Performance of Materials & Methods for Concrete Crack Sealants

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16. Abstract

The durability of concrete structures is closely tied to their ability to resist the ingress of water and aggressive agents such as chlorides. Cracks act as pathways for the penetration of these elements, posing a significant threat to the service life of concrete structures and raising concerns for infrastructure owners and operators. Sealants offer an effective solution to mitigate these issues, but the abundance of options in the U.S. market with varying qualities necessitates a thorough examination. This paper addresses a multi-part agenda related to sealant options. The study first presents a literature review discussing over 20 sealant options commercially available, examining their qualities and implementation. The review is organized into categories such as deck, joint, and crack sealants for a more detailed analysis. The study proposes adjustments to the existing Silane and Epoxy Resin specifications used by to the NCDOT, while also providing sample specifications for potential future use of emerging sealants such as Polyurethane and Methyl Methacrylate by the NCDOT. Lastly, the report introduces SEECS (Selection for Emerging and Explored Concrete Sealants), a systematically tabulated set of guidelines for concrete sealant selection based on various criteria.

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Executive Summary

The durability of concrete structures is directly linked to their ability to resist the ingress of water and corrosive agents, particularly chlorides. Cracks in concrete serve as vulnerable pathways for water and aggressive substances, posing a significant threat to the structures' service life. Owners and operators of infrastructure are particularly concerned about the presence of cracks.

To address this issue, the application of sealants is a commonly employed strategy. Sealants act as barriers to impede the intrusion of water and corrosive elements into concrete, preserving and protecting infrastructure. While numerous sealant options exist, comprehensive studies comparing their performance are limited.

This study delves into various concrete sealants available in the U.S. market, exploring ways in which they can increase resistance of concrete against ingress of water and aggressive agents. It categorizes over 20 sources into Deck Sealant Comparisons, Joint Sealant Comparisons, and Generalized Crack Sealant, presenting insights from literature. The study then evaluates and recommends adjustments to NCDOT sealant specifications, aiming for better alignment with industry standards.

Despite having only four established sealant specifications (Silane, Silicone, HMWM, and Epoxy Resin), the NCDOT has numerous concrete protection options. The study provides starting points for additional sealant specifications, focusing on Polyurethane, Poreshield, Acrylics, and Polysulfide. These recommendations aim to guide NCDOT in formulating comprehensive specifications that align with industry practices.

Finally, the study introduces SEECS – Selection for Emerging and Explored Concrete Sealants. SEECS is an Excel-based set of guidelines for systematic concrete sealant selection, considering various factors. The provided walkthrough exemplifies SEECS' practical application, offering NCDOT a structured approach to selecting the most suitable concrete sealants.

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1 Introduction

1.1 Background

The durability of concrete structures is related to the ability of concrete to impede the ingress of water and aggressive agents, such as chlorides. Cracks provide preferential pathways for the ingress of water and aggressive agents, and therefore contribute to the reduction of the service life of concrete structures. Cracks are, therefore, a major concern for the owners and operators of infrastructure.

Cracks are ubiquitous because of the quasi-brittle nature of concrete and its volume instability (e.g., shrinkage). In some instances, concrete elements are designed to crack to engage steel reinforcement. Therefore, in concrete structures, the influence of cracks and their adverse effect on the service life of concrete structures needs to be addressed. This is especially the case for existing structures and critical infrastructure, such as bridges, where extending their service life results in significant cost savings.

A common strategy to reduce the adverse effect of cracks on the service life of concrete structures is to seal cracks using a sealant to hinder or minimize the penetration of water and aggressive elements into concrete. A variety of sealants are commercially available and have been used for decades to protect and preserve concrete infrastructure. Despite the availability of a wide range of sealants, comprehensive studies comparing the performance of different sealants are limited.

The aim of this study is to delve further into many of the concrete sealants currently available in the United States market today, and discuss different ways that various sealants can aid North Carolina Department of Transportation (NCDOT) in sealing concrete failures in the future.

1.2 Research Tasks & Objectives

The specific objectives of the research project include the following:

i) Review existing published literature as well as individual material guidelines on the performance of different sealants and their installation methods. Existing literature on test methods and performance criteria will also be reviewed.

ii) After literature review is completed, we will compare the current NCDOT specifications with the specifications from other DOTs around the United States as well as the literature from Objective 1 so that we can propose a change if needed.

iii) Compile the data from Objective 1 and Objective 2 into a set of guidelines for selecting sealants. These guidelines will be in the form of a table with a variety of factors taken into consideration.

2 Literature Review

2.1 Overall Sealant Classification & Introduction

In this project, our aim is to explore a diverse range of sealants currently available in the United States market, specifically for potential use by the NCDOT in sealing various concrete failures. The sealants under consideration include Polyurethane, Methyl Methacrylate, High Molecular Weight Methacrylate, Silicone, Silane, Siloxane, Epoxy, Acrylic, Silicate, and a plethora of others. Our focus extends to evaluating their application capabilities across various concrete locations, encompassing bridge decks, joints, and general cracking scenarios.

2.1.1 Film Formers

Film Formers are topical sealants that coat the entirety of the concrete surface without seeping deeper into the concrete's pores [1] . These sealers create a highly effective top layer of protection for concrete. Sealants in this category include Polyurethane, PUMMA, Methyl Methacrylate (MMA), High Molecular Weight Methacrylate (HMWM), Epoxy, Acrylic, Silicone, Polysulfide, and Linseed Oil. While these sealants provide a powerful level of surface protection, it is important to note that their effectiveness can diminish over time with usage due to their topical nature, i.e., mechanical abrasion during their service life.

2.1.2 Penetrating Sealants

Penetrating sealants protect the concrete by seeping into the concrete's capillaries to form an effective barrier from outside contaminants [1]. Unlike Film Formers, these sealants will not wear down over time with usage. Sealants that we will discuss from this classification are Silane, Siloxane, Silicate, and Poreshield. Silicates are the only penetrating sealant in this list that act more as a densifier or pore blocker, where it reduces the porosity of the concrete to improve durability by reacting chemically within the capillaries that it plugs [2]. Poreshield is a penetrating and film forming sealer, however we are including it in this category as it acts as a competitive alternative to traditional penetrating sealants on the market today.

2.2 Deck Sealant Comparisons

This section will discuss sealants commonly used for sealing concrete bridge decks and similar structures across the United States. While these are not the sole sealants employed for such purposes, they are predominantly chosen for sealing bridge decks over other locations.

Methacrylate-based sealants have been found to be popular film formers for sealing various concrete structures such as bridge decks and pavements. The two options that have been evaluated are HMWM and MMA. Both sealants are notable for being able to seal extremely small cracks in horizontal orientations (such as bridge decks) and can withstand lower temperatures while maintaining their strength. HMWM's are composed of a three-component methacrylate polymer system that can become volatile if mixed incorrectly [3]. HMWM has a slightly higher viscosity than MMA due to its higher flash point and higher molecular weight [4]. MMA, a two-component system formed from reactive methyl methacrylate catalyzed by dibenzoyl peroxide powder, eliminates the volatility concerns associated with

HMWMs [3]. HMWM is explored exponentially more than MMA but both are very viable sealants for NCDOT's use.

In a study by the Air Force Institute of Technology (AFIT), HMWMs and Epoxies were evaluated for their ability to seal bridge decks and concrete pavements, especially in the context of airfield concrete pavements [4]. AFIT sought an alternative to Epoxy for sealing shrinkage cracks due to Epoxy's significantly higher viscosity compared to HMWM. HMWMs have viscosities around 12 to 1 cps, while Epoxies exhibit viscosities closer to 100 cps and above. AFIT's findings suggest that HMWM is a viable alternative to Epoxy for sealing deeper shrinkage cracks. They recommend using sealants with a viscosity of 50 cps maximum for cracks less than 0.4 mm and those with a viscosity greater than 50 cps for cracks larger than 0.4 mm.

