures (both old and new) is of high importance because complete replacement of deteriorated or partially deteriorated substructures is not practical, unlike with other bridge superstructure components such as deck slabs. In this regard, most departments of transportation (DOTs) have a specific schedule and procedures to monitor concrete bridges in different states across the United States (*4*, *5*). As per statistics from 2018 on bridge inspections in Texas, $5.7 billion was required for repair works on 11,310 bridges (*6*). Because of the huge costs associated with the repair of bridges, a need exists for the assessment and protection of concrete structures to prevent deterioration due to aging and corrosion, particularly for substructures (*7*).

Substructures are more susceptible to damage due to corrosion because in many cases these structures are exposed to moisture/bodies of water. The moisture rich in chloride from the environment or adjacent water bodies may lead to chloride ion ingression, which causes chloride-induced damage to the reinforcement. This effect is amplified drastically near the coastal areas (*2*, *8*). Other agents such as deicing salts also cause chloride ion ingress. The durability of concrete structures is also compromised by alkali-silica reaction (ASR), carbonation, cracking due to leaching and thermal changes, and sulfate attack (*2*, *8*, *9*). Deterioration of concrete substructures due to corrosion of reinforcement and other chemical attacks (e.g., alkali-aggregate reaction, sulfate attack, etc.) leads to volume increase and crack formation, which causes damage to concrete (e.g., spalling) over time and an overall reduction in the effective cross-sectional area (*10*–*14*). Currently, corrosion of reinforcing steel in existing concrete bridges creates maintenance and economic burdens for many transportation agencies (such as state DOTs) (*10*–*12*). Although different repair methods exist for the preservation of bridge concrete, sometimes these repair methods become costly and unreliable (*13*, *14*). Therefore, it is a common practice to prevent or reduce the penetration of moisture and other deleterious ions (e.g., Cl^-, SO_4^{2-}, etc.) into the concrete using coating or sealer materials (*12*, *15*) and prevent concrete deterioration due to the above-mentioned durability challenges (*16*–*18*). Coating materials also offer some protection (systematic evaluation of the effectiveness of commonly used coating materials is still lacking) against moisture and chloride ion migration by forming an impermeable layer on the applied concrete substrate, with the additional benefit of providing an aesthetic look. Some of the known benefits from the application of coating are (a) protection of concrete against deterioration caused by ultraviolet (UV) radiation from sunlight exposure; (b) limiting expansion and contraction cycles due to temperature and seasonal changes, moisture inflow, and other minor physical damages; and (c) reduction of accumulated dust, which makes the surfaces somewhat waterproof and easy to clean, etc. (*12*, *19*). Although the use of coatings is known to protect substructure concrete from deterioration and improve its durability, the adhesion performance of coatings with concrete substrate has not been investigated thoroughly. Again, for any coating material, suitable engineering judgment is crucial for determining the best compatibility of the protection requirement of the concrete structure and type of coating material.

The application of sealers (e.g., silane and siloxane) with different concentrations and coating materials (e.g., water-based [WB] and solvent-based [SB]) is a common practice to protect concrete bridge structures. Application of sealers on concrete substrates can mitigate the damage due to ASR, formation of calcium oxychloride, carbonation, sulfate attack, etc. (*12*, *14*, *20*, *21*). Sealer materials have very low viscosity and can penetrate through concrete micropores and form a thin hydrophobic layer (measured as the depth of penetration [DOP]). The DOP of sealer materials is dependent on several parameters, like type of concrete, pore structure, size of the sealer molecule, condition of the substrate (moist or dry) during the sealer application, direction of application (vertical or horizontal), etc. (*21–23*).

The effectiveness of the applied sealers and coating materials depends on the surface preparation, characteristics of the concrete substrate, method of application, etc. Concrete surfaces should be clean and free from any unforeseen materials (e.g., fungal growth, efflorescence, peeling of old paint, oil, or grease, etc.) (*12*, *24*). Common tests conducted to evaluate the performance of coating and sealer materials include chloride penetration, absorption, weatherability, water vapor transmission, adhesion strength (for coating only), etc. (*12*, *25*, *26*). However, in practice, good adhesion between concrete and applied coating primarily determines the coating's effectiveness in protecting concrete from chloride ion penetration as well as its long-term performance (*12*, *25*, *27–30*). Further, there is no recommended adhesion strength value by ASTM standards (*31*, *32*) for qualifying a suitable coating material to match the requirements for a specific project.

The use of sealers and coatings is known to protect substructure concrete from deterioration and improve its durability; however, a thorough performance evaluation of available sealers/coatings in Texas had not been attempted before this project. There is a need for guidelines and performance-based recommendations for sealer and coating materials on concrete substrates. Sealer materials are generally categorized based on chemical composition and structure, carrier solution, mechanism, function, and performance (*23*). Based on the deterioration mechanism, degree of protection, and durability performance requirements, the identification of suitable sealers is extremely important. Similarly, for any coating materials, suitable engineering judgment is crucial for the best compatibility of the protection requirement of the concrete structure and type of coating material. As a result, developing a laboratory-based test protocol to evaluate the performance of the most commonly used sealers and coating materials in Texas was identified as an important research need by TxDOT. Based on the outcomes and recommendations obtained from the research project conducted by Texas A&M Transportation

Institute (TTI), necessary changes in the current specifications, standards, and department guidelines of TxDOT will be made.

1.2 Objective

The main objective of this project was to develop a test protocol for evaluating the performance of different sealer and coating materials that are commonly used on concrete bridge substructures in Texas. The specific objectives to achieve the main objective are listed below:

1. Conduct a thorough review of the existing research studies related to the deterioration of concrete bridge substructures and state-of-the-art evaluation techniques to understand the effectiveness of sealer and coating materials to mitigate such deterioration.
2. Understand different commonly used surface preparation methods on concrete substructures and provide recommendations on surface preparation before the application of sealer and coating materials.
3. Identify a list of sealer and coating materials that are commonly used to protect concrete bridge substructures in Texas and evaluate their performance using suitable test methods in the laboratory under both normal and accelerated weathering (QUV and QFOG exposure) conditions.
4. Develop a rating system (for possible suggestion of a product) based on extensive laboratory performance evaluation of the tested sealers and coating materials (Item 3) under both normal as well as accelerated weathering conditions.
5. Conduct selective field validation by establishing an effective correlation between recommendations provided based on the extensive laboratory evaluation (Items 3 and 4) and field performance.
6. Develop guidelines, recommendations, and decision-making tools based on the understanding from extensive laboratory evaluation (Item 3), ranking system (Item 4), and field validation (Item 5).

1.3 Organization of the Report

The work that was performed under different tasks (according to the original proposal) is presented in this report as chapters.

Chapter 1 is an introduction addressing the research background and objectives, followed by an organization of the present research report.

Chapter 2 provides a comprehensive literature review that was conducted to understand the factors leading to the deterioration of substructure concrete and the effectiveness of applying suitable sealer and coating products to minimize the impact of these factors and enhance durability. A review of the commonly recommended sealers and coating systems and their effectiveness on concrete substructures are discussed. An overview of state-of-the-art practice as per national standards and research studies performed by different DOTs and universities across the United States to evaluate the performance of coatings and sealer systems is given.

Chapter 3 presents the performance evaluation of the selected commonly used sealer and coating materials on bridge substructure concrete. The chapter covers the selection and collection of sealer and coating materials, concrete mixing, curing of concrete specimens, application of sealers and coatings, curing of coating/sealer, selection of the most effective test methods, and performance evaluation under both normal and weathering conditions using the selected tests. A comparative assessment of the selected sealer and coating products is also presented based on the selected performance indicators.

Chapter 4 outlines the framework for developing a rating system using a step-by-step approach: (a) identifying critical performance indicators based on the test results from the extensive laboratory performance evaluation of the selected sealers and coating materials (Chapter 3), (b) ranking the products under each selected performance indicator, and (c) assigning a weightage factor for the selected performance indicators and determining a combined rating. This chapter also addresses the use of a minimum number of performance indicators (selection of key performance indicators) for rapid laboratory evaluation of sealer and coating products and assigning ratings with acceptable reliability.

Chapter 5 presents the results from the field evaluation of selective projects for both sealer and coating products. The chapter discusses the effectiveness of different surface preparation methods (water-blasting and sandblasting) on existing coated surfaces of concrete bridge substructures in the field. Observations related to the application of coating materials (WB and SB) on concrete bridge substructures are also documented. The use of adhesion strength measurements for condition assessment of the substructure concrete and the selection of a suitable surface preparation method is also discussed.

Chapter 6 discusses developing practice guidelines and recommendations in the form of a decision-making tool (systematic stepwise approach) to ensure the effective application of sealer and coating materials and adequate protection of substructure concrete from corrosion.

Finally, Chapter 7 provides a summary and conclusions based on the research findings from this research project and offers potential recommendations for further research followed by implementation.

CHAPTER 2: LITERATURE REVIEW

A thorough review of the existing research studies and state-of-the-art evaluation techniques to understand the effectiveness of sealer and coating materials for protecting concrete substructures was conducted. An overview of previous studies that have relevance to the present research work is presented in this chapter. Although the major research focus in the literature is related to concrete bridge superstructures, the merits of extending this available knowledge to concrete substructures were realized. The concrete substructures are more critical within a structural system, and thus there is a need for a special research focus to confirm its long-term durability through the application of sealer and coating materials. The findings from the literature review are documented in the following subsections.

2.1 Review Approach

Several factors impact the durability and serviceability of concrete bridge substructures. This chapter aims to provide an overview of the factors causing deterioration and damage to concrete bridge substructures and discusses the need for a protection system. The literature review addressed the following aspects:

- Understand the factors leading to the deterioration of substructure concrete and provide a detailed overview of the methods and techniques used for protection and repairs of the damages in bridge substructures.
- Review the commonly recommended sealer and coating products and their effectiveness to minimize damages and enhance durability.
- Document the state-of-the-art practice as per national standards to evaluate the performance of coatings and sealer systems.
- Review the research studies performed by different DOTs and universities across the United States related to enhancing durability through the applications of sealer and coating products.

2.1.1 Understanding Deterioration Mechanisms and the Need for Monitoring and Inspection

This section elaborates on various factors that cause damage to concrete structures—which impacts durability—along with highlighting the practices (current as well as advanced) of monitoring and inspection.

2.1.1.1 Deterioration Mechanisms of Substructure Concrete

Various factors affecting the deterioration of concrete substructure surfaces are discussed below:

- Delayed Ettringite Formation (DEF) (Internal Sulfate Attack): This effect occurs when internal sulfates react with the hydration products of cement in concrete and form ettringite after the concrete has hardened. The sources of the sulfates can be gypsum-contaminated aggregate or cement with high sulfate content (*2*). The presence of external moisture, high concentration of sulfates, and high temperatures during the curing process (i.e., above 70–80°C; mass pours or heat or steam curing of precast elements are the common sources) are the conditions that accelerate the process, which results in cracks (*2*, *33*). DEF may not be responsible for structural collapse but can increase the risk of other forms of deterioration, such as freeze/thaw attack or reinforcement corrosion.

- Shrinkage Due to Early-Age Drying: Differential moisture content occurs across the depth of the concrete structures. The primary reason is the high rate of evaporation of moisture from fresh concrete during the placement stages. The stress created due to this difference in moisture may cause volume change, which may lead to delamination and spalling of concrete (*2*, *33–35*), depending on the degree of stress.
- Damage from Saturated Frost: When concrete is highly saturated with water in its pores, the freezing and thawing cycles tend to expand the volume of the pores. The resulting force when the water within the pore freezes creates pressure (that creates cracks) and opens large pores after thawing. This action exposes the concrete to further penetration, leading to incremental deterioration of concrete.
- Deicer Attack: This effect primarily occurs when concrete surfaces are exposed to deicing salt. A negative impact of the pore pressure developing in concrete leads to damage (*5*). Moreover, the dissolution of calcium hydroxide (a byproduct from cement hydration) results in leaching (*6*). This mechanism further increases the permeability and alkalinity reduction in concrete. The pressure develops due to the crystallization of salt at the locations where salt deposits are concentrated. The deleterious effect of expansive calcium oxychloride formation leads to damage to concrete at temperatures above freezing (*36*).
- Changes in Temperature and Moisture Content: This situation occurs due to differential exposure to sunlight and rainfall. The concrete microstructure undergoes stresses in its pores when there is resistance to the movements of moisture occurring during the thermal and moisture changes.
- ASR: The presence of reactive aggregates and moisture leads to the deterioration of concrete by the ASR. An expansive gel is formed when certain aggregates containing reactive silica react with alkali hydroxides (sodium and potassium) present within cement hydration products (*2*). The resulting alkali silicate gel creates expansive forces under the presence of adequate moisture, which results in cracks in concrete.
- Corrosion of Reinforcement Steel: Corrosion is an electrochemical process in which chloride ions penetrate the concrete matrix and react with the corrosion-resisting passivity layer on the surface of reinforcement steel in concrete structures. The corrosion of reinforcement within concrete is influenced by several factors (such as oxygen, pH, moisture, characteristics of the concrete substrate, carbonation, the concentration of chloride, temperature, relative humidity [RH], etc.) acting individually or in combination

(*2*, *7*, *37*). The formation of reaction product increases the volume, which further creates stress on the adjacent boundary. The loss of reinforcing steel area and formation of micro-macro cracks because of the electrochemical reaction also impact the structural capacity of the structure to bear the loading on it.

- Carbonation: This is a long-term reaction between the atmospheric CO_2 and the hydrated product of cement (primarily, calcium hydroxide and calcium silicate hydrate) under the presence of moisture (*2*). The final reaction product is calcite, and the process of carbonation reduces the alkalinity of the concrete surface, which promotes the deterioration of the passivity layer of steel reinforcement. Although the carbonation is a long-term and slow process, the final concrete surface may have less resistance for the protection of reinforcement.
- External Sulfate Attack: The hydroxides and aluminates of calcium present in hydrated cement paste react with the sulfates available in the surrounding soil, groundwater, or certain sulfate-containing aggregates and produce expansive sulfate-bearing hydrated phases (e.g., ettringite, gypsum) (*2*). The volume change due to the formation of these expansive phases creates stress in the concrete, leading to cracking and deterioration of the concrete substructure. The severity of the deterioration depends on the permeability and crack pattern of the concrete, the concentration and rate of supply of sulfates, and the type of sulfate compounds present.

2.1.1.2 Deterioration of Bridge Substructure and the Need for Monitoring

Along with the deterioration mechanisms discussed above, reinforced concrete substructures experience many challenges. Based on the literature, corrosion of reinforcement is the most common cause of deterioration of bridge substructure (*1*). Moreover, structural design, loading condition, geographic location, weather and environmental conditions, adjacent water bodies, temperature profile, and presence of harmful chemicals also play a major role in the overall deterioration of concrete bridge substructure (*2*, *3*). Unlike other structural components (e.g., deck slab), a complete replacement of a partially deteriorated concrete substructure is not feasible; therefore, a systematic approach consisting of periodic monitoring and applying a protection system is necessary. National Bridge Inventory Standards and the Federal Highway Administration (FHWA) maintain an inspection database for all public road bridges. According to the database for Texas, the total number of bridges is 55,701, out of which 774 (1.4 percent) bridges are structurally deficient (*6*).

The movement of moisture within a reinforced concrete system may cause long-term damage because the moisture may carry chloride ions or other harmful substances within the system, which can lead to corrosion of reinforcement. The chloride-induced damage (i.e., corrosion) is permanent damage to the reinforced concrete element as well as to the structural steel member of a bridge structural system. Moreover, further adverse effects can be seen in coastal areas (or marine environments) where both the chloride ion content and relative humidity of the surrounding environment are high. Normally, the failure of a structural member may damage the whole structural loading system. Similarly, the substructure of a bridge is a critical component within the bridge structural system. Moreover, substructures are sometimes directly exposed to a water body, which may further influence the rate of corrosion. Therefore, proper monitoring of the health of the substructure, along with bridge decks, is important. The movement of moisture within the reinforced concrete system can be monitored by nondestructive tests and advanced monitoring systems like the National Bridge Inventory rating system (*38*, *39*). Time domain and differential reflectometry can be applied to the field investigation to measure the moisture and chloride concentration within the concrete system (*38–40*). The temperature profile and moisture play a significant role in the overall dielectric constant of concrete. Therefore, a proper research method that considers field conditions needs to be established in the laboratory. Similarly, electrochemical impedance spectroscopy (EIS) can be applied to predict and determine corrosion of steel reinforcement within concrete bridge substructure systems. EIS is among the most common techniques used for the evaluation and study of corrosion in reinforced concrete. Based on the level of corrosion and age of the concrete bridge substructure, a calculative decision to select potential mitigation techniques can be made. Research has been conducted to verify the effectiveness of sealers in improving the durability of concrete bridge decks by forming a barrier that resists the penetration of chloride ions, water, etc., into concrete (*24*, *41*). However, this kind of systematic research to understand the effectiveness of sealer and coating products to protect concrete substructures is lacking, which is why it is the focus of the current research.

2.1.2 Prevention and Protection against Deterioration through the Application of Coating and Sealer Systems

This section summarizes the use of different types of coating and sealer materials for preventing deterioration and their effectiveness in improving the durability/service life of substructure concrete. The different types of available sealers and coating systems are explained, along with their effectiveness for a given purpose.

2.1.2.1 Paints and Coatings

Paints are impermeable coating materials that consist of four major compositions: (a) pigment, (b) binders, (c) solvent, and (d) additives. Pigment in paints provides color and protection from UV rays, and some of the commonly used pigments are TiO_2, ZnO, Pb_3O_4, Fe_2O_3, etc. The main role of the binder is to bind all the components of the paints. Different resins are the common binders in paint. Moreover, the binder also confirms the layer-forming process and bonds with the applied surface. Similarly, solvent dissolves the binder and provides a good viscosity of the paint. There are both organic and inorganic solvents, and the overall content of the solvent should be less in a paint material. Finally, the additives provide added benefits and can be used as driers, flow control agents, preventers of bubble formation, adhesion promoters, etc. One of the prime requirements of good paint is maintaining its opaque nature (which means nontransparent). Moreover, the paints should be chemically inert, weather resistant, and waterproof and should ensure good coverage (optimum film thickness).

2.1.2.2 Sealers

Similar to paint, a wide variation of the chemical composition of different sealers exists, depending on the types of applications. Sealers offer benefits like sealing the concrete surface, repelling water and oil, weather resistance, vapor permeability, a glossy appearance, etc. Sealers can effectively protect the concrete surface from its long-term deterioration by forming a stable chemical barrier on the applied surface. Sealers are generally classified as (a) penetrating (e.g., silanes, siloxane, silicates, siliconates) and (b) non-penetrating (acrylic, polyurethanes, epoxy). Penetrating sealers can have smaller or larger molecules and can penetrate small or bigger pores within concrete. For instance, silane has smaller molecules and can be effectively used to seal small pores in high-strength concrete with denser microstructures. In contrast, siloxane has larger molecules and can be used to seal larger pores in porous concrete. Penetrating sealers (e.g., silicates of Li, Ca) can also react with the hydrated product on the concrete surface and provide a hydrophobic barrier. Penetrating sealers provide invisible protection without a change in surface appearance. Therefore, the formation of any cracks due to the structural loading can still be easily visible after application and during the structural inspection. Similarly, non-penetrating sealers form a layer on the applied concrete surface that acts as a coating material. Some of the common non-penetrating sealers are acrylic, polyurethanes, and epoxy. This type of sealer (e.g., epoxy) is often used for repair work (i.e., filling of cracks) on concrete structures, which further enhances durability. Non-penetrating sealers provide a comparatively thicker coating layer, and the overall performance is almost the same as penetrating sealers. However, the life of non-penetrating sealers is comparatively shorter than a penetrating sealer. Further details on the effectiveness of different types of sealer and related research work are presented in Table 2-1.

2.1.2.3 Other Types of Coatings

Other coating materials include membranes that do not allow the penetration of water (*33*). ACI 515 (*42*) is dedicated to coatings that completely prevent moisture penetration into concrete. These coating systems employ fabric saturated with bitumen and either applied hot or cold. Other coating materials, such as elastomeric membranes, cementitious membranes, and metal oxides, are also being used in cold applications.

- Elastomeric membranes include epoxy-bituminous blends, neoprene, neoprene-bituminous blends, polyurethane, polyurethane-bituminous blends. These liquid-applied membranes require several coats to attain complete coverage.
- Cementitious membranes are not suitable for moving joints. The coefficient of thermal expansion of the membrane should be the same as that of the substrate to prevent cracking.

- Metallic oxides are applied in three to five coats and are cured to ensure proper finish and quality control.
- Single-component moisture-cured urethanes are often used as penetrating sealers. They are used in conditions where moisture is present in the atmosphere. They have a low curing temperature of 20°F (*43*).

Table 2-1: Summary of relevant previous research studies on sealers

Sealer Material	**Objective**	**Findings**	**References**
High-molecular-weight methacrylate (HMWM)	Performance of HMWM on the bridge deck with full-depth cracks	• Reduction in the leakage rate after the application of the sealer under conditions of continuous rain and standing water.	(*44*)
• Acrylic • Acrylic topcoat • Gum resin • Silane • Silicone	Performance of penetrating sealers in resisting the intrusion of chloride ions and carbon dioxide, water, and water vapor	• Performance of the silane sealers was superior for the resistance to chloride ion and water inflow and comparable to other sealers in terms of the carbon dioxide absorption. • The performance of silane and acrylic exposed to sulfates, weathering, and freeze-thaw cycles was found to be superior compared to the untreated specimens.	(*35*)
• HMWM	Performance of sealers on cracked slabs under varying temperatures and dry and moist conditions	• 75–85% range of the flexural strength was restored with the repair using HMWM under different test conditions. • 60–80% of the crack volume was filled using HMWM, and the cracks of sizes smaller than 0.1 mm were filled with the sealer. • Recommendation was made for the application of sealer on a dry surface under normal conditions for 3 days to achieve the best crack filling and strength gain performance.	(*45*)
• Linseed oil • Silane • Siloxane	Performance of linseed oil as a sealer for field application	• Linseed oil penetration in the field test was comparable to other sealers.	(*46*)
• Epoxies • Polyurethane • HMWM	Effectiveness of the sealers to repair unreinforced concrete flexure beams	• HMWM performed better in terms of the resistance to the crack formation during flexure loading of the beam. • HMWM has low viscosity, making it prone to leakage, high odor, challenging to mix, and likely to be explosive if it is not mixed properly. • Polyurethane was found to be nearly odorless and convenient to use; the sealant was not recommended for overhead surfaces because it leaks. • Epoxies ranged from low to high odor and ranged from convenient to difficult in terms of mixing, depending on the mixing ratios.	(*47*)

Sealer Material	Objective	Findings	References
• 40% silane • 100% silane • 2-coat silane-acrylic system • 2-coat silane-siloxane system	Impact of moisture on chloride penetration and the corrosion of reinforcing steel	• The effectiveness of the sealer depended on the moisture saturation before the application. • Completely dry specimens showed a higher penetration of the applied sealer. • Specimens with high moisture showed signs of corrosion of the steel reinforcement. • Sealer performance was comparable to each other among the different types tested in terms of reducing chloride ion penetration.	(*48*)
• Silane	Performance of silane treatments for 60 bridges that were in service between 6 and 20 years	• The effectiveness of the silane starts decreasing after 12 years of application. • After 12 years, 100% of the sealer applications were effective. The same effectiveness reduced to 68% after 15 years and to 16% after 17–20 years of service. • The primary deterioration of the silane layer over time was due to the alkaline pore solution, not any external abrasion or UV.	(*41*)

2.1.3 State of the Practice: Texas Department of Transportation

Table 2-2 lists the different types of coatings and sealers that are commonly used by TxDOT. The table also lists the TxDOT standards of the respective coating and sealers. Primarily, the coatings are listed in Item 427, which includes paint coatings as well as epoxies. Penetrating sealers and waterproofing are listed in Item 428 and Item 458, respectively.

Table 2-2: TxDOT Specifications for different types of coatings and sealers

No.	Coating/Sealer Type	Treatment Specification	Material Specification
1	Surface Finish: • Concrete Paint • Opaque Sealer • Silicone-Based Paint • Epoxy Waterproofing (Type I-X)	Item 427—Surface Finishes for Concrete	DMS 8110—Coatings for Concrete DMS 8141—Paint, Silicon Resin for Concrete DMS 6100—Epoxies and Adhesives
2	Penetrating Sealer	Item 428—Penetrating Concrete Surface Treatment	DMS 8140—Concrete Surface Treatment (Penetrating)
3	Waterproofing (Elastomeric, Urethane)	Item 458—Waterproofing Membranes for Structures	DMS 6300—Waterproofing
4	Others—Epoxy Intermediate	Item 446—Field Cleaning and Painting Steel	DMS 8101—Structural Steel Paints Performance

2.2 Surface Preparation

The effectiveness of the applied sealers and coating depends on the surface preparation. Concrete surfaces should be clean and free from any unforeseen materials (e.g., fungal growth, efflorescence, peeling of old paint, oil, or grease, etc.) (*12*, *24*). For a new concrete surface, the removal of efflorescence or laitance should be adequate, whereas for an old concrete surface, the removal of dust layers and deteriorated concrete layers caused by UV rays, corrosion, etc., and fixing cracks (if present) may be needed. There are several common methods for surface preparation: (a) wire brushing, (b) acid etching, (c) water-blasting, (d) abrasive blasting, etc. (*25*, *27*, *49*). Each method has its advantages and constraints. For example, wire brushing is suitable for small-scale applications. Some acid etching methods can dissolve hydrated products (e.g., calcium hydroxide), which causes the loss of cement paste from the surfaces and the creation of an exposed surface (*50*). The acid etching may damage the concrete and reinforcement if a higher concentration of acid is used. Although the surface preparation may vary based on project requirements, sandblasting and water-blasting are the most common methods used in the field for concrete bridge substructures. Sometimes, a combination of both methods is also reported. Although high-pressure water-blasting is effective in removing dust and other deposits (efflorescence, peeling of old coating, etc.) from concrete surfaces, proper drainage of water mixed with waste materials from the treated surfaces is needed. Abrasive blasting may include sand, slag, or wood as media to remove dirt, rust, or other impurities and is mostly used in the metal industry (*51*). However, the use of sandblasting before applying concrete paint or coating on a new or already coated surface is also a common practice. The media can be dry (i.e., air) or wet (i.e., water) based on its application. The sandblasting has the advantage of cleaning surfaces with contaminants within a short time; however, the creation of comparatively rougher substrate surfaces with exposing voids (sometimes micro-cracks), harmful effects on the environment (e.g., proper disposal of the waste generated after sandblasting sometimes faces challenges), and safety issues to the operator (*52*, *53*) are some of the limitations of sandblasting. The exposed voids may accumulate moisture and decrease the adhesion bond of the coating over time (*12*). It is prudent to mention that abrasive blasting (e.g., sandblasting) is prohibited by different DOTs (*12*, *54*).

A proper judgment related to the cost of surface preparation, effectiveness, accessibility issues, safety protocols, etc., needs to be applied by the engineer-in-charge or regulatory authorities before adopting any surface preparation method. Furthermore, the recommendation provided in the material safety data sheet should also be considered for selecting the most effective surface preparation for any coating material.

The International Concrete Repair Institute (ICRI) published a technical guideline on different surface preparation methods for coatings, sealers, overlays, and concrete repair (*49*). After a suitable surface preparation technique is applied, the concrete surface profile (CSP) by visual inspection (Figure 2-1) provides details about the roughness level of the concrete surface, which further helps to determine the thickness of the coating material (*49*, *55*). However, the use of CSP and its effectiveness in evaluating coating materials on concrete surfaces has not been reported in the research conducted by different DOTs so far. Moreover, the material data sheets for different coating materials recommend a specific narrow range (i.e., 1–3) of CSP. Therefore, further research is needed to understand if CSP-based qualitative assignment of surface roughness has any meaningful connection to the performance (wet film thickness [WFT], dry film thickness [DFT], pull-off adhesion strength [POAS], etc.) of coating material (*52*).

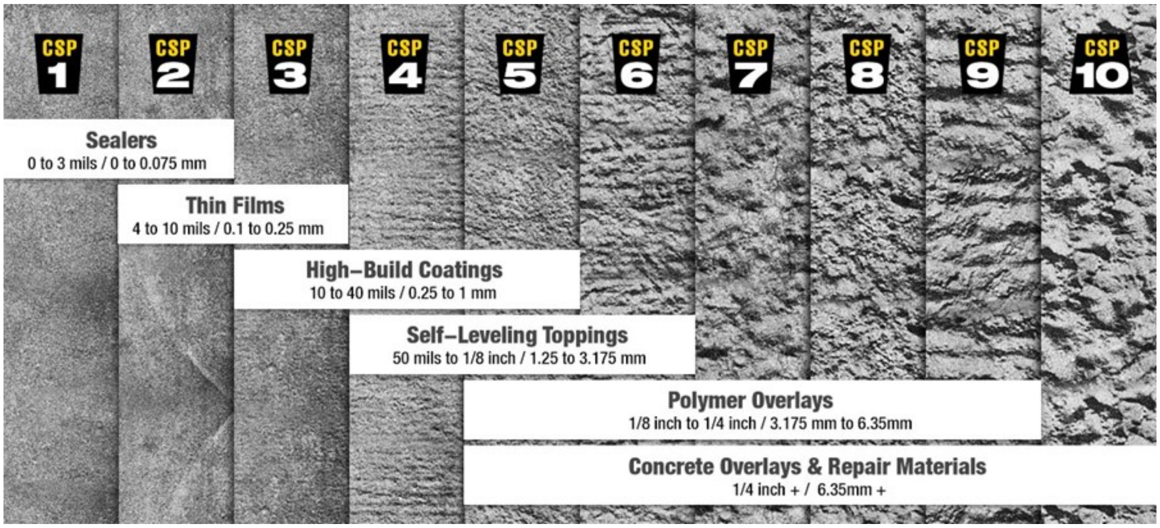


Figure 2-1: Different CSP and surface roughness (*49*, *55*)

2.3 National Codes and Specifications

2.3.1 AASHTO T-384

The standard method for selecting protective sealers for concrete focuses on the prequalification of sealers for the protection and longevity of concrete surfaces (*56*). The standard classifies the sealers into two categories. First are coatings that are only on the surface of the substrate. Second are penetrants that reach into the pores of the concrete up to a certain depth without altering the appearance of the surface. The standard describes the sealer/coating materials as functioning such that water penetration of concrete is reduced and thereby the service life is increased. The sealers and coatings are recommended to withstand the environmental conditions to which the structures are subjected. The standard also recommends vapor transmission in sealed surfaces to allow for evaporation of moisture in dry conditions. The standard explains that the drawback of incorrect application of nonbreathable sealers is that it leads to entrapped moisture causing further deterioration of the concrete. Prequalification tests recommended by the standard include the tests to evaluate water vapor transmission, saltwater absorption, chloride permeability, sealer penetration depth or coating thickness, UV weathering, cyclic saltwater ponding, and resistance to alkali. The sealer types listed by the standard include linseed oil, epoxy resins, silanes and siloxanes, methacrylates, sodium silicate, urethane, coal tar epoxy, and tar primer and seal.

2.3.2 National Transportation Product Evaluation Program

The National Transportation Product Evaluation Program (NTPEP) evaluates products employed in the transportation sector such as geotextiles and asphalt release agents (*57*). The public-private partnership effort is to provide data to the state DOTs of the frequently used products since 2013. These products are produced as per AASHTO standards. They also provide audits of facilities to DOTs. The information emanating from this program avoids redundant work by DOTs to evaluate the same products. AASHTO T 384 was used as the basis for selecting the concrete coatings and sealers. Among the focus areas of the program are the characterization of coatings and sealers, the transmission of water vapor, absorption of saltwater, permeability of chloride, penetration depth of sealers and thickness of coating, cyclical saltwater ponding and UV weathering, and alkali resistance. The overall effort is intended to make it more efficient in terms of time and economy by selecting only those tests that are needed for the evaluation of the sealer and coating products in the field performance.

2.4 Previous Relevant Research Studies

This section summarizes the findings of the past research conducted by different DOTs and universities on the evaluation of sealer and coating system performance. Tests and standard specifications used by different DOT-sponsored research studies on concrete sealers and coatings are presented in Table 2-3, whereas Table 2-4 presents the types of sealer and coating materials used in these studies. The recommendations from these studies are reviewed to identify the challenges, limitations, and research gaps related to concrete substructures.

2.4.1 Texas Department of Transportation—University of Texas, Austin (2004)

Eskridge et al. (*33*) investigated methods to reduce and repair the early damage of concrete due to ASR and DEF to increase the life cycle of the concrete structure. Laboratory tests and acoustic emission procedures were conducted to evaluate specimens under different environmental conditions (Table 2-3). Details regarding the sealer materials are listed in Table 2-4. Acoustic emission (AE) detected the cracks on small specimens, but due to the limitation of the size of the specimens, structural damage could not be verified using AE in this research program. The limitation of this research was the lack of exposure to large volumes of water at repeated intervals for outdoor testing. The use of water would have shown the efficacy of the different mitigation techniques (use of different sealers and coatings) adopted in the study. Laboratory-based product evaluation was not attempted in this study.

2.4.2 Kentucky Transportation Cabinet—University of Kentucky (2006 and 2017)

Palle and Hopwood II (*19*) tested properties such as the rate of water transmission, chloride penetration resistance, the impact of weathering on color changes, and adhesion to develop standard specifications for the Kentucky Transportation Cabinet and a list of products (Table 2-4) that qualified by these tests (Table 2-3). The authors cautioned that the results of ASTM 5894 may be skewed due to the use of Durock cement board as a substrate and recommended instead using cement panels as a substrate to verify the findings of the research. This study did not monitor the impact of freeze-thaw cycles, which is a major weathering factor of concrete deterioration. Also, this research study did not mention any surface treatment on concrete before the application of coating.

Wells et al. (*54*) assessed newly suggested sealer and coating materials by the Kentucky Transportation Center for concrete bridge decks (Table 2-3 and Table 2-4). Although the research study reported test results on the DOP measurement of sealers after cutting the concrete slices (using a water-soluble dye), the reported method (visual observation with blue dye) was not clearly understood.

Table 2-3: Tests and standard specifications used by different research studies on concrete sealers and coatings

Tests	**Texas (2004)**	**Kentucky (2006)**	**Missouri (2007)**	**Indiana (2015)**	**Oklahoma (2015)**	**Wisconsin (2016)**	**Kentucky (2017)**	**Ohio (2018)**	**Iowa (2022)**
DOP	—	—	—	✓ Remove surface to required depths	✓ Powder-Rit dye solution (new method)	—	✓ NTPEP Program—Food coloring dye (KTC-SOP-24)	—	✓ Fabric dye solution (*58*)
Chloride Penetration	—	✓ AASHTO T 259 ✓ AASHTO T 260	✓ AASHTO T 259 ✓ AASHTO T277	✓ ASTM C1556	✓ ASTM C1556	✓ AASHTO T 259 ✓ AASHTO T 260 ✓ Germann Rapid Chloride Test	✓ AASHTO T 259 ✓ AASHTO T 260 ✓ Germann Rapid Chloride Test	—	✓ AASHTO T 259 ✓ AASHTO T 260 ✓ ASTM C1152
Water Absorption	—	—	✓ OHD L-40 ✓ ASTM C642	✓ Modified ASTM C1585	—	—	✓ ASTM D6489	—	✓ ASTM C1585
Weatherability	—	✓ ASTM D5894 ✓ ASTM G85	—	—	—	✓ Modified ASTM D5894-10 (UV) ✓ ASTM D6695-08 (Xenon arc)	—	—	✓ ASTM D1148 (UV)
Freezing-Thawing	—	—	—	—	—	✓ Modified ASTM D5894-10	—	—	✓ Modified ASTM C666
Water Vapor Transmission	—	✓ ASTM E96	—	—	—	✓ ASTM E96-05	—	—	—
Scaling Resistance	—	—	✓ ASTM C672	—	—	—	—	—	—
Adhesion	—	✓ ASTM D4541	—	—	—	✓ ASTM D4541-09	✓ ASTM 7234	—	—

Tests	**Texas (2004)**	**Kentucky (2006)**	**Missouri (2007)**	**Indiana (2015)**	**Oklahoma (2015)**	**Wisconsin (2016)**	**Kentucky (2017)**	**Ohio (2018)**	**Iowa (2022)**
DFT	—	—	—	—	—	✓ ASTM D6132-08 ✓ ASTM D4138-07a	—	—	—
Degree of Blistering	—	—	—	—	—	✓ ASTM D714-02	—	—	—
Pencil Scratch Hardness	—	—	—	—	—	✓ ASTM D3363-05	—	—	—
Air Permeability	—	—	—	—	—	—	—	—	✓ University of Cape Town method (*59*)
Wettability	—	—	—	—	—	—	—	—	✓ ImageJ to determine the droplet contact angle
Low Temperature Differential Scanning Calorimetry (LT-DSC)	—	—	—	✓ Farnam et al. (*60*)	—	—	—	—	✓ AASHTO T 365
Moisture Testing	✓ Change in moisture is measured over time	—	—	—	—	—	—	—	—
Expansion Testing	✓ ASTM C 1293	—	—	—	—	—	—	—	—
AE Testing	✓ Project 1857 (*61*)	—	—	—	—	—	—	—	—

Table 2-4: Sealers used by different research studies on concrete sealers and coatings

State	Sealer Type/Brand	Reference
Texas (2004)	23 different sealers, including urethane, linseed oil, HMWM, epoxy.	(*33*)
Kentucky (2006)	Paints and coatings from 6 different suppliers, including Sherwin Williams, Tnemec, PPG, Porter EPC, and Rohm & Haas.	(*19*)
Missouri (2007)	• Linseed Oil—50/50, Double Boiled Linseed Oil/ Mineral Spirits • Reactive Silicate 1—Chem Tec One • Reactive Silicate 2—Radcon # 7 • Water Soluble 1:1—Star Macro-Deck • Silane 55—SIL-ACT ATS-55	(*24*)
Indiana (2015)	• Soy Methyl Ester-Polystyrene (SME-PS)	(*62*)
Oklahoma (2015)	• Silane	(*25*)
Wisconsin (2016)	10 coating systems selected, including acrylic, acrylic-siloxane, epoxy, and polyurethane binder materials.	(*12*)
Kentucky (2017)	• Pentreat 244-40 (WR Meadows) • SIL-ACT EP-700 (Advanced Chemical Technologies) • Duraguard 401-P (ChemMaster) • MasterProtect H 440 VT (BASF)	(*54*)
Ohio (2018)	• EPX/Duraguard 310 (ChemMasters) • Mark 124/73 (Poly-Carb) • Mark 58.6A/B (Poly-Carb) • Si-Primer/Rex03 (Klaas Coatings) • FX-460 (Fox Industries)	(*63*)
Iowa (2022)	• WB, contains silicic acid, lithium salt, potassium methylsiliconate • Colloidal silica solution • 40% silane • WB, contains sodium tartrate, potassium methylsiliconate • SME-PS	(*23*)

2.4.3 Missouri Department of Transportation (2007)

Wenzlick (*24*) studied the effectiveness of the most commonly used sealer material (linseed oil) to fill the cracks in newly constructed concrete bridge decks. It was noted that linseed oil is the only approved sealer material by Missouri's standards. The study also assessed the same performance (Table 2-3) with the other sealer materials (Table 2-4) in comparison to the previously approved sealer (i.e., linseed oil). Although the performance of linseed oil was tested in laboratory conditions with high-quality substrate concrete, the same performance in field applications is questionable.

2.4.4 Indiana Department of Transportation—Purdue University (2015)

Wiese et al. (*62*) experimented with the performance of SME-PS blends as sealer material to extend the life of the concrete pavement. The main aim was to make a barrier on the concrete pavement surface to limit the ingress of salt solution. The study also mentioned the assessment of the performance of the applied sealer material (Table 2-4) over time by a continuous monitoring system. Though this research shows the potential benefits of the use of SME-PS, its full performance can only be evaluated with long-term field testing and observation.

2.4.5 Oklahoma Department of Transportation—Oklahoma State University (2015)

Ley et al. (*25*) investigated the service life of the silane material on concrete bridge decks. The study aimed to find the effectiveness of the sealer materials over time. Based on the research carried out by the authors, a new nondestructive test method using X-ray radiography was used to calculate the early-age penetration of silane. A new test for the DOP using Powder-Rit dye solution was also suggested (Table 2-3). For the reapplication of sealer on the concrete bridge deck, the penetrability may not be as uniform on vertical surfaces as the first-time application of sealer on new concrete surfaces.

2.4.6 Wisconsin Department of Transportation—University of Wisconsin (2016)

Ghorbanpoor et al. (*12*) evaluated the coating systems for concrete bridges. The authors conducted a series of tests (Table 2-3) to evaluate the performance of the coating systems (Table 2-4). The authors also provided the technical information of the components used in surface coating. The testing of the products was recommended to be consistent with the specifications of the Northeast Protective Coatings Committee and NTPEP for AASHTO. Another test, ASTM B 5894 or ASTM C 6695, for cyclic weathering resistance was recommended. The authors highlighted the need for the evaluation of the recommended coating systems to be at actual field sites and observed for a period of at least 5 years. The research study aimed to cover a wide variety of coating systems; however, the study was restricted to only one color of coating and a limited sample size for a class of coating system. There is a goal to include more coating systems of different colors for evaluation since some colors are known to be more susceptible to UV damage. The authors ranked the different coating systems on a scale of 0–10 based on an aggregate score obtained by evaluating six performance criteria. The different performance criteria included the change in color due to three weathering exposures (UV, xenon arc, outdoor), chloride ion penetration, and defects due to UV/prohesion. The acrylic-siloxane hybrid system had the highest total aggregate score since the acrylic coating performed well with respect to color retention, while the hybrid system helped reduce the chloride ion penetration. In general, acrylic systems had the best color retention performance but had low chloride ion resistance, while epoxy-polyurethane systems had good resistance to chloride ions but poor color retention quality.

2.4.7 Ohio Department of Transportation (2018)

Kerestly (*63*) studied the assessment of concrete sealer and coating materials on concrete barrier walls. Different test methods were adopted to evaluate the effectiveness of the sealer/coating materials, as listed in Table 2-3 and Table 2-4. It was observed that the short duration (2 years) was not sufficient to confirm the effectiveness of the applied products. This study was focused on laboratory testing, which is not a true reflection of the performance of the sealers in field conditions. Therefore, further testing under field conditions is needed to evaluate the effectiveness of sealers.

2.4.8 Iowa Department of Transportation—Iowa State University (2022)

Kevern et al. (*23*) investigated the performance of sealers to improve the durability of concrete by providing resistance against deleterious attack from moisture and chloride ion ingress. The authors conducted a large-scale experimental study followed by field application (Table 2-3). The authors tested several sealers (Table 2-4), such as surface densifiers, pore liners, hydrophobic sealers, barrier coatings, and pore blockers. The DOP test adopted in this research did not yield useful results, as reported. Although this research was a good evaluation of sealers on joints, there is a need for the evaluation of the performance of these sealers on concrete substructure surfaces using the findings of this research.

The following research points were identified from the reports published by different DOTs:

- Confusion exists as to the proper identification of the coating and sealer materials. Standards need to define what products can be called coatings and what products can be called sealers. At present, the names are mixed, and clarity is missing. This issue was found in many reports published by different DOTs, as well as in the various standards.
- There is inconsistency in terms of selecting a standard method for the evaluation of different coating/sealer products by different DOTs. There should be a proper method/standard to evaluate different performances of sealer and coating materials. Moreover, a separate list of performance indicators can be suggested for sealer and coating materials. A minimum requirement of the same performance can be defined.

- Different DOTs have listed various test methods based on ASTM and AASHTO standards and others. However, different approaches for a particular experiment were observed. For instance, the chloride ion penetration experiment was carried out by different DOTs using AASHTO or ASTM standards. Moreover, the DOP test was carried out by different DOTs by following different techniques. Therefore, a critical evaluation of the test method that is adopted for various experiments plays a significant role in the final assessment of the performance of the sealer/coating material.
- The test results cannot be compared because the substrates used for lab evaluation by different DOTs were not the same. Using concrete substrates with varying quality (good, poor, etc.) is recommended to effectively evaluate commonly used sealers and coatings and have a comparative assessment to develop some kind of rating system, which is addressed in the present study.
- Monitoring changes in color due to three weathering exposures (as assessed by some DOTs) may not be an effective way to judge the weathering resistance property of the coating and sealer materials. A direct approach, that is, measuring resistance to chloride and moisture penetration after weathering, may be needed, which is also addressed in this study.
- Most of the studies highlighted that performance evaluation using a short-term lab evaluation without any field validation may not be effective for making decisions on field applications (i.e., product selection, application, and ensuring the expected protection). A minimum of 5 years of field evaluation was recommended by some DOTs.
- A variety of coating and sealer materials were used by different DOTs. Therefore, as Chapter 3 of the present research study discusses, similar products were investigated in this study, along with TxDOT-recommended products, for application on concrete bridge substructures.