Further, in an investigation conducted by the University of North Florida to evaluate bridge deck cracking solutions, MMA, HMWM, Polyurethane and Epoxies were assessed for their viability in sealing various forms of bridge crack failures [3]. NCHRP 244 standards [5] were utilized, involving depth of penetration, bond strength, chloride resistance, elongation and rate of seepage in both field and laboratory testing settings. All sealants performed well and were deemed as viable sealant solutions for bridge decks. However, HMWM sealants were found to best seal cracks less than 0.019 inches and Epoxies were most effective for sealing cracks larger than 0.02 inches.

In advocating for the use of HMWM, Rahim et al. [6] provide a comprehensive overview and conducts a national survey to shed light on this sealant's efficacy. The survey, encompassing responses from various states, reveals that among the state Departments of Transportation (DOTs), 52.5% opted for Epoxy (corresponding to 21 states) and HMWM closely followed with 42.5% preference (17 states). Other sealants, including Urethanes, Silanes, Siloxanes, Bituminous membranes, and Linseed Oils, were utilized by 37.5% of state DOTs. The study delves into specific preferences among state DOTs, indicating a prevalent inclination toward using HMWM as a crack sealer rather than a surface sealer. The recommended application occurs post-crack initiation, with surface preparation involving cleaning dirt, dust, and contaminants off with forced air. Notably, state DOTs preference lean towards HMWM application in cases where crack widths do not exceed 1.6 mm. Additionally, HMWM is observed to contribute to the restoration of structural bond strength and flexural strength under certain conditions. These conditions include narrow crack widths ranging from 0.05 mm to 12.7 mm, a lack of contaminants, and application within the temperature range of 7 degrees Celsius to 29 degrees Celsius (44.6 degrees Fahrenheit to 84.2 degrees Fahrenheit). The overall conclusion drawn from the research strongly encourages the utilization of HMWM for concrete sealing, emphasizing its efficacy in safeguarding concrete structures from further deterioration and failure. The findings offer valuable insights into the preferences and practices of state DOTs, positioning HMWM as a commendable choice for concrete protection and preservation.

In a report published by the University of Minnesota and Minnesota Department of Transportation (MnDOT), a detailed discussion of concrete deck and crack sealants was presented [7]. The followings provides a summary of their findings. Silane appeared to outperform Siloxane in most tests in terms of penetration depths and chloride ingress resistance. Solvent-based products outperformed water-based products, as water-based products were not seen as suitable for reapplication. In addition, HMWM and

MMA were found to be better penetrators for sealing a bridge deck than Epoxy-based sealants, which is most likely due to the higher viscosity that Epoxy has compared to the Methacrylate-based sealants. Contrary to that finding, Epoxy was found to have better bond strengths and freeze-thaw resistance than HMWM in the laboratory testing. The study concluded that Epoxies were the best option for larger bridge cracks and that HMWM-based sealants were preferable for narrower bridge cracks.

Most recently, a 2023 national survey was conducted on the topic of crack sealants such as HMWM, MMA, and Epoxy for the preservation of concrete bridge decks [8]. This paper has a wealth of information centered on bridge deck sealants, but we will summarize the pertinent information. From a list of 26 state DOTs that responded, a list of 18 states utilizing multiple generic sealers could be comprised. Out of the 18 state DOT responses, only 7 utilized MMA in addition to either Epoxy or HMWM. MnDOT, Missouri Department of Transportation (MoDOT), and New York City Department of Transportation (NYCDOT) were the only ones from this study that used all three sealant options. This is in contrast to state DOTs such as NCDOT, Arizona Department of Transportation (ADOT), Arkansas Department of Transportation (ArDOT), Iowa Department of Transportation (Iowa DOT), Nevada Department of Transportation (NDOT), New Hampshire Department of Transportation (NHDOT), North Dakota Department of Transportation (NDDOT), Utah Department of Transportation (UDOT), and Wyoming Department of Transportation (WYDOT) which utilized just Epoxies and HMWM as their sealant selections. The overarching choice was Epoxy, with HMWM being a close second. Beyond the survey, a discussion of HMWM surpassing the performance of Epoxy and MMA by various other studies ensued. While HMWM surpassed the latter options in deep penetrative abilities and chloride penetration hinderance, Epoxy had higher bond strengths and freeze-thaw resistance. Additionally, the study discussed how various DOTs and researchers advocated for the use of different sealants based on their crack widths or life spans. New York State Department of Transportation (NYSDOT), for example, recommends HMWM or Epoxies for working cracks greater than 0.007 inches and nonworking cracks greater than 0.012 inches while generalized penetrating sealants are recommended for working cracks under 0.007 inches and nonworking cracks under 0.012 inches [9]. Working cracks in concrete are characterized by variations in width over time, influenced by factors such as temperature fluctuations or the imposition of deck loads[8]. In contrast, nonworking cracks are those where the width remains relatively stable without significant fluctuations over time. One researcher discusses that HMWM is ineffective for sealing cracks wider than 0.08 inches and could be teamed with Silane for cracks under 0.08 inches in width while others dictate that HMWM should be used for cracking widths of 0.002 inches through 0.5 inches. Additionally, reapplication of Epoxies and MMAs ranges from every 3 years up to 15 years depending on the source. Overall, this study proves that HMWM, MMA and Epoxies are all very viable sealant options depending on the needs of the individual project.

Silane, a common sealant in today's market, is notable for its small molecules that can penetrate extremely well in a hydrophobic manner [10]. Derived from the Silicon family, Silane can permanently form a chemical bond to its substrate, protecting the concrete from water and chloride ingress. While it creates a protective barrier, it also has higher amounts of Volatile Organic Compounds compared to competing sealant options, is on the more-expensive side, requires a high pH to catalyze and cannot create a surface film to work against abrasion. In addition, this sealant (whether water-based or solvent-based) can work in full serviceability and strength conditions for up to 10 years before needing to be reapplied [11].

Application (and further reapplication) can only be done on clean and dry surfaces with either a roller, brush or low-pressure airless sprayer teamed with a broom or squeegee for even distribution [12–15].

Siloxane, also from the Silicon family, is a sealant that differs significantly from Silane [10]. Classified as a penetrating sealant, Siloxane's larger molecular size leads to a more film-forming seal on substrates. This sealant offers a lower cost, abrasion-resistant (depending on the strength of the film created) and is not dependent on a high pH for catalyzation. In addition, they are also less volatile, and provide good water-resistance. A common solution to mitigate the negative effects of both Siloxane and Silane is to use a hybrid Silane-Siloxane-based product, which will allow penetration as well as a protective surface film and doesn't require a high pH for catalyzation.

Boiled Linseed Oil has been employed since the 1960s for sealing concrete pavements and protecting them from external contaminants [16]. Derived from the flax plant, this natural sealant is specifically designed to inhibit scaling caused by freeze-thaw cycles and to prevent chloride ion penetration. Although it has been a popular choice for Departments of Transportation (DOTs) aiming to enhance concrete durability, a drawback of this product is the need for periodic reapplication [17, 18].

Research was conducted by the US Department of Agriculture to evaluate Linseed Oil's ability to protect concrete during freeze-thaw conditions [17]. Tests were conducted in the laboratory settings with water and 2% brine while field tests involved air-entrained concrete highways with Linseed Oil coatings subject to salt presence. The study found that Linseed Oil increased the concrete's durability and assisted in further damage prevention. In addition, they determined that Linseed Oil emulsions were as effective in field applications as Linseed Oil solutions for anti-scaling purposes.