2.5 Technical Discussion with Coating Manufacturer

Researchers from TTI conducted a discussion and demonstration session with one U.S. coating and sealer manufacturer. The technical discussion session covered material selection, surface preparation, coating application, national-level practices, and current challenges related to the application of coating and sealer materials. It was found that inconsistencies regarding the selection of materials, knowledge about surface preparation, and curing time post-application of the coating/sealer materials exist. Moreover, the degree of distress of the concrete structure, mode of application (horizontal or vertical), and environmental conditions play a significant role in the effectiveness of sealers and coating materials. This discussion further aids in identifying and planning for future laboratory and field tests to evaluate the performance of coating and sealer materials on bridge substructure, as described in Chapter 3 and Chapter 5.

2.6 Current Practices of Corrosion Control Measures

A corrosion control plan needs to be established from the outset before deterioration starts on the reinforcement. The more delay in the formation of the initial corrosion product, the better the resistance of the structure against corrosion. Another problem with corrosion is the link between the corroded and uncorroded parts of the reinforcement, which may cause further damage. Therefore, a very basic step to control corrosion is the adequate design of the structure against corrosion. The following measures can be taken once the structure is in service condition: (a) routine inspection and good quality maintenance of the structure, (b) application of a barrier coating system (epoxy, paint, urethane, etc.), (c) application of hot-dip galvanization, (d) use of stainless steel, (e) use of measures for cathodic protection, (f) use of high-performance concrete (HPC), (g) increase in clear cover, and (h) use of epoxy coated reinforcement (*64–66*).

Each of the aforementioned corrosion control measures has its own advantages and constraints. The barrier protection system (e.g., sealer or coating) is the easiest and most economical method to prevent corrosion. Moreover, the protective system can be adapted for any substructure if there is good compatibility. Other corrosion control measures may not be as direct as the coating system. For instance, hot-dip galvanization is applied to the reinforcement before the construction. Similarly, the use of stainless steel, the use of HPC, and an increase in clear cover should be considered during the construction phase. More challenges are with existing reinforced concrete structures where suitable field protection is needed. Therefore, the coating (or sealer) system was found to be the most convenient approach, and thus the present project aimed to evaluate the effectiveness of commonly used sealer and coating materials for corrosion protection.

2.7 On-Site Forensic Investigation

After conducting a thorough literature review, it was realized that a condition assessment of the structure is important to understand the effectiveness of any sealer/coating materials and possible product selection. Plans were made to identify and visit relevant bridges for on-site forensic investigation to understand the challenges associated with (a) the application of coating and sealer materials on bridge substructures, and (b) the selection of appropriate surface preparation techniques. With the help of TxDOT, the researcher from TTI collected information and coordinated with the project personnel to collect detailed information about the need for the application and type of sealer/coating material and to schedule field visits to observe and learn the application of coatings and sealers.

2.8 Significance of the Present Research

Although some research has taken place for the evaluation of the performance of sealers and coating to bridge structures, there is a lack of systematic evaluation of sealer/coating materials and performance on concrete substructures. Environmental factors such as humidity, temperature, moisture content, and the presence of harmful chemicals tend to impact the deterioration and the remediation methods of concrete significantly. The performance of sealer and coating materials is directly related to their interaction with the concrete surface and the environmental condition. Therefore, dedicated research must be conducted on the evaluation of sealers and coating materials applied directly to concrete substructures. From the literature review, it was found that surface preparation plays a key role in the adhesion and overall longevity of the sealer's performance. Therefore, a need to evaluate the surface preparation that will be acceptable for good sealer and coating performance on concrete substructures exists. By conducting a systematic laboratory and field evaluation, it was expected that the data generated from this study will help to understand the sealer and coating system better. Research conducted by different DOTs assessed the performance of different sealers and coating systems primarily by laboratory research. However, field conditions are different than a controlled laboratory situation. Furthermore, the product developers cover the performance of the product itself under controlled laboratory conditions, and recommendations are suggested in their product data sheet. However, the effectiveness of these products on concrete surfaces and corresponding performance improvements are not under the scope of material production. Based on the discussion with the coating/sealer manufacturer, a systematic study covering laboratory and field evaluation connecting with concrete performance improvement was identified as an important research gap. Since this was also the scope of the present research, it was anticipated that the research goal was well-aligned and expected to address the same aspects. Therefore, there is a need for the evaluation of the performance of the sealer and coating system at the practical location (on site) of the existing reinforced concrete substructure. Moreover, the study will also contribute toward the development of guidelines for consistent practice of surface preparation, application of the products, and effective performance evaluation for protecting concrete substructures in Texas.

CHAPTER 3: DEVELOP AND CONDUCT SEALERS AND COATING EVALUATION TEST PROGRAM

This chapter discusses developing a test protocol and conducting a laboratory evaluation of different sealer and coating materials as per the developed test protocol. The laboratory evaluation involved selection of sealer and coating products, materials collection for concrete mixing, test specimen preparation, application of coating and sealer followed by curing, and performance evaluation of the selected coating and sealer products by the developed test protocol.

3.1 Evaluation Methodology

The primary objective of task 3 was to develop a test protocol for evaluating the performance of commonly used sealer and coating materials on concrete bridge substructures in Texas to support development of a rating system (Chapter 4). The following work items were undertaken to achieve the above objective:

1. Selection and collection of sealer and coating products.
2. Comprehension of the concrete surface conditions before the application of sealers and coatings.
3. Application of different sealers and coatings on different concrete specimens made of a common TxDOT substructure concrete (Type C).
4. Performance evaluation of sealers and coatings on concrete substrate.

3.2 Materials and Method

This section describes materials selection and collection, concrete mixing, curing of concrete specimens, application of sealers and coatings, curing of applied coating/sealer materials, and performance evaluation using the selected tests.

3.2.1 Selection and Collection of Sealers and Coatings

Chapter 2 already summarized commonly used coating and sealer materials across the United States. Additionally, a recommendation based on a TxDOT specification was also outlined. For this research project, a total of eight sealer and coating materials (e.g., two sealers [i.e., 40 percent silane and 100 percent silane] and six coatings [i.e., three SB and three WB]) were considered. Table 3-1 shows the details of the sealer and coating materials that were selected and collected from the relevant suppliers/manufacturers.

Table 3-1: List of products selected for the research project

No.	TxDOT Specification	Coating/Sealer Type		Product Name
1	**Item 427** Surface finishes for concrete	Surface Finish	Acrylic Concrete Paint	Coat-A(WB)
			Opaque Sealer	Coat-D(SB)
			Silicone-Based Paint	Coat-S(WB)
			Epoxy Waterproofing (Type I-X)	Coat-R(SB)
			Waterproofing Masonry Coating	Coat-L(WB)
2	**Item 428** Penetrating Concrete Surface Treatment	Penetrating Sealer		Sealer-40%
				Sealer-100%
3	**Item 446** Field Cleaning and Painting of Steel	Others—Epoxy Intermediate		Coat-M(SB)

3.2.2 Materials for Concrete Mixing and Mix Proportion

A typical substructure concrete (TxDOT item 421) was selected as substrate concrete to evaluate the performance of the selected sealer and coating materials in the laboratory. Table 3-2 shows the concrete mix proportion details. The coarse aggregate (river gravel), fine aggregate (river sand), cement (Type I/II), and fly ash (Class F) were collected from Knife River, a construction materials and contracting company near Bryan, Texas. Based on the sieve analysis (Figure 3-1) of the coarse aggregate (maximum size 1 inch), the aggregates fall under Grade 5 as per ASTM C33. The coarse aggregate had a specific gravity of 2.60, with water absorption of 1.00 percent. Similarly, the fine aggregate had a specific gravity of 2.64, with water absorption of 1.03 percent. The chemical composition of cement and fly ash is given in Table 3-3.

Table 3-2: Mix proportion of concrete

Materials	**Quantity**	
	(kg/m^3)	**(lb/yd^3)**
Coarse aggregate (4.75–25 mm)	1074.52	1812.00
Fine aggregate (75 microns–4.75 mm)	818.34	1380.00
Cement (Type I/II)	253.51	427.50
Fly ash (Class F, 25% replacement of cement)	84.50	142.50
Water	141.96	239.40
Admixture 1: Water reducer (Zyla 610)	1.468	1.781
Admixture 2: Air entraining agent (Daravair 1000)	0.440	0.712
Water/cement ratio	0.42	

Note: Zyla 610 and Daravair 1000 both are listed on the approved chemical list by TxDOT (DMS-4640) and were obtained from GCP Applied Technologies, Houston, Texas.

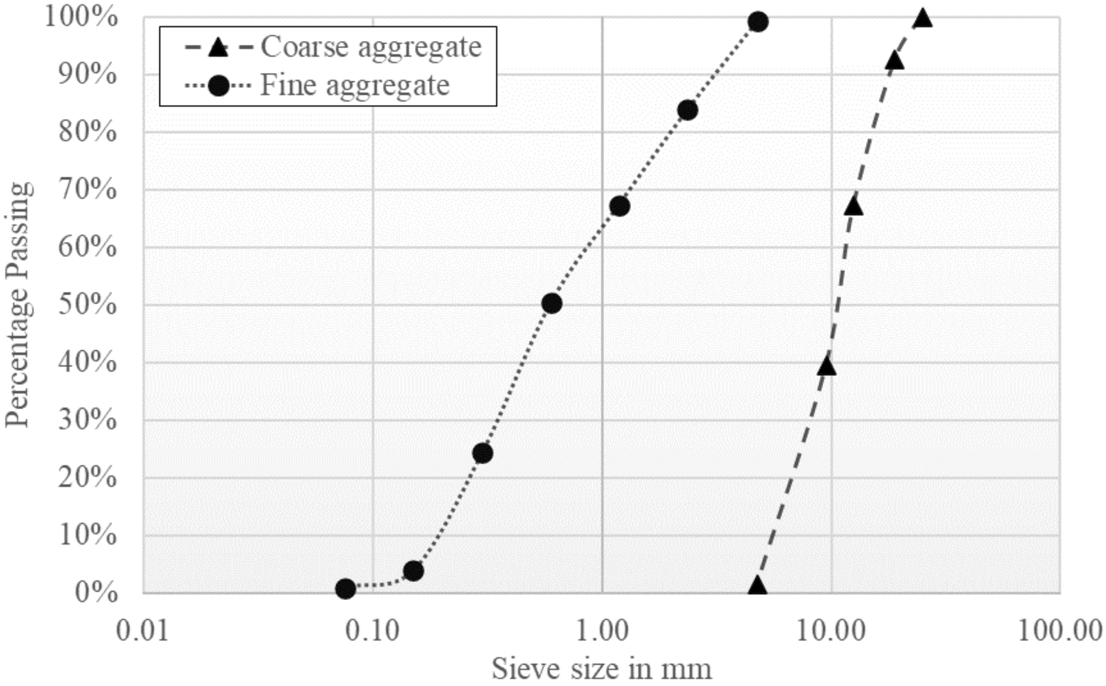


Figure 3-1: Grading curve of coarse and fine aggregates

Table 3-3: Chemical composition of cement and fly ash

Component	Percentage content	
	Cement	**Fly ash**
CaO	63.45	13.28
Al_2O_3	4.92	19.71
Fe_2O_3	3.70	4.66
SiO_2	19.81	54.44
MgO	1.80	2.67
SO_3	2.6	0.62
Na_2O	0.17	0.35
C_3S	62	N/A
C_2S	10	N/A
C_3A	7	N/A
C_4AF	11	N/A
Loss on ignition (%)	2.8	0.37

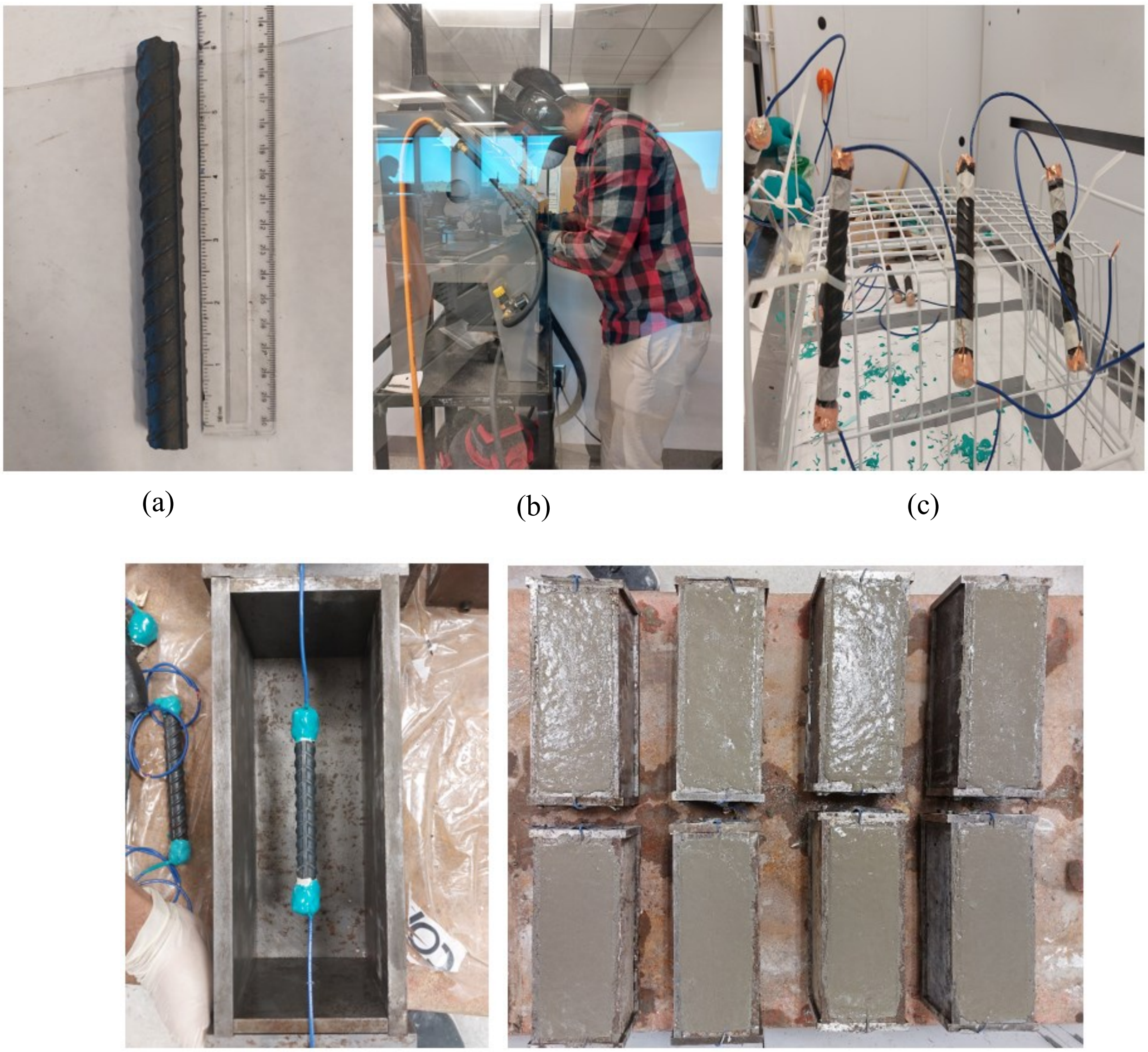
Note: N/A = not applicable.

The compressive strength measurement—using 4 × 8-inch cylindrical specimens of the substructure concrete (Table 3-2)—provided 4650 psi (32.00 MPa) and 6600 psi (45.50 MPa) at 28 days and 120 days of curing, respectively.

3.2.3 Selection of Tests for Product Evaluation

Based on test methods recommended in AASHTO T384, NTPEP, and tests used by different DOTs (details are provided in Chapter 2) and recommendations provided by TxDOT, the researchers selected the tests for product evaluation in this study (listed in Table 3-4). The details on specimen type, dimensions, and test conditions are also provided in Table 3-4. Test specimens for conducting all the tests in Table 3-4 were prepared as per the respective standards.

Concrete prisms with rebar were cast for corrosion monitoring under accelerated and steady-state conditions. Figure 3-2 shows the step-by-step procedure of the specimen preparation for corrosion monitoring. Since the steady-state corrosion takes a longer time (in years) to have active corrosion of the reinforcement, accelerated corrosion monitoring was planned to check the effectiveness of sealer and coatings within a short time (in months). For the corrosion monitoring under accelerated conditions, similar test specimens with different accelerating conditions (dry and wet cycle, 3.5 percent sodium chloride [NaCl] solution) were considered.



(a) (b) (c)

(d) (e)

Figure 3-2: Step-by-step procedure for concrete specimen preparation for corrosion monitoring: (a) 6-inch rebar (No. 5 [15.87 mm dia.]), (b) abrasive blasting process to clean the rebars, (c) epoxy coating followed by wire attachment at the ends of the rebar, (d) representation of the rebar position in an empty mold, and (e) fresh concrete specimen with one rebar in the middle

Table 3-4: Details of the test methods, specimen requirements, and exposure conditions

Tests	Specimen types with dimensions	Exposure condition	
		Normal	Accelerated weathering using QUV and QFOG
WFT	Measured during the application of coating	Yes	No
DFT	Concrete prisms (3 × 3 × 12 inch)	Yes	No
DOP test	Concrete slices	Yes	No
Direct measurement of DFT	Concrete slices	Yes	No
Water absorption (Sorptivity) (ASTM C1585)	Concrete slices (4-inch diameter, 2-inch thick)	Yes	Yes
Water absorption (ASTM D6489)	Concrete slices (3-inch diameter, 3-inch thick)	Yes	Yes
Wettability (Contact angle measurement)	No additional specimen	Yes	Yes
Pull-off adhesion test (ASTM D7234)	Concrete prism (3 × 3 × 12 inch)	Yes	Yes
Chloride penetration (ASTM C1556, chloride ponding test)	Concrete slices (4-inch diameter, 4-inch thick)	Yes	Yes
Chloride penetration (ASTM 1202, rapid chloride penetrability test [RCPT])	Concrete slices (4-inch diameter, 2-inch thick)	Yes	Yes
Corrosion (Accelerated)	Concrete prisms (4 × 4 × 12 inch) with rebar	Yes	No
Corrosion (Steady state)	Concrete prisms (4 × 4 × 12 inch) with rebar	Yes	No

3.3 Understanding of the Concrete Surface Conditions before the Application of Sealers and Coatings

As per the product data sheets, it is important to make sure that the concrete surface is clean and maintains adequate dryness before the application of any sealer and coating materials. Moreover, the CSP plays a significant role in achieving the optimum performance of sealer and coating materials on concrete substrates (*49*). The concrete specimens cast and cured in the laboratory satisfy the requirements of smooth (CSP value within 1–2) surfaces and are free from any contaminants. Cured concrete specimens were kept outside of the curing room for drying at room temperature for about 7 days before the application of any sealer/coating and materials.

During the field visit in San Antonio (Chapter 5), the water-blast method was adopted to clean the old existing coating and other contaminants (e.g., dust layer). After water-blasting, the concrete surface gets wet, which may not be suitable for sealers and coating applications. A similar situation occurs during rain. Therefore, maintaining adequate dryness of concrete surfaces after water-blasting or rain before applying coating and sealer materials is very important.

The use of a portable moisture meter was found to help in measuring surface moisture and judging if the concrete surface maintained adequate dryness or not. Figure 3-3 shows the measurement of surface moisture by using a portable moisture meter. Figure 3-4 shows the laboratory test results on actual moisture content versus the moisture measured by the portable moisture meter. The actual moisture was measured at different times, from a completely wet condition to dry condition, by keeping the specimen at 60°C in the oven for intermediate readings and at 105°C for final drying. It was observed that the surface moisture (up to 1-inch depth) can be measured easily by the studied moisture meter (Figure 3-4) with acceptable accuracy, which matches the claim by the product manufacturer. Therefore, this kind of moisture meter can be used to develop a relationship between moisture content and key performance indicator(s) of the selected coating and sealer materials in laboratory settings. Based on this relationship, a safe moisture content can be identified for each product and can be implemented in the field. To achieve safe moisture content for a particular product in the field, the wait time is expected to vary depending on the type of product, the nature of the concrete substrate surface, and ambient conditions. Because knowing the safe moisture content is important, it is highly recommended that a subsequent study be conducted for further research.

Figure 3-3: Moisture measurement on concrete slices

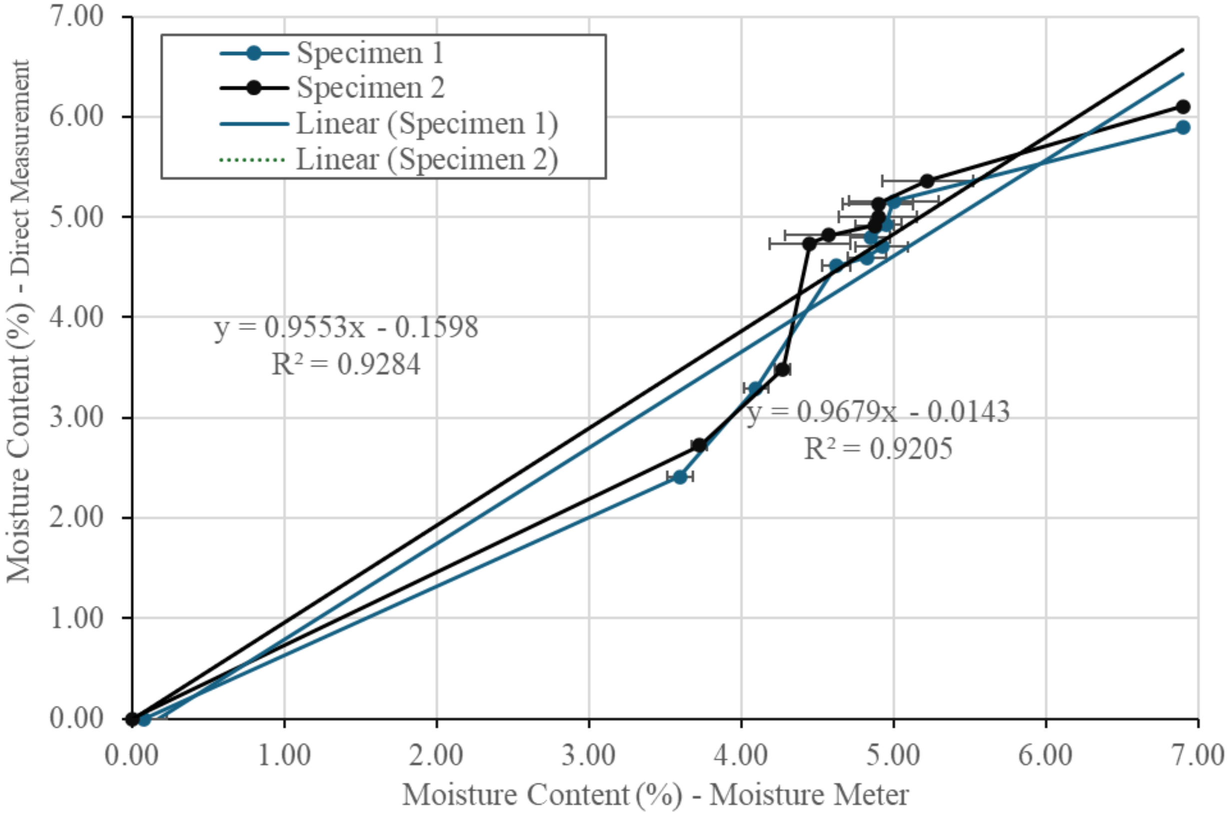


Figure 3-4: Moisture content of the concrete surface: using a moisture meter and direct measurement

3.4 Application of the Selected Sealers and Coatings on Different Concrete Specimens

To ensure accurate application of sealer and coating materials, three products (i.e., one sealer, one WB coating, and one SB coating) were initially applied under the supervision of a representative from a sealer/coating manufacturer. Researchers initially attempted to use a high-pressure (up to 3000 psi) spray gun to apply the coating materials. However, it was determined that a spray gun may not be suitable for small-scale application in laboratory settings. Moreover, cleaning the spray pump after each coating application was tedious. Because cleaning after each application using a large quantity of cleaning chemicals generates a high quantity of chemical waste, it was a concern. Instead, the application of coating materials using a hand roller was found to be more economical, safe, and convenient. Figure 3-5 shows the application of coating materials using a spray pump and hand roller. However, the use of a spray gun was expected to be useful for the application of coating materials on substructure elements during field evaluation (part of the research).

In this research project, all the laboratory test specimens were coated with hand rollers (Figure 3-5). For the sealer materials, a hand-pumped garden sprayer was used (Figure 3-6). The application of sealer and coating material was done outside the laboratory (open yard). A brief description covering product type, preparation before application, application procedure, and rate of application/WFT for each selected product is provided in Table 3-5. After the application of coating and sealer materials, the specimens were kept inside an enclosure in the open yard for up to 7 days, followed by transferring them to inside the laboratory. The curing period for both concrete prism and coating materials was a minimum of 1 month. After 1 month of coating/sealer application, the specimens were tested as per Table 3-4.

(a) (b) (c)

Figure 3-5: Application of coating material: (a) using a spray gun, (b) using a hand roller, and (c) coated specimen

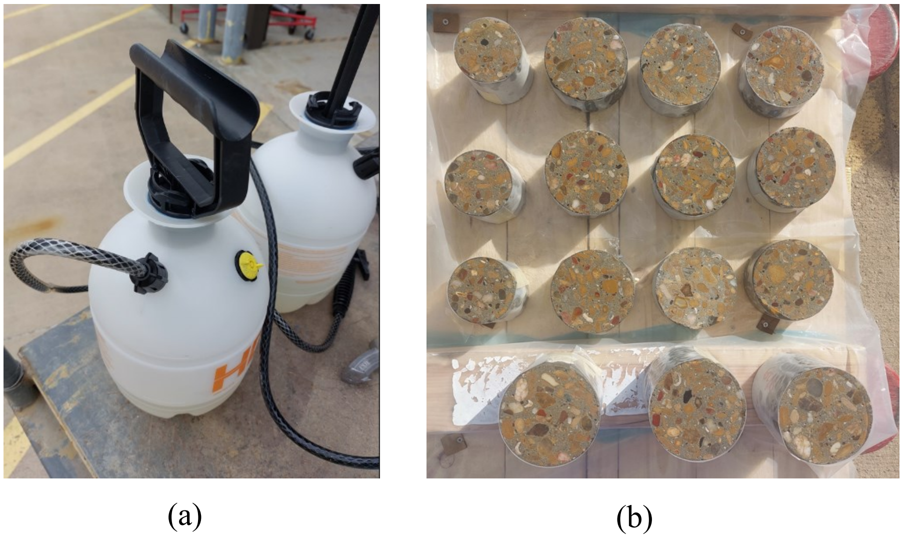

(a) (b)

Figure 3-6: Application of sealer products: (a) using hand-pumped garden sprayer, and (b) sealed specimens

Table 3-5: Details of the coating and sealer materials

Product	Materials ID	Type of coating/sealer	Application details
WB coating	Coat-A(WB)	Acrylic concrete paint	Before the application, the coating material was mixed well inside the container. The WFT was maintained at approximately 8 mils (approximately 230 sq ft/gal) for each coating layer, with a two-coat application (i.e., total WFT ~16 mils).
WB coating	Coat-S(WB)	Silicone-Based Paint	Before the application, the coating material was mixed well inside the container. The WFT was maintained at 5 mils (240–360 sq ft/gal average) for each layer, with a two-coat application (i.e., ~10 mils of total WFT).
WB coating	Coat-L(WB)	Waterproofing Masonry Coating	After mixing, once the homogeneous coating slurry was obtained, it was applied to the concrete specimens using a hand roller. A 14–15 mils (85–110 sq ft/gal) WFT was maintained for each layer, with a two-coat application (i.e., ~28 mils of total WFT).
SB coating	Coat-R(SB)	Epoxy Waterproofing	This is a SB two-part coating product. The mixing ratio was as per the product datasheet. The mixture of base and converter was applied to concrete specimens after 15 minutes of mixing. The WFT was maintained at 14 mils (100 sq ft/gal) during both coats, with a two-coat application (~28 mils of total WFT).
SB coating	Coat-D(SB)	Opaque Sealer	Before the application, the coating material was mixed well inside the container. Once the homogeneous coating slurry was obtained, it was applied to the concrete specimens using a hand roller. A 6 mils (360–470 sq ft/gal) WFT was maintained for each layer, with a two-coat application (~12 mils of total WFT).
SB coating	Coat-M(SB)	Epoxy intermediate	This SB product was applied as a mixture of epoxy (Part A) and hardener (Part B). Both the epoxy and hardener were mixed well separately in the container. The mixing ratio was as per the product datasheet, and the epoxy and hardener were added to a separate container and mixed well (~30 minutes of mixing). The epoxy-hardener mix was then applied to the concrete specimens as per the guidelines provided by the product data sheet. A 10 mils WFT was maintained (approximately 200 sq ft/gal) for each coating layer, with a two-coat application (i.e., total WFT ~20 mils).
40% Silane	Sealer-40%	Penetrating sealer	The 40% silane is a water-like viscous product and was applied directly on the test specimens using a low-pressure garden sprayer. The sealer was applied to cover the top surface (basically the intended surface) of the test specimens (at the application rate of approximately 150 sq ft/gal).
100% Silane	Sealer-100%	Penetrating sealer	100% silane is a water-like viscous product and was applied directly on the test specimens using a low-pressure garden sprayer (at the application rate of approximately 200 sq ft/gal).

3.4.1 Hazardous Waste Management

The SB coating materials (e.g., Coat-M[SB], Coat-R[SB], and Coat-D[SB]) need suitable cleaning chemicals (e.g., methyl ethyl ketone) to clean the spray pump, which needs a safe hazardous waste disposal method. The WB coating materials (e.g., Coat-A[WB], Coat-S[WB], and Coat-L[WB]) need fresh water to clean the spray pump, which needs a safe hazardous waste disposal method.

Both the sealer and coating materials are hazardous (flammable liquids, acute toxicity [inhalation], skin corrosion/irritation) with varying levels of severity. Therefore, after the coating and sealer application, the generated waste should be marked properly as a hazard with details for safe disposal. Proper personnel protective equipment should be considered as per the product safety data sheet to mitigate any health hazards.

In this project, during the application of different sealers and coating materials, a project safety risk assessment was made based on the risks at different stages (application of coating materials, application of sealer materials, disposal of waste, storage, and testing of coated/sealed specimen inside laboratory). After the risk assessment, the spray pump was not considered for small-scale use in the laboratory since more hazardous waste was generated. Instead, the hand roller was used for coating applications because it does not generate a significant amount of waste to dispose of for both small and medium-scale applications. However, for a large-scale coating application, the use of a spray pump is recommended.

3.4.2 Exposure to the Weathering Chambers

The performance of different sealers and coating materials was assessed under both normal and weathering conditions (i.e., equivalent to simulation of field UV exposure under sunlight). For normal conditions, the test specimens after the application of coatings/sealers and curing were kept inside room conditions for 14 days (23±1°C, 60±5% RH). On the other hand, for the evaluation of the degree of deterioration of sealer and coating materials under weathered conditions (ASTM D5894), the test specimens after the application of coatings/sealers and curing were first exposed to UV (UV at 0.89 W/[m^2.nm] at 340 nm at 60°C using UVA-340 lamps for 4 hours)/condensation (condensation at 50°C for 4 hours) inside a QUV chamber for 7 days, followed by exposure to fog (fog at ambient temperature [23°C] with 0.05 percent sodium chloride and 0.35 percent ammonium sulfate solution for 2 hours)/dry (dry off at 35°C for 2 hours) cycles inside a QFOG chamber for 7 days as per the standard (*29*). A similar method was followed by several other DOTs (*7*, *15*). For the fog-dry cycles inside the QFOG chamber, a 2-hour exposure time (instead of the standard 1-hour time) was selected to ensure effective equilibrium under given environmental conditions. Figure 3-7 and Figure 3-8 show the specimen placement inside the QUV and QFOG chambers, respectively.

(a) (b)

Figure 3-7: Weathering conditioning of the test specimen: (a) circular concrete specimens ready for weathering exposure, and (b) QUV chamber in operation with test specimen attached in the 3D box

(a) (b)

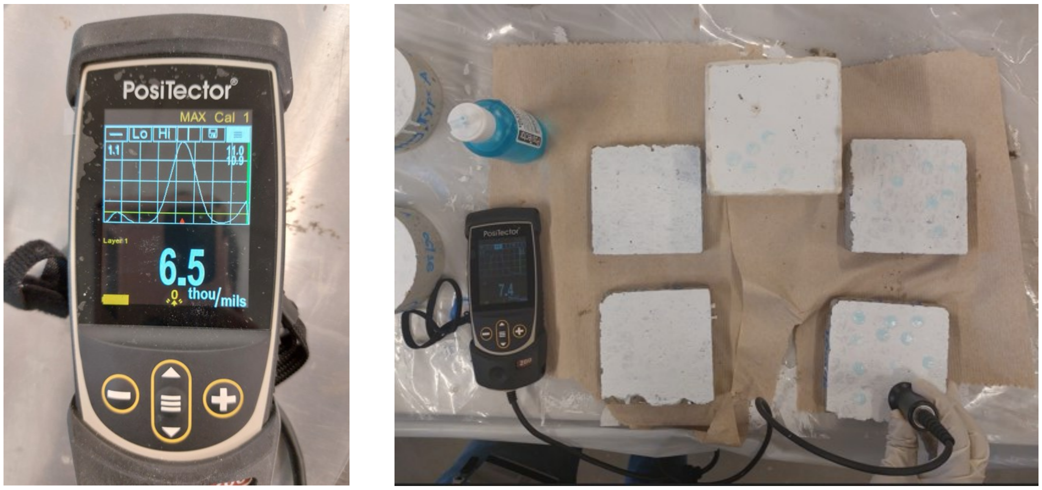
Figure 3-8: Weathering conditioning of the test specimen: (a) placement of test specimens inside QFOG chamber, and (b) QFOG chamber is in operation with the test specimen inside

3.5 Performance Evaluation of Sealers and Coatings on Concrete Substrate

The performance evaluation of the selected coating and sealer materials was conducted, and in the following sections, the results and observations from each test are discussed separately. The proposed selective tests under both normal and weathering effects (QUV and QFOG exposures) to evaluate the weathering effects on coating and sealer materials are also discussed. For the development of the ranking system, the data under normal conditions were used primarily with some support from the data on weathering effects. A detailed discussion on the development and application of the ranking system has been provided in Chapter 4.

3.5.1 DFT

After the curing period, the DFT of the tested coating materials was measured using a portable DFT measuring gauge (PosiTector 200) [an ultrasound-based nondestructive method]), and the results are presented in Figure 3-9. The variability in ultrasound-based DFT measurements for the same coated surface was obvious from the plot in Figure 3-10. The primary reason for the variation could be some limitations of the test method itself. However, the presence of aggregate underneath the coating at the testing point and real coating thickness variation at different locations within the test specimen can also be responsible for creating this kind of variability. It was also observed that defining an appropriate range (i.e., defining the lower and upper limits for the anticipated DFT) determines the accuracy of the measured DFT. For example, the lower and upper limits can be set at 2 to 8 mils to measure the DFT of 4–5 mils. However, for an unknown coating thickness in the field, refer to the product data sheet. Otherwise, a direct measurement by taking a small core cut (1–2 inch diameter with ½-inch depth) can be suggested in the field. Figure 3-11 shows details of the direct DFT measurement using a stereo microscope. The ImageJ software was used to analyze the representative images (Figure 3-11) and calculate DFT. It can be seen that both methods show similar results (Figure 3-10), which validates the use of the PosiTector 200 to measure DFT.



(a) (b)

Figure 3-9: DFT measurement using (a) a portable DFT measuring gauge (PosiTector 200), and (b) film thickness measurement on Coat-L(WB) coated test specimen

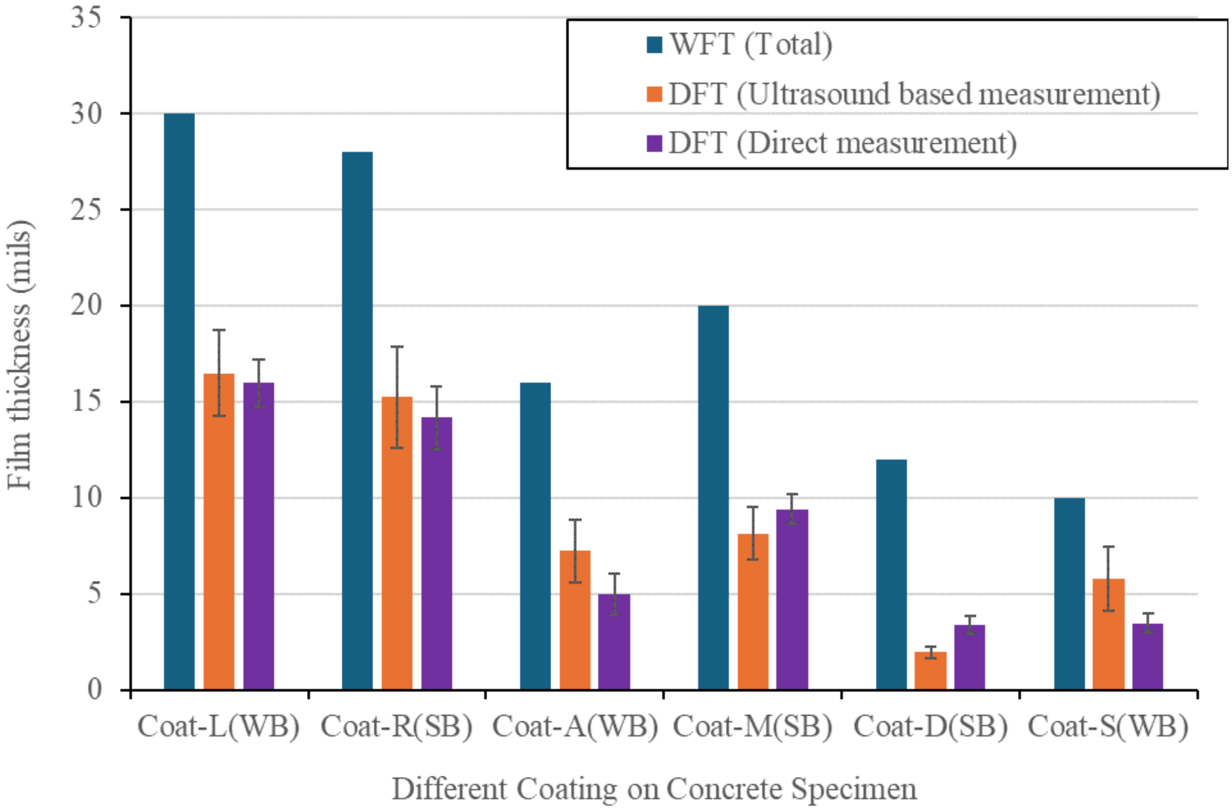
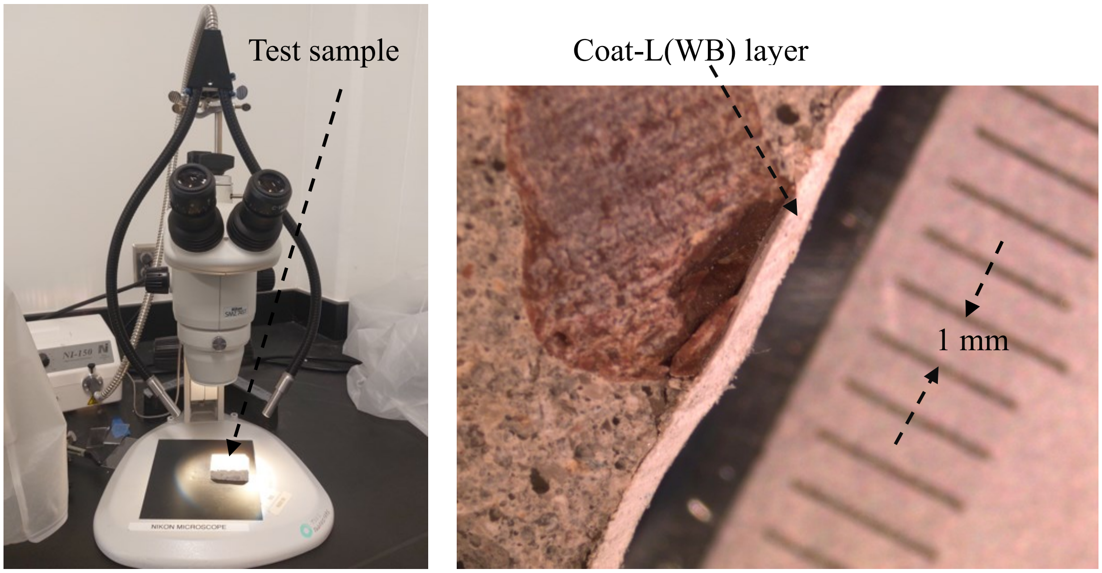


Figure 3-10: Test data for DFT measurement: ultrasound-based method (using a portable thickness measuring gauge) and direct measurement (stereo microscope)



(a) (b)

Figure 3-11: Dry film measurement using a stereo microscope: (a) microscope, and (b) obtained representative picture for Coat-L(WB) coating layer

3.5.2 DOP Measurement by the Microscopic Method

The penetration depth of the two tested sealers (e.g., Sealer-40% and Sealer-100%) on the prepared concrete substrate is manifested by the stereo-microscopic pictures (Figure 3-12). The penetrated (sealed) area and the non-penetrated moist area are demarcated by the silane boundary. It can be seen that the overall DOP for 100 percent silane (average, 3.28 mm [minimum 2.54 mm and maximum 4.73 mm]) is slightly higher than for 40 percent silane (average, 2.18 mm [minimum 1.73 mm and maximum 2.53 mm]). In general, the higher the DOP, the higher the protection against moisture ingress through the concrete substrate. Because the DOP for 100 percent silane is slightly higher than for 40 percent silane, the performance evaluation by different performance testing (presented later) for 100 percent silane is expected to be marginally better than 40 percent silane, which is discussed later. The DOP is dependent on several parameters, like type of concrete, pore structure, size of the sealer molecule, condition of the substrate (moist or dry) during the sealer application, and direction of application (vertical or horizontal) (*21–23*).

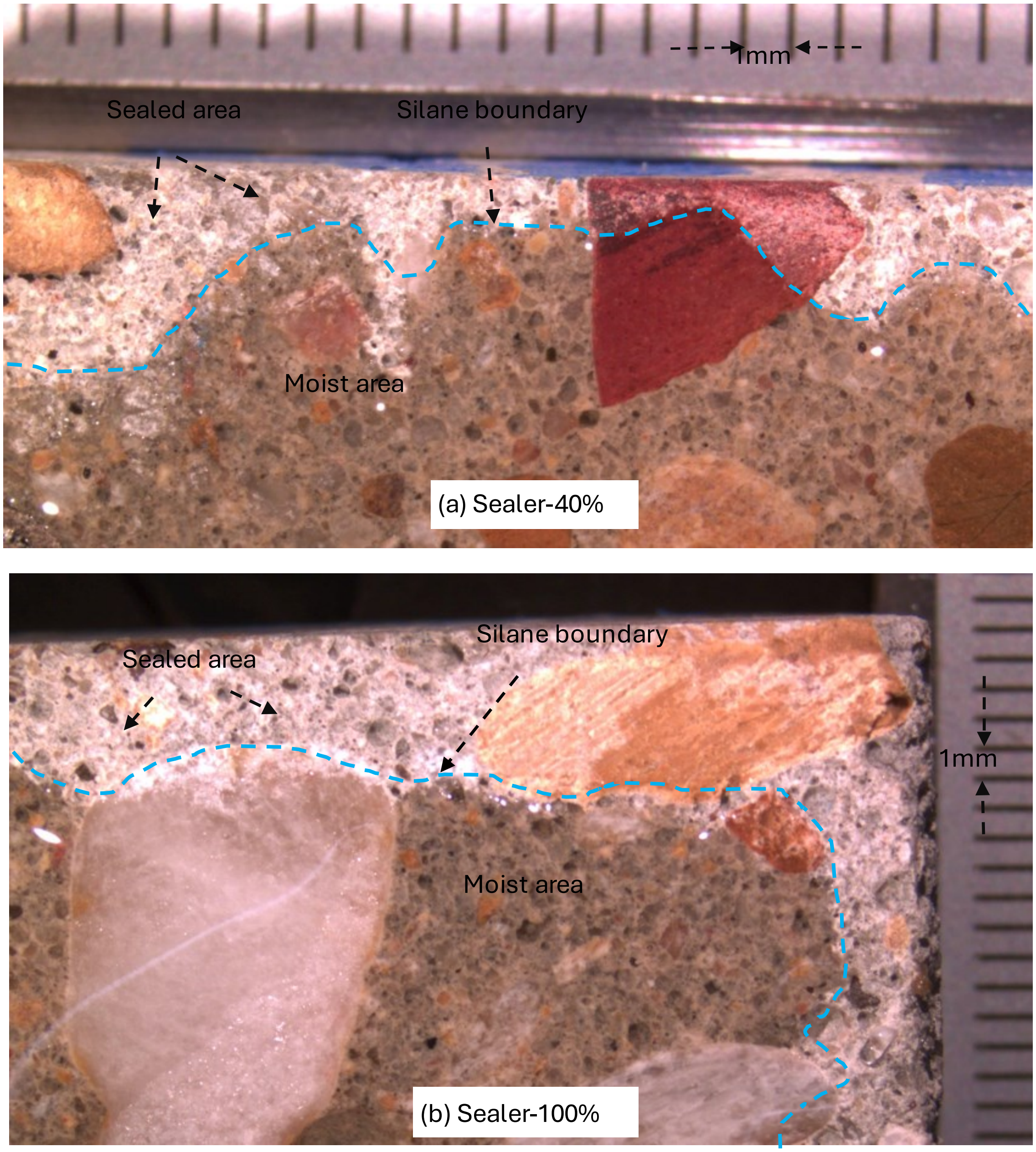


Figure 3-12: Measurement of DOP on concrete sealed with 40 percent and 100 percent silane

3.5.3 Color and Gloss Retention (Visual Observation)

Color and gloss retention can be measured quantitively by following ASTM standards (ASTM D2244 and ASTM D523). It was reported that most of the coating products show alteration in color and gloss to varying extents (*12*) after the weathering cycle. The detailed quantification of color and gloss retention was not considered under the scope of the present research project. However, photographs of different coating products on the concrete substrate under normal and weathered conditions were taken to document the product's aesthetic look visually. In Figure 3-13 and Figure 3-14, the top images represent the weathered (QUV and QFOG exposed) specimens, and the bottom images represent the specimens under normal conditions.