In a study investigating the efficacy of surface sealants for hydraulic structures exposed to lower temperatures, various sealants, including Silanes, Siloxanes, boiled Linseed Oil, Urethanes, and Epoxies, underwent comprehensive testing [19]. The methods employed included Water Absorption and Vapor Transmission Tests, primarily adhering to NCHRP 244 guidelines. Additional tests were conducted to assess the impact of application temperature and immersion in 15% NaCl solutions versus pH 5 solutions. The findings of the study revealed that Silanes and Siloxanes outperformed other sealants in terms of Water Absorption and Vapor Transmission Tests. However, their performance exhibited a decline in the presence of hydrostatic pressures. Interestingly, the reduction of application temperatures did not significantly affect the Silane- and Siloxane-based products, whereas it did impact the durability of Linseed Oil, Epoxies, and Urethanes. Notably, the study identified that Silane and Siloxane performed optimally in the presence of 15% NaCl, while other sealants demonstrated better performance in the presence of a pH 5 solution. Overall, Silane and Siloxane performed better than any of the other commercial sealants in the study when hydrostatic pressure is present.

In a 1993 study evaluating Silane – and Siloxane – based products effectiveness to that of boiled Linseed Oil sealants, the main objective was to compare their penetration and durability performances in field and laboratory testing within a three-year time span [16]. Field tests aimed to determine each sealant's ability to prevent chloride ion intrusion and salt-water absorption across three different testing sites. Laboratory tests evaluated the performance of each sealant in various categories, including chloride ion intrusion, salt-water intrusion, penetration, vapor transmission, and abrasion. In the field investigation, Linseed Oil penetrated deeper than Silane and Siloxane and slightly outperformed other sealants in preventing chloride intrusion. However, in the lab investigation, varying results were obtained compared to previous tests, suggesting a complex interplay of factors influencing sealant performance. Linseed Oil was able to penetrate deeper than its competition, reaching twice the depth of Silane and three times the depth of Siloxane. However, this could have also been affected by the age and permeability of the actual concrete itself. Field data also determined that Linseed Oil was the most effective of the three sealants at reducing both chloride ion penetration as well as salt-water absorption. Overall, both laboratory and field tests by The University of Manitoba over this three-year span prove that Linseed Oil is a viable alternative to Silane and Siloxane.

Silicates function as penetrating densifiers, plugging the capillaries of porous substrates, and creating a chemical barrier against water, abrasion, and other contaminants [2]. While not acting as a true repellent, the capillary plugging action enables the sealant to restrict the access of various contaminants from entering the concrete. Due to this, Silicas are not inherently water- or contaminant- resistant but they will restrict their access into the concrete through porosity reduction facilitated by densification [2]. There are four main types of Silicate-based products: Sodium Silicates, Potassium Silicates, Lithium Silicates, and Colloidal Silicates. Sodium Silicates are the oldest Silicates on the market today, whereas Colloidal Silicates are the newest. Among these, Lithium Silicates are the most common type and have successfully overcome many drawbacks associated with Sodium and Potassium Silicates.

The primary objective of a study undertaken by the Department of Defense Corrosion Prevention and Control Program was to assess penetrating surface sealants for military concrete floorings, focusing on both material degradation resistance and the reduction of overall maintenance costs [20]. The current method employing Epoxy-based sealants was found to be problematic due to its inherent brittleness and slipperiness when wet. As an alternative, the study evaluated the Pentra Protective Coating System—a water-based lithium silicate formulation comprising Pentra-Sil 244+ and Pentra Guard (HP). The performance of the Pentra Protective Coating System was scrutinized for a duration of one year post-installation, emphasizing the physical conditions of the floor and eliciting impressions from the building's users. At the six-month juncture, the floors were observed to remain in 'excellent condition,' and users reported enhanced ease of cleaning with the Silicate system. Nonetheless, certain adverse effects were noted, including persistent vehicular tread marks and curling at joint edges in high-traffic areas. Upon inspection one year into the study, the Silicate-based system retained its quality with minimal degradation. While previously identified deficiencies persisted, overall user satisfaction regarding the performance of all sealed areas was sustained. The study's conclusion underscores the critical importance of meticulous application of joint-sealants and crack sealants. Additionally, the Pentra Protective Coating System, despite incurring higher upfront costs (with an additional $21,500 designated as "other costs"), demonstrated lower maintenance costs compared to the previously utilized Epoxy systems. In summary, the Pentra Protective Coating System, characterized by its highly effective penetrative nature and cost-effectiveness, is recommended for implementation by the Department of Defense.

Fluorinated sealants represent a newer technology in the market but offer distinct benefits [2]. Not only is this sealant both hydrophobic and oleophobic, but it also stands out as a very stable (non-reactive) product with UV and heat resistance. Despite its expensive nature, Fluorinated sealants have primarily been used as an additive to other penetrating water repellents, such as Silane or Siloxane, to enhance durability and resistance to various contaminants. Unfortunately, there is limited research available on this form of sealant.

2.3 Joint Sealant Comparisons

This section is a discussion of sealants consistently chosen to seal concrete joints. These joints in concrete slabs are necessary to prevent cracking in the future but need to be sealed to protect it from outside contaminants as well as other traffic [21].

Silicone stands out as a prominent sealant, exhibiting enduring durability over decades and proving effective across a broad temperature range, even in freezing conditions. The two primary variants of Silicone are Neutral Cure and Acetoxy (Acid) Cure. Given that many state Departments of Transportation, including North Carolina, express a preference for Neutral Cure over Acid Cure, the focus here will be on the former. Neutral cure Silicones, particularly the flexible (low-modulus) variety, are characterized by their odorless nature and weatherproof properties. Within the realm of neutral cure Silicone, a further breakdown includes Alkoxy Neutral Cure Silicone and Oxime Neutral Cure Silicone. Alkoxy Silicones emit alcohol, are non-corrosive, and feature a slow cure, while Oxime Silicones emit ethyl ketoxime and are low-corrosive. In addition to the neutral cure breakdown, Silicones can be classified as Self-Leveling or Non-Self-Leveling. Silicones are not the only sealants with this specific classification, however it was seen most often with this sealant. Self-leveling Silicones exhibit a flow into joints, naturally leveling out over time. They do not require tooling. In contrast, non-self-leveling Silicone sealants necessitate tooling to be effectively worked into the area requiring sealing. This comprehensive breakdown of Silicone variants underscores its versatile nature, offering a range of options tailored to specific project requirements and preferences.

A comprehensive two-phase investigation, spanning a decade, was undertaken collaboratively by the US Army Engineer Research Development Center and Crafco Incorporated within the Construction Productivity Advancement Research (CPAR) program [22]. The primary objective centered on the meticulous evaluation of joint sealants, particularly comparing Silicone-based sealants with both jet-fuel-resistant and non jet-fuel-resistant hot-applied Asphalt-based sealants. While laboratory testing predominantly presented results for Asphalt-based sealants, our summary will pivot towards the more encompassing field investigation. Key milestones in this assessment were marked during the 6-month and 12-month evaluations, at the 22-month interval, and significantly, at the 117-month evaluation. Notably, between the 6-month and 12-month assessments, adhesion failures exhibited a marginal increase for asphaltic sealants. However, cold-applied single- and double-component sealants, including Polysulfide and Silicone, outperformed their hot-applied counterparts during this period. At the 22-month evaluation, distinctions in sealant performance surfaced. The Mobay 960SL material, a self-leveling Silicone-based sealant, displayed partial depth adhesion losses, an anomaly not observed in other Silicone sealants in the study. Similar effects were recorded for hot-applied sealants. The 117-month evaluation revealed that all sealants, barring the Dow 890 SL (a cold-applied single-component self-leveling, low modulus Silicone sealant), experienced failure by cohesive break, with the Dow 890 SL exhibiting adhesive loss. Notably, Crafco Improved Non-JFR, Dow 902 RCS, and Dow 890 SL demonstrated the highest percent elongation at 600%. Several conclusive findings emerged from this protracted study. Two hot-applied asphaltic sealants and four Silicone-based sealants demonstrated life expectancies exceeding 10 years. Furthermore, Silicone failures manifested as spalling, while Asphalt-based sealants predominantly experienced adhesion loss as their primary mode of failure. These outcomes underscore the importance of meticulous joint preparation for optimal field performance.

Polyurethane is an extremely durable topical sealant that has slowly been infiltrating the Qualified Products List of many state DOTs. Polyurethane-based sealants offer better resistance to abrasion, contaminants, and UV rays other comparable topical sealants (such as Epoxies, Acrylics and Silicones) [23]. Not only can the sealant be used alone, but Polyurethanes can be added as a top coat to Epoxies for a surface with maximum resistance.

Polyurethane, emerging as a notable sealant, has garnered global interest in its performance. In the Czech Republic, a team from Brno University of Technology conducted an experiment investigating Polyurethane's efficacy in sealing concrete joints [24]. The primary objective of this study was to evaluate two high-strength, one-component Polyurethane sealants from the same manufacturer. Polyurethane representatives selected for this study include Type I and Type II. Type I demonstrates lower elongation at break percentages (600% minimum) compared to Type II, which exhibits 700% minimum elongation at break. Additionally, Type I shows higher elastic recovery percentages (90% minimum) in contrast to Type II, which has 80% minimum elastic recovery. Given the widespread usage and availability of Polyurethane, this research sought to contribute insights into its applicability. Two tests were devised to assess the sealants: an extension test to determine the maximum elongation of the sealants at break and a test to analyze the failure modes of each sample. Type II emerged as a superior universal sealant material compared to Type I, which exhibited greater suitability for non-structural applications. Following tests conducted in both laboratory settings and natural climates, the results indicated that neither type significantly outperformed the other. Consequently, both Type I and Type II Polyurethane sealants were deemed suitable for application in various structural contexts. This research adds valuable knowledge to the understanding of Polyurethane sealants and their practical implications. The findings underscore the versatility of Polyurethane as a sealing material, offering applicability to diverse structural scenarios.

For scenarios where the joint might have constant contact with water, Polysulfide-based sealants could be an option [25–28]. This sealant comes in one-part and two-part systems. In a one-part system, mixing is not required and curing can take weeks. In a two-part system, mixing between the base and accelerator is required and curing will take significantly less time than one-part. This sealant can be applied to cracks of various orientations, whether horizontal, vertical, or even overhead. In addition, this sealant can maintain full strength and serviceability for up to 20 years, making it a competitive alternative to the commonly used Silicone sealants [29, 30].

NDDOT conducted a study pertaining to Polysulfide-based and Silicone-based products for the purpose of sealing concrete joints [31]. In this study, they found that Polysulfide performed better than Silicone for the first 3 years but then performed equally to Silicone for the remaining years. In addition, spalling-induced failures were found to be 7% higher for Polysulfide than Silicone, while failure due to adhesion loss was 7% higher for Silicone than for Polysulfide. Overall, Silicone- and Polysulfide- based sealants were found to perform similarly and therefore other factors came into play when deciding which to use in a product.

In a technical brief published by the Federal Highway Administration (FHWA) on performance of joint sealing, Silicone, Polysulfide, and Polyurethane are comprehensively examined in terms of their specifications and diverse material properties [32]. As of 2019, FHWA stipulates that Silicones should be single-component while Polysulfides and Polyurethanes should be two-component. In addition, these liquid sealants should abide by ASTM D 5839 or Fed Spec SS-S-200E Types M and H. They also advise that best results for Silicone installation occurs when non-self-leveling is tooled by a hose or a backer rod whereas self-leveling Silicone relies solely on the viscosity of the material to allow it to flow (and therefore no tooling required). Mitigation of potential issues includes sealing in temperatures over 40 degrees Fahrenheit, cleaning and drying the surface properly before application, and moving the joint before the sealant is fully cured. In addition, they specify to not trap moisture in the area between the bottom of the reservoir and the backer rod by allowing joints to dry fully. The document provides a wealth of application tips and preventative measures to avert potential damage, offering comprehensive insights into best practices for the effective utilization of Silicone, Polysulfide, and Polyurethane sealants in joint sealing applications.

Overall, joint sealants may be centralized for application on concrete joints but they are a multifaceted group of sealants. Silicone, while already an extremely notable sealant, has serious competition with the presence of Polyurethanes and Polysulfides entering the sealant industry at an increasing speed.

2.4 Generalized Crack Sealant Comparisons

Epoxy resin-based sealants are one of the most notable sealants, with applicability on many crack orientations and locations. This sealant's higher tensile strengths and lower viscosities make it appealing to various DOTs and even for commercial use. Epoxies are available in both water-based and solvent-based systems as well as one- and two- component systems. Typically, two-part and solvent-based systems perform better than the other options [23]. Unfortunately, this sealant is not inherently UV-resistant as it will become discolored [23]. On the other hand, Epoxies are water-resistant and can hold their strength and serviceability for up to 10 years [7, 23, 33]. Overall, Epoxies are a multifaceted option for many sealing scenarios.

To evaluate the effectiveness of Epoxy resin injection in cementitious cracks, researchers from the China University of Petroleum looked at the sealant's viscosity, compressive strength and brittleness index in order to determine its ability to seal shallow cracks [34]. Viscosity of Epoxy resins decreased as the viscosity reducer content increased. Lower viscosities allow for injection into narrower cracks, which heavily impacted the results. A 10% concentration of the viscosity reducer was chosen, leading to superior results of the Epoxy to penetrate and seal narrow cracks. Epoxy resin showed excellent strengths in both compression and shear, as well as lower elastic moduli and brittle index than conventional cement sealing. In addition, Epoxy resins exhibited lower elastic moduli. Overall, the use of Epoxy resins for sealing concrete proved to be extremely beneficial through this experiment.

In an experiment conducted on the repair of concrete cracks, researchers looked at Epoxy for its ability to restore concrete strength with a variety of factors [35]. By utilizing methods of Epoxy injection, impregnating, and impregnation with Epoxy, this test used flexural strength tests and durability tests (carbonation, freeze-thaw, and chloride) to see which sealant performed the best. Epoxy injection, a common structural repair technique, involves injecting liquid epoxy resin into cracks to restore the concrete's integrity. In contrast, epoxy impregnation is a surface application that saturates the concrete with a protective epoxy solution to prevent the penetration of various harmful substances. In the chloride resistance testing, the chloride depths of the Epoxy alone as well as Epoxy/impregnating yielded 1.5 times higher chloride depths than the controlled specimen. The freeze-thaw testing showed that none of these methods were necessarily standout in their performance, however the Epoxy/impregnating repair method performed slightly better than that of the impregnation method alone. In the carbonation resistance tests, Epoxy/impregnating repair methods appeared to perform the best with depths of carbonation continuing to reflect that of one week of age. Clearly, the addition of Epoxy sealants prove to be beneficial for repairing concrete.

Acrylic-based sealants are often compared to Epoxy-based sealants, however their performance is not always comparable to that of Epoxies. Available in the same system variations as Epoxy (one-component, two-component, water-based and solvent-based), Acrylic resin's perform best in solvent-based systems but tend to be found in mainly one-component systems [23]. They are easier to apply and less expensive than Epoxies, however they do not form as thick and durable of a protective film over the concrete than the other topical sealants can.

In a review by Louisiana-based researchers, various concrete joint and crack sealants were evaluated on their capabilities to prevent premature structural failures [36]. Some of the sealants evaluated were Acrylic, Polysulfides, Polyurethanes, and Silicones. Acrylics were found to adhere to a wide variety of substrates but encounter shrinkage due to evaporation of solvents. Solvent-based Acrylics were found to have good UV stability as well but their strong odor and slow curing were found as disadvantages. On the other hand, Polysulfides, Polyurethanes and Silicones encounter minimal shrinkage and are capable of handling large joint movements. Polysulfides, Polyurethanes, and Silicones also have great adhesion capabilities, but UV stability appeared to only be the best for Silicones. Countering to Silicones positive attributes is the fact that its cost normally is much higher than the competitor sealants. In addition to presenting commonly used sealants, the study also aimed to introduce some emerging research on shape memory polymers (SMPs). While their capabilities are predicted to rival some of the previously mentioned sealants, SMPs are still in their infancy stage of exploration.