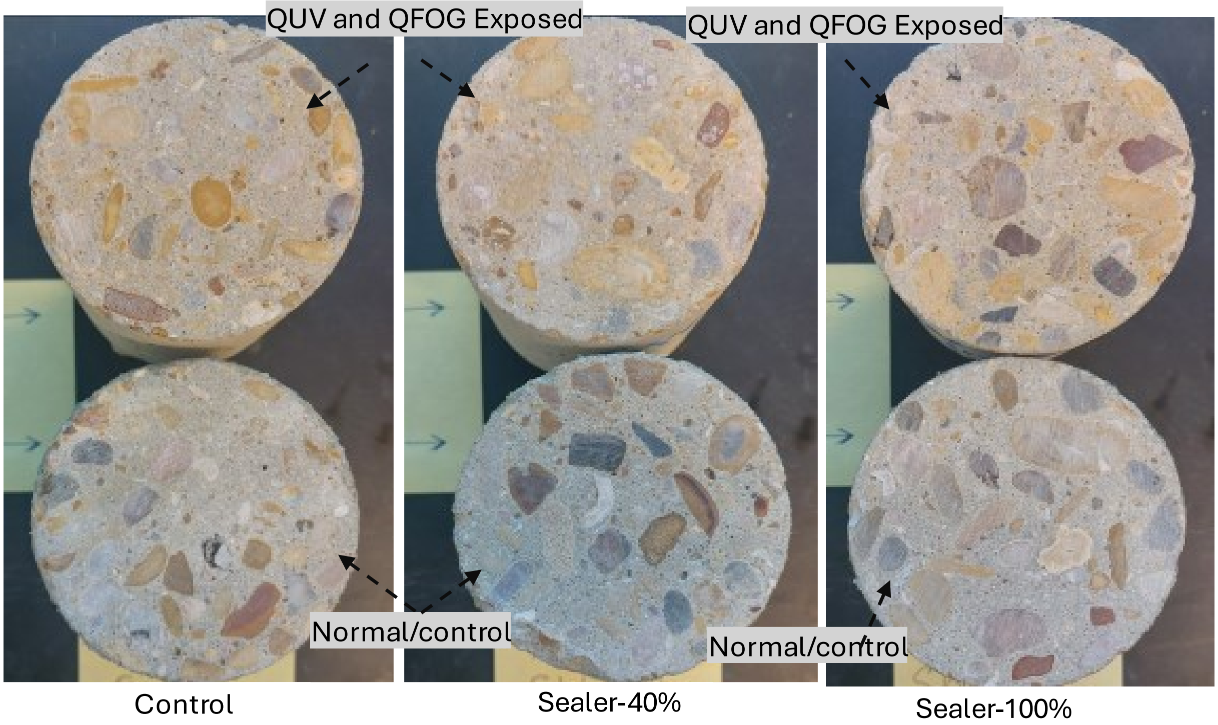
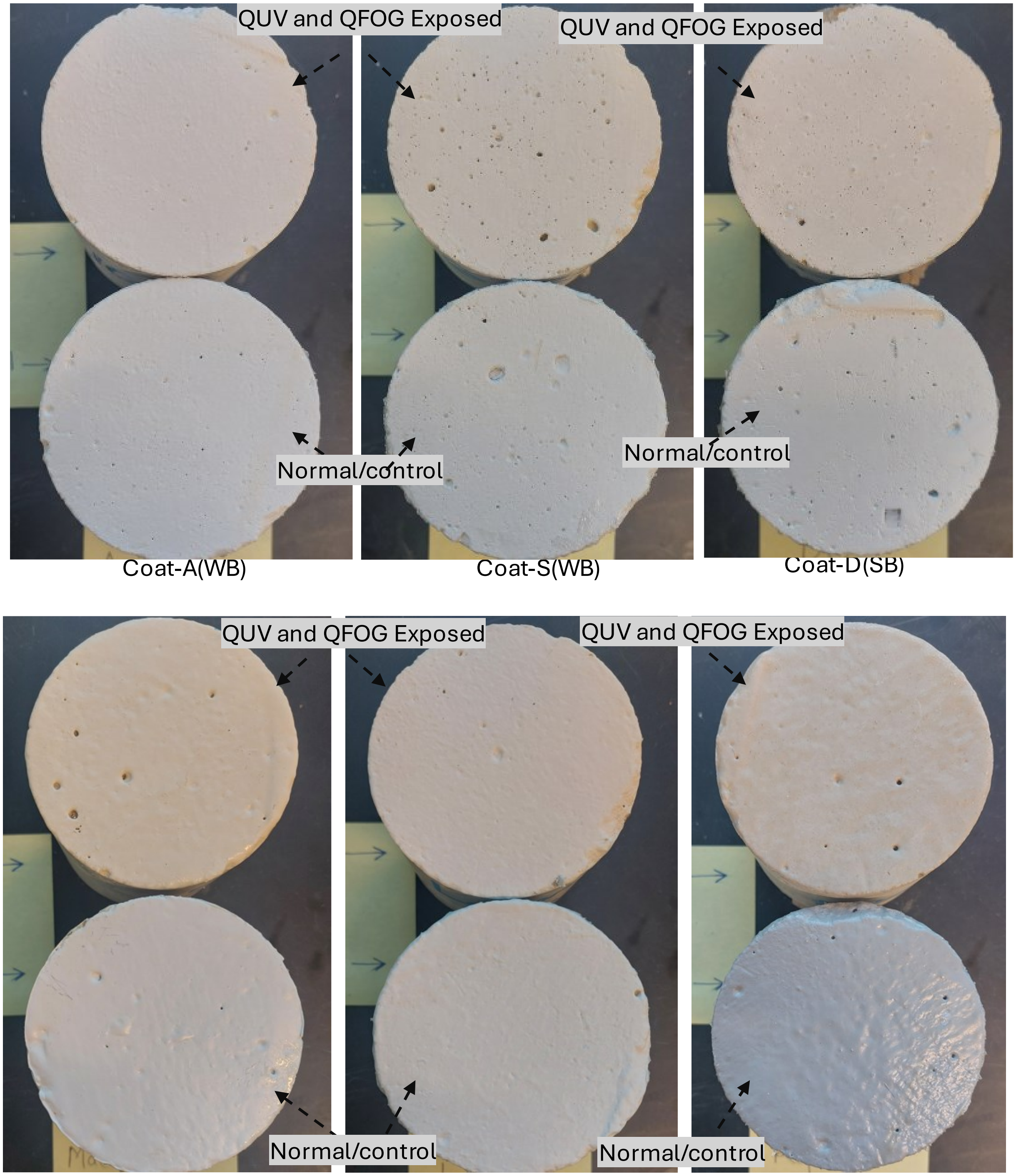


Figure 3-13: Test specimens before and after weathering (control concrete and sealed concrete specimens)



Coat-A(WB) Coat-S(WB) Coat-D(SB)

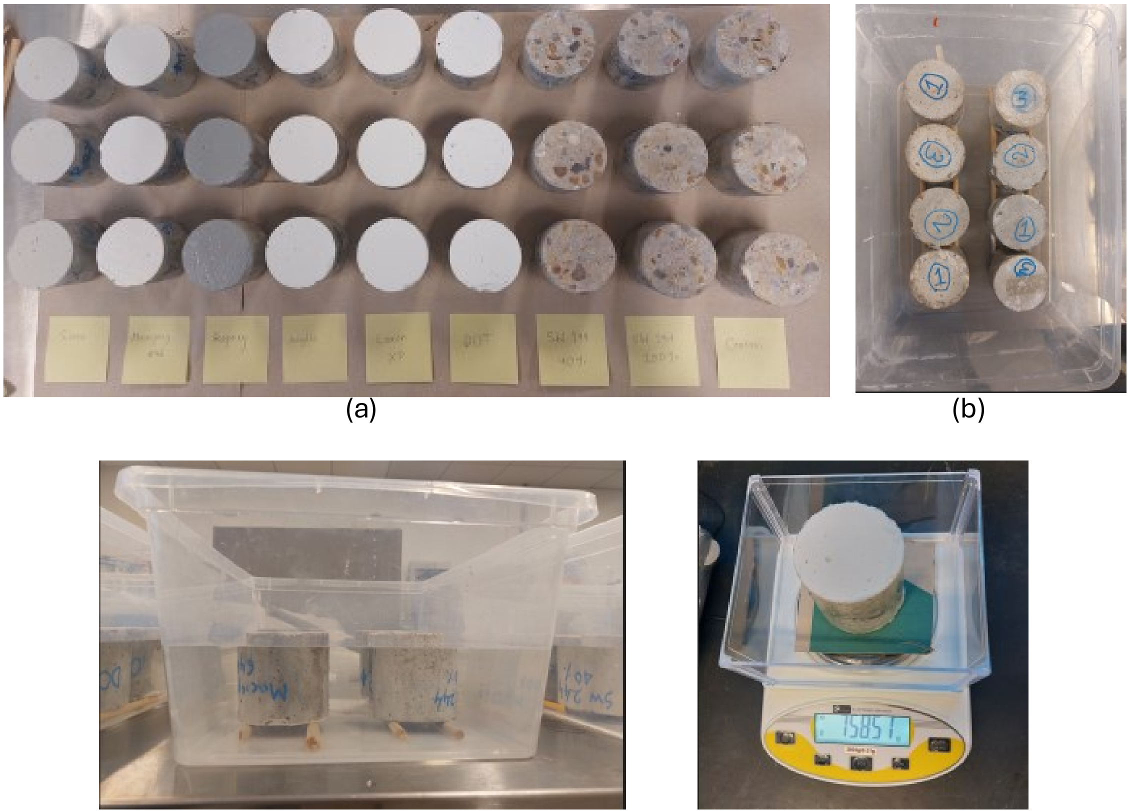
Coat-M(SB) Coat-L(WB) Coat-R(SB)

Figure 3-14: Test specimens before and after weathering (coated specimens)

3.5.4 Water Absorption (ASTM D6489)

The ASTM D6489 test was used to measure water absorption of concrete surfaces treated with water-repellent products. This test method is different from the sorptivity test (ASTM C1585). In this test, the water-repellent coated specimens are soaked (up to 2.5-inch depth from the coated surface) for 24 hours and 48 hours to check the absorption. Moreover, the precondition (kept at 75±5ºC for 24 hours until two successive weight changes are less than 0.2 percent) is different from the sorptivity test (50±2°C and RH of 80±2% for 3 days). Figure 3-15 shows the different steps involved in this test. For each coating/sealer product, three test specimens were monitored. It can be seen that the sealers have very low absorption (Figure 3-16), and, in comparison to control concrete, approximately 76 percent and 91 percent reduction in absorption is observed for 40 percent silane and 100 percent silane in 48 hours, respectively. The higher percentage of reduction in absorption for Sealer-100% is supported by the higher DOP measurement (Figure 3-12). Some coatings (Coat-A[WB], Coat-M[SB], Coat-D[SB]) resist water absorption to a certain extent. However, Coat-R(SB) and Coat-S(WB) have no positive effect on resistance to water absorption. In general, coatings are hydrophilic (water-loving), and sealers are hydrophobic (water-repellent) (presented in the next section). Therefore, the use of ASTM D6489 (especially for water-repellent products) may not be very effective for coating materials. The data from this test has been compared with the data from the sorptivity and resistance to chloride ion tests for the development of a rating system (Chapter 4) that provides further clarification on the applicability of this test for coating materials.

A comparison of the water absorption performance was made for both the normal and weathering conditions (Figure 3-16). From the overall test results for all the coating and sealer materials, it can be observed that most of the test specimens treated with the coating materials showed higher water absorption after weathering conditions than the specimens under normal conditions. However, test specimens sealed with 100 percent and 40 percent sealers showed almost no changes in water absorption performance when conditioning changes from normal to weathering conditions irrespective of testing ages. It can be seen that after the weathering effects by QUV-QFOG, the water absorption of control concrete specimens increased significantly (~48 percent) after 48 hours.



(a) (b)

(c) (d)

Figure 3-15: Water absorption test: (a) test specimens (sealed, coated, and control), (b) placement in a plastic container for soaking, (c) test specimens are in soaking condition (at least 2.5 inches from the coated/sealed surface [bottom]), and (d) measurement of weight (after 24/48 hours) up to two decimal places

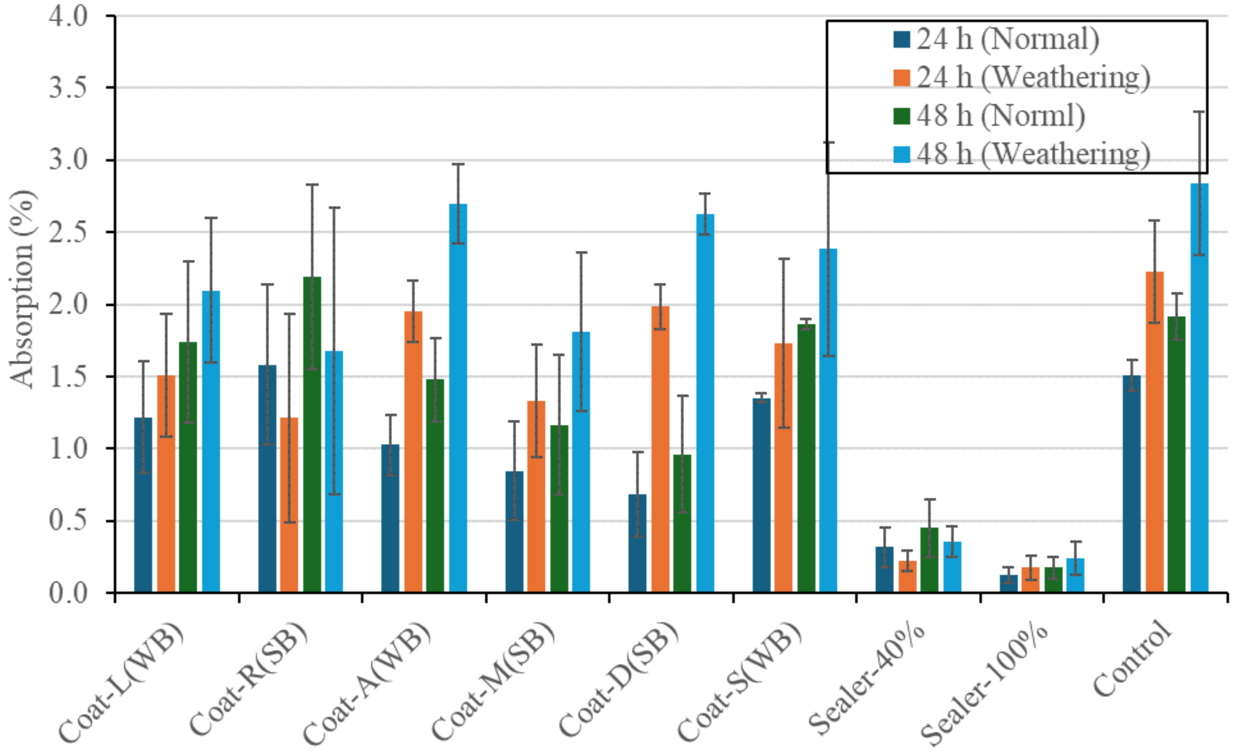
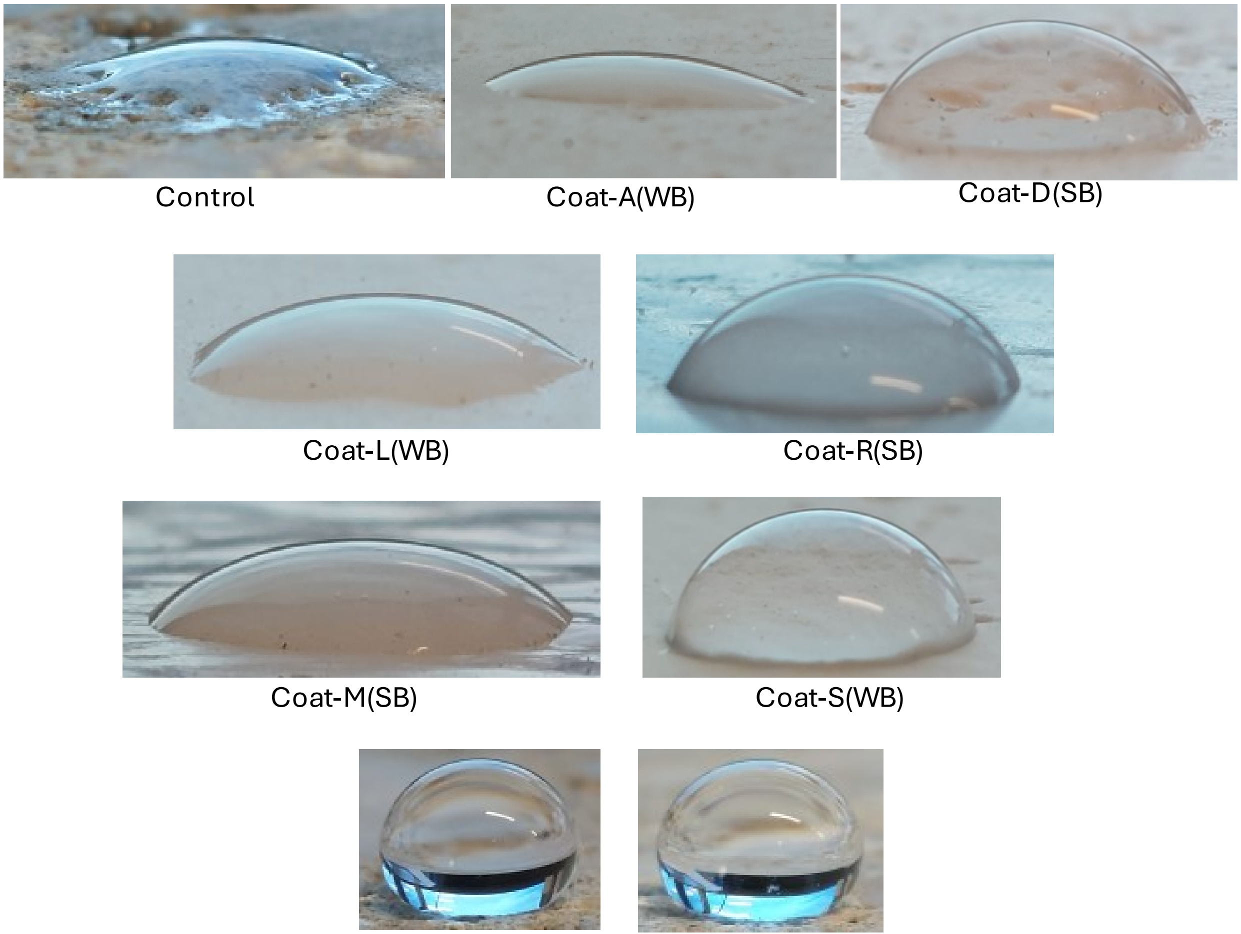


Figure 3-16: Water absorption test result under both the normal and weathering effects (QUV and QFOG)

3.5.5 Wettability (Contact Angle Measurement)

Contact angle measurement on the coated/sealed concrete surfaces can give an overall idea of whether the sealers and coatings behave as hydrophobic or hydrophilic. For example, if the contact angle is more than 90 degrees, the applied coated/sealed surface shows hydrophobic characteristics. Similarly, if the angle is lower than 90 degrees, the applied coated/sealed surface shows hydrophilic characteristics. The contact angles of all the tested coating and sealer materials were measured using ImageJ analysis of one drop of water on sealed/coated test specimens. Figure 3-17 shows a representative picture of the water drop on different surfaces. Table 3-6 shows the test results obtained from the analysis.



Control

Coat-A(WB)

Coat-D(SB)

Coat-L(WB)

Coat-R(SB)

Coat-M(SB)

Coat-S(WB)

Sealer-40%

Sealer-100%

Figure 3-17: Contact angle of a water droplet on concrete substrate treated with different sealer/coating materials

Table 3-6: Contact angle values for different sealed and coated surfaces

Material	Surface (sealed or coated)	Contact angle	Remarks
Concrete	Control	18	Hydrophilic
Coating	Coat-M(SB)	37	Hydrophilic
	Coat-R(SB)	56	Hydrophilic
	Coat-S(WB)	64	Hydrophilic
	Coat-A(WB)	23	Hydrophilic
	Coat-D(SB)	60	Hydrophilic
	Coat-L(WB)	32	Hydrophilic
Sealer	Sealer-100%	132	Hydrophobic
	Sealer-40%	136	Hydrophobic

3.5.6 Sorptivity (ASTM C1585)

The measurement of the rate of absorption of water (sorptivity) was carried out using 4-inch wide, 2-inch thick concrete slices per the ASTM C1585 method for all the studied sealer and coating materials. The exposed surface of the test specimens is either coated or sealed with one set without any coating or sealer (i.e., control specimens). The exposed surface was immersed in tap water and water ingress due to capillary suction (after initial contact with water), and absorption was monitored by measuring mass at specific intervals as per the standard. For each coating/sealer product, at least two test specimens were monitored as per the standard. Figure 3-18 shows the test setup for the sorptivity measurement. The plot for sorptivity test data over time under normal conditions can be found in Figure 3-19. The *x*-axis is the square root of the time (in seconds), and the *y*-axis (I) is the change in mass/area/density of water (unit in mm) as per the standard. Figure 3-20 shows an example plot with initial and secondary water absorption that can be obtained from a sorptivity test. The initial absorption is the rate up to 6 hours and beyond that the absorption is considered as secondary absorption. It can be observed that the initial rate of absorption (Figure 3-21) of control concrete under normal conditions is significantly higher than the secondary rate of absorption. With the application of coating and sealer, the initial rate of absorption is reduced by approximately 50–90 percent. The secondary rate of water absorption is higher than the initial rate of water absorption for the sealed and coated system. The sealer materials showed the best performance, which is obvious. Interestingly, the Coat-R(SB) coating material showed almost similar performance to the sealer materials (Sealer-40% and Sealer-100%). Within the rest of the coating materials, Coat-L(WB), Coat-D(SB), and Coat-M(SB) showed an overall good performance, whereas Coat-A(WB) and Coat-S(WB) performed poorly in terms of both the initial and secondary rate of absorption when compared to the sealers and Coat-R(SB). Figure 3-22 shows the average sorptivity measurement on test specimens after weathering conditions. The sorptivity measurement after the weathering effect (Figure 3-23) shows that the secondary rate of water absorption is higher than in normal conditions. A high rate of secondary absorption after QUV and QFOG exposure indicates damage to the coating and sealer layer. Coat-L(WB), Coat-M(SB), and Coat-R(SB) maintained lower damage, whereas Coat-A(WB), Coat-S(WB), and Coat-D(SB) performed poorly (higher damage) after exposure to the QUV and QFOG cycles. Although the rate of secondary absorption for the 100 percent silane remained almost unchanged, the 40 percent silane showed some increase in the rate of secondary absorption after weathering, which indicates some damage due to weathering for the 40 percent silane. The observation needs further validation from other tests, such as chloride ponding or RCPT.

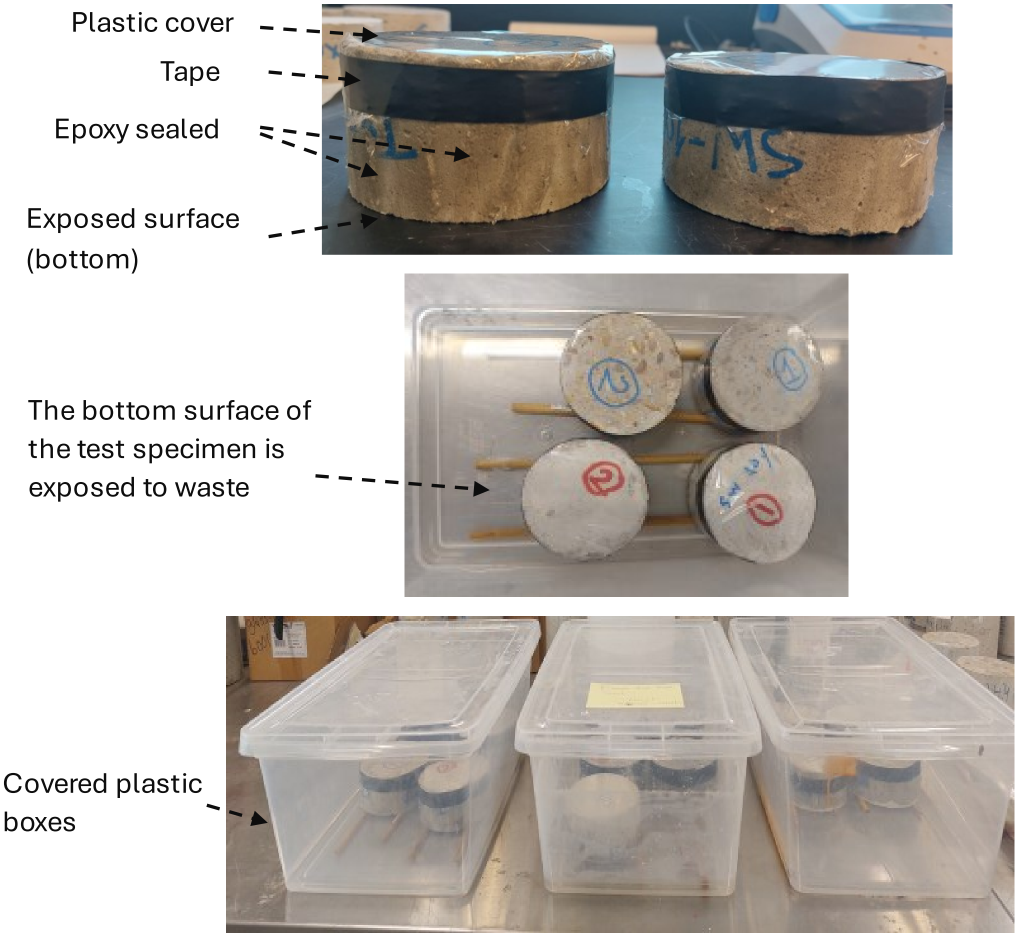


Figure 3-18: Test setup for the sorptivity measurement

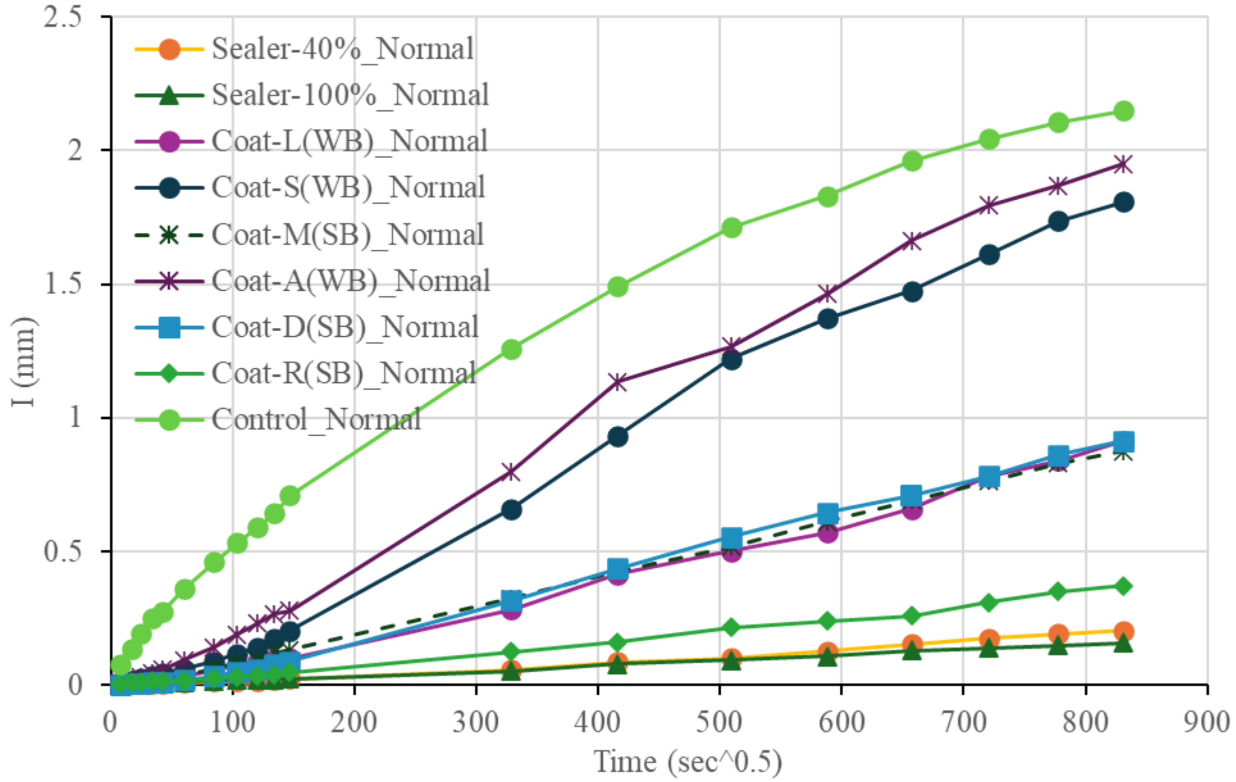


Figure 3-19: Plot for the sorptivity test data under normal conditions

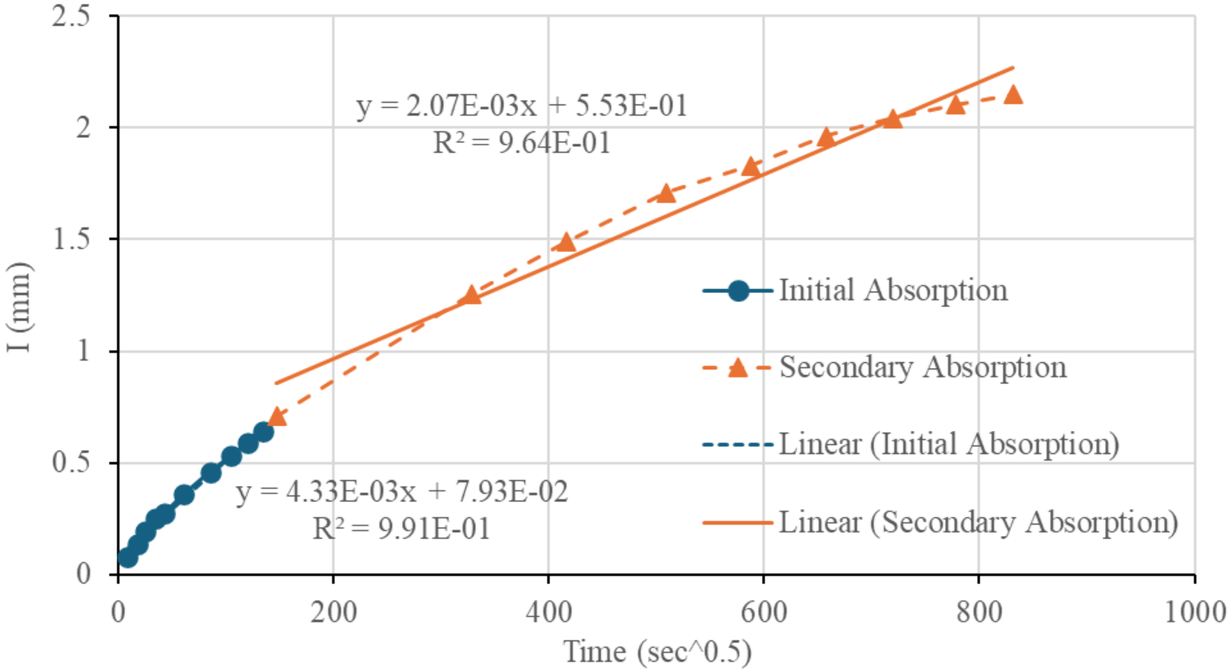


Figure 3-20: Example plot for the calculation for initial (first 6 hours) and secondary absorption (after 6 hours)

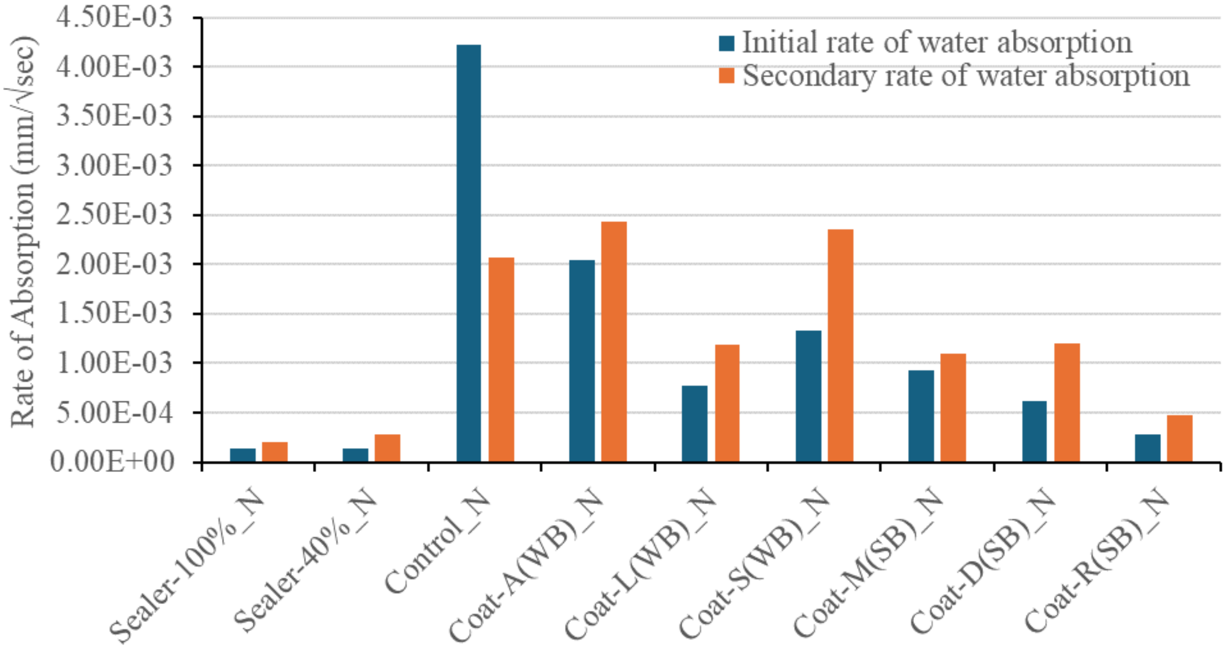


Figure 3-21: Initial and secondary rate of absorption under normal situation

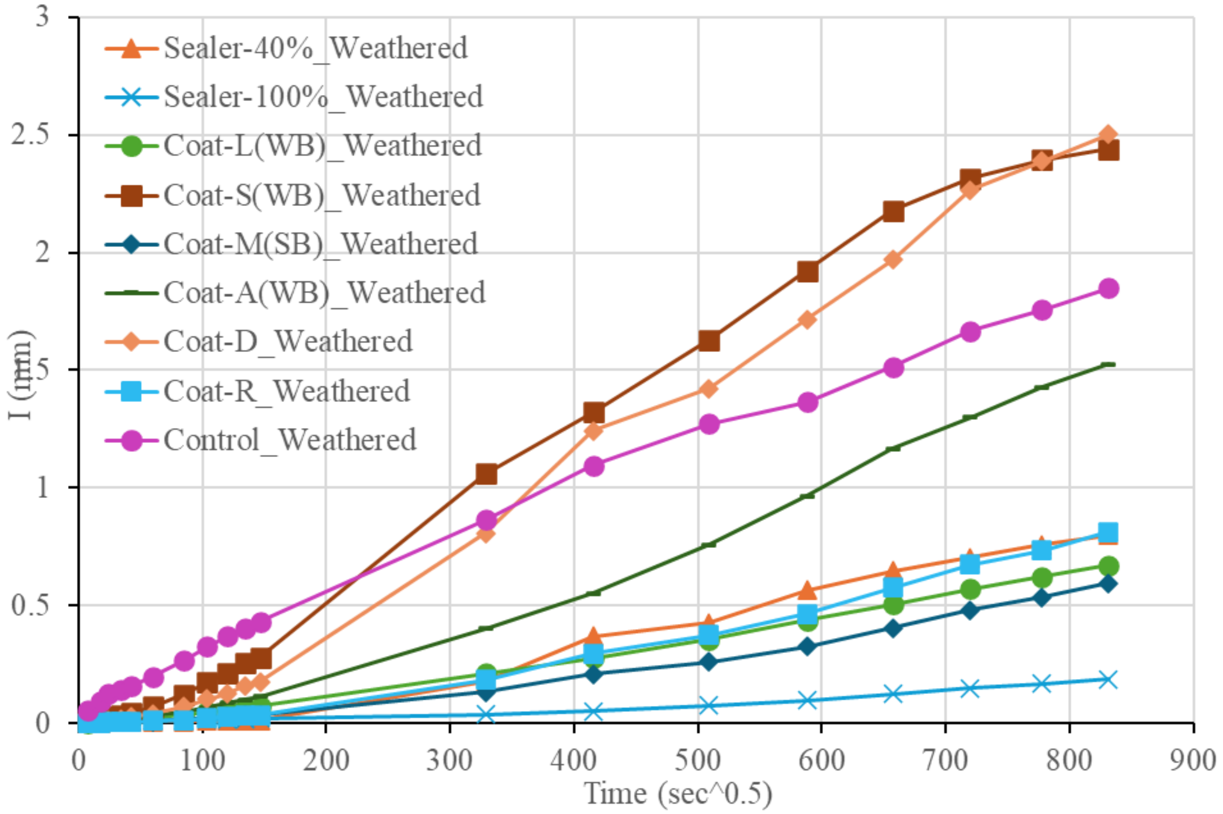


Figure 3-22: Plot for the sorptivity test data under weathered conditions

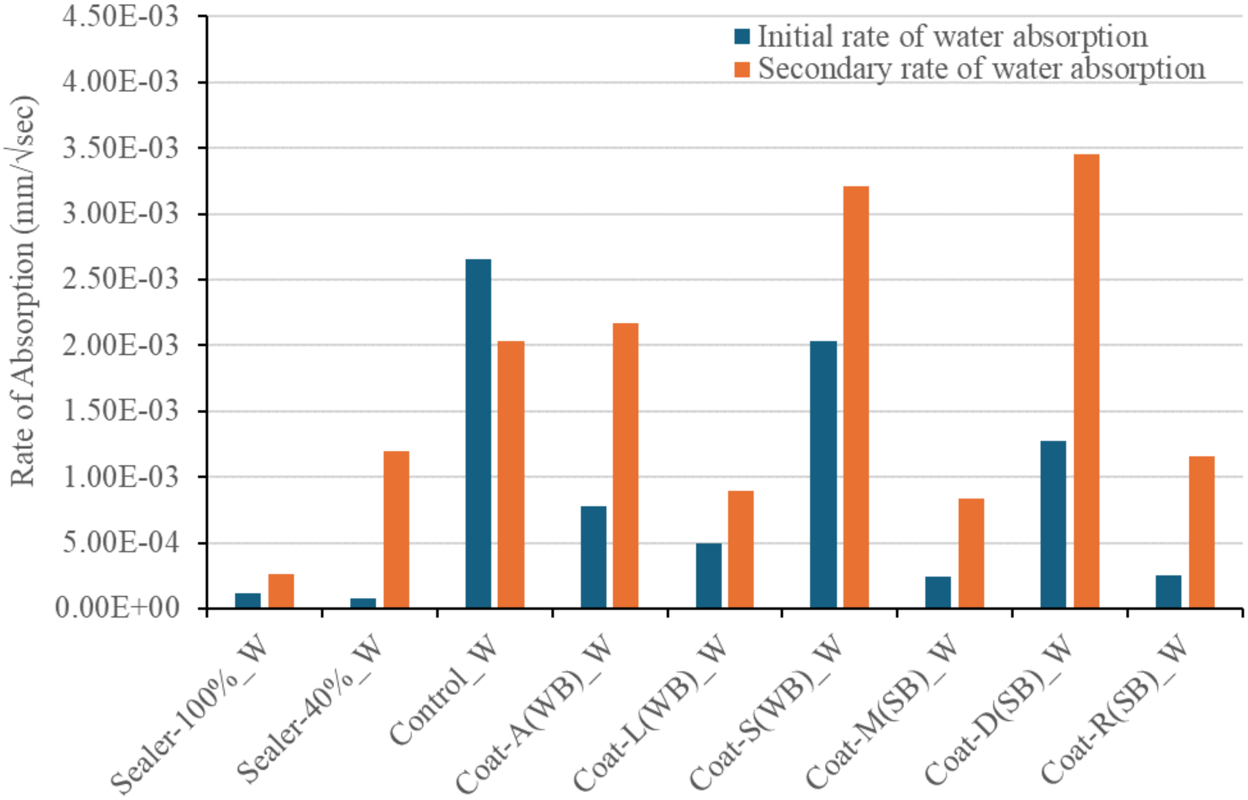


Figure 3-23: Initial and secondary rate of absorption after weathered conditions

3.5.7 Rapid Chloride Ion Penetration

The ability to resist chloride ion penetration was measured using test specimens with 4-inch diameter and 2-inch thick concrete slices, as per ASTM C1202. This test method is based on the electrical conductance of the concrete sample, which provides a rapid indication of the resistance to chloride ion penetration. The test duration was 6 hours, and a voltage of 60V was applied. Figure 3-24 shows the test setup for the RCPT. For each coating/sealer product, three test specimens were monitored. Because the present research project deals with different coated and sealed surfaces along with conventional concrete specimens, the coated/sealed surface was in contact with the NaCl solution (3 percent by mass) cell, and the other surface (not coated or sealed) was in contact with the NaOH solution cell (0.3 N). Figure 3-25 shows the test results obtained from the RCPT under normal and weathered conditions. It is prudent to mention that the chloride ion-based permeability classification ranges per ASTM C1202 are wide. For example, the coulomb passes for concrete with moderate chloride ion penetrability is within the 2000–4000 range. In the current study, the control concrete had low (1000-2000) chloride ion permeability as per the standard (Table 3-7). On the other hand, all the sealed and coated test specimens showed very low (100–1000) chloride ion penetrability. Since all the studied sealer and coating materials caused improvement from low to very low, judging the effectiveness of individual products based on permeability classification may not be very useful. However, based on the absolute coulomb values, the improvement, in decreasing order, showed the following trend: Sealer-100% > Coat-M(SB) > Coat-R(SB) > Sealer-40% > Coat-L(WB) > Coat-D(SB) > Coat-S(WB) > Coat-A(WB) > Control. Based on this trend, the sealers, Coat-M(SB), and Coat-R(SB) showed the highest resistance to chloride ion penetration compared to the control test specimen. After exposure to QUV and QFOG, the test specimens showed some increase in charge passed with the following increasing order: Coat-R(SB) < Coat-M(SB) < Coat-L(WB) < Coat-D(SB) < Sealer-100% < Sealer-40% < Coat-A(WB) < Coat-S(WB) < Control. This trend indicates that Coat-R(SB), Coat-M(SB), and Coat-L(WB) suffered negligible deterioration due to weathering (better protection of concrete), whereas Coat-D(SB), Sealer-100%, and Sealer-40% showed some deterioration (this result needs further validation to ascertain whether this kind of mild deterioration of sealers due to weathering is real under field condition); and the other two products (Coat-A[WB] and Coat-S[WB]) showed considerable deterioration (i.e., concrete protection over longer period may not be assured, reapplication with shorter interval may be needed in the field). Although Coat-R(SB), Coat-M(SB), and Coat-L(WB) did not show any classification change and the remaining products showed a classification change from very low to low due to weathering, the evaluation of weathering effects based on classification change is not sensitive. In the control concrete, there was a significant increase in coulombs due to weathering compared to the normal condition. In the next paragraphs, aspects that explain this trend are considered in order to understand the consequences.

During the QFOG cycle (dry and wet) the unprotected control specimens may have experienced some physical and chemical damage. During UV exposure (inside the QUV chamber), some degree of deterioration was observed on the top surface (exposed to UV) of the control specimen in comparison to the coated and sealed specimens. As a result, the penetration of the chemicals (0.05 percent sodium chloride and 0.35 percent ammonium sulfate used in the QFOG chamber) through the previously QUV deteriorated top surface was expected to be higher in the control specimens than in the coated and sealed specimens. Since the QUV-QFOG deteriorated surface stayed in direct contact with the 3 percent NaCl solution in the RCPT test, it may have possibly caused high RCPT value in the weathered control specimens (i.e., low [normal] became high [weathered]).

Based on the above observations, some deterioration of the bare substructure concrete over time under sunlight and weather cycles (the degree varies with the severity of exposure conditions) is expected in the field, which can cause some change in transport properties (i.e., from low to intermediate–high permeability classification) of the concrete (at least the topmost portion) over time (*67*, *68*). The application of the selective coating and sealer materials was found to be effective in minimizing this kind of change in concrete (topmost portion as a minimum) transport properties under an aggressive weathering chamber (simulation of field exposure conditions in close approximation) in the laboratory (*67*). Therefore, the application of suitable sealer and coating materials (lab-based evaluation supports a better selection based on the project requirements) is expected to protect concrete over a long period in the field.

Figure 3-24: Test setup for the RCPT

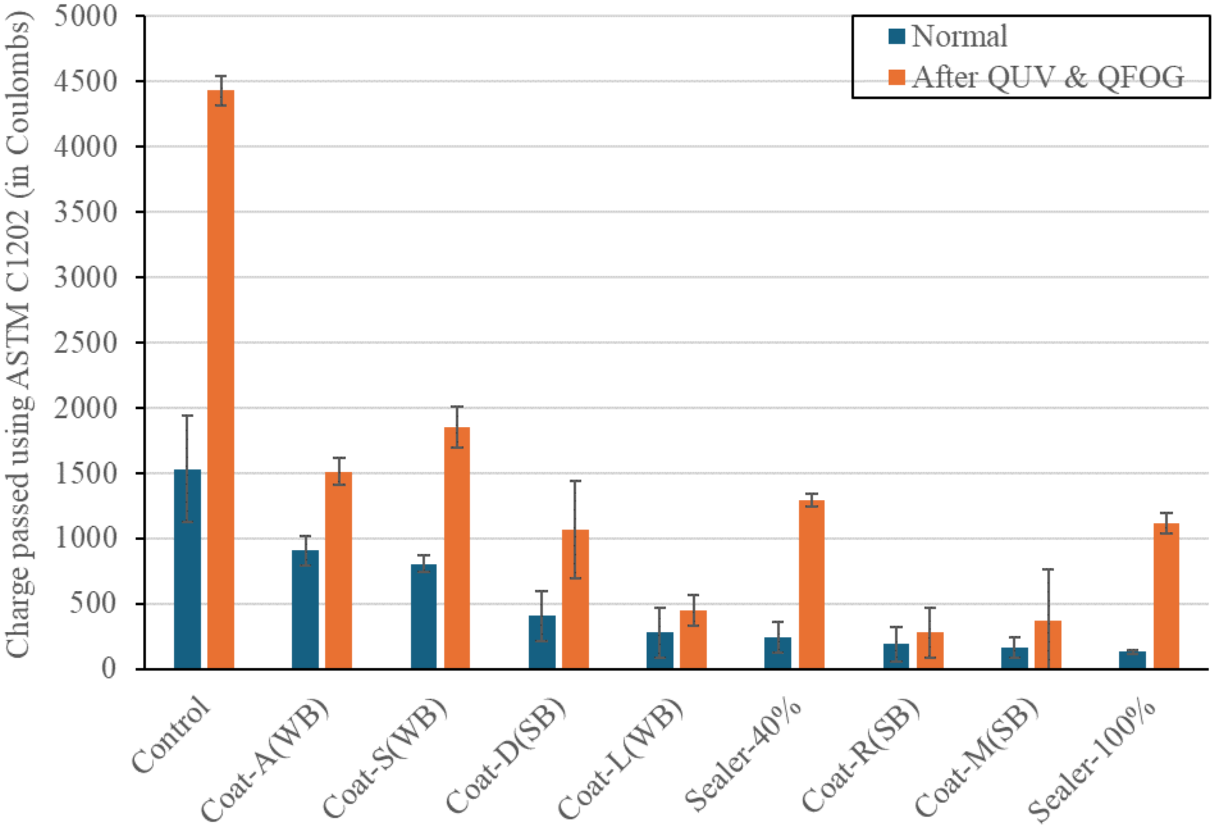


Figure 3-25: Results obtained from RCPT on different test specimens

Table 3-7: Results of the ASTM C1202 standard test (chloride penetrability [coulombs]: high [>4000], moderate [2000–4000], low [1000–2000], very low [100–1000])

Specimen details	Charge passed (Coulombs)—Normal	Chloride penetrability—Normal	Charge passed (Coulombs)—Weathered	Chloride penetrability—Weathered
Control	1532	Low	4432	High
Coat-A(WB)	907	Very low	1514	Low
Coat-S(WB)	807	Very low	1854	Low
Coat-D(SB)	407	Very low	1068	Low
Coat-L(WB)	282	Very low	451	Very low
Sealer-40%	245	Very low	1294	Low
Coat-R(SB)	192	Very low	278	Very low
Coat-M(SB)	166	Very low	370	Very low
Sealer-100%	131	Very low	1116	Low

3.5.8 Chloride Ponding Test (ASTM C1556)

The concentration of chloride ingress within concrete is considered one of the important measures of the durability parameter. The present research project directly deals with the substructure concrete, and protecting the reinforcement of concrete bridge substructure is of high priority. Corrosion of reinforcement is directly related to the concentration of chloride adjacent to reinforcement. The concentration of chloride at different depths of concrete was evaluated per ASTM C1556 and ASTM C1152 (method for acid-soluble chloride analysis) using 4-inch diameter with 4-inch height cylindrical concrete specimens. Epoxy glue was applied on all surfaces except the exposure surface before soaking in solution. Test specimens were immersed in saturated calcium hydroxide solution (3g/l) until the change in mass was less than 0.1 percent as per the standard (*28*). Next, the test specimens (control and coated/sealed) were ponded in salt solution (salt concentration 165 g/l) for 40 days. For each coating/sealer product, two test specimens were ponded. After 40 days of ponding in salt solution, concrete slices were cut at different depths. Four different depths were selected (0–5/32 inch [~0–4 mm], 5/16–1/2 inch [~8–12 mm], 5/8–3/4 inch [~16–20 mm], 1.181–1.338 inch [~30–34 mm]) for each specimen. Each slice was marked well based on depths and dried to make powder. A milling machine was used to make powder from the concrete slices. Finally, an 850-micron sieve was used to sieve the powder. Powder passing through an 850-micron sieve was collected (10 g) for the chloride analysis. A total of 128 powder samples were prepared from both normal and weathered test specimens for the chloride analysis using titration with silver nitrate. Additionally, 16 powder samples were prepared from control test specimens (without any coating/sealer).

The acid-soluble chloride analysis was performed as per the standard (*31*). An autotitrator (Orion Star T930 Titrator) was used for the chloride analysis, and before starting the main analysis, proper calibration and trials were performed with different known concentrations of chloride solution. Figure 3-26 shows the test setup for the chloride analysis of concrete. Figure 3-27 shows the chloride contents at different depths under normal conditions. From the analysis, it can be observed that the chloride contents at the first depth (0–4 mm) and second depth (8–12 mm) from the top are higher than the third (16–20 mm) and fourth depth (28–32 mm). The chloride content of the concrete without any salt ponding was 0.00997 percent w/w of concrete. The sealer materials showed the lowest chloride contents at all depths, that is, they offered the best protection. Based on the chloride data at the first and second depths, Coat-L(WB), Coat-D(SB), Coat-M(SB), and Coat-R(SB) showed good barrier protection, which is supported by the overall trends from other tests (sorptivity/RCPT). Coat-A(WB) and Coat-S(WB) showed relatively poorer performance in preventing chloride ingress than the above coating materials that offer good protection. Although Coat-A(WB) and Coat-S(WB) showed higher chloride concentrations at the first layer (0–4 mm) than the control, the chloride contents in the second layer (8–12 mm) for these two products were lower than the control concrete. A possible reason for the high chloride contents in the first layer might be an accumulation of chloride below the Coat-A(WB) and Coat-S(WB) coating layers because they do not offer much protection against water inflow (confirmed by sorptivity). Coat-A(WB) (DFT~5 mils) and Coat-S(WB) (DFT~3.5 mils) is a thin coating system. Therefore, for WB coating materials to have similar protection to SB coatings (e.g., Coat-M[SB] or Coat-R[SB]), maintaining a relatively higher DFT than the current practice may provide improved performance. This aspect should be evaluated in future research.

It can also be observed that the concentration of chloride content increased after the weathering effects (Figure 3-28). The normal concrete after QUV and QFOG showed the highest chloride ingress at the first and second layers (i.e., 0.4768, 0.322, 0.1459, 0.079 percent chloride weight/weight (w/w) of concrete at depth 0–4, 8–12, 16–20, 28–32 mm, respectively). The coating and sealer showed a significant increase in chloride content at the second layer (8–12 mm) compared to the normal conditions. The partial damage of the coating/sealer layer due to weathering allowed more chloride ingress, resulting in an increase of chloride content in the second layer. Therefore, along with the first layer (immediate bottom of coating/sealer), knowing the chloride concentration at the second layer (8–12 mm) is important for checking the effectiveness of the coating/sealer product under accelerated weathering through QUV-QFOG exposures. Again, the WB coating products (Coat-S[WB] and Coat-A[WB]) performed poorly under weathered conditions; however, Coat-L(WB) performed better among WB coating products. The SB coating products performed well under weathered conditions, and the product Coat-M(SB) had better barrier protection against chloride ingress than the other SB coating materials. Sealer-100% performed better than Sealer-40%. The 40 percent sealer product may not show significant protection under weathering conditions. Interestingly, RCPT test data also show some deterioration of the sealer materials (more in 40 percent silane than 100 percent silane, Figure 3-25, Table 3-7).

Figure 3-26: Test setup for the chloride analysis using an auto titrator

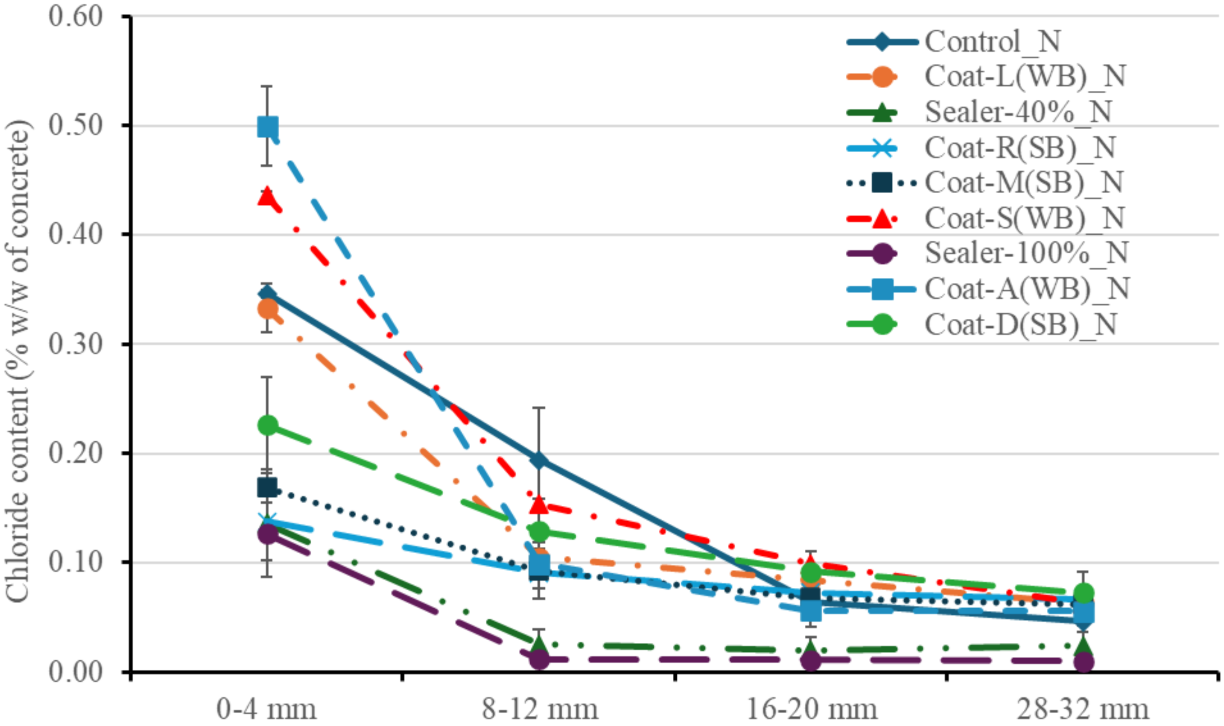


Figure 3-27: Chloride contents at different depths under normal conditions

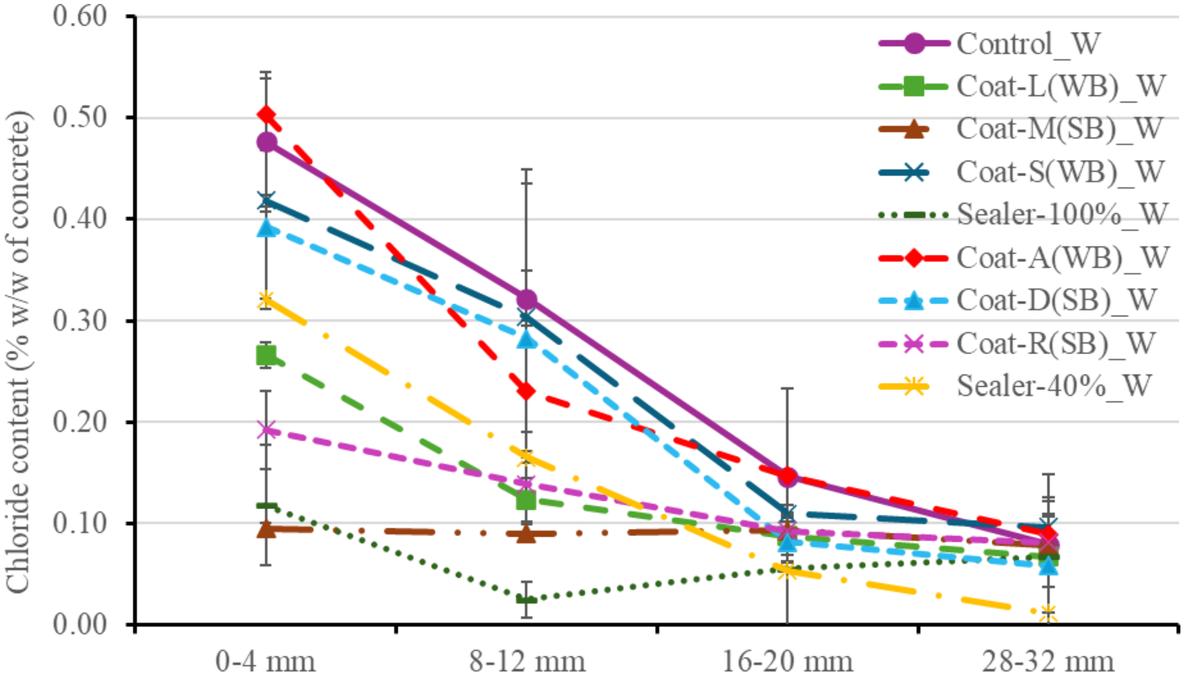


Figure 3-28: Chloride contents at different depths after weathering effects (exposure to QUV and QFOG chamber)

3.5.9 Pull-Off Adhesion Test in the Laboratory

There are two standards for pull-off adhesion tests using a portable adhesion tester: (a) ASTM D4541-coating system on a metal substrate, and (b) ASTM D7234-coating system on a concrete substrate. ASTM standards do not recommend any threshold adhesion strength values to judge if the measured adhesion strength is adequate or not. Therefore, the adhesion strength is for comparison purposes only and can be checked with the product data sheet for the recommended/tested value. However, not all coating product data sheets report the POAS value.

Since the present work involves the evaluation of coating materials on concrete substrates, the ASTM D7234 was followed. Aluminum dollies of 50 mm (2.0 inch) in diameter were selected for adhesion strength measurements. The steps that were followed to install dollies on different surfaces and for the measurement of POAS are presented in Figure 3-29 and described below:

- Step 1: Create a circular cut mark of 50 mm diameter with 2–3 mm depth using a core cutter to break the continuity of the coating layer.
- Step 2: Attach the dollies on the circular mark (Step 1) using a two-part epoxy glue with a full curing time of 1 hour. Hold the dollies in place for at least 2–3 minutes, followed by applying duct tape for additional support to ensure firm attachment of the dollies on a horizontal surface.

- Step 3: Remove the duct tape after a curing period of 3 hours and measure POAS using a portable pull-off adhesion tester (the Elcometer Model 510T Automatic Adhesion Tester was used for this study).

The schematic representation of the dolly attachment on a concrete surface with different interfaces (i.e., Glue-Dolly [G/D], Coat X Glue [X/G], and parent concrete—Coat X [P/X]) and failure modes through these interfaces are shown in Figure 3-30. Figure 3-31 shows the representative POAS test result for Coat-R(SB). For each coating product, at least four test data points were considered. Based on ASTM D7234-22, any test data that show more than 25 percent area with glue failure was discarded.

Figure 3-32 shows the average POAS values on different coated surfaces. It can be observed that the adhesion strength values for Coat-A(WB) (avg. 302 psi), Coat-S(WB) (avg. 244 psi), and Coat-L(WB) (avg. 173 psi) are lower than Coat-M(SB) (avg. 394 psi), Coat-R(SB) (avg. 503 psi), and Coat-D(SB) (avg. 454 psi). The control concrete (without any coating) showed an adhesion strength value of 473 MPa, indicating a good substrate concrete. The adhesion test data (Figure 3-33) under weathering conditions showed that the weathering effect impacted the adhesion strength significantly for Coat-A(WB), Coat-S(WB), and Coat-L(WB) coating materials in comparison to Coat-M(SB), Coat-R(SB), and Coat-D(SB). The adhesion performance of Coat-M(SB), Coat-R(SB), and Coat-D(SB) coating materials remained almost unchanged due to weathering.

Three possible reasons have been identified regarding the difference in POAS of different coating materials. First, the type of coating materials, which are Coat-A(WB), Coat-S(WB), Coat-L(WB), Coat-M(SB), Coat-R(SB), and Coat-D(SB), might be a cause. It was observed that the SB coating materials have higher POAS values than the WB coatings. Second, the condition of the concrete substrate (strength as well as surface roughness) could be an issue as well. For the POAS test, the CSP value of the concrete surface was close to 1 (smooth surface), which may be one of the reasons for showing relatively lower POAS for the WB coatings. However, the SB coatings performed well with the same concrete substrate. At present, it can be observed that SB coating materials can exhibit high POAS on a smooth concrete substrate (CSP 1) in comparison to WB coating materials. A separate study is recommended to evaluate this aspect further. Third, the thickness of the coating layer may play a crucial role in POAS. In this research, the two-coat application was adopted as per the product data sheet for all the coating products. For the SB coating materials, two coats may be fine to achieve adequate DFT and adhesion strength; however, for the WB coating products, two coats may create a relatively thick DFT, which may be responsible for creating weak interfaces. This aspect has already been addressed in this project by making a new set of concrete test specimens, and coating was applied accordingly (one coat and two coats). Figure 3-34 shows the difference in adhesion strength of different coating materials under the one-coat and two-coat systems. It can be observed that Coat-A(WB), with one coat, showed higher (17.65 percent) POAS than the two-coat system. Similarly, the

Coat-L(WB) two-coat system showed 60 percent lower POAS than the one-coat system. In contrast, the SB coating (Coat-M[SB]) showed almost similar POAS for both one-coat and two-coat systems. The thick layer for the WB coating may show low POAS; however, for the SB coating, both coat options are fine. In the future, a study with a specific focus can be performed to assess the performance of just one coat of both the WB and SB coating products to mitigate chloride and moisture ingress and maintain good adhesion strength. If good performance is observed by applying a layer coating product, a huge material cost and effort can be saved by TxDOT for all concrete bridge-related projects in Texas.

Another important consideration related to the POAS measurements on vertical surfaces was made. Figure 3-35 shows the test specimen prepared for the assessment of POAS on vertical surfaces. It was observed that the adhesion strength on the vertical surface was slightly lower for most of the coating products (Figure 3-36). The situation was similar for both one-coat and two-coat systems (Figure 3-37). The Coat-L(WB) showed higher adhesion strength on the vertical surface for two two-coat systems; however, for a one-coat system, the same strength was lower. The difference in adhesion strength on the vertical surface should be considered while performing the same test in the field, and for each product the variation may be different.

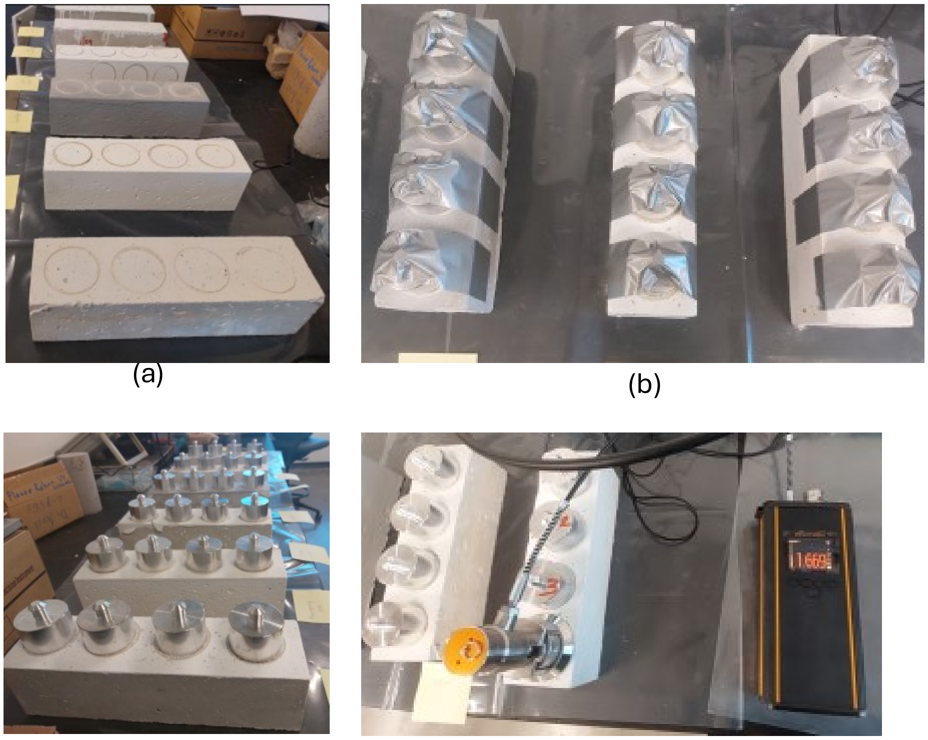

(a) (b)
(c) (d)

Figure 3-29: Pull-off adhesion test in the laboratory: (a) circular cut mark for dolly placement, (b) attached dollies using glue and supported by duct tape, (c) attached dollies ready for the test, and (d) adhesion test in process

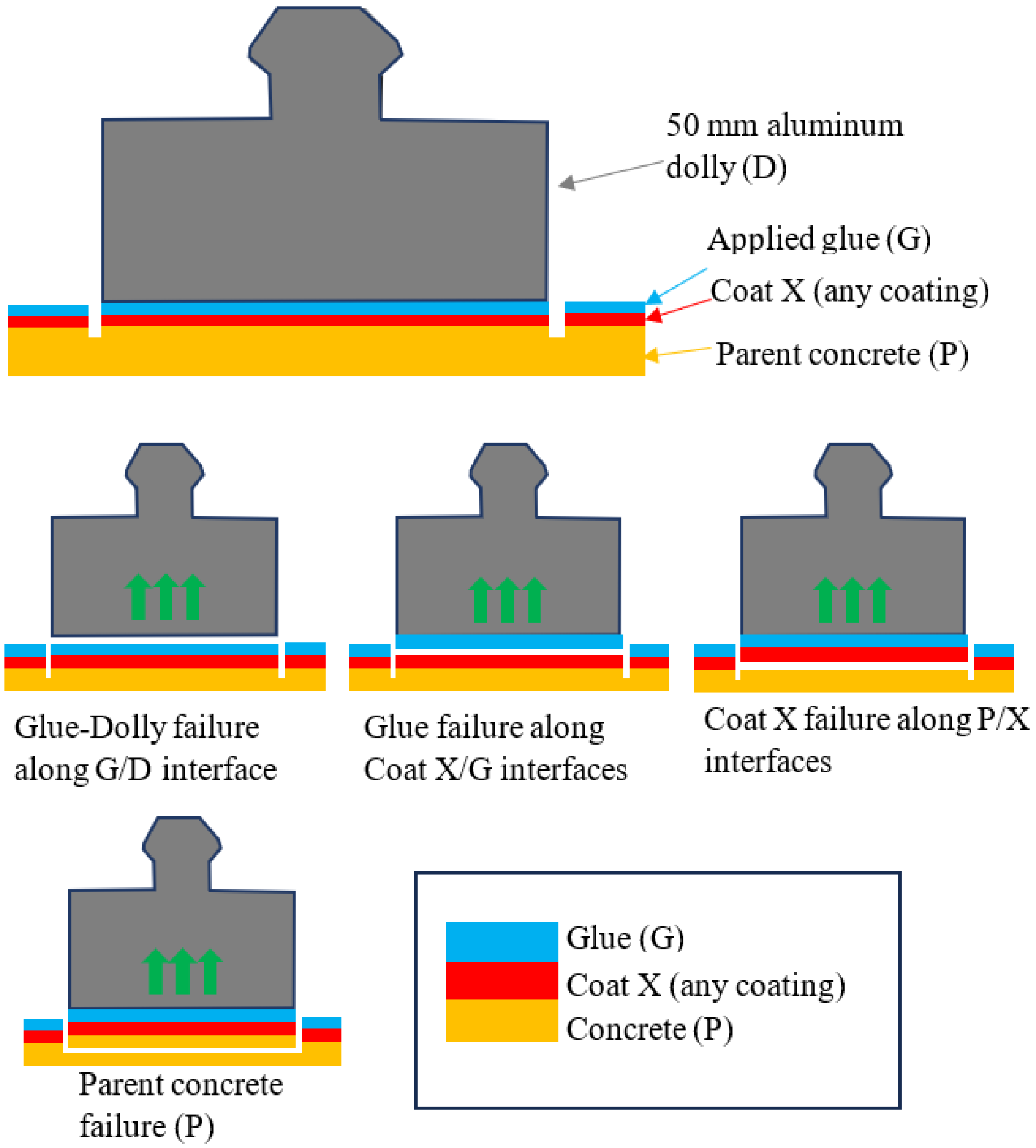


Figure 3-30: Schematic diagram for dolly attachment on the coated surface in the laboratory and different failure modes (Coat X = any coating)

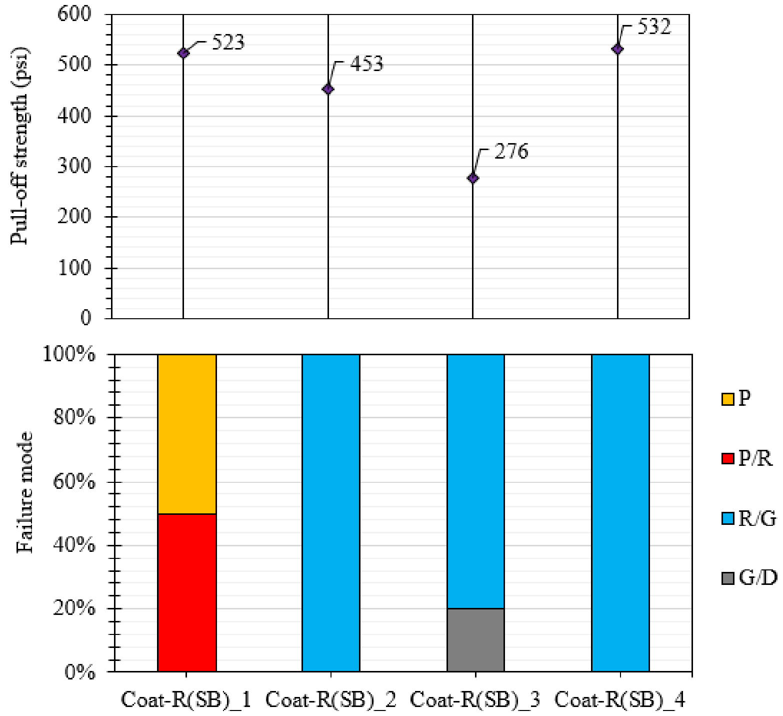


Figure 3-31: Representative test result details during the POAS (example of Coat-R[SB] coating [mentioned as R])

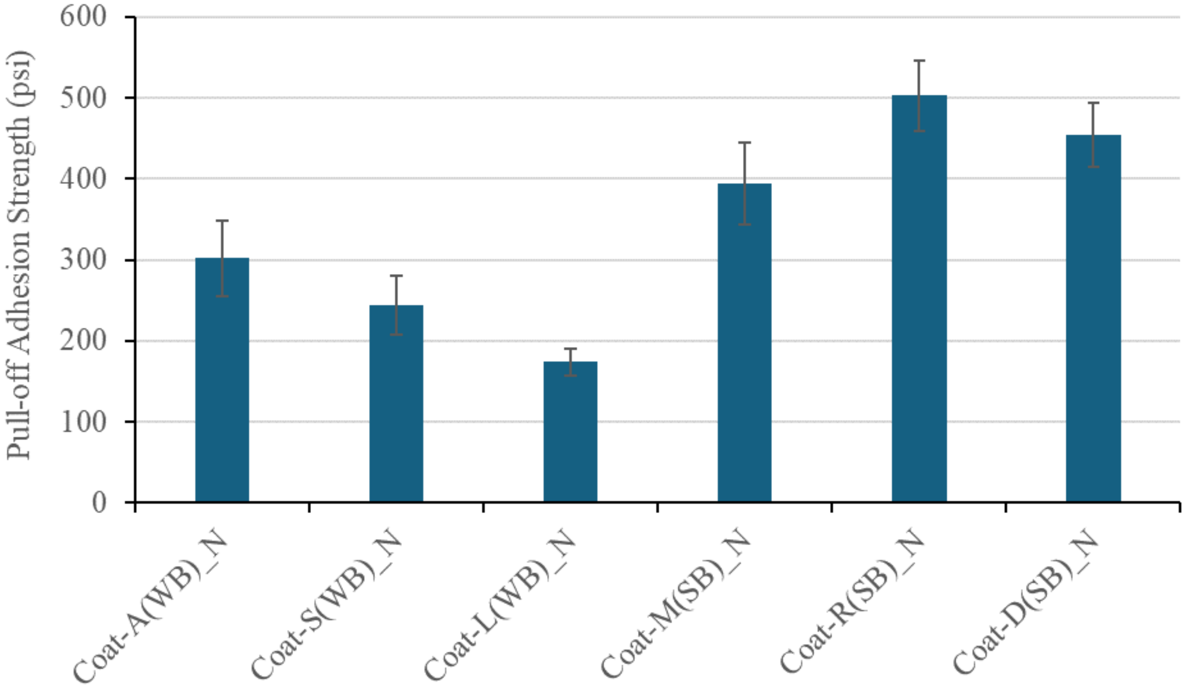


Figure 3-32: Average POAS of different coating materials under normal conditions

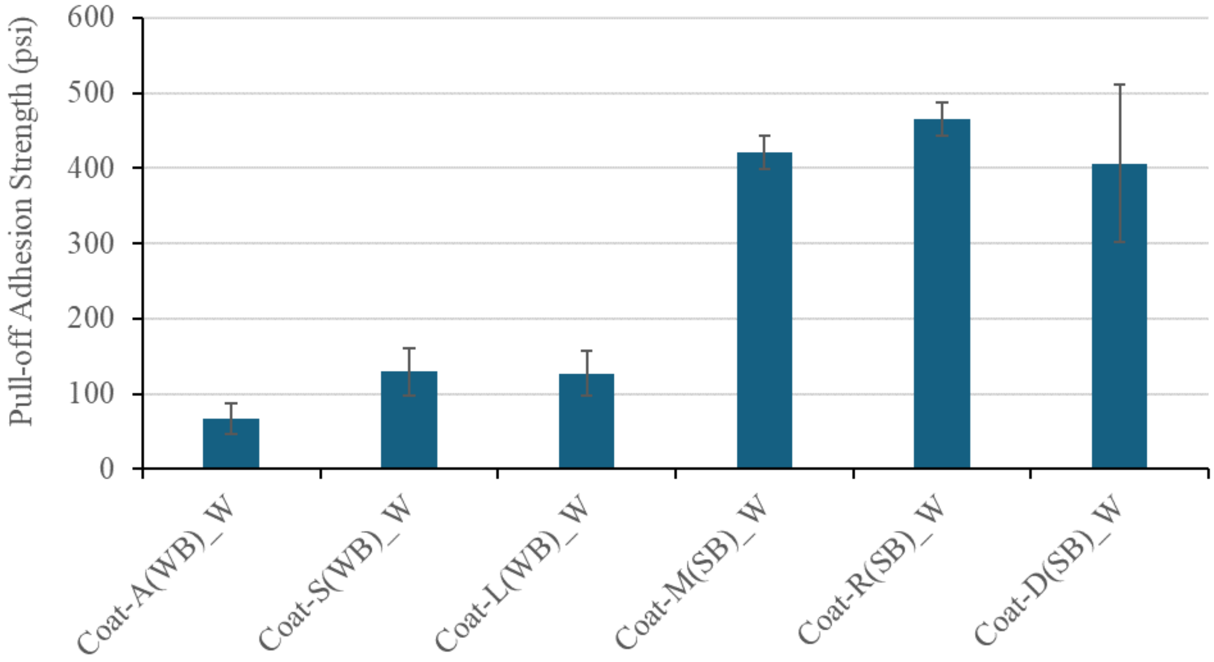


Figure 3-33: Average POAS of different coating materials after weathering (exposed to QUV and QFOG chamber) effects

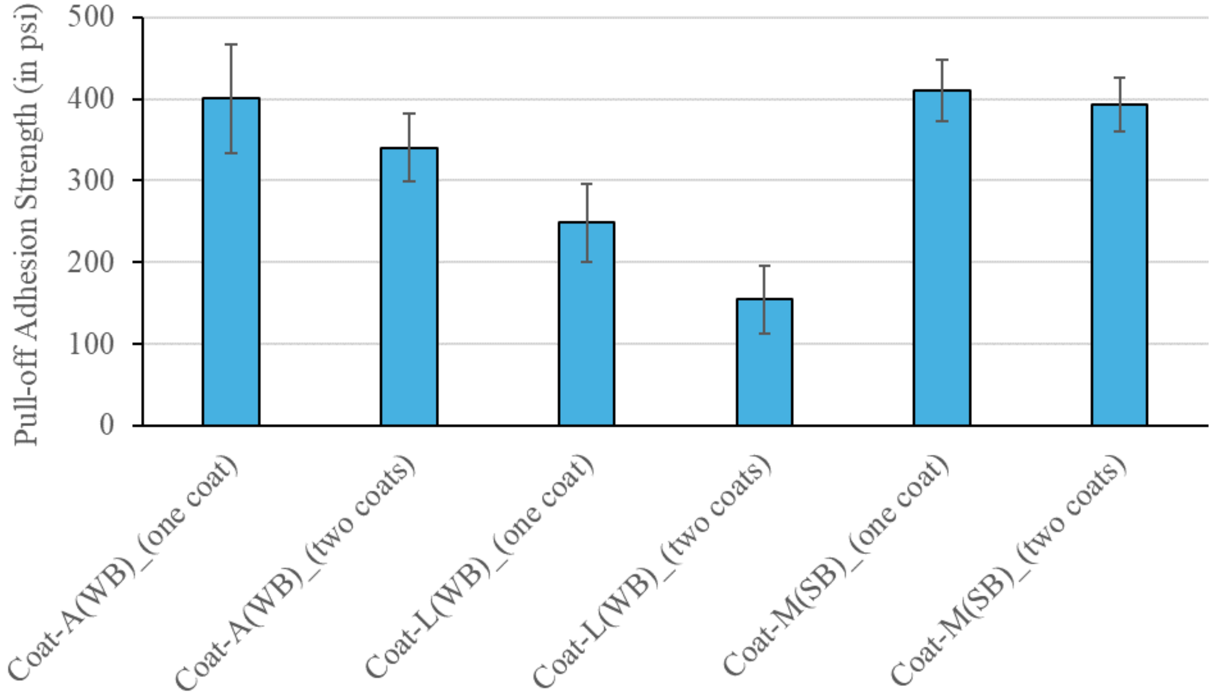
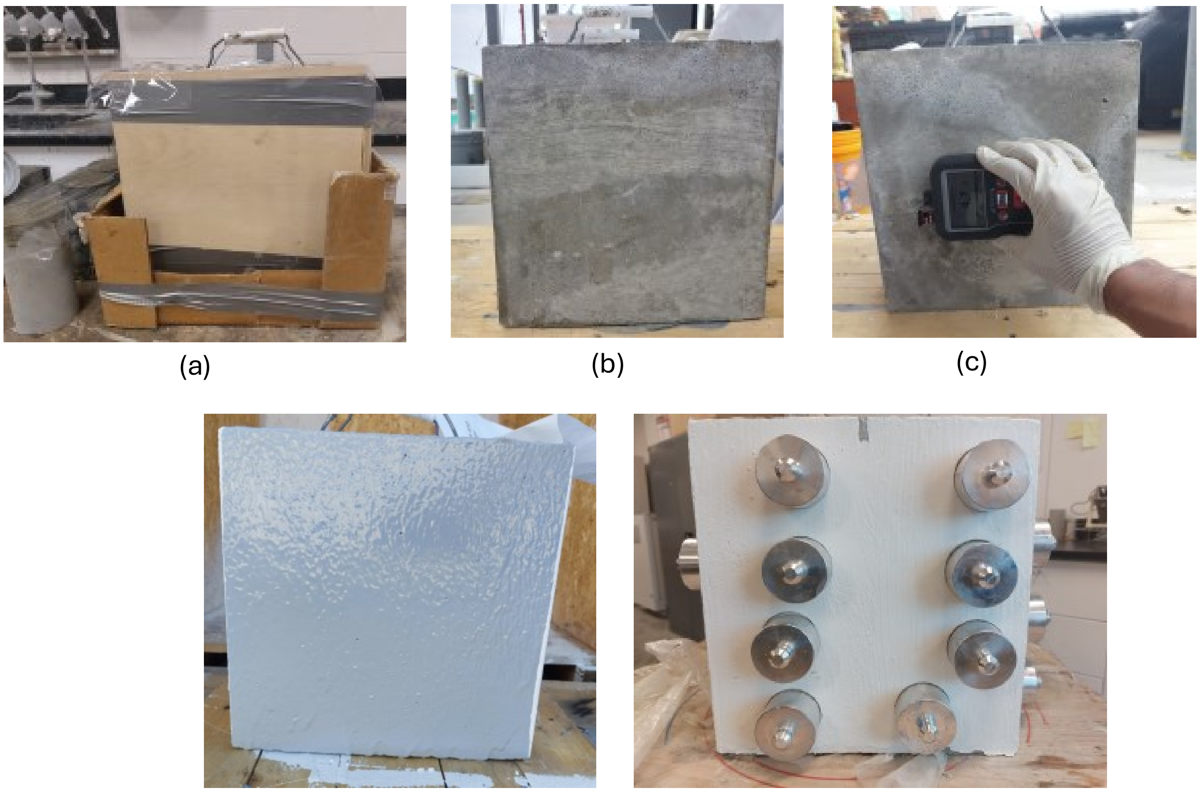


Figure 3-34: Average POAS of different coating materials with one-coat and two-coat system



(a) (b) (c)

(d) (e)

Figure 3-35: Test specimen prepared for the assessment of POAS on vertical surfaces: (a) 1 cubic ft concrete (fresh stage), (b) 1 cubic ft concrete (after 28 days of curing), (c) surface moisture measurement, (d) two-layer Coat-R(SB) coated surface, and (e) placement of dollies on the vertical surface

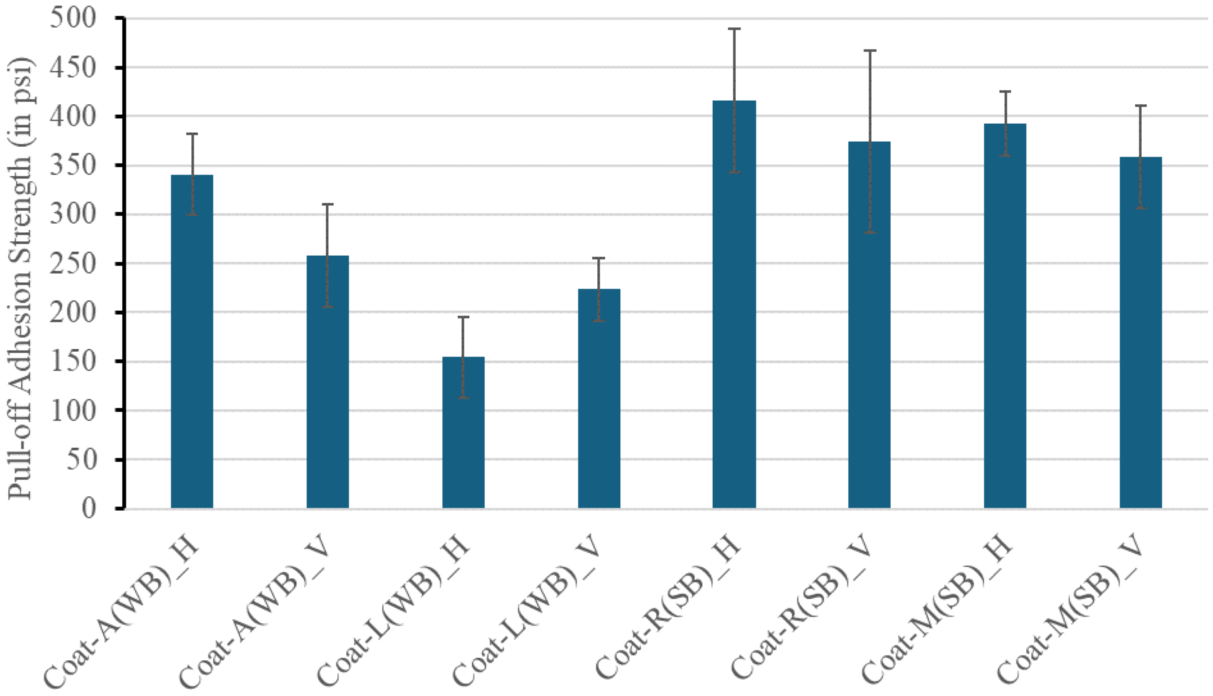


Figure 3-36: POAS on vertical and horizontal surfaces with two coats (H=horizontal, V=vertical)

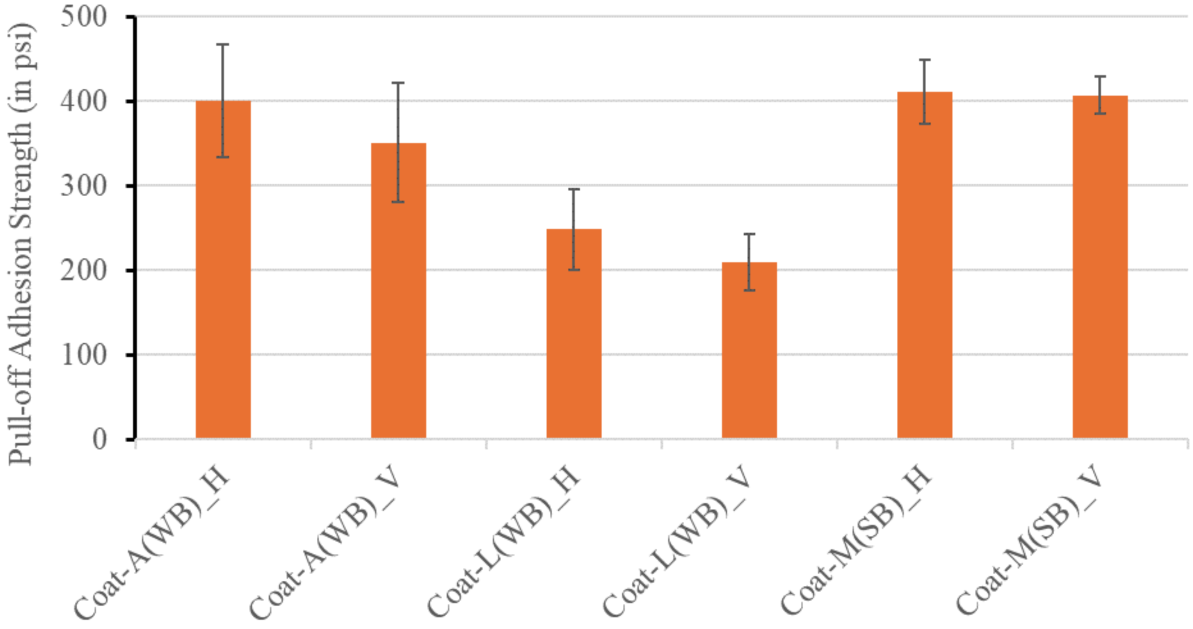


Figure 3-37: POAS on vertical and horizontal surfaces with one coat (H=horizontal, V=vertical)

3.5.10 Corrosion Monitoring (Electrochemical Testing)

3.5.10.1 Steady-State Corrosion Testing

The main aim of corrosion monitoring was to compare the degree of protection of the structural rebar inside the concrete bridge substructure after a sealer and coating application. Based on the degree of protection offered by different coating and sealer materials, suitable products can be suggested for different projects. Details of the specimen preparation for corrosion monitoring have already been provided in Figure 3-2. Both the ends of the rebars (No. 5, ASTM A615/A615M)—with a wire protruding that acts as a working electrode—were coated in glue. Saturated Calomel and Platinum mesh were used as reference and counter electrodes, respectively. Figure 3-38 shows the details of the experiment setup. Electrochemical measurements were conducted using the Gamry 1010 Potentiostat and an ECM8 Multiplexer. A conventional three-electrode cell was used at room temperature. The coated rebar worked as the working electrode, an Ag/AgCl was used as a reference electrode, and a Platinum mesh electrode was used as a counter electrode. The electrochemical testing procedure is shown in Figure 3-39, along with the parameters. For all the coating and sealer materials, at least two test specimens were monitored (electrochemical tests) to ensure the reproducibility of the open circuit potential and EIS measurements. The performance of reinforced concrete under steady-state conditions can be illustrated in three different phases with time. Figure 3-40 illustrates the initiation phase, or water uptake mechanism. When the accumulation of corrosion or depassivation (chloride ions) precursors reaches a threshold magnitude (or concentration), the passive layer breaks down to transition to active conditions (or Phase II). The last phase is when the breakdown of the layer is complete, and the corrosion increases (Phase III). Figure 3-41 shows the test results obtained during the first 4 months of the steady-state corrosion monitoring in the project. During steady-state conditions, the corrosion rate is very low due to the passive layer effect on the surface of the rebar. The control sample showed the highest magnitude of corrosion after 2 months of exposure. However, the Phase I on each coating can be more quantitative with time. The steady-state takes a longer time (in years) because the corrosion initiation under the steady-state process is slow. An accelerated corrosion test may be helpful to obtain the effectiveness of different sealers and coating materials.