Poreshield is an emerging sealant comprised of soy methyl ester polystyrene (SME-PS) that is proving to be a competitive alternative to other penetrating sealants in a variety of locations [37]. This sealant not only provides a durable hydrophobic barrier for concrete, but can also be applied to concretes with a wide range of ages, densities, and orientations. Poreshield is a non-hazardous, durability-enhancing sealant with over 10 years of service life until needing to be reapplied. This sealant is utilized by many states currently, however it is not included in any Standard Specifications yet. We will explore a few instances where Poreshield was utilized by various states and proved to yield successful results.

In Indiana's Wabash County, Poreshield was applied to the surfaces of four separate bridges to enhance their durability [38]. The product had a quick application process, low levels of Volatile Organic Compounds (ensuring that the sealant is environmentally- and applicator- friendly), and cost-effective. A Wabash County highway superintendent said in 2020 that their goal was to have all bridges treated with Poreshield within five years and that "this practice will add years to the life of critical infrastructure, for less than 0.1% of the cost to replace the structure"[38]. Overall, Wabash County has found with confidence that Poreshield is a very viable alternative to previous concrete sealing solutions.

Another instance of successful Poreshield utilization in Indiana occurred when it was chosen to treat I-65's pavement joints [39]. This product was applied to 55,000 feet of joints along this roadway, and included two applications. One of the main benefits found within this application process was the speed of the application and the durability of the product after time had passed. Tony Korba, the concrete operations manager in charge of this project, is said to look forward to Poreshield being utilized in more projects and being included in standard specifications by DOTs in the future[39].

In addition to being an increasingly prominent sealant choice by Indiana Department of Transportation (INDOT), Wisconsin Department of Transportation (WisDOT) has also found success within the use of Poreshield for their concrete highway open joints [40]. The focus of this project was to ensure protection from chloride ion diffusion long-term. WisDOT evaluated seven products in this project including Silane, Siloxane, Silicates, and Poreshield. The study saw that Poreshield was able to reduce chloride ion diffusion over twice as the other sealants. With these results combined with Poreshield's sustainable and non-toxic qualities, it continues to be a very viable alternative to traditional penetrating sealants.

A recent study by Drexel University focused on an evaluation of Poreshield for its ability to mitigate the effects of calcium oxychloride (CAOXY) in concrete pavements and bridge decks [41]. CAOXY is a chemical that negatively affects concrete by forming and expanding cracks (especially during freeze-thaw cycles). Referencing studies by Wang and Monical et al, SME-PS was seen to have been able to reduce almost 90% of CAOXY formation, reduce 70% of further expansion, and its effectiveness surpassed many of the commercial products on the market today. In Drexel University's quest to validate these references, they found that the reduction of CAOXY in concrete was greater than 90% for a 28 day exposure and concluded that SME-PS is a successful approach to CAOXY mitigation.

Polyurethane Methyl Methacrylate (PUMMA) is a slightly less explored sealant alternative, however its composition presents itself as a promising option. With combined properties of the upcoming sealers of Polyurethane and MMA, it has been seen to have some very promising option. This sealant choice is flexible and durable, allowing blockage from debris and water on surfaces such as bridge decks [42]. Currently, North Carolina DOT employs Polyurethane Methyl Methacrylate as a viable option in their Approved Products List, however its use is not specified in detail within any other documentation such as the Standard Provisions or any Special Provisions. Even if this sealant doesn't have much public support currently, its positive combined qualities of Polyurethane and MMA prove that it has the potential to be a beneficial option to explore in the future.

2.5 Summary

Concrete sealants have a wide range of characteristics. No two sealants are unequivocally the same, as there are ranging differences between the various sealants in the United States market today. In Section 2, we discuss a multitude of sealants currently available for NCDOT use, and various literature in which these sealants were applied in laboratory or field experimentation.

In the realm of concrete crack repair, various sealants are commonly employed, each with its unique characteristics and applications. Silicone, known for its ability to maintain durability over decades and its effectiveness across a broad temperature range, proves to be particularly suitable for joint sealants. Silane, a long-lasting sealant with notable chloride penetration resistance and penetrative capabilities, can create a protective barrier on its own or in tandem with other sealants such as Siloxane. HMWM exhibits lower viscosity levels, making it favorable for sealing narrower cracks. Moreover, HMWM showcases superior penetrative abilities while simultaneously being able to form a thick surface barrier to provide notable chloride penetration resistance. Epoxy, garnering the most state DOT preference, boasts higher viscosity, making it well-suited for sealing wider horizontal cracks as well as vertical and overhead crack orientations. Epoxy sealants are recognized for their higher bond strengths and resistance to freeze-thaw cycles. While these sealant options are highly regarded and widely utilized in North Carolina, we also wanted to bring light to alternative options that not only rival the qualities of the current sealants employed but may also offer competitive advantages.

Certain sealants are emerging as significant players in the sealant industry. Poreshield, composed of soy methyl ester polystyrene, stands out as a non-hazardous durability-enhancer, featuring quick and straightforward application and demonstrating superior chloride ion diffusion, evident in numerous state DOT implementations. Polyurethane maintains effectiveness across a broad temperature range and provides enhanced resistance to abrasion, contaminants, and UV, surpassing commonly used sealant options like Epoxy and Silicone. This comprehensive overview underscores the rising prominence of these sealants in the industry.

Depending upon the criteria specific to the project at hand, certain sealants distinguish themselves as optimal performers. Epoxies present a versatile option. In broad temperature ranges, both Silicone and Polyurethane exhibit superior performance by demonstrating the ability to sustain durability in frigid conditions. Film formers like HMWM emerge as commendable choices for deck sealants, showcasing excellence in maintaining durability amidst recurrent abrasive encounters. In scenarios involving joint applications with potential water submersion, Polysulfides prove to be a commendable and effective option.

Conversely, certain sealants are not recommended due to various shortcomings. Linseed oil, while exhibiting chloride ion resistance and penetrative abilities comparable to Silane and Siloxane, necessitates more frequent reapplication. It stands as an older choice, with diminishing reliance in the industry due to its shorter lifespan compared to other, more durable sealants.

Overall, Section 2 underscores the extensive capabilities of sealants. While not all sealants are created equal, they possess individualistic characteristics that render them optimal for a diverse array of concrete sealing scenarios.

3 Evaluation of NCDOT Specifications & Proposal for New Specifications of Emerging Sealants

3.1 Evaluation of Current NCDOT Specifications

We evaluated the current NCDOT specifications for various sealants. Currently, NCDOT has 4 specifications: Silane, HMWM, Silicone, and Epoxy Resin. Out of these 4 sealants, Silicone was the only one listed in the Standard Provisions document while the other 3 sealants were listed in North Carolina DOT's Special Provisions documents. The provisions for Silicone and HMWM were found to align with that of many other states and therefore no change was needed. We recommended changes for Silane and Epoxy resin specifications, so that they will align with that of various other states around the country. The greyed portions of various Figures represent limited information provided by other states.

3.1.1 Silane Specification Evaluation

In our evaluation of Silane sealants, we aimed to assess both chloride ion penetration reduction percentages and water absorption capabilities using various testing methods. One of the primary testing resources commonly employed by North Carolina, as well as many other states, is the National Cooperative Highway Research Program (NCHRP) 244 Series Tests. The NCHRP 244 includes four distinct series, with Series I through III utilizing the Water Absorption Test, and Series IV utilizing the Accelerated Weathering Tests. In **Figure 1** below, we present a detailed comparison of the different NCHRP 244 Series Tests. This document will focus on Series II and Series IV (Southern) in particular. The percentages provided in the fifth column of this figure represent data from a study conducted by the Transportation Research Board of the National Research Council, and these values serve as baseline recommendations for each of the Series Tests [5].