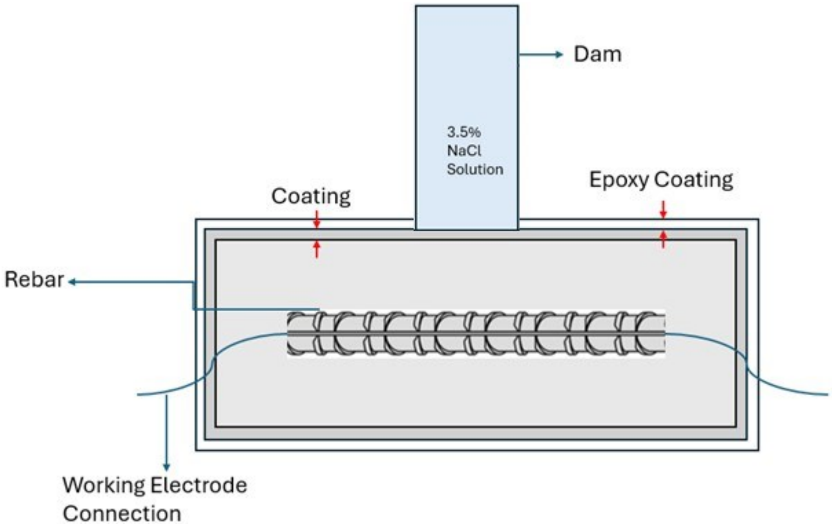


Figure 3-38: Experiment setup for steady-state corrosion monitoring

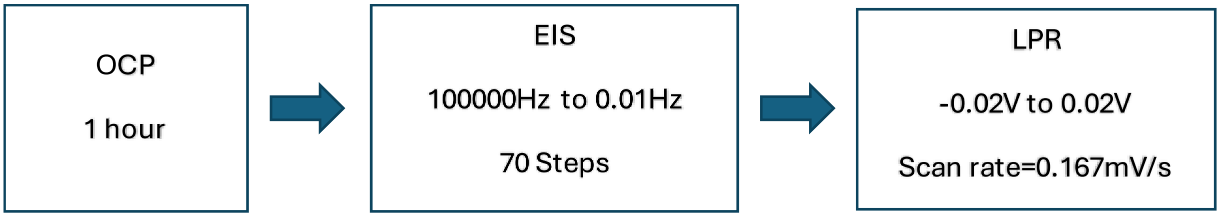


Figure 3-39: Electrochemical tests and parameters used for steady-state testing

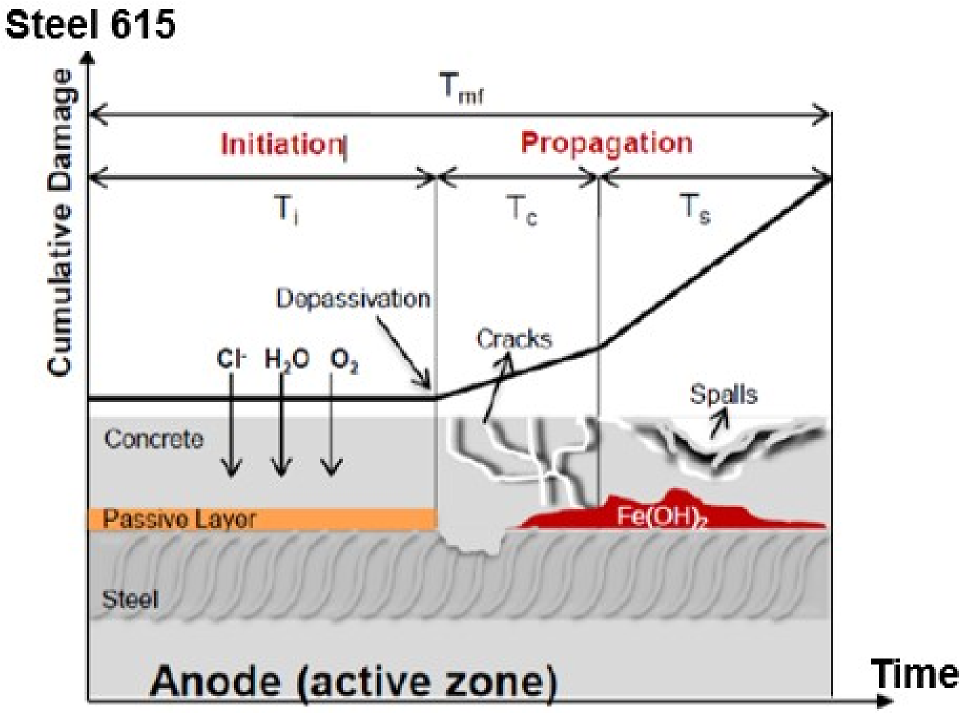


Figure 3-40: Corrosion mechanism of steel (rebar) in concrete

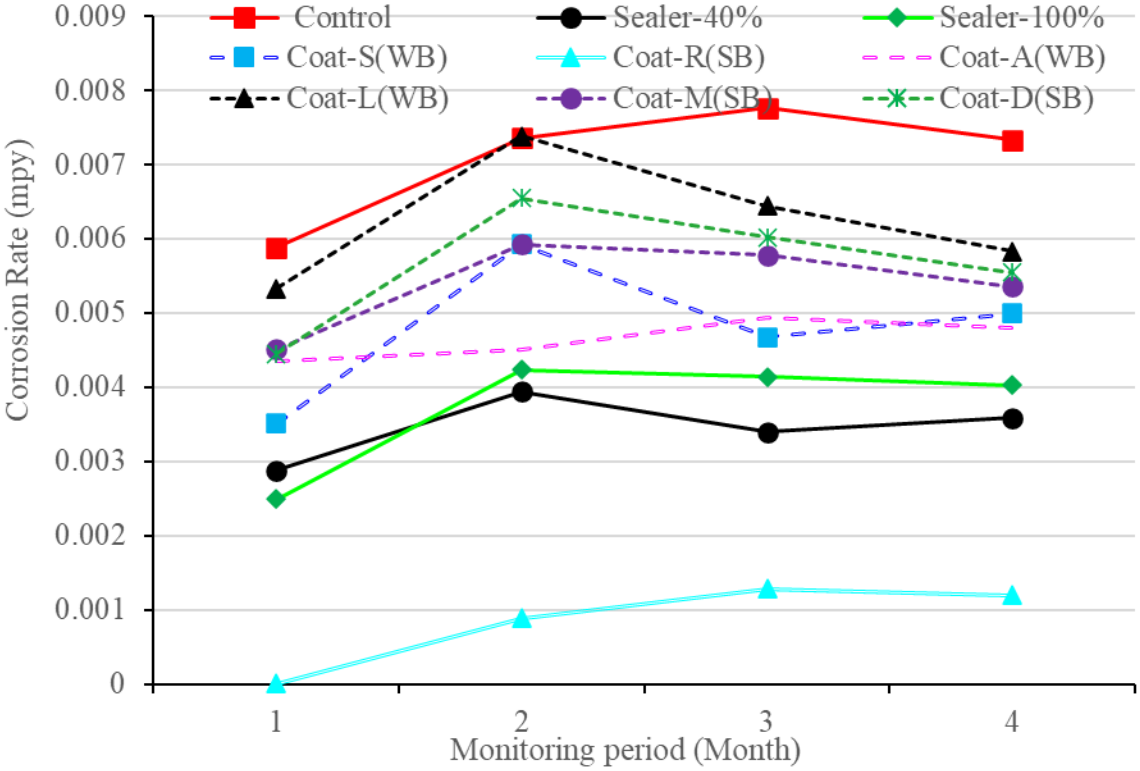


Figure 3-41: Corrosion rate (mpy) for the steady-state testing

3.5.10.2 Accelerated Corrosion Testing

Salt spray testing is a common accelerated corrosion test (in QFOG cyclic corrosion chamber) method that exposes metallic and nonmetallic materials to a highly corrosive environment over an extended period to assess their relative corrosion resistance. The testing can also be used to determine the effectiveness of paints and coatings in protecting the substrate material from corrosion. For the present experiment, an ASTM 615 rebar was embedded inside the concrete and subsequently coated/sealed with the different coating and sealer products selected in this project. Salt spray testing is usually carried out using ASTM B117 standard salt spray test for 60 days or 1440 hours. The testing involved using a 5 percent NaCl solution that was atomized within a sealed chamber (QFOG) to create a saltwater mist to accelerate the corrosion of the materials being tested. The test specimens were inspected at regular intervals to monitor and record the degradation of the samples. Figure 3-42 shows the test specimen for the accelerated corrosion test in a QFOG chamber. For each coating/sealer product, two test specimens were monitored.

The test specimens were taken out during the dry cycle as per the standard (ASTM B117), and subsequently, electrochemical testing was done according to the parameters shown in Figure 3-43. Electrochemical measurements were conducted using the Gamry 1010 Potentiostat in a two-electrode setup. The rebar used the working electrode, and a stainless steel mesh was used as the reference and counter electrode.

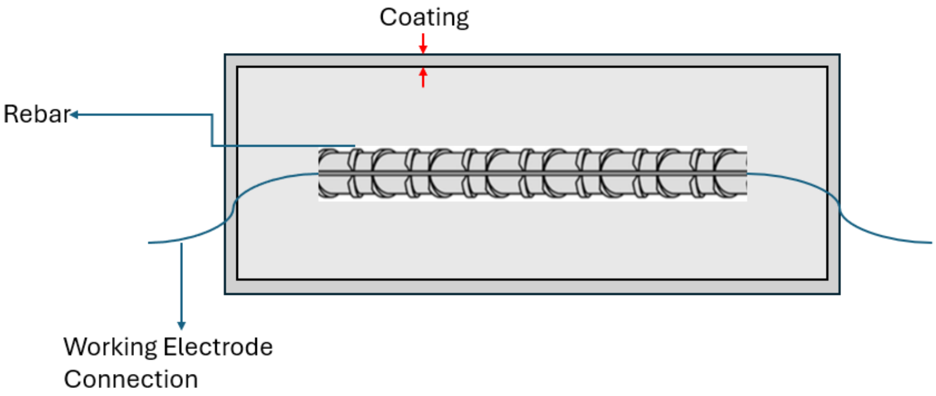


Figure 3-42: Schematic diagram of the test specimen used for the accelerated corrosion test

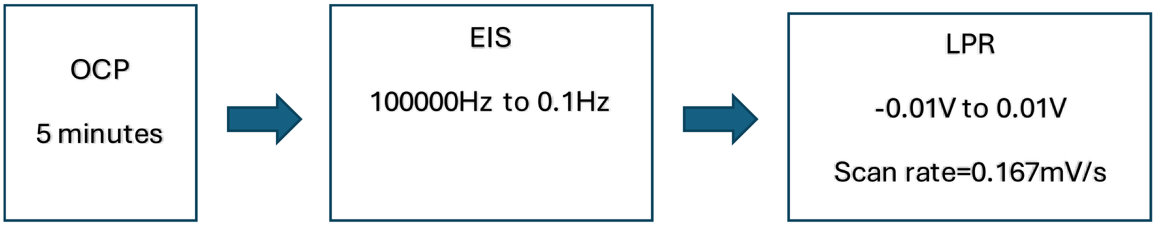


Figure 3-43: Electrochemical tests and parameters used for accelerated corrosion testing

Figure 3-44 depicts corrosion rates observed in accelerated testing conditions. Test data up to 60 days for the accelerated condition remain always higher than the steady-state data (up to 4 months) for all the eight selected sealer/coating materials except for the control concrete. Test specimens coated with Coat-A(WB), Coat-S(WB), and Coat-D(SB) showed a higher rate of corrosion at 60 days of monitoring. Similarly, test specimens coated/sealed with Coat-R(SB), Coat-M(SB), and sealers performed better (i.e., lower corrosion rate). Accelerated corrosion monitoring offers the following advantages over steady-state corrosion monitoring:

- The accelerating method decreases the time to reach such a threshold and the activation of the surface in a few days. The electrolyte includes a wet-dry cycle producing stress conditions and accelerating the transport mechanisms.
- The corrosion rate during accelerated testing exceeds that observed in steady-state conditions. Accelerated testing typically achieves this rate in approximately 1 month, whereas steady-state testing requires more than 2 years.
- Transitioning to the next phase under accelerated conditions typically takes shorter times, whereas steady-state conditions require more than 2 years.
- Complete breakdown, attributed to the third phase, is estimated to occur in a few weeks for accelerated testing and more than 3 years for steady-state conditions.

These findings underscore the influence of testing conditions on corrosion progression, highlighting the accelerated nature of degradation under controlled environments when compared to real-world steady-state conditions.

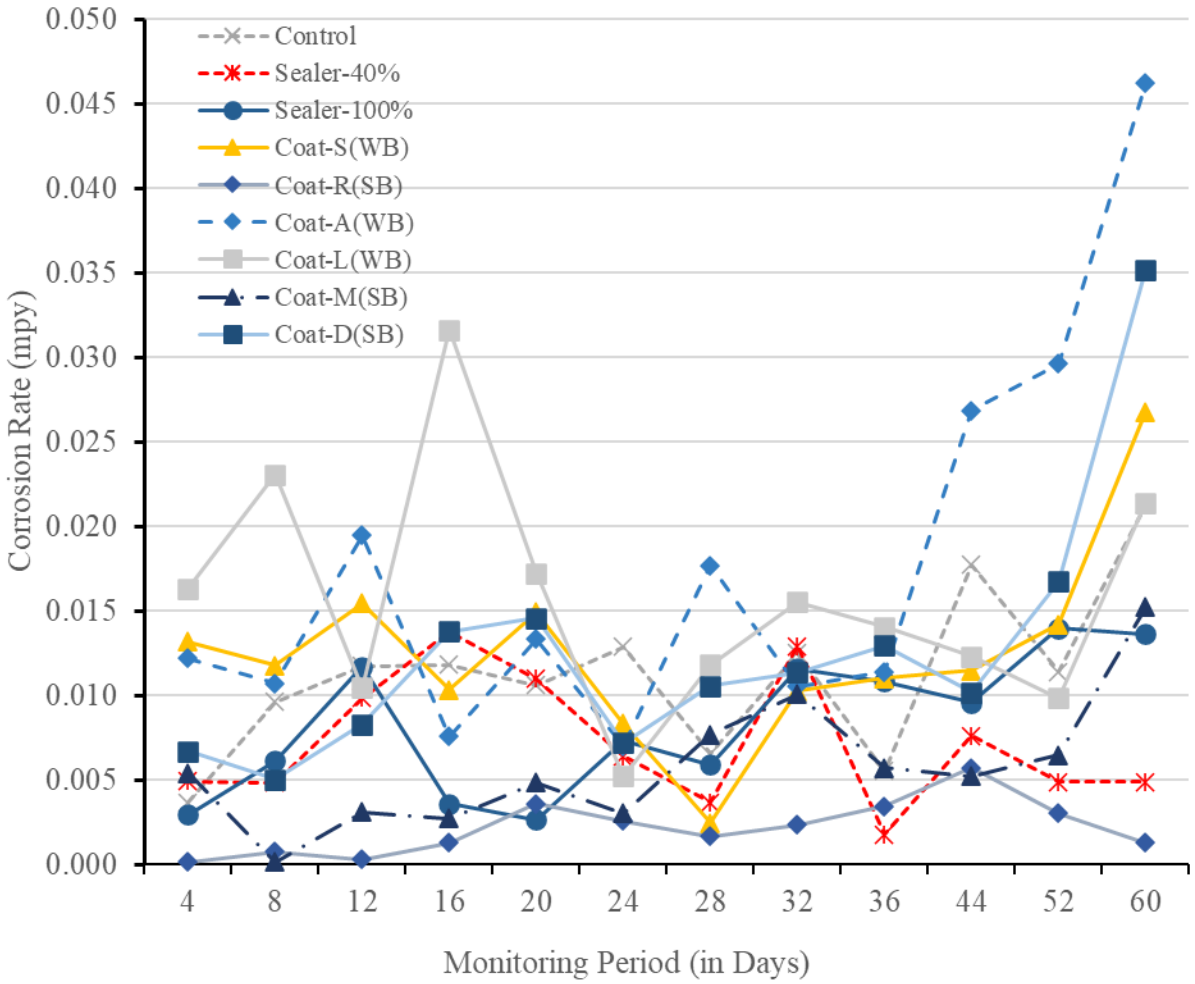


Figure 3-44: Corrosion rate (mpy) over time obtained from accelerated corrosion monitoring

Table 3-8: Summary of the performance of different coating and sealer materials

Performance assessment	**Control**	**Coat-A(WB)**	**Coat-S(WB)**	**Coat-L(WB)**	**Coat-M(SB)**	**Coat-D(SB)**	**Coat-R(SB)**	**Sealer-40%**	**Sealer-100%**
DFT (mils)		5	3.5	16	9.4	3.4	14.2		
DOP (mm)								2.18	3.28
Water absorption (in %, 48h)	1.92	1.48	1.86	1.74	1.17	0.96	2.19	0.45	0.18
Contact angle (degree)	18	23	64	32	37	60	56	132	136
Initial absorption (mm/√sec)	4.23E-03	2.04E-03	1.33E-03	7.77E-04	9.26E-04	6.15E-04	2.84E-04	1.41E-04	1.35E-04
Secondary absorption (mm/√sec)	2.07E-03	2.44E-03	2.36E-03	1.19E-03	1.10E-03	1.20E-03	4.72E-04	2.75E-04	2.02E-04
Charge passed using (in Coulombs)	1532	907	807	282	166	407	192	245	131
% chloride content (0-4 mm)	0.3460	0.4999	0.4361	0.3325	0.1685	0.2261	0.1377	0.1361	0.1268
% chloride content (8-12 mm)	0.1939	0.0987	0.1537	0.1051	0.0927	0.12915	0.0907	0.0251	0.0115
POAS (psi)	—	302	244	174	394	454	503		
Corrosion rate (mpy) Accelerated (60 days)	0.0213	0.0462	0.0268	0.0214	0.0152	0.0352	0.0013	0.0049	0.0136

3.6 Conclusion

The research project aimed to develop a test protocol for evaluating the performance of different sealer and coating materials that are commonly used on concrete bridge substructures in Texas. A laboratory test protocol containing useful tests was developed. Based on the extensive evaluation of the selected coating and sealer products using the developed test protocol, a very good idea about the effectiveness of different products was obtained (ref. Table 3-8). The main findings are summarized below:

- Concrete substrate plays a crucial role in terms of the performance of coating and sealer products. Concrete surfaces should be clean and free from moisture, and surface roughness should be as per the ICRI guidelines. A moisture meter was found to be effective in monitoring the concrete surface moisture condition before the application of coating/sealer materials.
- Effective application of different coating materials can be assessed by measuring the DFT using a portable DFT measuring gauge. The direct measurement of DFT by using a stereo microscope and a small cut specimen of the coated layer from the concrete substrate can be used to validate (if needed) the DFT by the portable gauge. For sealer material, the same confirmation can be obtained by the DOP test (using a stereo microscope).
- The performance of different sealer and coating materials can be measured by following a group of tests and not by a single test. For example, to assess protection against moisture, sorptivity (ASTM C1585) and RCPT (ASTM C1202) tests should be performed. To ensure reinforcement protection by minimizing the chloride ingress within concrete substrate via sealed or coated surface, RCPT (ASTM C1202) and chloride ponding (ASTM C1556) tests are suitable and effective. To check the performance of the existing coated surface over time, both tests can be suggested (concrete core from the field). Adhesion strength (ASTM D7234) is a very good measure to ensure the effectiveness of coating materials in the long run and can be suggested for both laboratory and field. The effectiveness of sealer and coating materials can also be assessed in the laboratory by an accelerated corrosion test.
- Water absorption by ASTM D6489 may be suitable for the sealer materials but may not be effective for coating products. Instead, sorptivity test can be suggested for the coating materials. The initial absorption rate was higher for control concrete, and for the sealer/coated test specimen, the same rate was lower, which confirms the effectiveness of the sealer and coating products.
- The RCPT was found to be effective in assessing the performance of coating and sealer materials, and coated or sealed surfaces should be in contact with the NaCl chamber (3 percent solution). In addition to RCPT, the chloride ponding test was effective in assessing the barrier protection against chloride ion ingress. Chloride concentration at different depths should be considered for the final assessment.

- The POAS of the one-coat system was comparatively higher than the two-coat system. POAS on the horizontal concrete substrate was slightly higher than on the vertical surface. This aspect should be considered when performing POAS in the field. It was also observed that SB coating materials have higher POAS than WB coating materials.
- The accelerated corrosion test showed that to achieve a meaningful acceleration effect, extending the test for a longer duration (more than 1 month) is needed. The time can be minimized by altering the concrete substrate (concrete with poor transport properties and high water/cement ratio), dicing chemicals ($CaCl_2$, $MgCl_2$), etc., which can be studied further.

CHAPTER 4: DEVELOP A RATING SCHEME FOR LAB AND FIELD CONDITIONS

In this chapter, the development of a rating system is described based on the results from the extensive laboratory-based performance assessment of different sealer and coating materials, as reported in Chapter 3. First, the evaluation methodology and framework for the rating system were defined, and then the individual ranking of the products was obtained from different performance indicators. A compound rating system was then developed by combining all the individual rankings along with assigning a suitable weightage factor.

4.1 Evaluation Methodology

The primary objective of Task 4 (original research proposal) was to develop a rating system based mainly on extensive laboratory performance evaluation of different sealers and coating materials (Task 3, Chapter 3) under both normal as well as accelerated weathering (QUV and QFOG exposure). The specific objectives related to the formulation of the rating system are as follows:

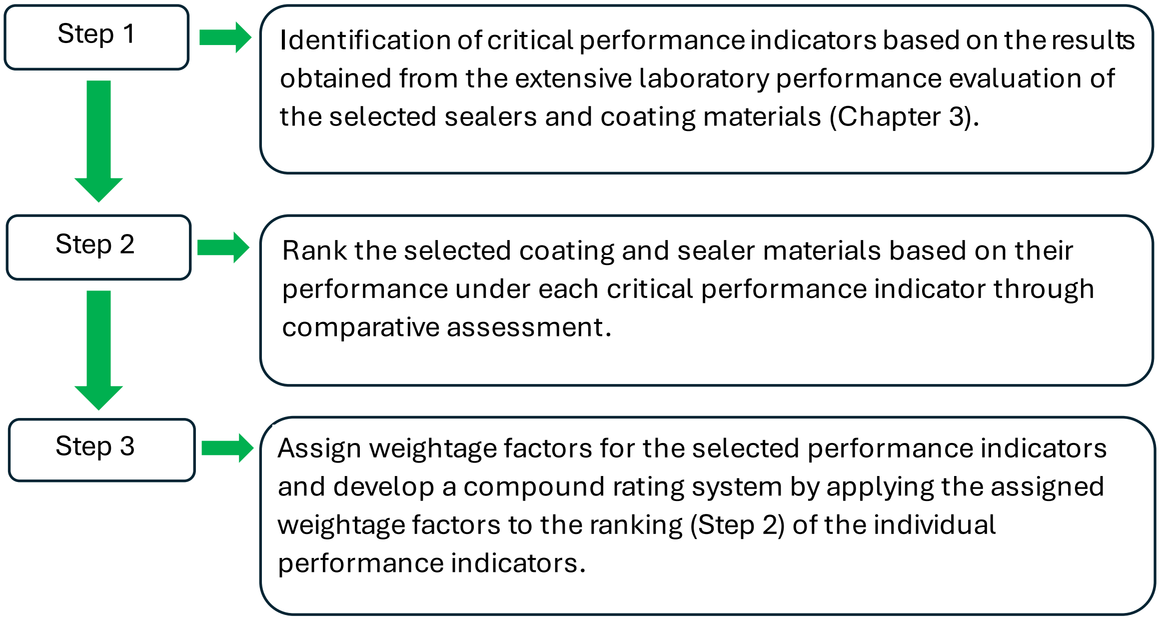
1. Identification of critical performance indicators based on the results obtained from the extensive laboratory performance evaluation of the selected sealers and coating materials (Chapter 3).
2. Development of a rating system using the identified critical performance indicators for the selected coating and sealer materials:
    a. Rank the selected coating and sealer materials based on their performance under each performance indicator through comparative assessment.
    b. Assign weightage factors (WF) for the identified performance indicators (e.g., rapid chloride ion penetration, evaluation based on chloride ponding test, measurements of the rate of corrosion of reinforcement steel, water absorption/sorptivity, degree of deterioration due to UV exposure, POAS, etc.) based on their level of importance.
    c. Development of a compound rating system (a simple weighted average method) by applying the assigned WFs (Item B) to the ranking for the individual performance indicators (Item A) for all the studied coating and sealer materials. A similar rating system was developed by the Wisconsin DOT (*12*).

4.2 Development of a Rating System

4.2.1 Framework of the Rating System

The framework for the development of the rating system is given in Figure 4-1. Step 1 involves the identification of critical performance indicators. In Step 2, the selected coating and sealer materials are ranked based on their performance under each performance indicator through comparative assessment. Step 3 involves the development of a compound rating system.

It is prudent to mention that the chloride ion ingress parameters (RCPT, chloride ponding, and accelerated corrosion) were considered to have higher WFs for all the tested products. Similarly, POAS was considered a parameter with higher WF for all the coating materials. It was realized that the ranking of coatings and sealers should be considered separately since some of the tests are not common between them. For example, POAS is applicable for coating materials but not applicable for sealers.



Step 1

Identification of critical performance indicators based on the results obtained from the extensive laboratory performance evaluation of the selected sealers and coating materials (Chapter 3).

Step 2

Rank the selected coating and sealer materials based on their performance under each critical performance indicator through comparative assessment.

Step 3

Assign weightage factors for the selected performance indicators and develop a compound rating system by applying the assigned weightage factors to the ranking (Step 2) of the individual performance indicators.

Figure 4-1: Framework for the development of a rating system

4.2.2 Identification of Different Performance Indicators for the Development of a Rating System

Table 4-1 shows different performance indicators that were considered for the development of the rating system. Other performance assessments such as WFT, DFT, DOP, color, and gloss retention were not considered in developing the rating system. However, it is important to maintain an effective WFT/DFT for coating materials and a proper coverage (sq ft/gal) to achieve an optimum DOP for sealer materials.

Table 4-1: Identified performance indicators for the development of a rating system

Performance indicators	Conditions	Reason for considering
Water absorption (ASTM D6489)	Normal and weathering	The test has the potential to assess the absorption performance on sealed surfaces.
Water absorption (Sorptivity) (ASTM C1585)	Normal and weathering	The test has the potential to assess the rate of absorption performance on sealed/coated surfaces.
Pull-off adhesion test (ASTM D7234)	Normal and weathering	The test has the potential to evaluate the adhesion strength performance of a coating material.
Chloride penetration (ASTM 1556, chloride ponding test)	Normal and weathering	The test has the potential to measure the chloride content at different depths of concrete on sealed/coated surfaces.
Chloride penetration (ASTM 1202, RCPT)	Normal and weathering	The test has the potential to assess the resistance in chloride ingress performance on sealed/coated surfaces.
Corrosion (Accelerated)		The test has the potential to measure the rate of corrosion performance within a short period on sealed/coated surfaces.

4.3 Comparative Assessment of Individual Performance Indicators

Assessment of relative performance based on the selected performance indicators has already been discussed previously on individual performance indicators (Chapter 3). After obtaining all the data for the selected performance indicators under both normal and weathered conditions, a score (ranking) was assigned for each test (performance indicator) for the tested sealer and coating materials based on their relative performance. For example, 1 represents the highest ranking, and 8 represents the lowest ranking. The lower the score (higher rank) the better the performance in protecting substructure concrete.

4.3.1 Water Absorption (ASTM D6489)

Water absorption test results can be found in Figure 3-16 (Chapter 3). The average absorption at 24 and 48 hours of all the tested products were compared, followed by the assignment of ranking: Rank 1 corresponded to the lowest absorption value and Rank 8 corresponded to the highest absorption value. After the weathering effects, Coat-D(SB) and Coat-A(WB) performed similarly, with a common rank of 7, which represents poor performance due to the weathering effects. The ranking of Coat-R(SB) under normal conditions was 8, which may not be true and needs further confirmation. It was observed that the absorption test by ASTM D6489 is suitable for hydrophobic materials (e.g., sealer materials) and may not provide useful data for coating materials.

Table 4-2 shows the individual ranking obtained from water absorption test results.

After the weathering effects, Coat-D(SB) and Coat-A(WB) performed similarly, with a common rank of 7, which represents poor performance due to the weathering effects. The ranking of Coat-R(SB) under normal conditions was 8, which may not be true and needs further confirmation. It was observed that the absorption test by ASTM D6489 is suitable for hydrophobic materials (e.g., sealer materials) and may not provide useful data for coating materials.

Table 4-2: Ranking of products based on water absorption

Products	**Ranking**	
	Normal	**Weathered**
Sealer-100%	1	1
Sealer-40%	2	2
Coat-R(SB)	8	3
Coat-M(SB)	4	4
Coat-D(SB)	3	7
Coat-L(WB)	6	5
Coat-A(WB)	5	7
Coat-S(WB)	7	6

4.3.2 Sorptivity (ASTM C1585)

The sorptivity test data can be found in Figure 3-19 and Figure 3-22. The average value of initial and secondary absorption rates of the individual product were compared for ranking the products, with Rank 1 corresponding to the lowest absorption rate and Rank 8 corresponding to the highest absorption rate. Table 4-3 shows the individual ranking obtained from sorptivity test results. The higher-ranking products maintain the same ranking (better weathering resistance) after weathering and vice versa, with some minor changes in ranking. The weathering effect had a lower impact on Coat-L(WB) ranking than other WB coatings (Coat-A[WB] and Coat-S[WB]). The rankings of Coat-D(SB) and Coat-A(WB) were the same after weathering; a similar long-term water absorption performance can be expected from both products.

Table 4-3: Ranking of products based on sorptivity

Products	Ranking	
	Normal	Weathered
Sealer-100%	1	1
Sealer-40%	2	3
Coat-R(SB)	3	4
Coat-M(SB)	4	2
Coat-D(SB)	5	7
Coat-L(WB)	6	5
Coat-A(WB)	8	6
Coat-S(WB)	7	7

4.3.3 Rapid Chloride Ion Penetration (ASTM C1202)

Test results observed from the rapid chloride ion penetration test can be found in Table 3-7 (Chapter 3). Table 4-4 shows the individual ranking based on the average charge passed (coulombs) at 6 hours, with Rank 1 corresponding to the lowest value and 8 corresponding to the highest value. In general, the ranking after the weathering effect showed some considerable changes. For example, a slight decrease in the ranking for Sealer-100% and Sealer-40% (some weathering effects) and a slight increase in the ranking (no negative effect due to weathering) for Coat-D (SB) and Coat-L (WB) were observed, whereas Coat-M(SB) and Coat-R(SB) showed negligible changes in the ranking (i.e., maintained their top ranking, indicative of no such negative effect due to weathering). Coat-A(WB) and Coat-S(WB) ranked poorly both before and after the weathering effect, which is consistent with their ranking based on sorptivity and absorption test results.

Table 4-4: Ranking of products based on RCPT

Products	Ranking	
	Normal	Weathered
Sealer-100%	1	5
Sealer-40%	4	6
Coat-R(SB)	3	1
Coat-M(SB)	2	2
Coat-D(SB)	6	4
Coat-L(WB)	5	3
Coat-A(WB)	8	7
Coat-S(WB)	7	8

4.3.4 Chloride Ponding Test (ASTM C1556)

The test results observed from the chloride ponding can be found in Figure 3-27 and Figure 3-28 in Chapter 3. Appropriate WFs for the four tested layers were applied (e.g., 60 percent for the 0–4 mm layer; 30 percent for the 8–12 mm layer; 7 percent for the 16–20 mm layer, and 3 percent for the 28–32 mm layer) to estimate a representative average value of chloride content for each product. The average values for all the products were compared to assign the ranking, with 1 corresponding to the lowest value and 8 corresponding to the highest value. Table 4-5 shows the individual ranking of the tested products. Coat-S(WB) and Coat-A(WB) performed poorly and are less resistant to chloride ingress. The weathering effect impacted the ranking of Sealer-40%, and a similar observation was obtained from the RCPT results.

Table 4-5: Ranking of products based on chloride ponding test

Products	Ranking	
	Normal	Weathered
Sealer-100%	1	1
Sealer-40%	2	5
Coat-R(SB)	3	3
Coat-M(SB)	4	2
Coat-D(SB)	5	6
Coat-L(WB)	6	4
Coat-A(WB)	7	8
Coat-S(WB)	8	7

4.3.5 Pull-Off Adhesion Test in the Laboratory

The test results observed from the pull-off adhesion test under normal and weathered conditions are presented in Figure 3-32 and Figure 3-33, respectively. The average POAS values for all the products were compared to assign a ranking, with 1 corresponding to the highest adhesion strength value and 6 corresponding to the lowest adhesion strength value. Table 4-6 shows the individual ranking of the tested products based on POAS. The weathering effect has less impact (i.e., ranking remains almost the same) on POAS, that is, the ranking of the SB products (i.e., Coat-M[SB], Coat-R[SB], and Coat-D[SB]) maintained their higher ranking, and WB coatings (Coat-L[WB], Coat-A [WB], and Coat-S[WB]) maintained their lower ranking after weathering.

Table 4-6: Table 6: Ranking of products based on POAS

Products	Ranking	
	Normal	Weathered
Sealer-100%		
Sealer-40%		
Coat-R(SB)	1	1
Coat-M(SB)	3	2
Coat-D(SB)	2	3
Coat-L(WB)	6	5
Coat-A(WB)	4	6
Coat-S(WB)	5	4

4.3.6 Corrosion Monitoring under Steady State

Figure 3-41 show the test results observed from the corrosion monitoring under steady-state conditions. Since the corrosion rate observed from the steady state is based on 4 months of test data and the corrosion process under steady state is a long-term process, ranking of coating/sealer product based on the steady state was not attempted. However, the test result will be monitored till the active corrosion is encountered (may take around 1.5–2 years), and the results will be very valuable for validating the rate of corrosion measurements with the accelerated corrosion test.

4.3.7 Corrosion Monitoring under Accelerated Conditions

Corrosion monitoring under accelerated conditions has already been reported in Figure 3-44. The average corrosion rate (mpy) of eight coating/sealer materials for up to 60 days of monitoring was compared, and a ranking was developed. The lowest corrosion rate corresponds to the highest ranking (Rank 1), and the highest corrosion rate corresponds to the lowest ranking (Rank 8). Table 4-7 shows the corrosion rate-based ranking of the tested products. In general, Sealer-100%, Sealer-40%, Coat-R(SB), and Coat-M(SB) are identified as higher-ranking products, whereas Coat-D(SB), Coat-L(WB), Coat-A(WB), and Coat-S(WB) are identified as lower ranking products, which is broadly consistent with the ranking based on other tests described previously. Because a good substrate concrete with improved transport properties (low permeability) was used for evaluation, the measured corrosion rates till 60 days mostly represent passive corrosion and it is expected to take more time to detect the transition from passive to active corrosion. The ranking based on active corrosion is expected to improve, but a long wait time is not advisable. In the future, assessing the corrosion rate (detecting active corrosion) using a poor concrete substrate (use of high w/c ratio to create poor transport properties) is recommended, which is expected to make the test duration shorter and improve product ranking.

Table 4-7: Ranking of products based on accelerated corrosion test

Products	Ranking
Sealer-100%	3
Sealer-40%	2
Coat-R(SB)	1
Coat-M(SB)	4
Coat-D(SB)	7
Coat-L(WB)	5
Coat-A(WB)	8
Coat-S(WB)	6

4.4 Importance/Priority Levels for the Identified Performance Indicators

Based on the test results presented in Chapter 3 for the identified performance indicators (Table 4-1) and the above description of product ranking under each test, it is prudent to mention that not all performance indicators have similar significance in terms of performance assessment of sealer and coating systems. Therefore, based on the significance of the performance indicators, a WF depending on the importance level can be set. Table 4-8 shows the selected WFs. In this research, three different levels of WFs were considered (low WF [0–5], medium WF [6–15], and high WF [16–25]), and the levels are completely based on information from this research project.

The following considerations were adopted for selecting the WF levels:

- Performance indicators with low significance/importance should be assigned a WF value within the low range.
- Similarly, performance indicators with high significance should be assigned a WF value within the high range.
- Any single performance indicator should not get more than a certain WF (in the present study, the highest level was fixed as 25).
- The total WF score should be 100.

Table 4-8: Assigned WFs for the individual performance indicators

Performance indicators	WFs for Coatings	WFs for Sealers
Water absorption (ASTM D6489)	5	6
Water absorption (sorptivity) (ASTM C1585)	15	19
Pull-off adhesion test (ASTM D7234)	20	
Chloride penetration (ASTM 1556, chloride ponding test)	20	25
Chloride penetration (ASTM 1202, RCPT)	20	25
Corrosion (accelerated)	20	25
Total	**100**	**100**

4.5 Development of a Compound Rating System

The compound rating system was developed by considering all the individual scores and multiplying them by the corresponding WF as per Table 4-8. Figure 4-2 shows the compound rating system for the coating materials. The compound rating for the SB products (Coat-R[SB], Coat-M[SB], and Coat-D[SB]) is higher (Rank 1 best performance) than the WB coatings (Coat-A[WB], Coat-S[WB], and Coat-L[WB]). The change in ranking after considering the weathering effect is marginal for Coat-A(WB), Coat-S(WB), and Coat-D(SB), which indicates that the poorly performing products under normal conditions continue to perform poorly under weathered conditions (negative effects due to weathering). In contrast, Coat-R(SB), Coat-M(SB), and Coat-L(WB) showed a slight improvement in ranking after weathering (i.e., performed well with no negative effects due to weathering). Based on the compound rating estimations for the sealers using WFs in Table 4-8, Sealer-100% ranked higher than Sealer-40%.

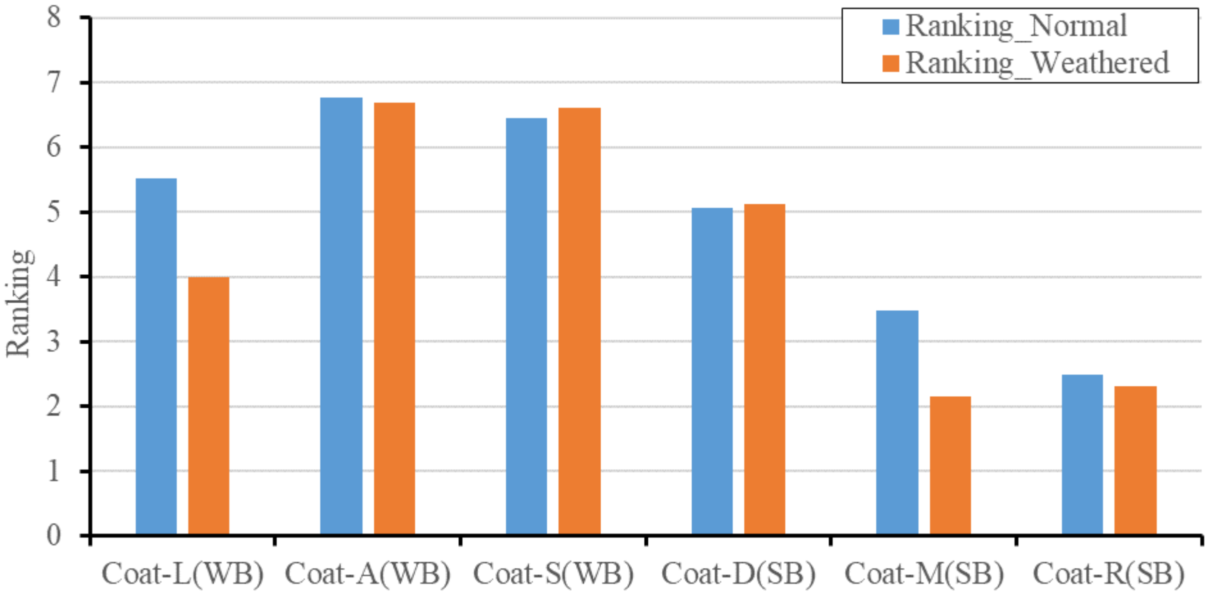


Figure 4-2: Summary of the ranking considering all priority levels

4.5.1 Sensitivity Assessment on the Developed Rating System Considering a WF for the Weathering Condition

For the recommendation of a product for a project, conducting all these performance tests (i.e., assessment of all performance indicators) under weathered conditions may not be feasible. Performance under weathering conditions can be considered in the laboratory just for one-time evaluation and understanding. Figure 4-2 represents the ranking of the tested coating materials under both normal and weathering conditions with 100 percent weightage (either normal or weathered). To incorporate the weathering effects with varying levels, a combined rating with varying percentages of normal and weathered conditions (70 percent normal + 30 percent weathered, 50 percent normal + 50 percent weathered, and 30 percent normal + 70 percent weathered) was considered (Figure 4-3). The change in ranking after incorporating weathering effects (30 percent, 50 percent, and 70 percent) is negligible. With increasing weathering effects, Coat-L(WB), Coat-M(SB) Coat-R(SB) show some slight improvement in ranking (indicative of better weathering resistance), whereas Coat-A(WB), Coat-S(WB), and Coat-D(SB) show a slight decrease in ranking (indicative of relatively poor weathering resistance).

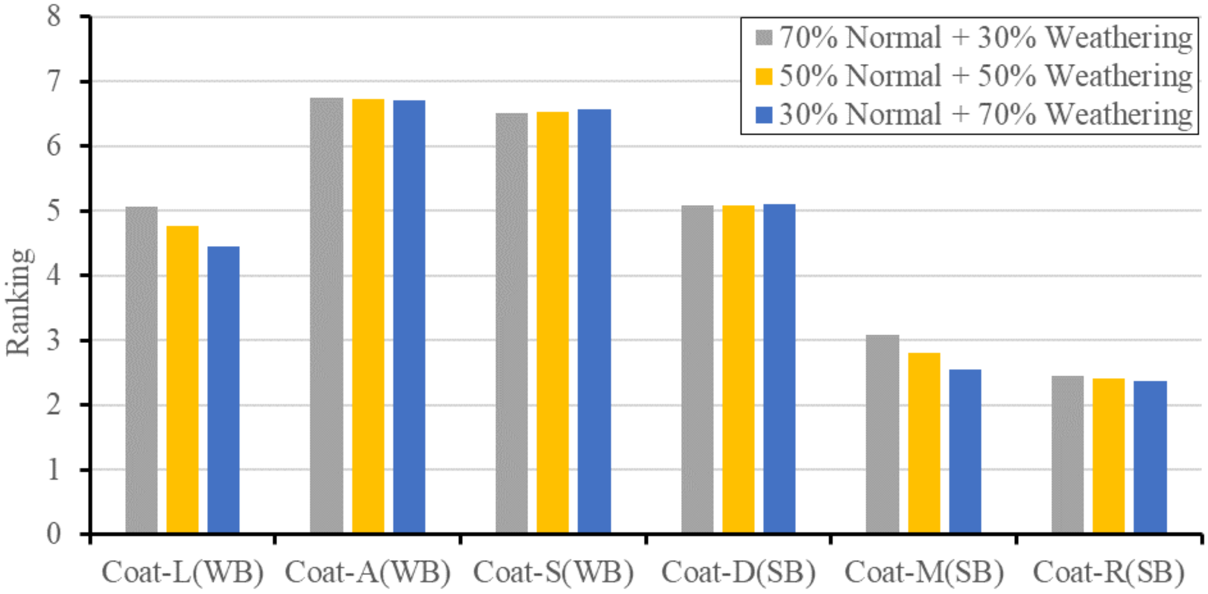


Figure 4-3: Sensitivity of the rating system considering different weightage for the weathering effects

4.5.2 Assessment of the Coating Materials with a Minimum Number of Performance Indicators

Chloride ponding and corrosion monitoring experiments are tedious and take approximately 3–4 months to complete. For a relatively quicker assessment without compromising reliability, optimizing the number of experiments (i.e., reducing the number of tests) was attempted. Figure 4-4 shows the ranking of coating materials based on three performance indicators (Sorptivity, RCPT, and POAS test). The WFs for the Sorptivity, RCPT, and POAS were considered as 33.33 percent, 33.33 percent, and 33.33 percent, respectively. The compound ranking (Figure 4-4) is almost similar to Figure 4-2 (ranking considering all performance tests). Therefore, the proposed performance evaluation using the minimum number of performance tests should be useful to rank the products, but it needs more product evaluation to check the validity of the proposed approach.

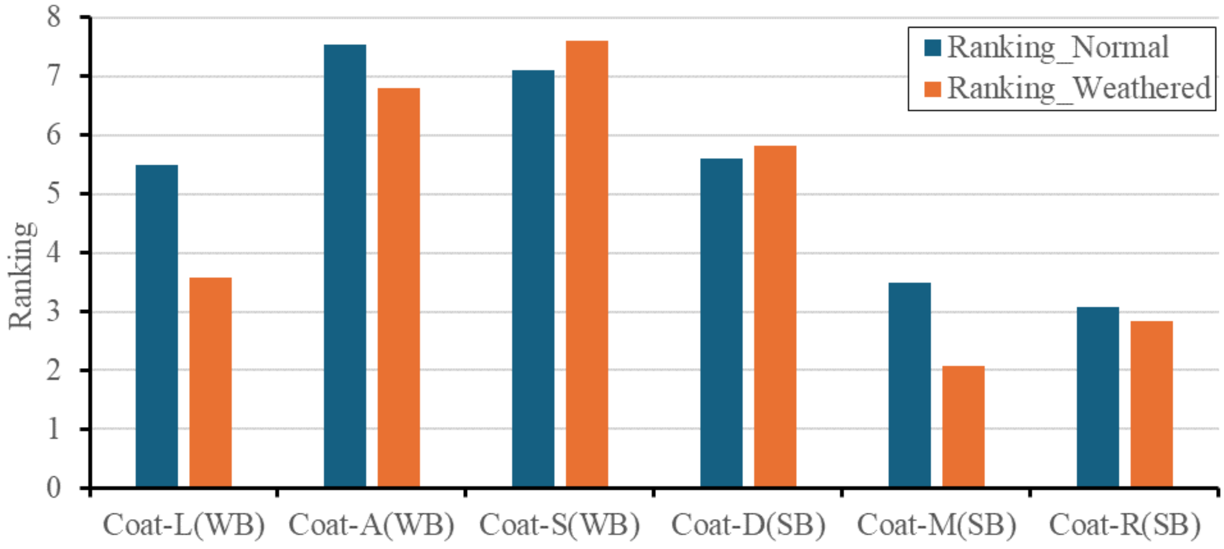


Figure 4-4: Ranking of the coating materials based on minimum performance indicators (sorptivity, RCPT, and POAS)

4.6 Conclusion

In the present research project, the focus was to develop a laboratory-based test protocol to evaluate the effectiveness of sealer and coating materials. Identification of critical performance indicators based on the results obtained from the extensive laboratory performance evaluation of the selected sealers and coating materials (Chapter 3) for developing a rating system was determined. The rating system was developed using the identified performance indicators under both normal and weathered conditions. The main findings from the work under Task 4 are summarized below:

- Different performance indicators under normal conditions show almost similar individual ranking systems. Sealer-100% and Sealer-40% performed well for most of the performance assessments. However, the individual ranking under weathering conditions showed a change. Coat-A(WB) and Coat-S(WB) performed poorly for most of the performance indicators and thus have a lower rank.
- The combined ranking was based on the preselected WFs depending on the importance levels (low to high) of different performance indicators.
- The compound rating system shows the overall performance of different coating materials from which a product can be selected. It is better to rank sealers and coatings separately because some of the performance indicators (e.g., POAS) are not common between sealers and coatings.
- Some products are more sensitive to the weathering effect; to have an idea about the long-term performance of the selected coating products, the weathering effect with a suitable WF can be considered.

- It might be possible to conduct a minimum number of experiments (e.g., sorptivity, RCPT, and POAS, etc.) in the laboratory for a relatively quicker product evaluation without compromising reliability. However, more product evaluation to check the validity of the proposed approach is highly warranted.

CHAPTER 5: ESTABLISH FIELD VALIDATION SITES

This chapter reports the details of the field visits and work performed related to the assessment of the effectiveness of sealer and coating materials on concrete bridge substructures. Different surface preparations, their effectiveness, and recommendations on surface preparation have also been provided. The application of a trial coating product in the field and the pull-off adhesion performance of two different coating materials were evaluated and the same performance evaluation was performed in the laboratory.

5.1 Objective

The primary goal of Task 5 was to establish a field validation of the observations and correlate them with the laboratory results. Initially, it was proposed that the dielectric rating and corrosion rate be assessed on concrete bridge substructures within Texas. However, due to some limitations of such proposed technology in field application/monitoring, the present observations are completely based on surface preparation, inspection of old and existing coatings, assessment of the adhesion strength of new coating products in the field, performance assessment of coating product in the field, DOP of already sealed substrate, etc. The specific tasks that were covered within the scope of the Task 5 are as follows:

- Effectiveness of different surface preparation methods (water-blasting and abrasive-blasting (using sand) on existing coated surfaces of concrete bridge substructures. Recommendation on surface preparation and moisture measurement.
- Observation of application of coating materials (WB and SB) on concrete bridge substructures.
- Application of a trial coating product both in the field (on concrete bridge substructure) and in the laboratory. Performance assessment (POAS) of the applied coating materials in the field and laboratory.
- Assessment of the DOP (taking small cores followed by observation under a microscope in the lab) on a sealed concrete substrate in the field.

5.2 Field Visit Details

Researchers from TTI visited four different field projects related to the coating and sealer materials. Based on the scope of the projects, the researchers from TTI observed surface preparation methods (sandblasting and water-blasting), concrete substrate moisture measurement (using a portable moisture meter), application of coating materials (using hand and spray pump), performance assessment (POAS) on a coated surface, assessment of DOP (using a stereomicroscope) on already sealed concrete substrate, etc. The details of the field visits are given as follows:

- San Antonio (IH 10/IH 35).
- Dallas (IH 345).
- Dallas (IH 20 at IH 35E).
- Bryan (SH 6).

5.3 San Antonio (IH 10/IH 35) Project

A detailed field visit was conducted at the San Antonio project. The location was near Guadalupe St. (IH 10/IH 35). Four bridge piers (columns)—AA50, BB50, CC48, and DD48—were selected for the observation of surface preparation, a pull-off adhesion test, and the application of new coating material (Coat-L[WB]). Multiple visits were made to the San Antonio project, and the work was performed in two phases:

- Phase I: Summary of the observations: Performance of Coat-L(WB) and Coat-A(WB) coating on different concrete surfaces in the field (San Antonio).
- Phase II: Summary of the observations: Performance of Coat-L(WB) and Coat-A(WB) coating on different concrete surfaces at the laboratory (TTI).

Researchers have assessed the trial performance of a new coating material (Coat-L[WB]) on different prepared column surfaces. Since Coat-A(WB) (a commonly used coating product) was the selected coating for this field project, the adhesion performance of Coat-A(WB) was also evaluated. The selected concrete bridge substructure elements were more than 35 years old, with an existing coating layer on them. Based on the inspection, it was decided to apply a new coating layer to extend the life of the structure and improve the aesthetic look. The old existing coating (Texcote XL70) on these columns was applied between 1987 and 1991. Two surface preparation methods—(a) water-blasting (working pressure 5000 psi) and (b) sandblasting (working pressure 100 psi)—were employed by the contractor in the presence of the TxDOT engineer and the TTI researchers. Figure 5-1 and Figure 5-2 show the surface preparation by water-blasting and sandblasting, respectively. It was observed that the water-blasting was effective in removing the dirt from the coated surface, with isolated spot removal of the old coating layer (Figure 5-3 and Figure 5-4). Although sandblasting was successful in removing the old paint completely (Figure 5-3), it exposed voids (varying in size and shape) on the concrete surface (Figure 5-4), meaning it created a concrete surface with higher CSP (CSP 3-4), which sometimes may lead to the creation of weak interfaces between the sandblasted surface and new coating (here Coat-L[WB]). It was decided that surface preparation by water-blasting should be adequate before the application of the new coating layer (of Coat-A[WB]) on the concrete substrate. Following are the details of the two products that were applied in the San Antonio field:

- Coat-L(WB): The Coat-L product (as a new trial coating material) was applied on different prepared surfaces by a hand roller on April 14, 2023. The WFT of 15–16 mils (one coat) was maintained as per the product datasheet. After a curing period of more than a month, the performance evaluation of the applied products was conducted.

- Coat-A(WB): The Coat-A product was applied to the bridge substructure after the water-blasting using a spray pump in the field by the contractor. The same coating product was applied on concrete specimens in the laboratory (TTI) using a hand roller by maintaining proper WFT 6–7 mils (one coat). After more than a month of curing, the performance evaluation of the applied products was conducted.

On May 22–23, 2023, the pull-off adhesion test was performed in the field according to ASTM D7234-22 to evaluate the adhesion performance of this newly applied product (Coat-L[WB]) and Coat-A(WB) coating. A 50 mm dolly was used for the pull-off adhesion test of the applied coatings on the concrete substrate.

Water-blasting

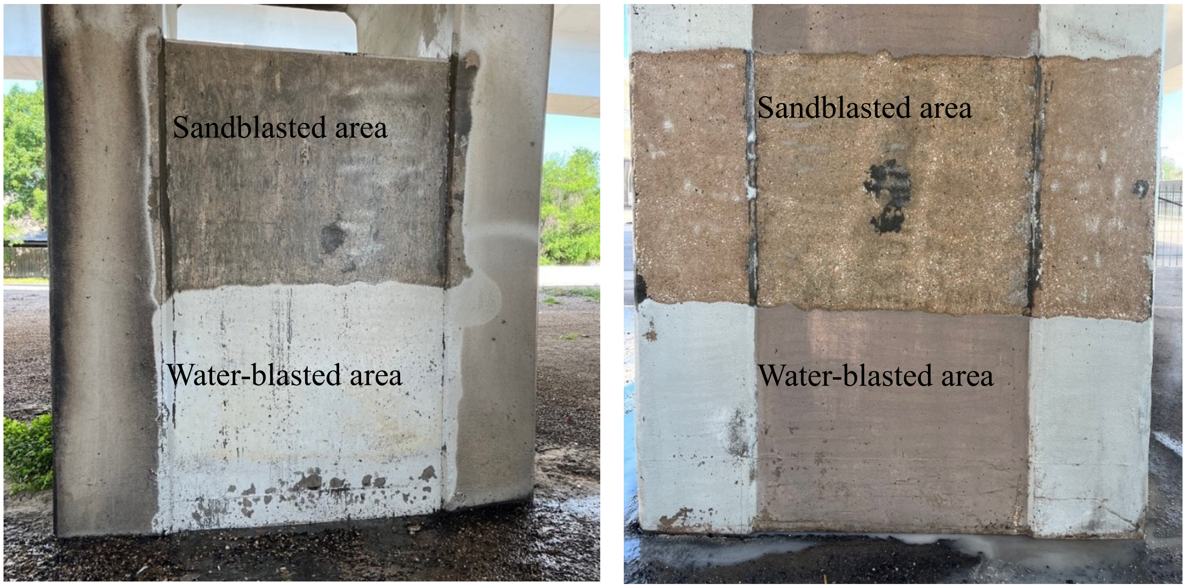
Surface before and after water-blasting

Figure 5-1: Water-blasting on concrete bridge substructures (Column BB50)

Sandblasting

Surface before and after sandblasting

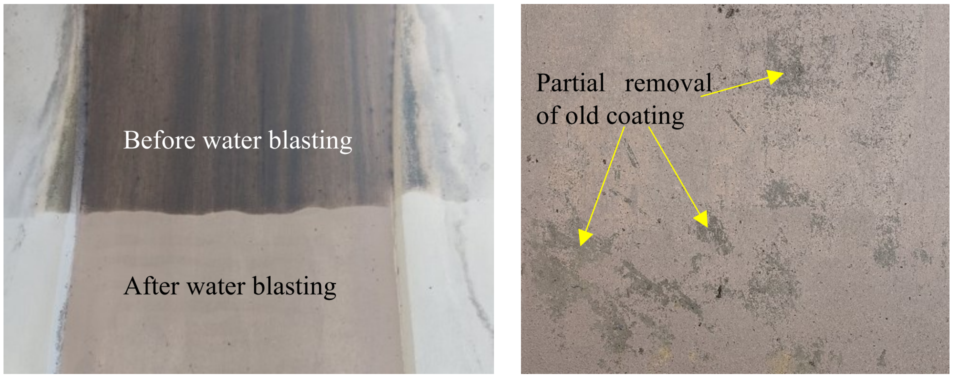
Figure 5-2: Sandblasting on concrete bridge substructures (Column CC48)



Column AA50

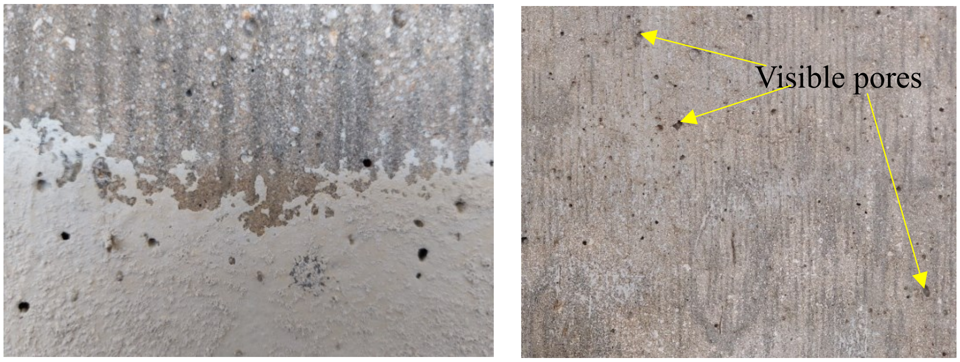
Column CC48

Figure 5-3: Concrete substrate after sandblasting and water-blasting



(i) Water blasted and control surface

(ii) Water blasted surface



(iii) Sand blasted surface (top) and controlled surface with visible chalking on coating (bottom)

(iv) Sand-blasted surface (with visible pores)

(v) UV-affected surface (water blasted)

(vi) Partial removal of UV-affected old coating material after water blasting

Figure 5-4: Different prepared and UV-affected surfaces

5.3.1 POAS on Water-Blasted and Sandblasted Surface

The schematic representation of the dolly attachment on a water-blasted surface with different interfaces (i.e., Glue-Dolly [G/D], Coat-L[WB] [or Coat-A(WB)]-Glue [L(or A)/G], Texcote-Coat-L[WB] [or Coat-A(WB)] [T/L(or A)], and parent concrete—Texcote [P/T]) and failure modes through these interfaces is shown in Figure 5-5. Similarly, the schematic representation of the dolly attachment on a sandblasted surface with different interfaces (i.e., Glue-Dolly [G/D], Coat-L[WB]-Glue [L/G], and parent concrete—Coat-L[WB] [P/L]) and failure modes through these interfaces are shown in Figure 5-6.

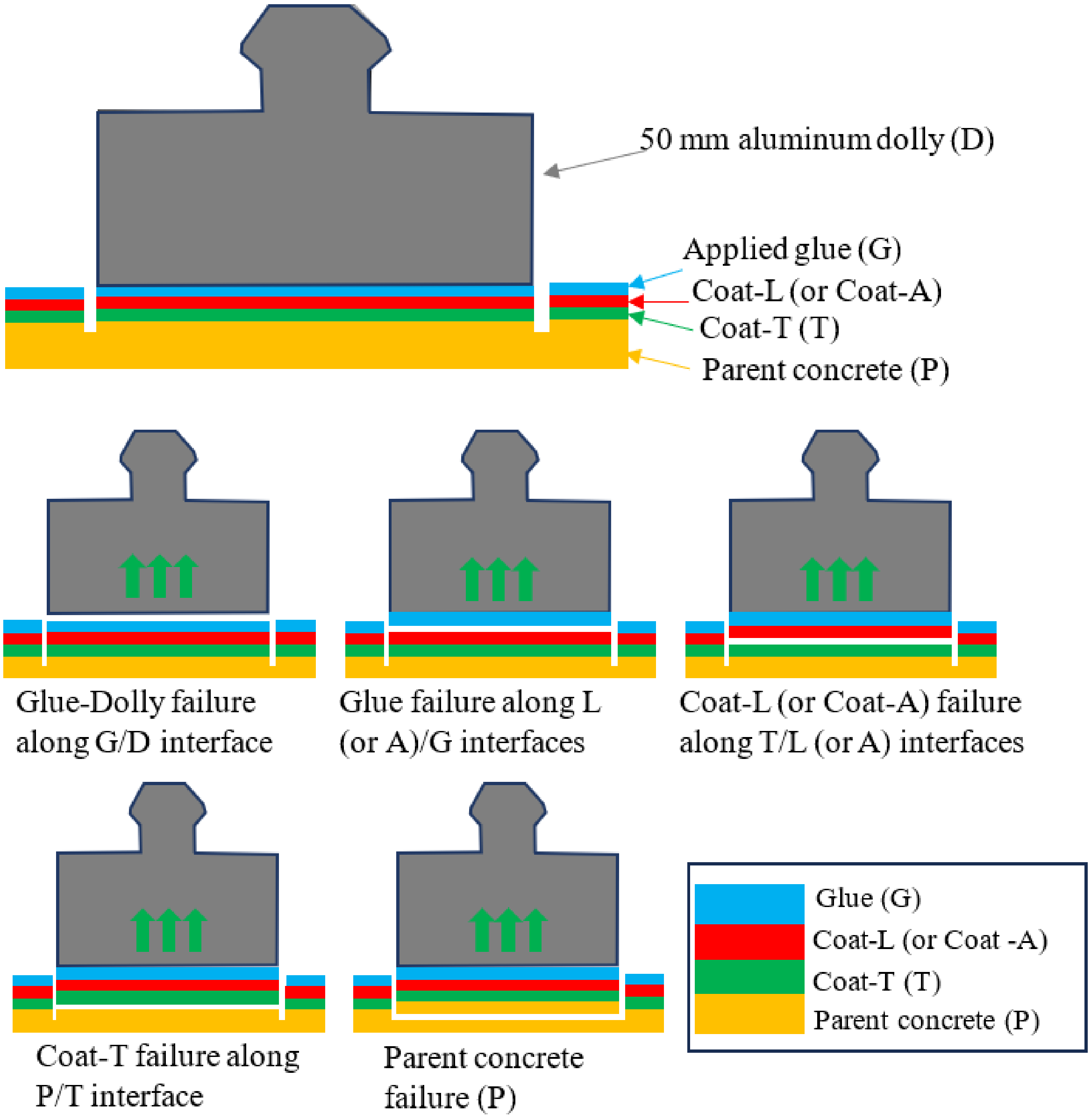


Figure 5-5: Schematic diagram showing failure modes along different interfaces for a water-blasted surface

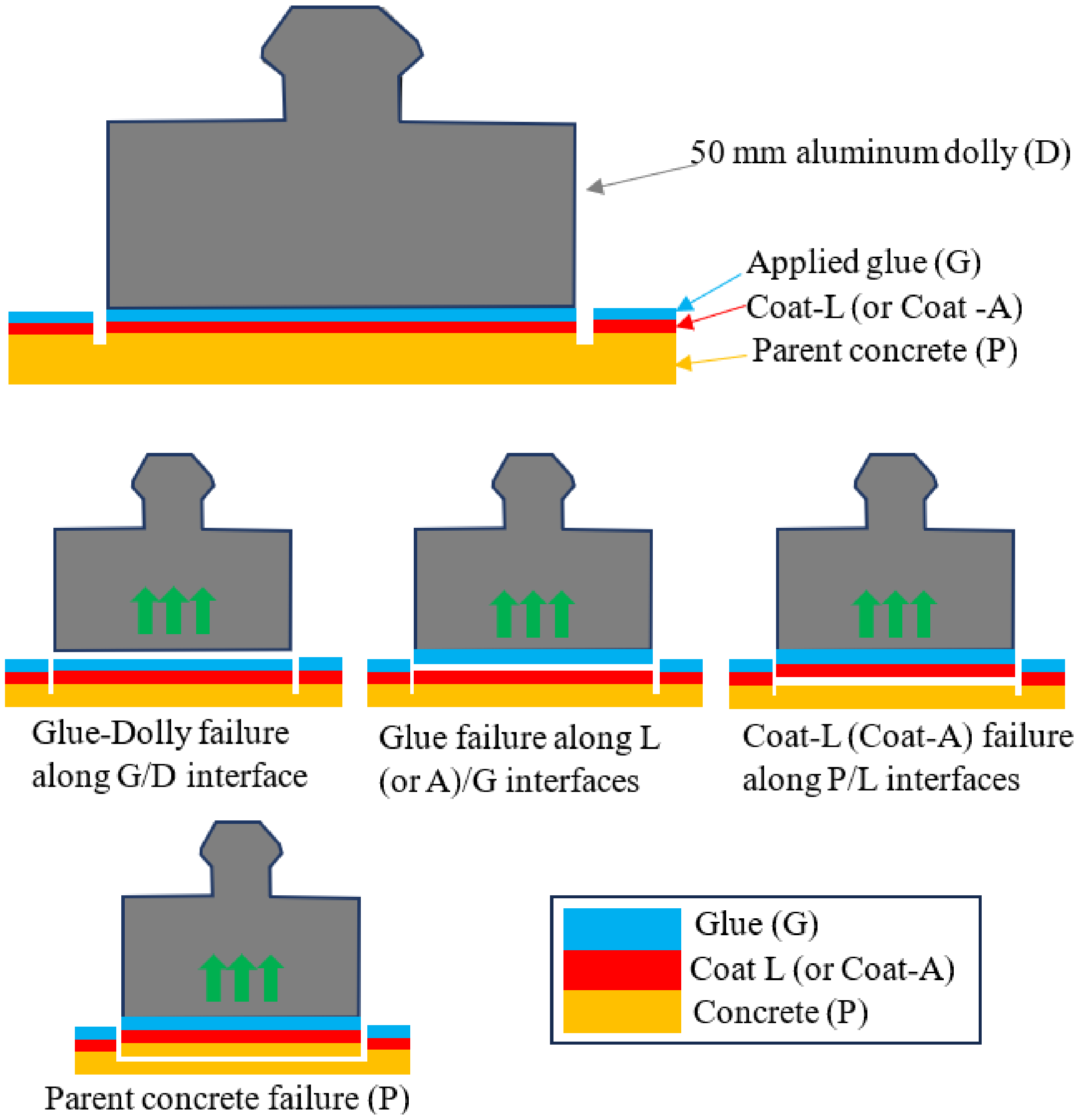


Figure 5-6: Schematic diagram showing failure modes along different interfaces for a sandblasted surface

5.3.2 Different Prepared Surfaces and POAS

5.3.2.1 Water-Blasted Surfaces

CWB-L represents the location on the column (bridge substructure element) with negligible sunlight exposure (i.e., under shade, no UV exposure effect) and with an applied coating of Coat-L (WB). The POAS values are presented in Figure 5-7. After the pull-off adhesion test, the failure surface underneath the dolly as well as the concrete substrate was carefully assessed visually to estimate the failure mode and corresponding percentage of failure. Two data points (i.e., CWB-L1 and CWB-L3), as presented in Figure 5-7, show the primary failure along the G/D interface (i.e., poor glue adherence with the dolly) and were discarded as per the standard (ASTM D7234 recommends any test data that show more than 25 percent area with glue failure should be discarded). At test point CWB-L2, the primary failure occurred along the Coat-T and Coat-L interface (T/L), and the corresponding POAS is 243 psi. The test point CWB-L4 showed failure along the parent concrete and Coat-T interface (P/T), with a POAS of 300 psi. The nature of failure surfaces is represented in Figure 5-8. The results indicated that the adhesion of Coat-L (new) with Coat-T (old coat) was better at CWB-L4 when compared to the CWB-L2 location, which is reflected in a higher adhesion strength (300 psi) at CWB-L4 than at the CWB-L2 location (241 psi).

Overall, the adhesion strengths (Figure 5-7) between Coat-L and water-blasted surfaces with old coatings were lower than the POAS provided in the data sheet (~375 psi). It seems varying moisture conditions of the field concrete substrate after water-blasting were responsible for creating this kind of lower POAS between Coat-L and water-blasted surfaces. Concrete absorbs moisture from water-blasting then retains that moisture within the old coating (depending on the degree of absorption of the old coating) along the interface between the old coating (Coat-T) and concrete surface (the poorer the adhesion, the higher the water accumulation) and inside the topmost portion of the water-blasted concrete (depending on the water absorption capacity of the substrate concrete). The moisture-retaining time varies depending on the ambient temperature, moisture conditions, and coating thickness. Based on a simple blotting paper test in the field at different locations of the studied column, the presence of moisture (physical water) was found to be negligible after 48 hours. As a result, Coat-L was applied 48 hours after water-blasting, which was also supported by earlier research (*12*, *28*). Because the thin coat (Coat-A with WFT 6.5–10.0 mils) offers breathability to some extent, the moisture effect on POAS may be less. However, for the thick coat (e.g., Coat-L with WFT 15–18 mils), maintaining a relatively dry concrete surface before applying the coating is important for obtaining optimum POAS and ensuring effective coating performance. When a dolly is attached for the pull-off adhesion test, the glue may receive moisture from the concrete ± old coating underneath, which possibly caused the glue failures observed at the CWB-L1 and CWB-L3 location points during the pull-off adhesion tests (Figure 5-7).

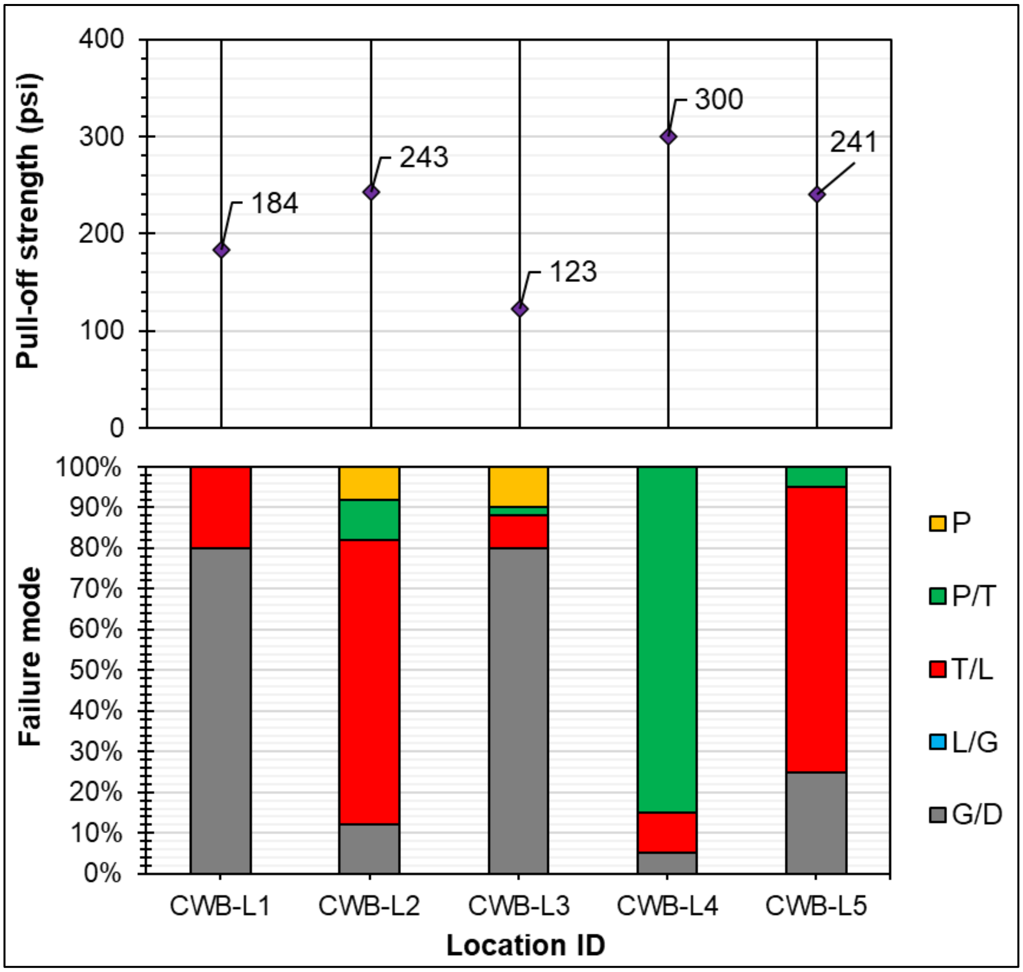


Figure 5-7: Pull-off adhesion test results on water-blasted surface (concrete column with negligible sunlight exposure, Coat-L [Coat-L(WB)])

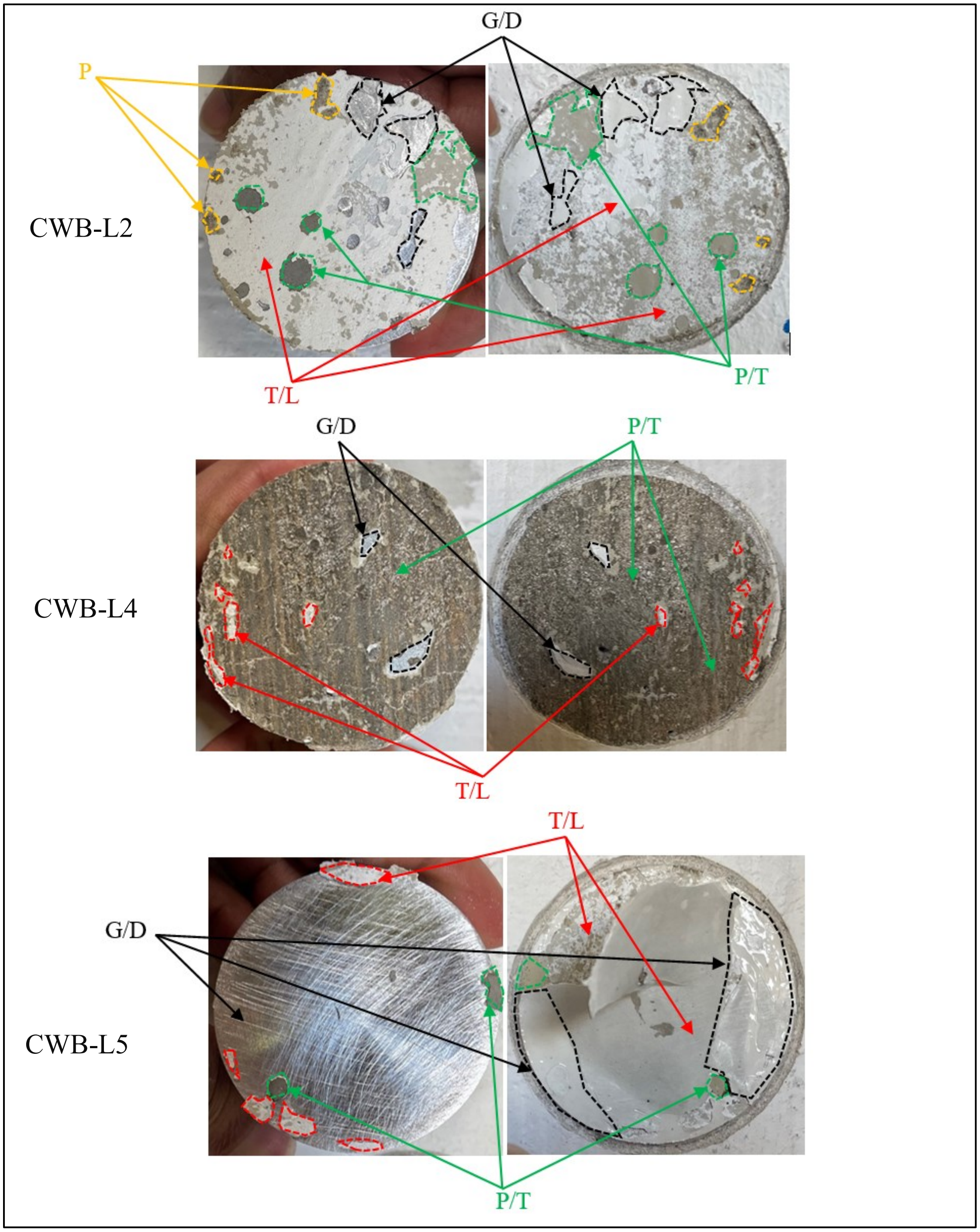


Figure 5-8: The nature of failures observed at some of the location points (of Figure 5-7) during pull-off adhesion test (left images represent the dolly surface and right images represent the concrete surface after the test)

CWB-A represents the location on the same column that was used for CWB-L but with an applied coating of Coat-A(WB). The POAS values are presented in Figure 5-9. All four data points showed the failure of parent concrete (10–45 percent), with minimum glue/dolly failure (5–15 percent). Because the glue/dolly failure (5–15 percent) was within the recommended limit (i.e., 25 percent) of ASTM D7234, all the data points in Figure 5-9 can be considered for the analysis. Overall, the failure was primarily at the old coat (T)-A (T/A) interface. At data point CWB-A2, approximately 90 percent of failure was through the T/A interfaces, with a maximum POAS value of 273 psi. A slightly lower POAS value (194 psi) for data point locations CWB-A3 and CWB-A4 than at data point CWB-A2 may be related to slightly weaker parent concrete (since P failure is more in these locations than at CWB-A2). Since the CWB-A1 shows some amount (~30 percent) of P/T failure [indicative of a weaker bond between parent concrete and old coating (T)], the average POAS value (i.e., 160 psi) in this location is significantly lower than the highest POAS (273 psi) in the CWB-A2. Because the POAS is not reported in the product data sheet for Coat-A, whether 273 psi (max. field POAS) is adequate to maintain an acceptable field performance of this coating material is unknown.

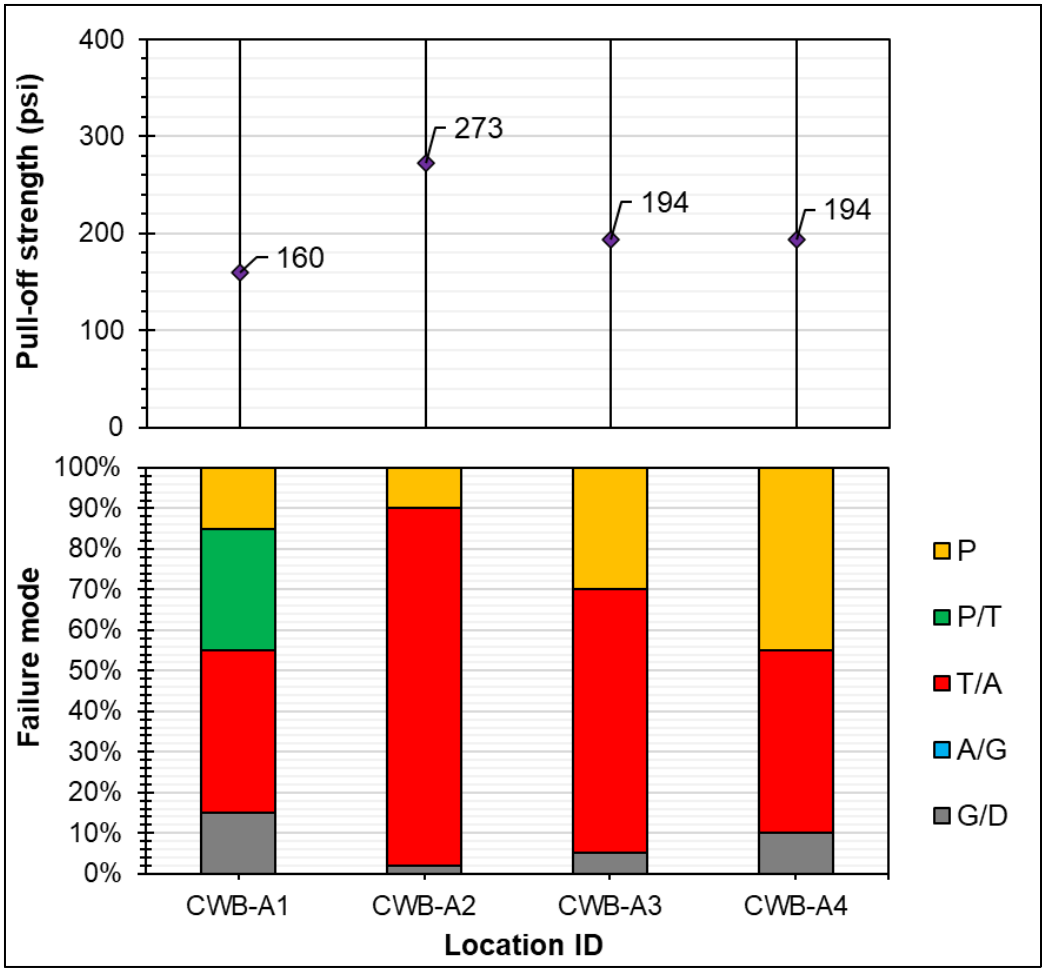


Figure 5-9: Pull-off adhesion test results on water-blasted surface (concrete column with negligible sunlight exposure, Coat-A)

5.3.2.2 Sandblasted Surfaces

CSB-L represents a different location on the same column with negligible sunlight exposure, as in location CWB-L, but with a sandblasted surface and Coat-L. For most of the test data points

(Figure 5-10), the failure was along the Coat-L coating and the parent concrete (P/L) interfaces. The average POAS value was 195 psi. Because of sandblasting, the surface roughness of CSB is comparatively higher (manifested by CSP 3-4 with some weaknesses) than that of a water-blasted surface (e.g., CWB) (Figure 5-8 and Figure 5-11), which may have caused relatively lower POAS (i.e., 169–246 psi) for CSB-L than the POAS (i.e., 241–300 psi) for CWB-L for Coat-L. The presence of bigger pores/voids and dust may also have added additional effects for failure along P/L interfaces. This observation suggests that water-blasting should be adequate for the project.

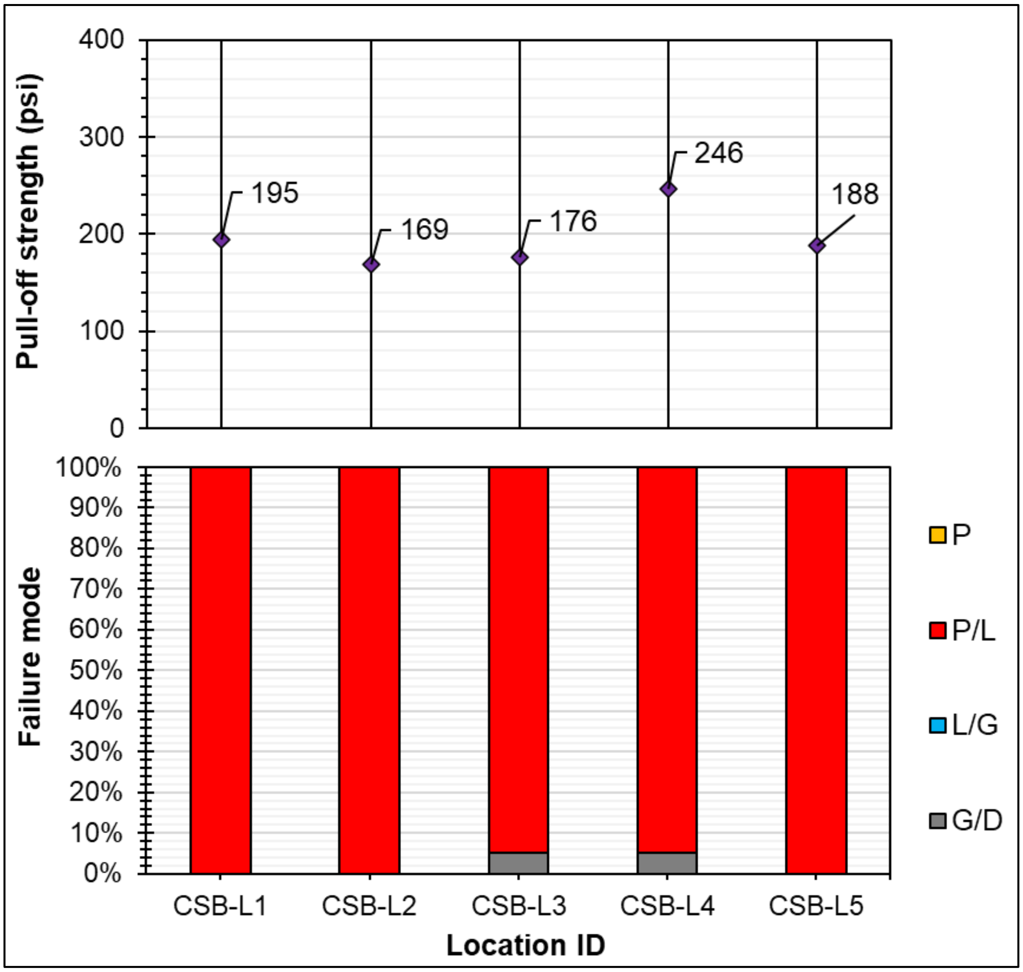


Figure 5-10: Pull-off adhesion test results on sandblasted surface (concrete column with negligible sunlight exposure, Coat-L)

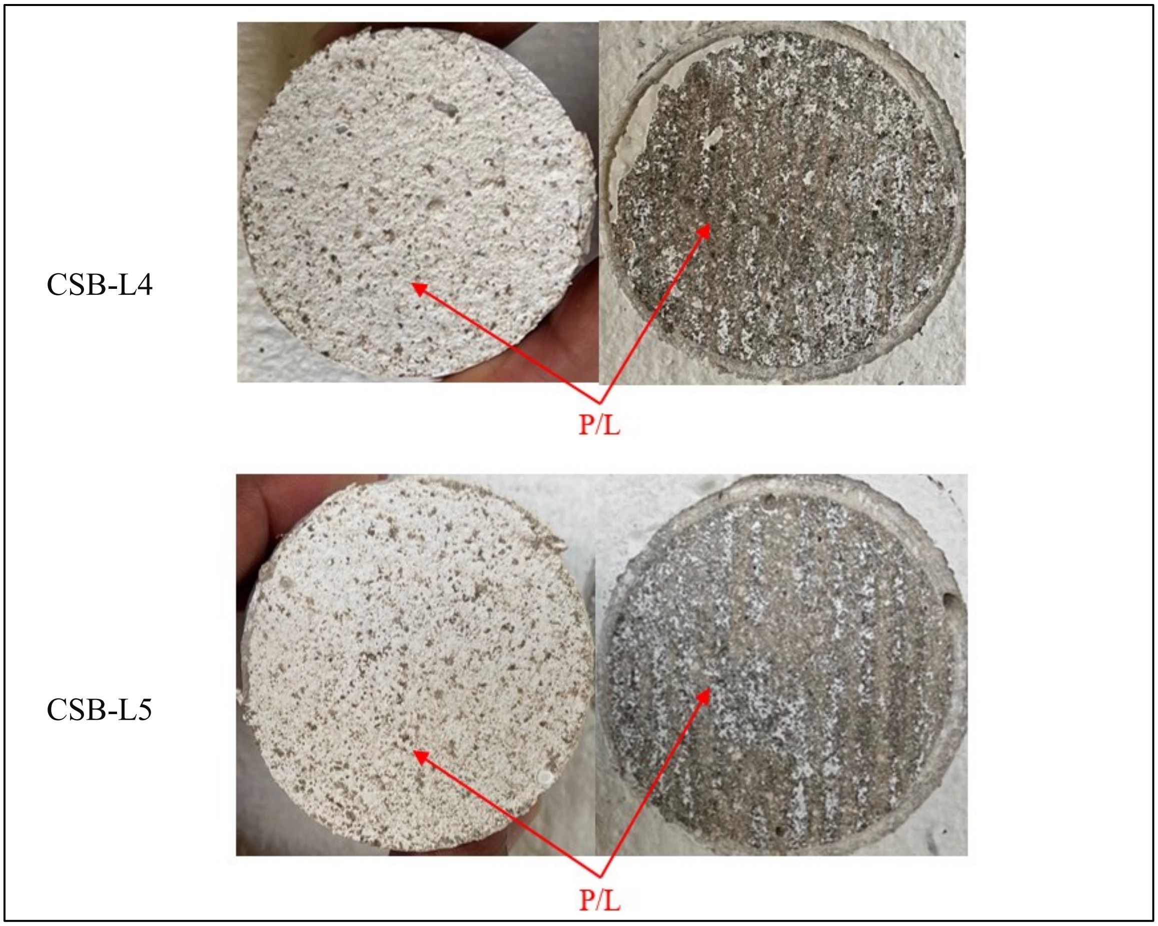


Figure 5-11: The nature of failures observed at some of the data points (of Figure 5-10) during pull-off adhesion tests (left images represent the dolly surface and right images represent the concrete surface after the tests)

CSB-A represents a different location on the same column with negligible sunlight exposure as in location CSB-L but with Coat-A. The average POAS value at this location was 209 psi for the thin coating (Coat-A), with mostly failure along the parent concrete and Coat-A (P/A) interfaces (Figure 5-12). Moreover, the failure of the glue/dolly was below 10 percent, which indicates that all the data points can be considered for analysis. At data point CSB-A2, approximately 5 percent parent concrete failure was observed. Location CSB-A1 showed the highest POAS (i.e., 230 psi). Overall, the performance of the thin coating (Coat-A) was comparable with the thick coating (Coat-L) on the sandblasted concrete surface.