Row	NCHRP Series	Test Method	Test Method Explanation	a) % Reduction with Silane	b) Chlorine Ion Content % by weight	Meaning of "Reduction"
1	I	Water Absorption	Similar to Series II but 6 days inside the plastic bags instead of 21 days	a) 79% b) 0.050 %		After soaking concrete cubes for 21 days in NaCl, ground half of a cube and measure acid-soluble chloride ion concentration and compare to uncoated control cubes
2	II	Water Absorption	21 days inside plastic bags of water soaking and then concrete allowed to air dry for 1, 5, and 21 days following the 21 days of initial curing. Coatings applied to three different ages which provided different moisture conditions that could be in the field.	a) 87%		After soaking concrete cubes for 21 days in NaCl, ground half of a cube and measure acid-soluble chloride ion concentration and compare to uncoated control cubes
3	III	Water Absorption	Similar to Series I and II	a) 89%		After soaking concrete cubes for 21 days in NaCl, ground half of a cube and measure acid-soluble chloride ion concentration and compare to uncoated control cubes
4	IV (Southern)	Accelerated Weathering tests	The southern climate test emphasized alternate exposure of a coated slab surface at 70F to a solution of 15 percent NaCl saltwater followed by exposure to ultraviolet light and infrared heat at 100F with the saltwater solution removed.	a) 76% b) 0.547 percent chloride content (uncoated) decreased by 97% with use of silane		After weekly cycle (for 24 weeks) of ponding concrete slabs with ½ inch of 15% NaCl solution for 100 hours, measure acid-soluble chloride concentration (exposed to different environmental conditions)
5	IV (Northern)	Accelerated Weathering tests	The northern climate test method used an accelerated weathering cycle in which the coated slab surface was exposed to a wider range of environmental conditions which included acid, saltwater, infrared heat, ultraviolet light, fresh water rinse, freezing and thawing.	a) 97% b) 0.182 percent chloride content (uncoated) decreased by 76% with use of silane		After daily cycle (5 days a week for 24 weeks) of 3 hours of soaking slabs in 15% NaCl & 0.02 M sulfurous acid solution, measure acid-soluble concentration (exposed to different environmental conditions)

Figure 1 Explanation of NCHRP 244 Series Tests

NCHRP 244 Series II Test employs the Water Absorption Test to determine Water Weight Gain reductions and Absorbed Chloride reductions. Currently, NCDOT specifies that Silane should achieve an 85% reduction in Water Weight Gain and an 87% reduction in Absorbed Chloride. While these values are slightly lower than those recommended by the Transportation Research Board, NCDOT still sets higher standards than many other states across the country that use Silane sealants. For instance, South Carolina Department of Transportation (SCDOT) requires an 80% reduction for Water Weight Gain and Absorbed Chloride [43]. MnDOT also sets lower reduction values than NCDOT, with a minimum of 80% for Water Weight Gain reduction and 85% for Absorbed Chloride reduction[44]. Idaho DOT has one of the lowest standards among the states, with a minimum requirement of 75% reduction in Water Weight Gain and Absorbed Chloride [45]. Florida Department of Transportation(FDOT) aligns with NCDOT's Series II values for Water Weight Gain and Absorbed Chloride reduction percentages [46]. One approach in modification of NCDOT specification can be a change to align NCDOT values with those of other state DOTs that use lower values that 80% reduction for Water Weight Gain and Absorbed Chloride.

NCHRP 244 Series IV Test employs Accelerated Weathering Tests to determine Chloride Ion Reduction percentages. This test exposes treated slabs to different environmental conditions, and it is divided into Series IV (Southern) and Series IV (Northern) criteria. NCDOT currently stipulates a minimum of 95% Chloride Ion reduction through the NCHRP 244 Series IV (Southern) Test. FDOT, once again, aligns with NCDOT's values for the Series IV (Southern) criteria [46], and MnDOT also agrees with the 95% reduction minimum [44]. However, many other states, such as Delaware Department of Transportation (DelDOT), INDOT, Idaho Transportation Department (ITD), and SCDOT, require a minimum of 90% Chloride Ion reduction [43, 45, 47]. Given these information, one approach to make NCDOT specification less restrictive would be to align our NCDOT reduction values with those of other state DOTs by reducing it to 90%.

State	Silane Content	Resistance to Chloride Ion Penetration	Water Absorption Test	NCHRP 244	
				Series I - III	Series IV
North Carolina	100% solids Silane minimum	Less than: 0.52 lbs./yd^3 at ½ inch level 0.00 lbs./yd^3 at 1 inch level	0.50% maximum/48 hours 1.5% maximum/50 days	Series II: Water Weight Gain: 85% reduction minimum Absorbed Chloride: 87% reduction minimum	Southern: 95% reduction minimum
Arkansas		0.76 lbs./cy at depths ½ inch to 1 inch	1% by weight/ 48 hours 2% by weight / 50 days		
Delaware	40% solids Silane minimum	Less than: 0.52 lbs./yd^3 at ½ inch level 0.00 lbs./yd^3 at 1 inch level	0.50% maximum/48 hours 1.5% maximum/50 days		90% reduction minimum
Florida	40% solids Silane minimum	Less than: 0.52 lbs./yd^3 at ½ inch level 0.00 lbs./yd^3 at 1 inch level	0.50% maximum/48 hours 1.5% maximum/50 days	Series II: Water Weight Gain: 85% reduction minimum Absorbed Chloride: 87% reduction minimum	Southern: 95% reduction minimum
Idaho			1% maximum/ 48 hours	Series II: Water weight Gain: 75% reduction minimum Absorbed Chloride: 75% reduction minimum	90% reduction minimum
Minnesota	40% solids Silane minimum	Less than: 0.55 cl content ratio of sealed/unsealed at ½” depth		Series II: Water Absorption: 80% reduction minimum Absorbed Chloride: 85% reduction minimum	Southern: 95% reduction minimum
Missouri		80% reduction in Cl and 0.50 lbs./cy at ½” to 1” depth	0.5% max /48 hours 1.5% max/ 50 days		
North Dakota	100% solids Silane minimum	0.75 lb./cy at 0.5” to 1.0” depth	1% by weight/48 hours 2% by weight/ 50 days		
South Carolina		Less than 500 ppm (0.843 lbs./cy) at a depth of 1.5 inch		Series II: Water Weight Gain: 20% of uncoated cubes Absorbed Chloride: Limited to 20% of uncoated cubes	Southern: absorbed chloride is 10% of uncoated slabs at end of 24 weeks

Figure 2 Silane Sealant Specification Criteria from Various State DOTs

Figure 2 provides an overview of the criteria stipulated by different states for Chloride Ion reductions and Water Absorption reductions in various tests. The gray boxes represent the limited criteria provided by other states compared to the comprehensive information provided by NCDOT. Non-NCHRP 244 Series Tests are also vital for comparison with NCDOT’s criteria. In both 'Resistance to Chloride Ion

Penetration' and 'Water Absorption' categories, many states seem to align with NCDOT's values. Therefore, we did not see the need to propose any changes in these two categories.

To address the disparities in NCHRP 244 Series II and Series IV (Southern) values across the United States, adjustments may be considered to align NCDOT's standards with those of other states. For NCHRP 244 Series II, one adjustment may be lowering the Water Weight Gain reduction percentages as well as the Absorbed Chloride reduction percentages to around 80-85%, in harmony with the requirements set by various states such as MnDOT and SCDOT. Another possible adjustment may be a reduction in the NCHRP 244 Series IV (Southern) values for Chloride Ion reduction from 95% reduction minimums to 90% reduction minimums. This adjustment would bring NCDOT standards in line with those of many other states across the country. By adopting these changes, NCDOT may be able to expand its options in the selection of Silane sealants for use by the DOT, fostering greater consistency and collaboration with other states in the process.