Because the adhesion strengths of the studied coating materials (i.e., Coat-L and Coat-A) on the water-blasted surface were distinctly higher than that of sandblasted surfaces, the use of the water-blasting method was recommended. Moreover, the sandblasting method has other disadvantages, such as (a) is not environment-friendly, (b) can create micropores, and (c) reduces the overall dimension of the concrete column by trimming a thin layer (less than 3/16 inch [~5 mm]) of concrete.

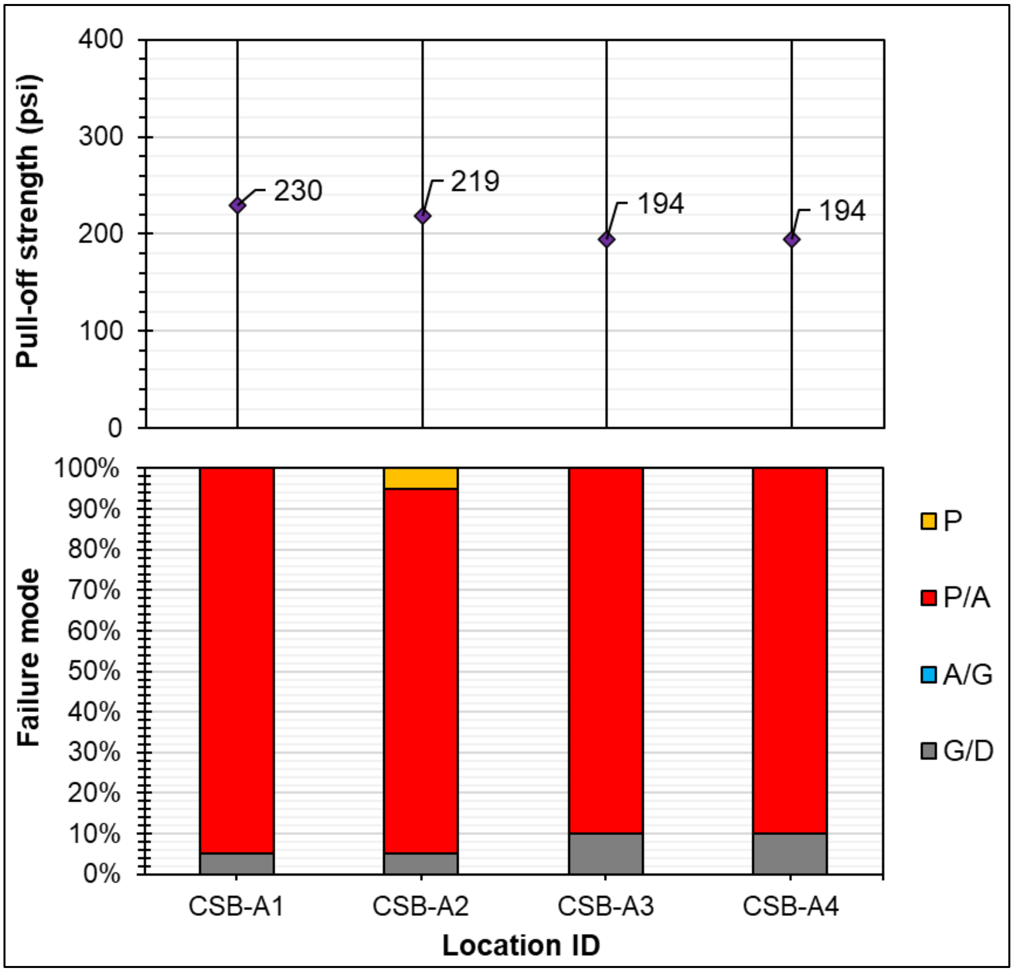


Figure 5-12: Pull-off adhesion test results on sandblasted surface (concrete column with negligible sunlight exposure, Coat-A [WB])

5.3.2.3 UV-Affected Surfaces

CUV-L was on the column with the highest sunlight exposure. It was expected that the effects due to long-term UV exposure of old coating (T) and the topmost portion of the concrete should be captured in the POAS measurements. Since the CUV-L1 data point showed glue failure (i.e., failures along the G/D and L/G interfaces), these data were not considered (Figure 5-13) for analysis. The results show a low range of POAS values (i.e., 59–162 psi), with failure mostly through the parent concrete and Coat-T (old coat) interfaces (i.e., P/T) (Figure 5-14). The deterioration of the old coating (T) due to long UV exposure most likely caused the prominent failures along the P/T interfaces. Some deterioration (e.g., swelling) was also observed in the parent concrete surface because of the long-term UV exposure and weathering, which can be correlated to the measured parent concrete failure (15–30 percent).

The low level of POAS (59–162 psi) measurements with primary failure along P/T interfaces in the UV-affected areas indicates failure before reaching the max POAS (measured in the CSB [246–273 psi] and CWB [273–300 psi] locations with negligible UV exposure) and do not represent the true POAS for the newly applied coating materials (i.e., Coat-L and Coat-A). However, several representative columns affected by UV exposure with varying degrees need to be evaluated to draw meaningful conclusions.

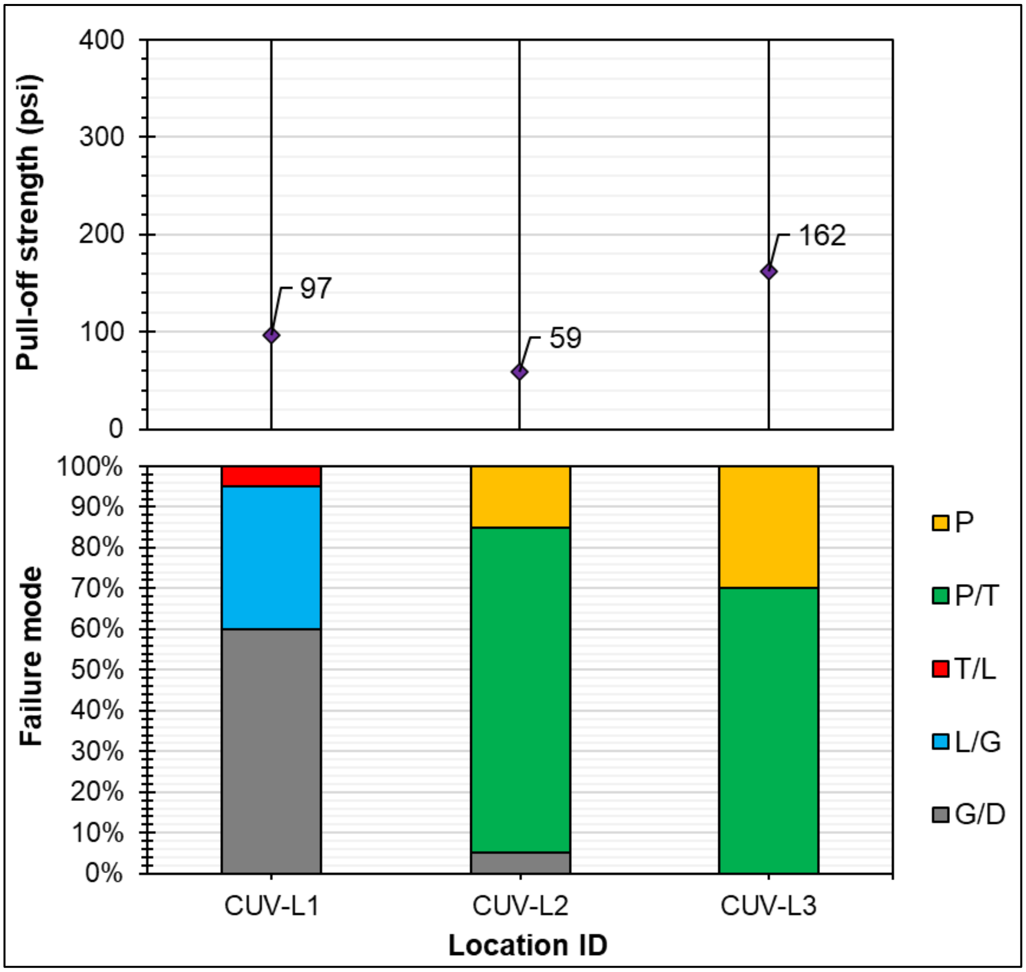


Figure 5-13: Pull-off adhesion test results on a UV-affected surface (concrete column with highest sunlight exposure, Coat-L)

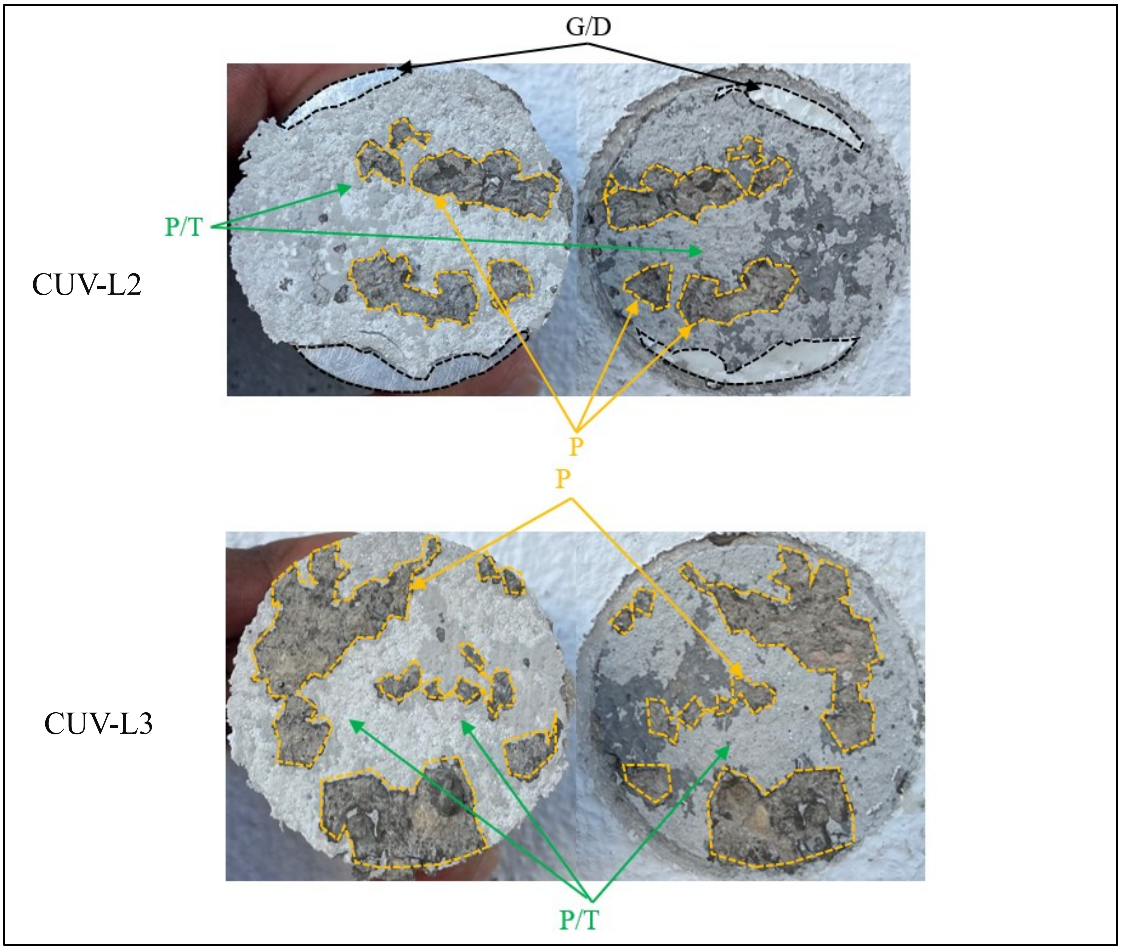


Figure 5-14: Nature of failures observed at some of the data points (of Figure 5-13) during pull-off adhesion (left images represent the dolly surface and right images represent the concrete surface after the test)

CUV-A represents a different location on the same column with the highest sunlight exposure as in CUV-L but with Coat-A. The POAS results from the multiple testing points in this location are presented in Figure 5-15. Overall, the major failure was the old coating failure (existing old coating) (Figure 5-15). Since significant glue/dolly (G/D) failure (~60 percent) was observed at the CUV-A2 testing point, these data were not considered for analysis. Because the G/D failure in the testing point, CUV-A1, was slightly above the 25 percent threshold limit, this data point was also not considered for data interpretation. The results show a low-medium range of POAS values (i.e., 149–157 psi), with failure both along the old Coat-T (old coat) and new Coat-A interfaces (i.e., T/A) and within the parent concrete (P failure). The absence of P/T failure (the main failure for CUV-L, Figure 5-13) might be due to the combined effects of relatively lower degrees of coating deterioration and higher degrees of concrete deterioration due to long-term UV exposure and coating thickness (low WFT for Coat-A vs high WFT of Coat-L) in this location, unlike at CUV-L. However, the average pull-off adhesion values were higher than location CUV-L where the thick coating was applied. In summary, the UV-affected locations showed a similar range of POAS values (i.e., lower than the POAS of CWB and CSB locations with negligible UB exposure) for both the coatings (Coat-L and Coat-A), and it is primarily due to the deterioration of the topmost portion of the concrete as well as the old coating over time, which match with the findings from earlier research (*30*). Therefore, concrete substrate plays a significant role in the adhesion strength of coating materials (*69*). The weaker concrete substrate results in poor adhesion strength. The coating thickness (thick or thin coat) does not matter in this case.

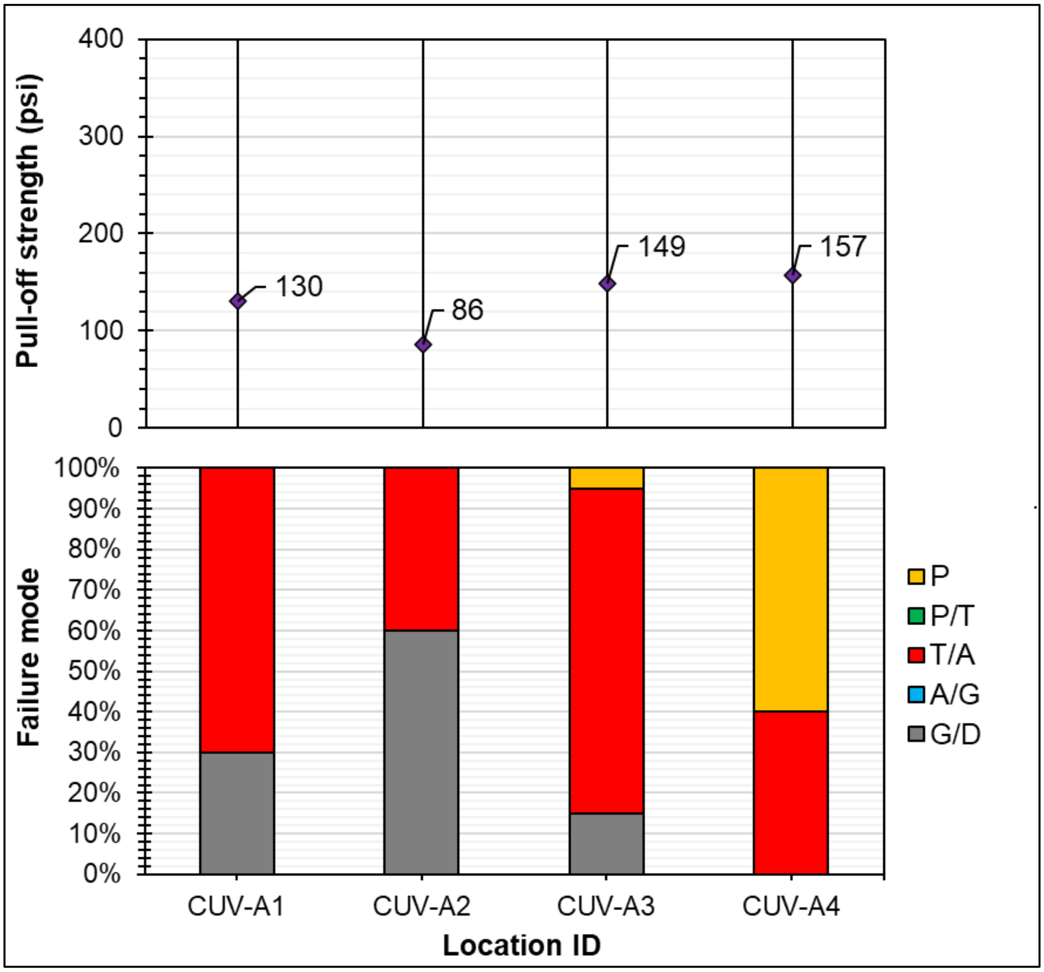


Figure 5-15: Pull-off adhesion test results on UV-affected surface (concrete column with highest sunlight exposure, Coat-A (WB))

5.3.3 Pull-Off Adhesion Performance under Laboratory Conditions

The POAS given in any product data sheet is based on laboratory measurements using concrete or metallic surfaces. Moreover, the substrate type generally remains unknown when POAS is reported in the product datasheet. Sometimes, POAS is also not reported in the datasheet for certain products. In the present study, old concrete prisms (3 inch × 3 inch ×12 inch) covering good and relatively poor conditions representative of field concrete substrate conditions instead of newly made (28 days cured) concrete prisms were considered as representative substrates. The compressive strength (28 days) and water absorption (24 hours) for the concrete prisms with good conditions were 5100 psi and 5.5 percent, respectively, whereas these values for the concrete prisms with relatively poor conditions were 3030 psi and 11.0 percent, respectively. The concrete surface under consideration was free from dust and other impurities (e.g., efflorescence), with a CSP value of 1–2 for the application of the coating materials and subsequent adhesion test. Both Coat-L and Coat-A were applied (one layer of coating application) on both concrete substrates (i.e., good and poor concrete). The application of the coating materials was carried out using a hand roller following the guidelines mentioned in the respective coating material product datasheet. WFTs for both Coat-L and Coat-A coatings were maintained as per the product datasheet. After 7 days of room curing (at 73°F with 50 percent RH), the POAS testing as per ASTM D7234-22 was conducted using the procedure outlined previously.

For Coat-L, the performance evaluation in the form of measuring POAS of the tested coating materials was also assessed under laboratory conditions using concrete substrates with relatively good and poor conditions (described earlier). Figure 5-16 and Figure 5-17 show the summary of the POAS test results of Coat-L with both good and poor-quality concrete substrates, respectively (Note: LG-L indicates laboratory condition, the good concrete substrate with Coat-L; LP-L indicates laboratory condition, the poor concrete substrate with Coat-L). A good performance of Coat-L on the good concrete substrate was observed, with an average POAS value of 331 psi and a consistent high range of 297–355 psi, which is close to the reported POAS value of 375 psi (ASTM D4541-22) for Coat-L in the product data-sheet.

Most of the data points showed primary failure (60–76 percent) along the substrate (parent concrete)–coat-L interface (P/L), with some failure (20–35 percent) within the concrete substrate. The higher the adhesion strength, the higher the percentage of failure within the substrate concrete, which indicates that when adhesion strength between coating and concrete substrate is high (closer to the datasheet value), certain percentages of substrate concrete can come out (with dolly) depending on concrete quality (i.e., substrate condition). In contrast, the poor concrete substrate showed reduced pull-off strength (194 psi average) and primarily failed at parent concrete (Figure 5-16). Out of the total four data points at location LP-L4, approximately 10 percent failure through Coat-L and parent concrete interface was observed, with a POAS value of 200 psi. The bond between poor concrete and Coat-L was good, but the failure occurred within the poor concrete before reaching the maximum P/L bond strength (e.g., 300–355 psi in the case of good concrete substrate) because of the weak concrete substrate. This result is an indication that the measured bond strength is also controlled by the quality of the substrate concrete and a lower measured bond strength does not necessarily indicate a poor bond between the new coating and concrete substrate.

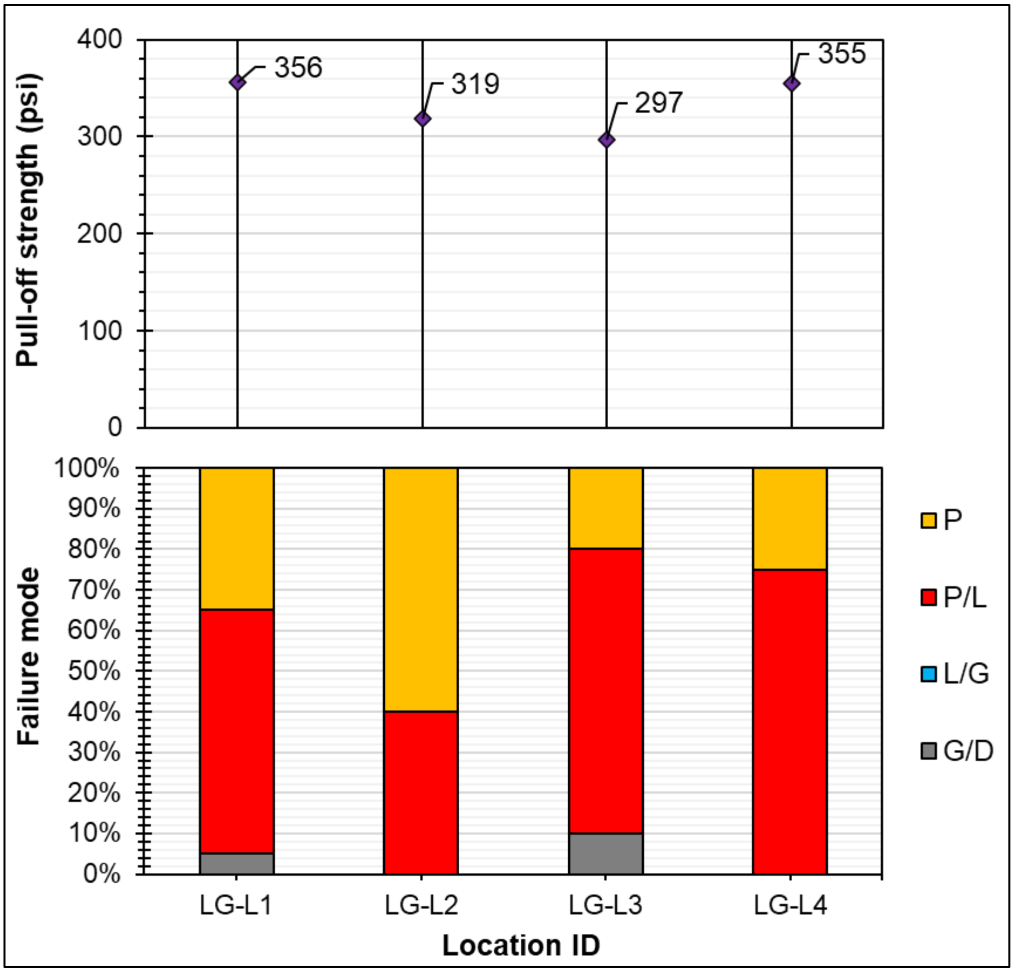


Figure 5-16: Pull-off adhesion test results on a good concrete substrate with Coat-L (laboratory condition)

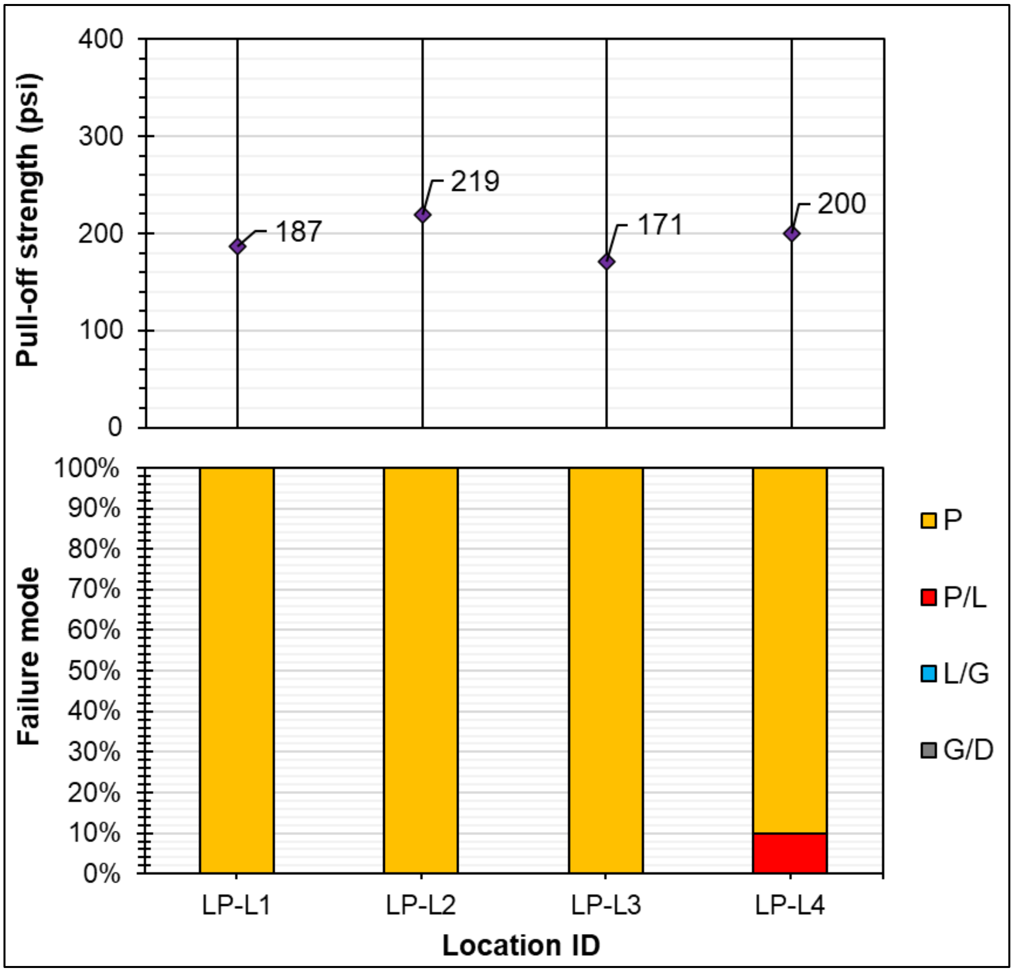


Figure 5-17: Pull-off adhesion test results on a poor concrete substrate with Coat-L (laboratory condition)

A summary of the performance of Coat-A on concrete substrates with relatively good and poor conditions is shown in Figure 5-18 and Figure 5-19. For good concrete substrate (Figure 5-18), P/A failure dominates (50–65 percent), with considerable failure (30–50 percent) within the substrate concrete, which indicates that when adhesion strength between coating and substrate is high (closer to the datasheet value) certain percentages of substrate concrete come out during the adhesion test at isolated relatively weaker spots in the substrate concrete. The higher the P/A bond, the higher the percentage of failure within the substrate concrete. The highest POAS value was observed at the LG-A1 data point, with less than 5 percent glue failure. The average POAS of Coat-A on the good concrete substrate was 405 psi, which is higher than Coat-L under the same condition. The thin coat (i.e., Coat-A with a DFT of 4 mils) showed higher POAS results than the thick coat (i.e., Coat-L with a DFT of 8 mils). Therefore, in summary, the adhesion strength of different coating materials cannot be generalized.

The POAS values for Coat-A with the poor concrete substrate were lower (180–336 psi, with an average of 261 psi, Figure 5-19) than the POAS with the good concrete substrate (425–482 psi).

It can also be observed that the main failure was on the concrete substrate, and a similar performance was observed for Coat-L on poor concrete substrate. Therefore, with the same coating application on two different concrete substrates, the pull-off adhesion performance can be different. Overall, the performance of adhesion strength depends on the coating material composition, thickness, substrate roughness, quality of the substrate concrete, etc. (*12*, *70*, *71*). In the field test, the substrate condition was not as good as newly made concrete. Over time it has deteriorated, which created some deficiencies in the adhesion of Coat-L or Coat-A.

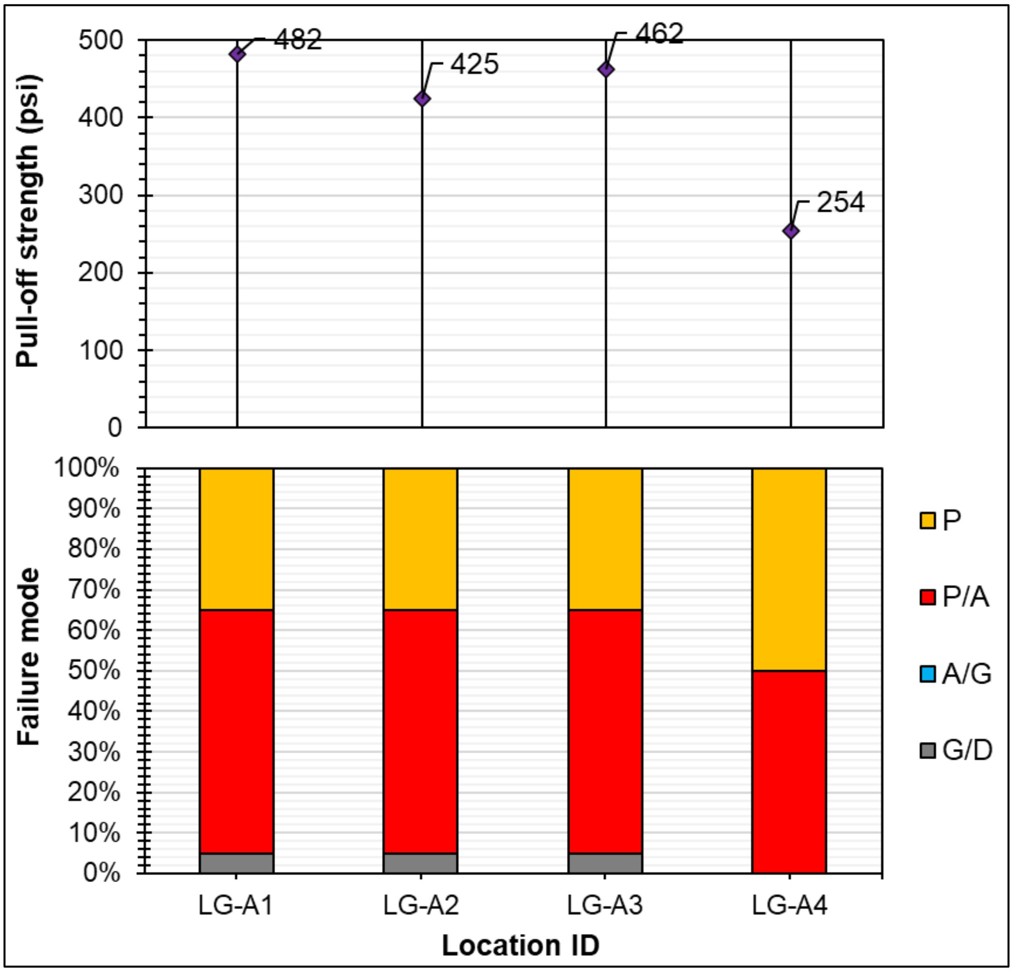


Figure 5-18: Pull-off adhesion test results on a good concrete substrate with Coat-A (laboratory condition)

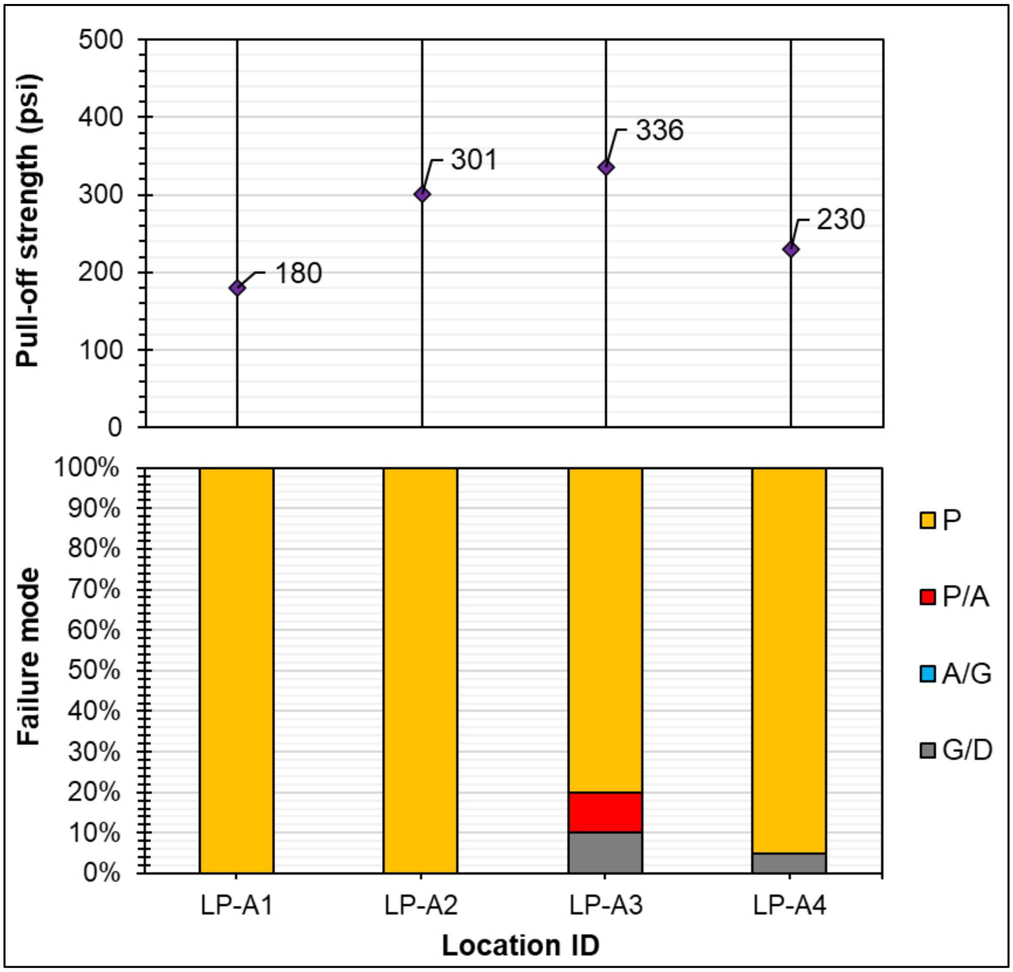


Figure 5-19: Pull-off adhesion test results on a poor concrete substrate with Coat-A (laboratory condition)

The researchers aimed to evaluate the performance of the selected coating materials in the field with different prepared surfaces. A detailed field performance evaluation followed by a selective laboratory evaluation approach was adopted to achieve this objective. The important findings from the field visit in San Antonio and related performance assessments in the laboratory are summarized below.

- Surface preparation plays a significant role in the effectiveness of coating material. Sandblasting and water-blasting are the most common surface preparation methods adopted by most DOTs. Between these two surface preparation methods, water-blasting was suggested in the present study because of its effectiveness in providing better adhesion performance and ease of application.
- CSP plays an important role in the bond between the concrete substrate and the applied coating layer on it. In general, the higher the CSP value, the higher the thickness of a coating material. Sandblasting created surfaces with higher CSP (3-4), but it also created

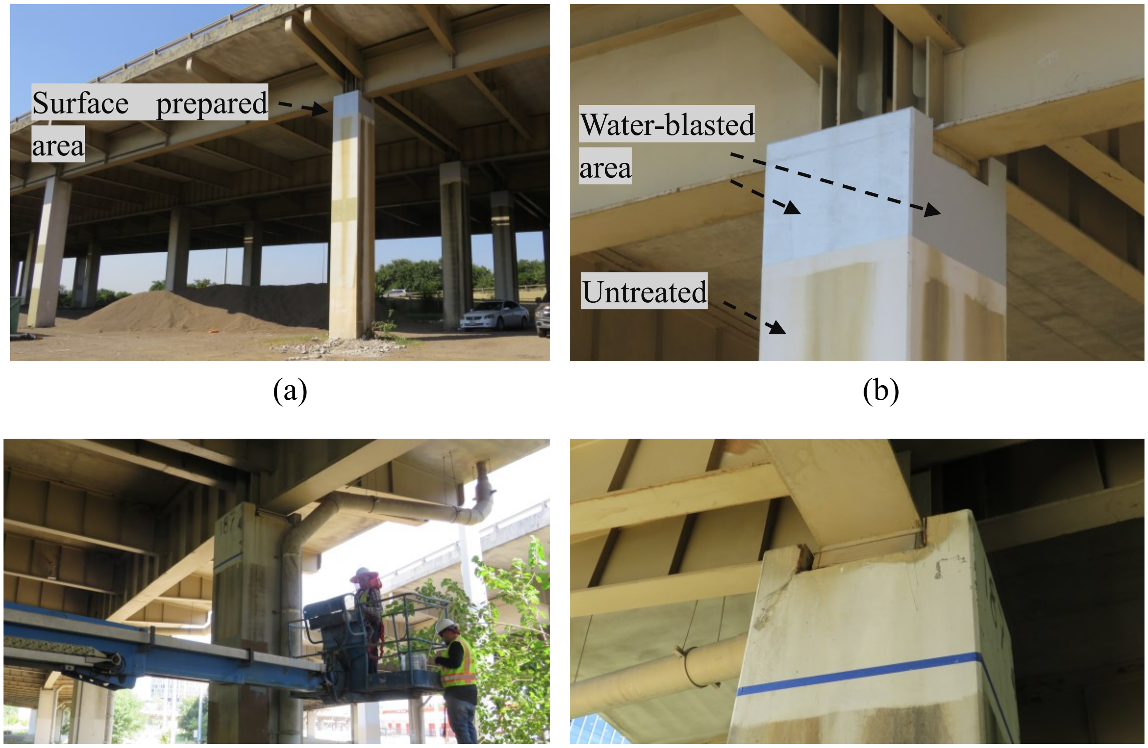
weaknesses (exposing voids and other weaknesses) that resulted in lower POAS values than the water-blasted surfaces.

- Although, POAS depends on several factors (e.g., coating properties, coating thickness, application methods, concrete substrate characteristics, etc.), concrete substrate conditions play the most important role. Even with the same coating material (thick or thin coat) on two different concrete substrates (sound vs. compromised substrates), the adhesion performance may vary significantly. Approximately, 35–40 percent reduction in average POAS was observed when the studied coatings (both Coat-L and Coat-A) were applied on the compromised (relatively poor) concrete substrate with visible surface defects.
- Good concrete substrate with a sound surface (i.e., no visible surface defects) showed consistently better adhesive performance of Coat-L or Coat-A, both in field and laboratory testing. Conversely, concrete substrates with some noticeable defects in the field showed low adhesive performance of the studied coating materials. The same findings were observed for concrete surfaces previously coated with Coat-T but with relatively lower adhesive strength. The concrete surfaces with a previously applied old, deteriorated (due to UV exposure) coating (Coat-T) also showed a relatively lower range of POAS than surfaces with a sound concrete substrate.

Therefore, it can be summarized from both the extensive field and controlled laboratory tests that both Coat-L and Coat-A have good adhesion performance on new concrete surfaces as well as old concrete with sound surfaces (no noticeable defects) or concrete with an old coating (Coat-T) that has experienced negligible deterioration due to UV exposure.

5.4 Dallas (IH 345) Project

A short field visit was conducted to the Dallas project on 19th July 2024. The location was near 2395 Elm St (IH 345). Several bridge piers (columns) were observed for the effectiveness of the surface preparation, moisture condition, and application of coating materials. Surface preparation using water-blasting (3000 psi pressure) had already been completed by the contractor. Figure 5-20 shows some pictures of the columns after the water-blasting. Similar to the San Antonio field project, water-blasting was effective in removing the dust and some of the old coating layer from the columns. However, the water-blasting was not effective in removing the old coating layer completely. Figure 5-21 shows the partial removal of the old coating layer in the water-blasted area. Some of the paint chips were coming out easily, and it was expected that the bond between the newly applied Coat-R(SB) coating may be poor in those areas. This aspect needs further investigation. The impact of a weak old coating layer after water-blasting on adhesion strength performance should be studied further. Another way to minimize the effect of such a weak layer might be the initial inspection and pull-off of adhesion strength measurements on the existing old coated areas. If the adhesion strength of the old coating is good, probably there will not be any such weak zone, and the bond between the new coating should be good. In contrast, during the inspection, if the old coated layer shows poor adhesion strength, water-blasting on such surfaces may lead to the creation of further weak zones if the old coated layer is not completely removed. Figure 5-22 shows the moisture measurement, application of Coat-R(SB) coating, and the coated surface. The coating material was applied on a dry surface (surface moisture content was approximately 3 percent) using a hand roller. Although the product data sheet recommends a two-coat application, the projected selected a one-coat application of Coat-R(SB).



(a) (b)

(c) (d)

Figure 5-20: Picture of the surface prepared area: (a) bridge with columns (top) showing the location of surface preparation, (b) water-blasted area and an untreated portion of the column, (c) marking of the location before coating application, and (d) marked area on the column

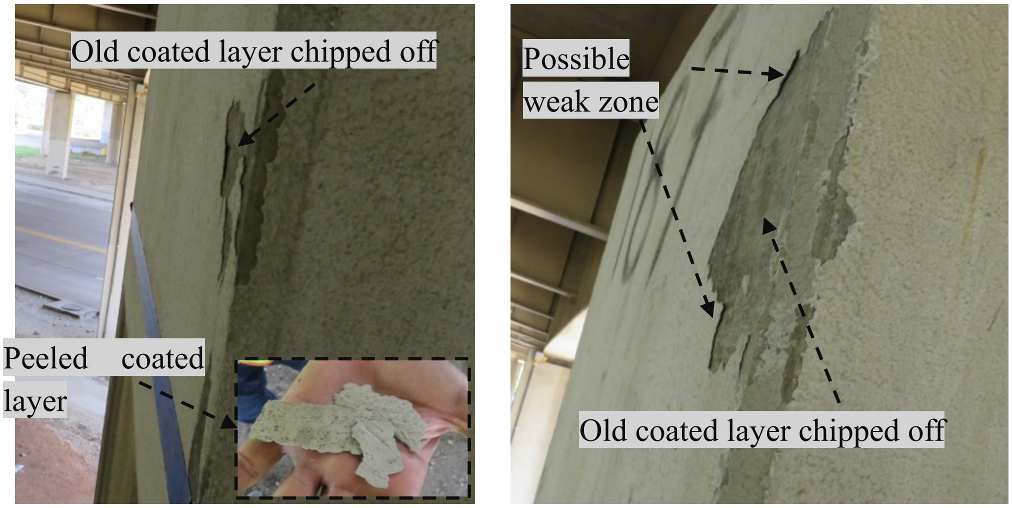
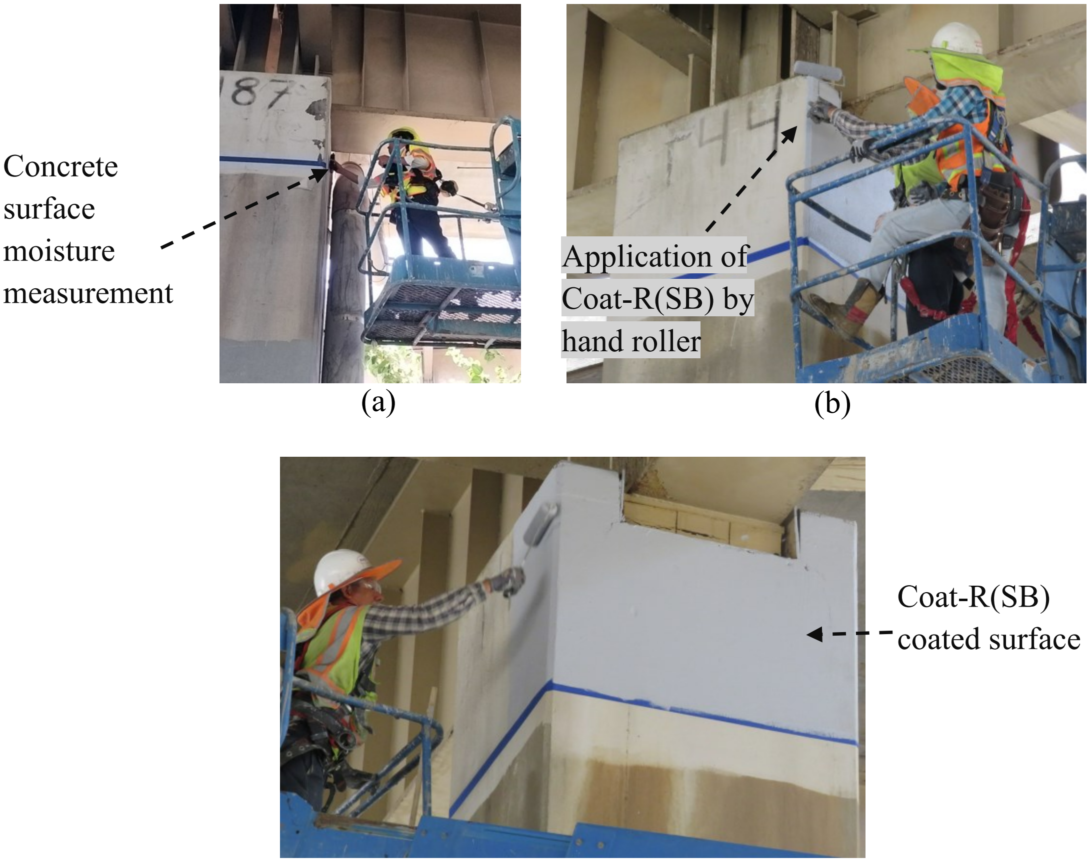


Figure 5-21: Picture of the possible weak coated zone within the blasted area



(a) (b)

(c)

Figure 5-22: Concrete surface moisture measurement (a) and application of coating (b, c)

5.5 Dallas (IH 20 at IH 35E)

A field visit related to the application of Item 428 was conducted in Dallas during January 2023. The location was near 39025 LBJ Service Road (IH 20 at IH 35E). This project was related to the concrete bridge deck, not a substructure. Surface preparation with water-blasting followed by application of sealer material (SIL-ACT® ATS-42) was observed. The sealer was applied within 24 hours of water-blasting. Figure 5-23 shows the surface preparation on the bridge deck. Figure 5-24 shows the application of sealer materials using a spray gun. The sample (SIL-ACT® ATS-42) was collected from the field for preliminary laboratory evaluation.