3.1.2 HMWM Specification Evaluation

Next, we conducted an evaluation of NCDOT's specifications for High Molecular Weight Methacrylate (HMWM) by comparing various criteria, including viscosity, flash point, and volatile content of the sealant, with the values specified by a range of other states. In **Figure 3** below, we provide a comparison between NCDOT's criteria and those of various other states across the United States.

State	Viscosity (Brookfield RVT with UL adapter, 50 RPM at 77 F)	Volatile Content	Specific Gravity (at 77 F)	Flash Point	Vapor Pressure (at 77 F)	Tensile Strength ~75 F
North Carolina	25 cps maximum	30% maximum	0.90 maximum	180 F minimum	0.02 psi (140 Pa or 1.0 mm Hg) maximum	1500 psi minimum
Florida	14-20 cps			200 F minimum		1300 psi minimum
Delaware	0.025 Pa s, maximum	30% maximum	0.9 minimum	10 C	1.0 mm Hg	
Oklahoma	10 - 25 cps	30% maximum		200 F minimum	1.0 mm Hg	
Colorado	0.36 E-5 psi-sec maximum	30% maximum	0.9 minimum	180 F minimum	0.4 inch Hg	
Tennessee	25 cps, maximum			180 F minimum	1.00 mm Hg	1500 psi minimum
Ohio	25 cps maximum		0.9 minimum	200 F minimum	1.0 mm Hg	1500 psi
Texas	25 cps maximum	30% maximum	0.9 minimum	180 F	1.0 mm Hg	1500 psi

Figure 3 HMWM Specification Evaluation from Various State DOTs

Upon comparing the standards of numerous states across the country, it becomes evident that most states' criteria for this sealant are in alignment with those of NCDOT. Specific Gravity, Vapor Pressure, and Volatile Content percentages, among other factors, appear to be consistent with the standards set by NCDOT. However, differences are observed when we examine Viscosity and Flash Point values. Several DOTs, including DelDOT, Colorado Department of Transportation (CDOT), Tennessee Department of Transportation (TDOT), Ohio Department of Transportation (ODOT), Texas Department of Transportation (TxDOT), and ArDOT, all concur on a Viscosity requirement of 25 cps maximum [48–53] . Since states such as FDOT and ODOT have values well below this 25 cps maximum, we determined that no changes needed to be proposed in this regard. Additionally, an examination of Flash Point criteria from various states reveals a range between 180 degrees Fahrenheit and 200 degrees Fahrenheit, all of which align with the minimum set by NCDOT. Thus, we concluded that no modifications are necessary in this area as well.

Overall, NCDOT's High Molecular Weight Methacrylate specification aligns with that of state DOT's across the country. Therefore, we do not propose any changes to the current HMWM specification.

3.1.3 Silicone Specification Evaluation

Silicone sealants are typically specified within the standard specifications section within the concrete joint sealant section, and in NCDOT's case this is no exception. NCDOT stipulates that Silicone sealants must be low modulus, cold-applied, single component, include bond breakers, and be either non-sag or self-leveling. Non-sag will require tooling to be worked into the joint while self-leveling with work itself into the joint using gravity and time. The bond breakers specified by NCDOT are Type L Backer Rods, Type M Backer Rods, and Type N Bond Breaking Tape. Type L Backer Rods are comprised of closed cell expanded polyethylene foam while Type M Backer Rods are made of closed cell polyolefin foam. Type N Bond Breaking Tape is comprised of extruded polyethylene.

State	Location Specification	Low Modulus?	Single Component?	Non-Sag &/or Self-Leveling Specified?	Peel	Movement Capability & Adhesion			Bond Breaker (s)
						Extension (+)	Compression (-)	Cohesion or Adhesion Failure after 10 cycles?	
North Carolina	Joint	Yes	Yes	NS, SL	20 lb./inch of width with 75% cohesion failure	100%	50%	No	• Closed cell expanded polyethylene foam backer rod (Type L) • Closed cell polyolefin foam backer rod (Type M) • Extruded polyethylene bond breaking tape (Type N)
California	Joint	Yes	Yes	NS, SL		100%	50%	No	• Closed cell expanded polyethylene foam
Georgia	Joint	Yes	Yes (Except Type D)	NS, SL			50%		• Closed cell expanded polyethylene foam (Type L) • Closed cell, polyolefin foam (Type M)
Florida	Joint	Yes	Yes (Also Two-Part)	NS, SL		100%	50%		• Backer rod & tape are compatible with joint sealant
Kansas	Crack Repair		Yes	NS	32 lb./inch	25%			
Kentucky		Yes	Yes (Also Two-Part)	NS, SL		100%	50%		• Closed cell polyethylene foam backer rod
North Dakota	Joint	Yes	Yes	NS		100%	50%	No	• Compliant to ASTM D 5249 Type 1 or Type 3

Figure 4 Silicone Sealant Specification from Various State DOTs

By comparing NCDOT's Silicone specification with that of other state DOTs, it is evident that a multitude of specifications around the country align with that of NCDOT. From neighbors of North Carolina (such as Georgia Department of Transportation (GDOT) [54] and SCDOT [55]) to DOTs in other coasts (such as California Department of Transportation (Caltrans) [56]), the consensus is mutually agreed. **Figure 4** above shows this conclusion visually. A plethora of state DOTs agree that a low modulus Silicone that's either non-slag or self-leveling is best. Additionally, various state DOTs agree that Type L and/or Type M for bond breakers are optimal.

If we were to look at the individual criteria of North Carolina's neighboring states, we can see that GDOT [54] and Virginia Department of Transportation (VDOT) [57] agree heavily on their preferred Silicone sealant test methods and their bond breakers, which also agree with the choices of NCDOT. **Figure 5** and **Figure 6** below visually represent this.

SILICONE JOINT REQUIREMENTS	Virginia				Georgia			
	A	B	C	D	A	B	C	D
Tensile Stress at 150% Strain (max. psi)	45	40	15	25	45	40	15	25
Durometer Hardness, Shore	10-25	40-80	20-80	40-80	10-25	40-80	20-80	40-80
Bond to Concrete Mortar (min. psi)	50	40	35	35	50	40	35	35
Tack Free Time (Skin-over) (max.minutes)	180	180	180	30	90	90	90	30
Extrusion Rate (min. grams/minutes)	75	90	100	200	75	90	100	200-550
Non-Volatile (min. %)	90				90			
Specific Gravity	1.1-1.5	1.1-1.5	1.1-1.5	1.2-1.5	1.1-1.5	1.1-1.5	1.1-1.5	1.2-1.5
Shelf Life	6 months				6 months			
Movement Capability & Adhesion	No adhesive or cohesive failure after 10 cycles at 0 F				No adhesive or cohesive failure after 10 cycles at 0 F			
Ozone/ UV Resistance	No chalking, cracking or bond loss after 5,000 hours				No chalking, cracking or bond loss after 5,000 hours			

Figure 5 Silicone Joint Requirement for Neighboring States

Joint Test Methods for Neighboring States	Virginia	Georgia
Silicone	ASTM C 1135 ASTM D 2240 ASTM D 792 ASTM C 793-75 VTM-90	ASTM D 412 ASTM D 2240 ASTM D 792 ASTM D 793
Bond Breaker	ASTM D 1622 ASTM D 1623 ASTM C 509	ASTM D 1622 ASTM D 1623 ASTM C 1016

Figure 6 Silicone Joint Requirement Standards for Neighboring States

With the representation of VDOT and GDOT's Silicone testing methods in the above **Figures 5 and 6**, it is evident that both neighboring states are in agreement with what they require for Silicone sealants. While NCDOT does not go as in depth with their Silicone testing methods beyond stating it to be in agreeance with ASTM D5893, NCDOT does state to align their bond breaker criteria with the neighboring states (ASTM D1622, ASTM D1623, and ASTM C509).