Figure 5-23: Water-blasting on the bridge deck

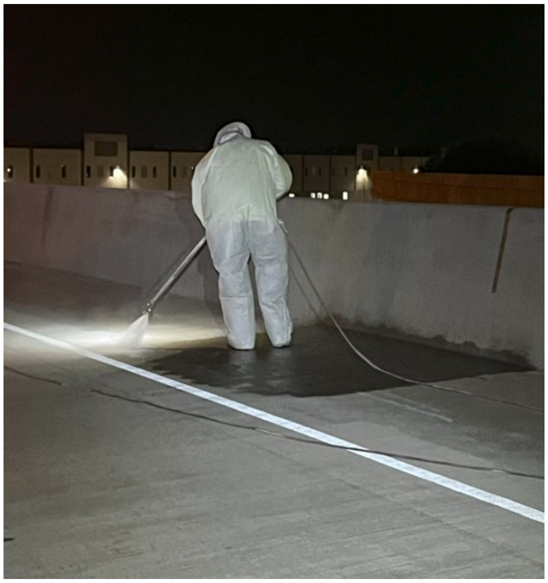
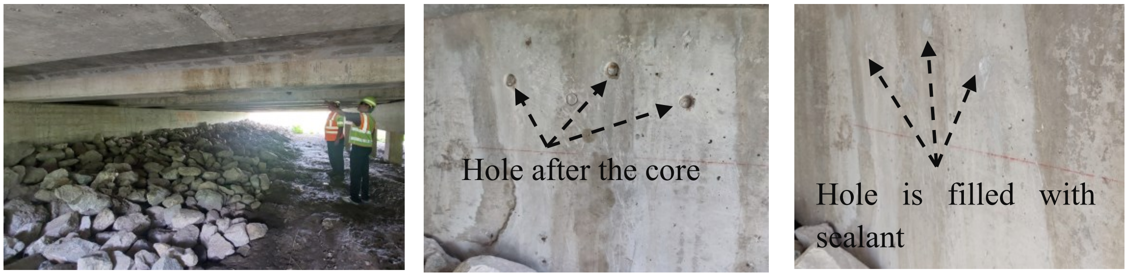


Figure 5-24: Application of sealer on concrete bridge deck using spray gun

5.6 Bryan (SH 6) Project

A field visit related to the assessment of sealed concrete substrate (sealer product was applied approximately 1 year ago) through the measurement of DOP was attempted near Navasota, Texas on 14th August 2024. The location was near SH 6 WFR at Millican Creek (near Westward Ho). Taking concrete cores 1 inch in diameter and 1 inch in height was attempted; however, the cutting of a small diameter core on a vertical surface was a challenge. Figure 5-25 shows the concrete substrate from which the core was collected for the DOP test. The researchers from TTI have filled the holes using a concrete sealant.



(b) (a) (c)

Figure 5-25: Details of the fieldwork: (a) observation on the sealed surface, (b) hole after the core was collected, and (c) hole was filled using sealant

5.7 Summary

Although Task 5 consisted of several field projects related to sealer/coating materials, the projects had different aims and objectives. Similarly, the knowledge and understanding of each project were different. The following points can be summarized based on the finding from the field-related projects:

- In the field, the quality of the substrate concrete varies. Higher degrees of weathering under environmental exposure conditions with high severity and/or some mix design deficiencies (e.g., relatively poor transport properties due to the use of relatively higher w/cm) can sometimes lead to the creation of a relatively poor concrete substrate. After the initial inspection of the concrete substrate, a suitable surface preparation can be suggested based on the situation.
- In the San Antonio project, Coat-L and Coat-A (one coat) have shown good adhesion performance on new concrete surfaces as well as old concrete with sound surfaces (no such defects) or concrete with an old coating (here Texcote) that has experienced negligible deterioration due to UV exposure. The role of moisture effects (i.e., the moisture contribution from the underneath concrete and/or old deteriorated coating) on the adhesion of thick coating (Coat-L or similar) in the field as per the product data sheet (two coats) needs further evaluation.
- Similarly, the adhesion strength of coating on a comparatively weak concrete substrate may not show the actual adhesion performance of the products. Therefore, laboratory-based performance assessment with some predefined conditions (e.g., one coat vs. two coats) of any coating materials and validations in the field can give a better understanding.
- Monitoring concrete surface moisture ensures suitable concrete substrate conditions (dry or wet) before the application of any sealer and coating applications.

- After water-blasting, if a weak existing coating layer is present (as observed in the Dallas IH 345 project) on the concrete substrate that may lead to poor adhesion of the coating and concrete substrate. This issue can be minimized by conducting an initial condition assessment (e.g., measuring the POAS of the old existing coating).
- The collection of small cores from the concrete bridge substructure for the DOP is a challenge (as observed in Bryan project) and needs to be solved soon by establishing a suitable procedure.

CHAPTER 6: DEVELOP GUIDELINES, RECOMMENDATIONS, AND DECISION-MAKING TOOL

This chapter focuses on the development of practice guidelines, practice recommendations, and a decision-making tool (systematic stepwise approach) to ensure the effective application of sealer and coating materials and adequate protection of substructure concrete from corrosion. Subsequently, the effective application of sealer/coating materials and protection of field substructure concrete along with product selection is discussed.

6.1 Framework for the Guidelines, Recommendations, and Decision-Making Tool

The overall guideline for the effective application of sealer/coating materials and protection of field substructure concrete in the form of a decision-making tool is presented as a flowchart (Figure 6-1). The flowchart shows a step-by-step approach covering (a) condition assessment of field substructure concrete, (b) product selection based on condition assessment and project requirements, (c) selection of appropriate surface preparation and optimum substrate concrete surface moisture contents to maintain before application of any product, (d) product application followed by assessment (e.g., use of WFT/DFT) to ensure effective application, and (e) selective field performance monitoring after application. Each aspect (i.e., A1–A8) is discussed, with necessary details subsequently highlighting the areas of further recommended research. The step-by-step guideline for product evaluation in the laboratory before selecting a suitable product for a field project was presented in Chapter 3. To select the right product for a particular project, a prior lab evaluation of the commonly used products that apply to this guideline is highly recommended. A total of eight products were evaluated in this project to develop the lab test protocol. However, it is recommended that all commonly used products along with potential new products be evaluated and a database with an in-built ranking system be created. Because lab-based product evaluation using the developed protocol takes time (~5–6 months), it may not be practical to check the suitability of a product during the planning stage for a project application. Consequently, a database with product ranking based on a one-time detailed evaluation will facilitate a rapid selection of a suitable product for a field project with no need for a long-term protocol-based product evaluation (unless any new products have not yet been added to the database through evaluation) before selection for a project application.

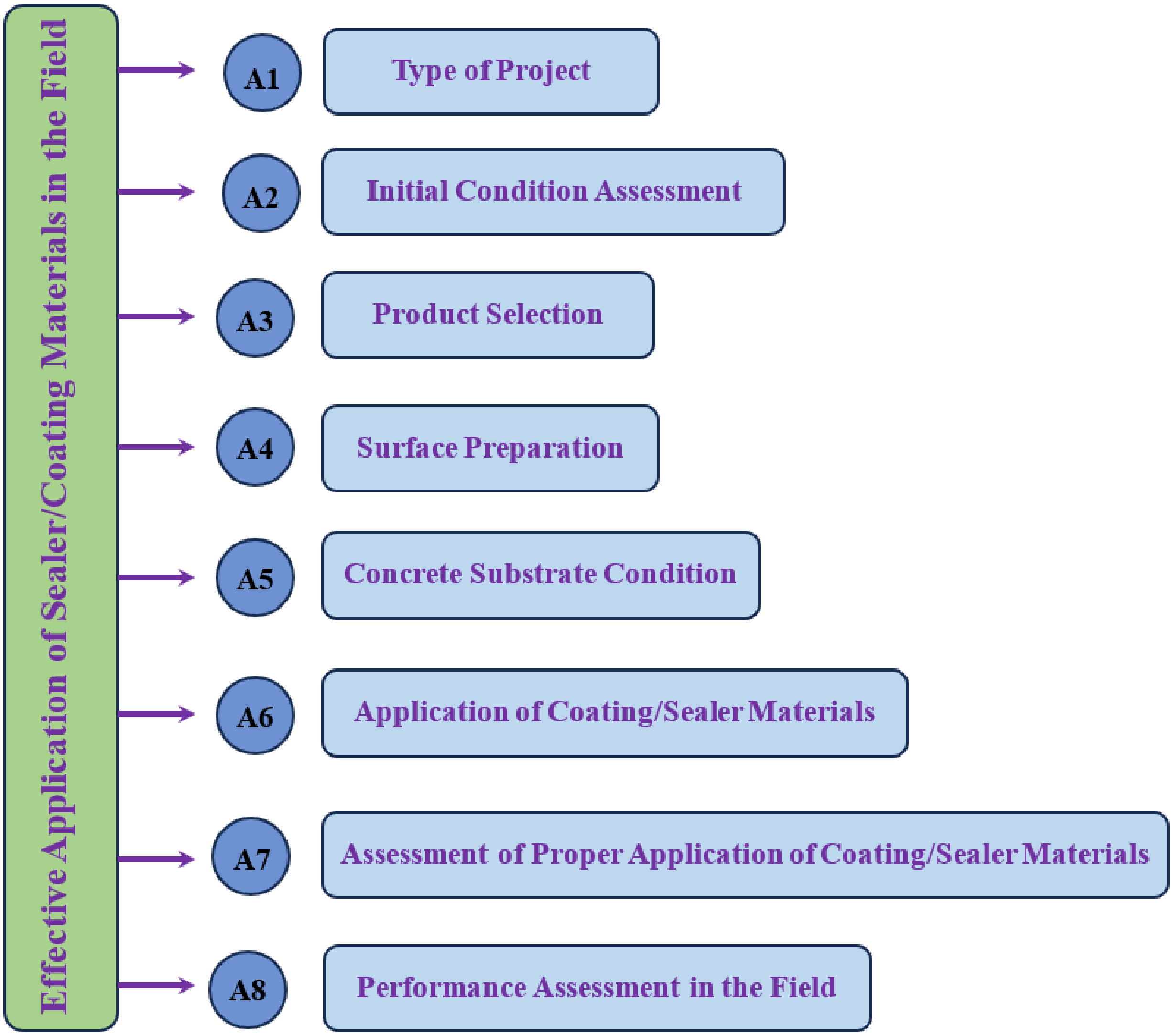


Figure 6-1: Flowchart for effective application of sealer/coating materials to protect field substructure concrete

6.2 A Brief Description of Each Step in the Flow Chart

A brief discussion of each step in the flowchart for the effective application of sealer and coating materials on concrete substrate is provided below.

A1 Type of project:

The type of project can be as follows:

- New construction.
- Old construction (without any previously applied coating/sealer products).
- Old construction (with previously applied coating/sealer products).

A2 Initial condition assessment:

The following aspects can be considered for the initial condition assessment:

- New construction: Assess CSP and check for any visible defects.
- Old construction (no previously applied coating/sealer products): Perform concrete substrate inspection through (a) POAS measurements of the concrete substrate, where POAS values within the acceptable range indicate sound substrate concrete; (b) assessment of CSP (Note 1); (c) determination of depth-wise chloride contents (if possible) by taking small cores from substructure concrete (Note 2); and (d) assessment by visual observation and POAS measurements of the effect of weathering caused by UV rays (sunlight) and rain on the substrate concrete—poor POAS measurements are an indication of high weathering effect on substrate concrete.
- Old construction (with previously applied coating/sealer products): Perform concrete substrate inspection through (a) POAS measurements of the old existing coating (in case of previously applied coating product) with the concrete substrate; (b) assessment of CSP (Note 1); (c) determination of depth-wise chloride contents (if possible) by taking small cores from substructure concrete (Note 2); (d) DOP measurement (in case of previously applied sealer product); and (e) assessment by POAS measurements of the effect of weathering caused by UV rays and rain on the previously applied coating products.

Note 1: The role of CSP in concrete substrate to achieve optimum POAS is not known. The product data sheets recommend CSP 1–3 in general, which does not address the CSP of field concrete substrate. Sometimes, field CSP can be more than 3 (e.g., after sandblasting or other types of blasting methods), and it is important to know if a relatively higher CSP (i.e., > 3) can have any detrimental effects on achieving optimum POAS. The applicability of any suitable device to measure surface roughness directly may be more effective than the estimation of CSP (qualitative approach), which needs further testing to check if this method provides acceptable results.

Note 2: Chloride analysis at different depths should be useful for understanding the status of corrosion potential before applying any product if corrosion protection is the main purpose of product application. The available data (if maintained by TxDOT on selective projects) on depth-wise chloride contents will be very useful in selecting projects with low, medium, and high corrosion potential. If the chloride data are not available, depth-wise chloride contents can be determined using small core samples. The guidelines for product selection based on the ranking system developed by the lab protocol and the degree of field corrosion potential can be effectively developed.

A3 Product selection:

A suitable product needs to be selected for its effectiveness in the laboratory from the list of products that have already been assessed (Chapter 3). A total of eight products were evaluated using a good quality (i.e., low w/cm [0.42], low permeability with denser microstructure) substrate concrete (Type C concrete, TxDOT Item 421) in this project to develop the lab test protocol (Chapter 3). Higher degrees of weathering under environmental exposure conditions with high severity and/or some mix design deficiencies (e.g., relatively poor transport properties due to the use of relatively higher w/cm) can sometimes lead to the creation of a relatively poor concrete substrate. Lab evaluation using a good-quality substrate concrete may be representative of relatively newly made substructure concrete in the field but may not be representative of this kind of poor-quality concrete substrate. Although the data using a good quality concrete substrate were useful to do a comparative assessment (develop ranking) of tested coating/sealer products, rapid evaluation of the corrosion protection effectiveness of the products was not satisfactory. Further work using poor concrete substrate (high w/c ratio) is recommended, which should be useful for rapid and comprehensive product evaluation (especially chloride protection effectiveness) and improving the ranking system of the products. It is expected that corrosion protection evaluation using this kind of poor substrate concrete can be considered standard practice in the specification.

Based on the evaluation of eight products, the ranking system using six performance indicators (e.g., water absorption, POAS, sorptivity, RCPT, chloride ponding, and corrosion rate measurements by the accelerated test) compared well with the ranking system using three performance indicators (e.g., POAS, sorptivity, and RCPT).

Once the lab testing protocol using a standard substrate concrete (expected to be poor concrete) and the ranking system are finalized through the abovementioned work, evaluating more products is recommended (all potential products that TxDOT is currently using plus new potential products) to validate the applicability of the testing protocol and ranking system and generate an extensive database. The above comprehensive evaluation using several products will be useful to validate the acceptability of the ranking system based on three performance indicators instead of six, which saves time for future evaluation. This kind of database, with an in-built ranking system based on a one-time comprehensive evaluation, can be used to select products depending on project requirements in the future. The product ranking in the extensive database will be used to choose products depending on the condition assessment results (mainly corrosion potential) for a project. An example of product selection guidelines based on product evaluation so far (a total of eight products) is provided in Table 6-1. Life-cycle cost analysis also needs to be considered for the product selection. However, for new products (new formulations or ones never used in field projects before), evaluation based on the developed lab testing protocol followed by determining ranking is mandatory. It is expected that selecting the best-performing materials—by the above product selection guidelines—in a new project will extend service life, be economical (reapplication will be minimal), and offer sustainable options (less consumption of material and waste generation if reapplication is minimal).

Table 6-1: Example of product selection using applicable selection criteria

Potential	**Coating materials**	**Sealer materials**	**Life-cycle cost analysis**
Application	Easy to apply on vertical surfaces by maintaining proper WFT/DFT and coverage	It can be effectively applied on vertical surfaces by maintaining proper coverage/DOP	
High corrosion potential	Coat-M(SB), Coat-R(SB)	Sealer-40%, Sealer-100%	
Medium corrosion potential	Coat-D(SB), Coat-L(WB)		
Low corrosion potential	Coat-A(WB), Coat-S(WB)		

Note: The degree of corrosion potential (low, medium, high) can be assessed through depth-wise chloride content measurements using small cores or the application of suitable nondestructive testing (NDT) evaluation techniques.

A4 Surface preparation:

Based on limited field studies, the following guidelines for selecting appropriate surface preparation methods are recommended:

- For a newly constructed structure, water-blasting is recommended to remove any dust.
- For old construction with and without any previously applied coating, the guidelines for selecting a suitable surface preparation method in Table 6-2 can be used.

Table 6-2: Recommendation on surface preparation based on initial inspection and adhesion strength

Surface preparation	Old construction (without any previously applied coating)	Old construction (with previously applied coating)
Water-blasting should be adequate (minimizes cost, effort, and environmental impact compared to sandblasting)	If the POAS measurements directly on the concrete substrate are within the acceptable range	If the POAS measurements of the old coating are within the acceptable range
The use of sandblasting or any kind of suitable blasting method (for complete removal of the old coating ± topmost portion of the substrate concrete) may be recommended	If the POAS measurements directly on the concrete substrate are << the acceptable range	If the representative POAS measurements of the old coating are << the acceptable range and the concrete below the coating is weaker due to weathering

The above guidelines on surface preparation are preliminary. More field evaluation covering different products in different bridges is needed to validate the above guidelines (Table 6-2).

A5 Concrete substrate condition:

Before the application of coating/sealer, the substrate concrete surface should be assessed for the following:

- Measure concrete surface moisture content (CSMC) by using a portable moisture meter (Note 3).
- Ensure concrete substrate is clean and dry, as per the product datasheet.
- Estimate concrete surface roughness in terms of assigning a CSP value, as per the ICRI guidelines (Note 4).

Note 3: Concrete substrate surfaces should be free from moisture, as per the ICRI guidelines. However, guidelines on assessing CSMC and providing recommendations on optimum CSMC and the time needed in hours to achieve that CSMC do not exist. A moisture meter was found to be effective in monitoring CSMC before applying coating/sealer materials. Further research is recommended to evaluate the impact of substrate moisture conditions (low to high moisture) on the performance of sealer and coating materials.

Note 4: After surface preparation (sandblasting), the CSP value may change from the initial surface roughness. The final CSP value should be matched with the selected product datasheet.

Further, more field evaluation covering different products in different bridges is needed to validate the above guideline.

A6 Application of coating/sealer materials:

The guidelines for application of coating/sealer materials are provided below:

- Coating (spray pump, roller, brush):
    - For small-scale applications, a hand roller can be used.
    - For large-scale applications, a spray pump can be used.
    - Other applications should be based on the product datasheet.
    - WFT and coverage need to be defined and maintained properly (Note 5).
    - Select a one-coat or two-coat application based on the project requirements.
- Sealer (small spray pump):
    - A small spray pump can be used.
    - Other applications should be based on the product datasheet.
    - Coverage or rate of application needs to be defined and maintained properly.

Note 5: A guideline on maintaining the required WFT along with the conventional practice of maintaining specified coverage (sq ft/gal) should be developed to ensure an effective application. Monitoring WFT with the corresponding specified coverage rate and linking with key performance measurements (e.g., monitoring POAS and others) in several field projects is recommended to develop WFT-based guidelines.

A7 Measure/assessment of the proper application of coating/sealer materials: For coating materials, DFT can be measured by the NDT-based method (DFT gauge, Note 6) or direct measurement (small core under a stereo microscope). For sealer materials, the DOP can be checked (small core under a stereo microscope, Note 7).

Note 6: Effective application of different coating materials can be assessed by measuring the DFT using a portable DFT measuring gauge. The direct measurement of coating thickness by a stereo microscope using a small cut specimen of the concrete substrate with an attached coated layer was found to be useful for validating the gauge-based DFT measurements. Monitoring DFT with the corresponding specified coverage rate and linking with key performance measurements (e.g., monitoring POAS with WFT/DFT and others) in several field projects is recommended to develop DFT-based guidelines.

Note 7: For sealer material, the DOP test using a stereo microscope was found to be effective. More lab testing is in progress to check the effectiveness of this method. Once the effectiveness is verified in the lab, monitoring DOP in several sealer projects is necessary to check the validity of this method.

More field evaluation covering different products in different bridges is needed to validate the above guideline.

A8 Performance assessment in the field:

The following points can be considered for performance assessment in the field:

- Performance assessment for coating through POAS measurements over time.
    - If the reduction of POAS value over time (in years) is less, the coating should work well for a longer period, and reapplication with a longer interval (e.g., 10–15 years) can be recommended.
    - If the rate of reduction in POAS is significant over time compared to the initial adhesion strength, reapplication with a shorter interval (within 5 years) can be suggested.
- Other NDT-based assessment (e.g., corrosion monitoring).

Note 8: Based on the POAS measurements on both vertical and horizontal surfaces in the lab, POAS on the horizontal concrete substrate was slightly higher than on the vertical surface. This result is a limitation of the test itself and should not be considered as a reduction of POAS in the field with vertical surfaces. A certain percentage reduction (which needs to be evaluated through further testing) needs to be assigned for each product based on a one-time lab versus field POAS assessment study.

Note 9: POAS may vary based on the CSP value of the concrete substrate. After sandblasting, the CSP value can be 3–4, and POAS on such substrates may differ from POAS on CSP 1–2. More field evaluation coverage is needed to evaluate this aspect further by considering field conditions.

CHAPTER 7: CONCLUSIONS, RECOMMENDATIONS, AND PROPOSED FUTURE WORK

This ongoing research project aimed to develop a test protocol for evaluating the performance of representative sealers and coatings that are commonly used on concrete bridge substructures in Texas. After conducting an extensive laboratory evaluation of the selected sealer and coating products (Chapter 3) by suitable test methods and with limited field evaluation/validation (applicability and effectiveness of certain tests in the field, Chapter 5), a ranking system for effective product evaluation (Chapter 4) was developed. A stepwise combined approach of product evaluation and selection using the lab-based ranking system (Chapter 4) followed by selective field evaluation became the basis for developing a framework for developing guidelines and recommendations in the form of a decision-making tool (Chapter 6). Although the developed evaluation protocol in its current state can be used to evaluate and select products that satisfy field requirements, including offering some guidance on surface preparation, some gaps in effective evaluation and further work to fill those gaps were identified. It is highly recommended to complete the proposed further work to make the evaluation protocol complete, effective, and ready to be implemented.

7.1 Conclusion

Deterioration of concrete bridge substructures over time due to corrosion of reinforcing steel through chloride and moisture ingress and other chemical attacks (e.g., alkali-aggregate reaction, sulfate attack, etc.) is a big concern. Different state agencies such as DOTs face challenges in protecting such concrete bridge substructures from steel corrosion and other chemical attacks during their designed service life. The use of suitable sealer and coating products was found to be effective in protecting substrate concrete from the above deterioration processes. However, a performance evaluation of sealers and coatings using an established lab test protocol before suggesting a suitable product for the field project is highly recommended, which was the prime objective of this research. The following are the findings obtained from the present research:

- Surface preparation plays a significant role in the effectiveness of coating material. abrasive-blasting and water-blasting are the most common surface preparation methods adopted by most DOTs. Between these two surface preparation methods, water-blasting was found to be effective in removing the dust layer from the concrete substrate. In contrast, abrasive-blasting (using sand) was found to be effective in removing old coating layers (if any) and deteriorated weak concrete from the top of the concrete substrate. Abrasive-blasting may increase the surface roughness (high CSP), as observed from the field visits.
- Concrete substrate plays a crucial role in evaluating the performance of coating and sealer products. Concrete surfaces should be clean and free from moisture, and surface roughness should be as per the ICRI guidelines. A moisture meter was found to be

effective in monitoring the concrete surface moisture condition before the application of coating/sealer materials.

- Effective application of different coating materials can be assessed by measuring the DFT using a portable DFT measuring gauge and direct measurement (by using a stereo microscope and a small cut specimen of the coated layer from the concrete substrate). For sealer material, the same confirmation can be obtained by the DOP test (using a stereo microscope).
- The performance of different sealer and coating materials should be evaluated by a group of tests and not by a single test. For example, to assess protection against moisture, sorptivity (ASTM C1585) and RCPT (ASTM C1202) can be performed. To ensure reinforcement protection by minimizing the chloride ingress within concrete substrate via sealed or coated surfaces, RCPT (ASTM C1202) and chloride ponding (ASTM C1556) tests, along with judicious use of the accelerated corrosion test, are recommended. To check the performance of the existing sealed/coated surface over time, both tests—using concrete core from the field—are suggested. Adhesion strength (ASTM D7234) is a very good measure to ensure the effectiveness of coating materials in the long run and is suggested for both laboratory and field.
- Water absorption by ASTM D6489 is suitable for sealers but may not be suitable for coatings. Instead, the sorptivity test (ASTM C1585) was found to be effective for the coating products. The initial absorption rate measured by the sorptivity test was higher for the control concrete than for the sealer/coated concrete specimen, which confirms the effectiveness of the sealer and coating products.
- The chloride ponding test was very effective in assessing the barrier protection by the tested sealers and coatings against chloride ion ingress. Comparative assessment based on chloride concentration at different depths was found to be effective for product evaluation and developing a meaningful rating system. The RCPT was also found to be effective in assessing the performance of coating and sealer materials, and coated or sealed surfaces should be in contact with the NaCl chamber (3 percent solution).
- The accelerated corrosion test using a commonly used substructure concrete (good quality concrete) as substrate concrete showed the need for a relatively longer testing duration (more than a month) to achieve a meaningful acceleration effect. The testing time can be reduced by altering the concrete substrate (a relatively poor substrate concrete with a high water/cement ratio) and the type of chemicals (CaCl2 instead of NaCl), which is recommended for further study.
- The POAS of the one-coat system was comparatively higher than the two-coat system for both WB and SB coatings. POAS on the horizontal concrete substrate was slightly higher than on the vertical surface. This aspect should be considered while performing POAS in the field. It was also observed that SB coating materials have higher POAS than WB coating materials.

- Different performance indicators under normal conditions show almost similar individual ratings for the tested coatings and sealers. Sealer-100% and Sealer-40% performed well in most of the performance assessments. However, the same individual ranking under weathering conditions showed a change. Coat-A(WB), and Coat-S(WB) performed poorly for most of the performance indicators and thus have a lower rank. It was found that individual ranking considering the corresponding performance indicator is important to form a better assessment of a sealer and coating product.
- The present assessment for combined ranking is based on preselected importance/priority levels for different performance indicators. Low to high priority can be set based on the significance of different performance indicators. The compound rating system shows the overall performance of different coating materials from which a product can be selected. It is recommended that sealers and coatings be ranked separately because some of the performance indicators (e.g., POAS) are not common between sealers and coatings.
- Some products are more sensitive to the weathering effect; to have an idea about the long-term performance of sealers/coatings, the weathering effect with a suitable WF can be considered in the rating calculation.
- It might be possible to conduct a minimum number of experiments (e.g., sorptivity, RCPT, and POAS, etc.) in the laboratory for a relatively quicker product evaluation without compromising reliability. However, more product evaluation to check the validity of the proposed approach is highly warranted.
- In the field, the quality of the substrate concrete varies. Higher degrees of weathering under environmental exposure conditions with high severity and/or some mix design deficiencies (e.g., relatively poor transport properties due to the use of relatively higher w/cm) can sometimes lead to the creation of a relatively poor concrete substrate. After the initial inspection of the concrete substrate, a suitable surface preparation can be suggested based on the situation.
- The adhesion strength of coating on a comparatively weak concrete substrate may not show the actual adhesion performance of the products. Similarly, the POAS of a one-coat system differs from the POAS of a two-coat system. Therefore, laboratory-based performance assessment with some predefined conditions (e.g., one coat vs. two coats, substrate using a standard substructure concrete, etc.) of any coating materials and validations in the field can give a better understanding.
- Lab-based product evaluation using the developed protocol takes time (~5–6 months); this kind of high evaluation time may not be practical for checking the suitability of a product for a project. Therefore, developing a product database with an in-built ranking based on a one-time detailed evaluation is recommended; it will facilitate a rapid selection of a suitable product for a field project without conducting further lab-based product evaluation (unless any new products have not yet been evaluated) in the future.

7.2 Recommendation and Proposed Future Work

7.2.1 Further Work to Improve the Lab Testing Protocol (i.e., Make It Rapid and Comprehensive) with Improvement in the Ranking System

This study used a good quality [i.e., low w/cm (0.42), low permeability with denser microstructure] substrate concrete (Type C concrete, TxDOT Item 421). Because of using a good quality concrete substrate, the chloride ponding test showed chloride concentrations at a 1.25-inch (~32 mm) depth lower than the threshold chloride concentration limit for corrosion initiation (ACI 222) for all the tested products. The RCPT test showed very little changes, that is, a low to very low permeability range, due to the application of all the products. Similarly, the measured corrosion rates for all the products show a lower range (still in the passive state) with less separation after a longer testing time (~60 days) in the accelerated corrosion test. Based on the above data from the RCPT, chloride ponding test, and accelerated corrosion test, all the tested products are expected to provide adequate chloride protection. However, for bridges in service with high corrosion potential, the tested products will provide varying levels of protection; that is, some will provide adequate protection for a longer period, some will provide short-term protection, and some are expected to provide negligible protection. This finding is an indication that the corrosion protection effectiveness of the products cannot be properly judged rapidly under laboratory conditions using good quality concrete substrate, but the data can be utilized to do a comparative assessment (develop ranking) of tested coating/sealer products.

In the field, the quality of the substrate concrete varies. Higher degrees of weathering under environmental exposure conditions with high severity and/or some mix design deficiencies (e.g., relatively poor transport properties due to the use of relatively higher w/cm) can sometimes lead to the creation of a relatively poor concrete substrate. Lab evaluation using a good quality substrate concrete may represent applying coating/sealer on relatively newly made substructures with good concrete but may not be representative of relatively poor concrete substrates.

Proposed further work includes the following:

- Product evaluation using both poor (high w/c ratio) and good (low w/c ratio) concrete substrates is recommended for a comprehensive evaluation. Since the work using good concrete substrate is completed in this project, further work using poor concrete substrate is recommended. Evaluation using relatively poor concrete is expected to create a high driving force that is expected to be useful for on the one hand rapid and comprehensive product evaluation (especially chloride protection effectiveness, described in Table 7-1) and on the other hand, improving the ranking system of the products.
- Because the accelerated corrosion test was conducted using a good quality substrate concrete and 3.5 percent NaCl, the transition from passive to active corrosion was still not detected after 60 days of testing time. By altering the concrete substrate (high w/c ratio,

high permeability) and suitable chemicals (deicing salts such as $CaCl_2$, and $MgCl_2$), the same assessment can be performed within a short period (e.g., 1 month). Therefore, it is recommended to evaluate the corrosion protection effectiveness of the selected sealer/coating materials using a poor-quality substrate and an aggressive deicing chemical (e.g., $CaCl_2$) to establish a rapid but effective procedure to measure the corrosion rate (expected to reach active corrosion stage). It is expected that this proposed evaluation using a poor substrate concrete will improve the correlation between corrosion rate measurements by the accelerated test, RCPT, and chloride ponding test and improve the ranking in terms of corrosion protection. It is expected that corrosion protection evaluation using this kind of poor substrate concrete can be considered standard practice in the specification.

- Once the lab testing protocol using a standard substrate concrete (expected to be poor concrete) and the ranking system are finalized through the abovementioned work, it is recommended more products be evaluated (all potential products that TxDOT is currently using plus new potential products) to validate the applicability of the testing protocol and ranking system and generate an extensive database. This kind of database, based on a one-time comprehensive evaluation, can be used to select products, depending on project requirements in the future. However, for new products (new formulations or never-been used-in-field projects before), evaluation based on the developed lab testing protocol followed by determining ranking is mandatory.
- Based on the evaluation of eight products, the ranking system using six performance indicators (e.g., water absorption, POAS, sorptivity, RCPT, chloride ponding, and corrosion rate measurements by the accelerated test) compared well to the ranking system using three performance indicators (e.g., POAS, sorptivity, and RCPT). However, the above comprehensive evaluation using several products will be useful to validate the acceptability of the ranking system based on three performance indicators instead of six, which saves time for future evaluation.

Table 7-1: Effective evaluation of coating and sealer using different concrete substrates

Test	Good substrate concrete (w/cm 0.42 with good transport properties)	Poor substrate concrete (~0.6 w/cm with poor transport properties)
RCPT	Does not create an adequate driving force for Cl^- ion migration	Creates adequate driving force for Cl^- ion migration—effective for product evaluation and ranking system
Chloride ponding	Chloride content at 32 mm depth is < threshold value for all tested products—comparative ranking is good but misleading regarding corrosion protection effectiveness	Chloride penetration is expected to be high and up to steel depth for control concrete—creates adequate driving force and effective corrosion protection evaluation and improving ranking system
Rate of corrosion (accelerated)	Good substrate with 3.5% NaCl-not adequate acceleration to reach active corrosion—ranking based on 60 days of data is acceptable, but corrosion protection may not be effective	Poor substrate with $CaCl_2$ solution—expected to create adequate acceleration (high driving force) to reach active corrosion—effective evaluation of corrosion protection as well as improving the ranking system
Rate of corrosion (steady state)	Anticipated to be around 2 years	Expected to be within a year—a very effective one-time validation to establish accelerated corrosion test
Pull-off adhesion test	Representative of field concrete substrate	May not be representative

7.2.2 Condition Assessment of Field Substrate Concrete before Application of Coating/Sealer Materials

The quality of concrete substrates in the field may vary due to variability in mix design (especially change in w/c) and/or degrees of deterioration of concrete substrate over time from environmental exposure. Therefore, concrete substrate inspection in the field by suitable test methods [e.g., measuring POAS, assessment of CSP, depth-wise chloride analysis, etc.] for initial condition assessment is recommended before applying the selected sealer/coating product in a field project. The following inspection approaches are recommended for the initial condition assessment:

- **The use of POAS measurements to check the quality of concrete substrate and selecting a suitable surface preparation method:** POAS measurements on concrete columns were found to be effective at the San Antonio project to check the variability of substrate concrete quality as a function of weathering and develop guidelines for selecting a suitable surface preparation method (e.g., water-blasting or sandblasting) depending on the substrate condition. Water-blasting was found to be adequate for effective cleaning (i.e., complete removal of dust and dirt) along with isolated removal (wherever the adhesion between the old coating and concrete surface is weak) of an old coating (applied previously) from the inspected areas of the studied concrete columns. In contrast, sandblasting was effective in the complete removal of the old coating along with the removal of the top concrete layer (wherever concrete deteriorated due to weathering). It was observed that wherever the POAS of the old coating is good, complete removal of the old coating through sandblasting may not be needed, and water-blasting should be adequate. Water-blasting minimizes cost, effort, and environmental impact compared to sandblasting. **Proposed further work:** more fieldwork covering different products in different bridges is needed to validate this recommendation.

- **Concrete surface roughness (based on CSP) should be as per the ICRI guidelines**. However, the role of CSP of concrete substrate to achieve optimum POAS is not known. The product data sheets recommend CSP 1-3 in general, which does not address the CSP of field concrete substrate. Sometimes, field CSP can be more than 3 (e.g., after sandblasting or other types of blasting methods), and it is important to know if a relatively higher CSP (i.e., > 3) can have any detrimental effects on achieving optimum POAS. **Proposed further work:** the applicability of any suitable device to measure surface roughness directly (the researchers have attempted one method [i.e., using a separate attachment (for CSP) in the coating thickness-measuring device] to generate some preliminary data in the San Antonio project) may be more effective than the estimation of CSP (qualitative approach); further work is needed to check if this method provides acceptable results.
- **Concrete substrate surfaces should be free from moisture** as per the ICRI guidelines. However, guidelines on assessing CSMC and providing recommendations on optimum CSMC and the time needed to achieve that CSMC does not exist. **Proposed further work:** A moisture meter was found to be effective in monitoring CSMC before applying coating/sealer materials. Further research is recommended to evaluate the impact of substrate moisture conditions (low to high moisture) on the performance of sealer and coating materials and provide recommendations on optimum CSMC and the time (the time gap after surface preparation and before applying the products) needed to achieve that CSMC, depending on the surface preparation method and ambient conditions (e.g., RH, temperature, wind speed, etc.) for each product.
- **Chloride analysis at different depths** should be useful to ascertain the status of corrosion potential before applying any product if corrosion protection is the main purpose of product application. **Proposed further work:** This work has not been attempted in this project but is recommended to be conducted in selected sealer/coating field projects to check the effectiveness. The available data (if maintained by TxDOT in selective projects) on depth-wise chloride contents will be very useful in selecting projects with low, medium, and high corrosion potential. If the chloride data are not

available, depth-wise chloride contents can be determined using small core samples. The guidelines for product selection based on the ranking system developed by the lab protocol and the degree of field corrosion potential can be effectively developed.

7.2.3 Product Selection

There should be a performance-based approach for selecting suitable coating/sealer materials for a concrete project. The product ranking in the extensive database will be used to choose products, depending on the condition assessment results (mainly corrosion potential) for a project. An example of guidelines based on product evaluation so far (8 products) is provided in Table 6-1. However, for new products (new formulations or never been used in field projects before), evaluation based on the developed lab testing protocol followed by determining ranking is mandatory.

It is expected that the best performing materials in a new project will have more service life, be economical (reapplication will be minimal), and have sustainable options (less consumption of material and waste generation if reapplication is minimal). TTI will also perform a life-cycle cost analysis for the same situations to identify the most suitable options conforming to the key performance indicators.

7.2.4 Application of Coating/Sealer Materials

The following monitoring approaches are recommended to be considered for the effective application of coating/sealer materials:

- During field visits, it was observed that the application of coating materials was based on the coverage (i.e., rate of application in sq ft/gal) and one-coat versus two-coat applications (per the product data sheets). However, the practice of checking whether the specified rate of application criteria is satisfied was not observed while performing limited field studies in this project. The practice of checking the required/specified WFT through the suitable direct measurement was found to be in general missing. Therefore, a guideline on maintaining the required WFT, along with the conventional practice of maintaining specified coverage (sq ft/gal), should be developed to ensure an effective application. **Proposed further work:** Monitoring WFT with the corresponding specified coverage rate and linking with key performance measurements (e.g., monitoring POAS and others) in several field projects needs to be conducted to develop this kind of guideline.
- Effective application of different coating materials can be assessed by measuring the DFT using a portable DFT measuring gauge. The direct measurement of coating thickness by a stereo microscope using a small cut specimen of the concrete substrate with an attached coated layer was found to be useful to validate the gauge-based DFT measurements. **Proposed further work:** Monitoring DFT with the corresponding specified coverage rate

and linking with key performance measurements (e.g., monitoring POAS with WFT/DFT and others) in several field projects is recommended to develop DFT-based guidelines.

- For sealer material, the DOP test using a stereo microscope was found to be effective. **Proposed further work:** Monitoring DOP in several sealer projects is necessary to check the effectiveness of the developed method. A reliable measurement of DOP will be useful to assess the effectiveness of sealers for protecting substrate concrete against chloride and moisture ingress.

7.2.5 Performance of Coating/Sealer Materials

The following measures/approaches are recommended to be considered for performance verification of coating/sealer materials:

- Based on the POAS measurements on both vertical and horizontal surfaces in the lab, POAS on the horizontal concrete substrate was slightly higher than on the vertical surface. This is a limitation of the test itself and should not be considered as a reduction of POAS in the field with vertical surfaces. A certain percentage reduction (which needs to be evaluated through further testing) needs to be assigned for each product based on a one-time lab versus field POAS assessment study. The condition of the concrete substrate (strength as well as surface roughness) is one of the important parameters when assessing the adhesion performance. For the lab POAS test in this project, the CSP value of the concrete surface was close to 1 (smooth surface), which may be one of the reasons for showing relatively lower POAS for the WB coatings. However, the SB coatings performed well with the same concrete substrate. From this ongoing research project, it was observed that SB coating materials can exhibit high POAS on a smooth concrete substrate (CSP 1) in comparison to WB coating materials. **Proposed future work:** A separate study that considers field conditions is needed to evaluate this aspect further. At least two different concrete substrate surfaces can be prepared based on surface roughness (e.g., CSP 1-2 and CSP 3-4), and adhesion strength for both the WB and SB coating materials can be performed.
- The adhesion strength is for comparison purposes only and can be checked with the product data sheet for the recommended/tested value. However, not all coating product data sheets report the POAS value. There is no minimum recommended pull-off strength requirement by ASTM standards (ASTM D7234) for coating material. **Proposed future work:** A study needs to be conducted to obtain a minimum POAS for different coating materials. This finding will help to establish a minimum requirement of the POAS value that should be achieved for a coating material on a concrete substrate by following the standard.
- Determining reapplication intervals for coatings and sealers:
  - Maintaining an effective DOP of a sealed substrate over time (in years) is necessary to ensure effective protection of substrate concrete against chloride and

  moisture ingress. **Proposed further work**: Therefore, further work on assessing DOP over time (years) in several field projects is necessary to on one hand check the substructure concrete protection effectiveness of the commonly used sealers and on the other hand determine the need for the reapplication (along with reapplication intervals).
  - Further work to develop guidelines for determining reapplication intervals for coating materials involves the reapplication of coating materials on an existing concrete substrate can be assessed by monitoring POAS data over time. If the change in POAS (i.e., reduction of POAS) value over time (in years) is less, the coating should work well for a longer period, and reapplication with a longer interval (e.g., 10–15 years) can be recommended. In contrast, if the rate of reduction in POAS is high, reapplication with a shorter interval (e.g., within 5 years) can be suggested. This proposed work needs to be assessed in both the laboratory and field over time.
  - Reapplication with a longer interval can be suggested for the product that has a higher resistance to weathering and vice versa—the weathering resistance of the selected sealer and coating products were successfully evaluated using the QUV-QFOG chambers in the laboratory. It is recommended to evaluate the weathering resistance property of all commonly used current products as well as potential new products (i.e., all evaluated products in the A2 to create a database) and generate a good database on weathering resistance.
- Some WB coating materials (Coat-A[WB], and Coat-S[WB]) showed higher chloride and moisture ingress. For WB coating materials to have similar protection as SB coatings (e.g., Coat-M[SB] or Coat-R[SB]), maintaining a relatively higher DFT than the current practice may provide improved performance. This aspect can be evaluated in future research.
- The use of a suitable primer and product for UV protection is recommended by some of the suppliers and may be used in some projects. The use of a primer before the application of any coating product and the use of UV-protected products (such as urethane) can now be effectively evaluated using the developed lab protocol, which is recommended to verify if the use of a primer or application of UV protection layer is effective. If not, the benefit of cost saving can be justified.
- Utilization of knowledge gained from past field projects to validate the proposed evaluation guidelines: The reasons for failure (some failure field cases need to be selected) can be identified based on what the proposed evaluation guidelines (covering product selection, surface preparation, application, and performance evaluation) suggests and see which suggested guideline items were not followed that caused failures. The suggested evaluation guidelines should show a good match with the successful field cases.

7.2.6 Verification of the Necessity of Two-Coat Application for Certain Coating Materials

It was observed that the POAS of the one-coat system was comparatively higher than the two-coat system. Coat-A(WB) with one coat showed higher (17 percent) POAS than Coat-A(WB) with a two-coat system. Similarly, the Coat-L(WB) one-coat system showed 40 percent higher POAS than the two-coat system. In contrast, the SB coating (Coat-M[SB]) showed almost similar POAS in the case of both one-coat and two-coat systems. The thick layer for WB coating may show low adhesion strength; however, for SB coating, both coat options are fine. **Proposed further work:** A study (with a specific focus) is needed to assess the performance of just one coat of both the WB and SB coating products to mitigate chloride and moisture ingress and maintain good adhesion strength. If good performance is observed by applying a one-layer coating product (especially for WB coatings), huge savings in material cost with a significant reduction in effort are the expected benefits.

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