NCDOT's Silicone specification aligns with that of other states across the United States (including neighboring states). Therefore, we do not believe any revisions to this sealant's criteria is necessary.

3.1.4 Epoxy Resin Specification Evaluation

Examining Epoxy Resin Specifications posed a challenging endeavor, revealing a notable variation in the extent of research among different states. North Carolina emerges as a state with more comprehensive research compared to several others. **Figure 7** provides a visual representation of state DOTs that furnish their test methods and associated numerical criteria, specifically aligning with the criteria categories employed by the NCDOT.

The grey portions in the figure signify the limited criteria available from other states, as previously discussed. This scarcity of information in certain regions underscores the varying nature of research efforts across state DOTs. The focused inclusion of criteria pertinent to NCDOT aims to facilitate a focused evaluation of whether NCDOT's Epoxy specification requires revision, drawing attention to potential disparities or areas for enhancement in comparison to other states.

State	Viscosity	Ultimate Tensile Strength (ASTM D638)	Tensile Elongation at Break (ASTM D638)	Compressive Yield Strength (ASTM D695)
North Carolina *	Grade 1: 2,000 cps maximum Grade 2: 2,000 cps (minimum) - 10,000 cps (maximum) (ASTM C881)	2,000 psi minimum (Type II), 2,500 psi minimum (Type III) 5,000 psi minimum (Type I), 6,000 psi minimum (Type IV)	1 - 30% minimum	Strength: 5,000 – 10,000 psi minimum
New York	2000 cps (Brookfield RVT Spindle No. 3 @ 20 rpm - AASHTO T237)			Strength: 8,000 psi
Oklahoma	50 cps maximum (ASTM C881)	2,500 psi minimum	2% minimum	
Texas *	125 cps (bridge deck) - 1,000 cps (crack injection) (Brookfield RVT Spindle @ 20 rpm - AASHTO T237)			Strength: 5,000 psi minimum
Kansas *	Grade 1: 2,000 cps maximum Grade 2: 2,000 cps (minimum) - 10,000 cps (maximum) (ASTM C881)	2000 - 5000 psi	30 - 80%	Strength: 5,000 psi minimum at 24 hours
Arizona *	4,000 – 8,000 cps (ASTM D2393)	900 psi minimum	85% minimum	
Georgia			Type VIII: 5% maximum Types IV & VI: 30%	
Colorado *	Component A No.2: 700 cps maximum Component B No.2: 240 cps maximum	8000 psi minimum		Strength: 15,000 psi minimum
Hawaii *		3,500 psi minimum	0.5 - 2%	Strength: 5,500 psi minimum at 24 hours 12,500 psi minimum at 28 days
Idaho *	700 - 2500 cps (Brookfield RVT Spindle No.3 @ 20 rpm - ASTM D2393)	2,000 - 5,000 psi	40 - 80%	Strength: 5,000 psi
Indiana *	Appendix A: 800 cps maximum Appendix B: 2000 - 4000 cps			
Iowa	1000 cps maximum			
Louisiana *		350 psi (Type I, Type IV), 150 psi (Type II, Type V) 250 psi (Type III)		Strength: 5000 psi (Type I, Type IV), 3000 psi (Type III)
Minnesota	125-250 cps maximum	150-6000 psi minimum	2.5 - 25% minimum	Strength: 500- 4000 psi minimum

Figure 7 Epoxy Resin Specifications from Various State DOTs

By comparing NCDOT’s stipulations with that of other state DOTs, we were able to analyze Epoxy Resin’s specifications for potential revisions. We looked at criteria such as Viscosity, Tensile Elongation, Compressive Yield Strength and Tensile Strength.

Viscosity measurements in the context of state Departments of Transportation (DOTs) exhibit variability, contingent upon each entity's preferences. Primary testing methodologies adhere to standards established by AASHTO T237, ASTM C881 (also known as AASHTO M235), and ASTM D2393. Viscosity values span a wide range, from 50 cps to 10,000 cps, with NCDOT specifying values between 2000 cps to 10,000 cps. Given that NCDOT's criteria aligns with the broader range observed in other states, no adjustments were deemed necessary in this category. Beyond surface-level considerations, NCDOT recently updated its preference to adhere to ASTM C881 standards, also known as AASHTO M235. This criterion comprises 7 Types, 3 Grades, and 6 Classes for the classification of Epoxy Resins [58]. This decision resonates with the choices made by numerous DOTs nationwide. In **Figure 7**, states that adhere to any part of their Epoxy Resin specification to ASTM C881 are denoted with an asterisk next to the state name. However, this list is not mutually exclusive. Massachusetts Department of Transportation (MASSDOT), among others, specifies adherence to ASTM C881 standards, specifically mandating that their Epoxy Resin criteria meet Type IV Grade 1 standards [59]. Similarly, several other Department of Transportations, including those in SCDOT, TDOT, New Mexico Department of Transportation (NMDOT), Maryland Department of Transportation (MDOT), MoDOT, and Kentucky Department of Transportation (KYDOT), also align with the ASTM C881 standards, providing a standardized framework for Epoxy Resin classification [60–65]. It is noteworthy that NCDOT aligns itself with the collective decision of various other state DOTs in terms of viscosity for Epoxy resins. This harmonization underscores a concerted effort within the transportation sector to ensure consistency and compatibility in the classification and utilization of Epoxy Resins across state boundaries.

Moving to Tensile Elongation at Break, a parameter with preferences varying from 0.5% to 85% across states, NCDOT's choice was on the lower end of the range with values from 1% to 30%. This was consistent with the preferences of states like GDOT, MnDOT, Hawaii Department of Transportation (HDOT), and ODOT [66–69], led to the conclusion that no alterations were warranted in this domain.

Revisions may be considered for Compressive Yield Strength. The range for Compressive Yield Strengths extended from 500 to 15,000 psi minimums, with the prevalent value being 5,000 psi. NCDOT's considerably higher stipulation of up to 10,000 psi for compressive yield strength suggests a proposed adjustment to align with the national trend, suggesting values around 8,000 psi minimums.

In the realm of Tensile Strength assessment, where the spectrum typically spans from 150 to 8000 psi, it is noteworthy that the NCDOT’s Epoxy Resin Tensile Strength values reside predominantly at the upper end of this range. Specifically, while common strengths generally fall within 2000 to 3500 psi, the Epoxy Resin formulations utilized by NCDOT exhibit strengths varying between 2,000 psi to 7,000 psi, contingent upon the specific Epoxy Type employed. It is observed that only Type II and Type III variants align closely with the values reported by other states, which typically range from 2000 to 2500 psi. Considering these observations, a plausible course of action could involve revising the Tensile Strength specifications to establish a minimum threshold of approximately 5000 psi. Such an adjustment would serve to harmonize the NCDOT's standards with those adopted by other states.

3.2 Sample Specifications for Emerging Sealants

Considering the array of sealants available to the NCDOT without existing specifications, we aim to highlight emerging sealant specifications adopted by various state DOTs across the United States. It is our hope that these examples may assist the NCDOT in formulating criteria for new sealants if such an endeavor is undertaken. Our examination will delve into potential specification samples for Polyurethane, Poreshield, Acrylics, and Polysulfide.

3.2.1 Polyurethane Sample Specifications

Polyurethane has rapidly garnered support from state DOTs nationwide, with numerous agencies acknowledging its utilization as a sealant. However, the absence of a standardized specification for this sealant is notable. Our investigation revealed that among the states embracing Polyurethane, FDOT and TxDOT stand out for having well-defined specifications. This distinction is attributed to similarities in climate, population, and geographical proximity to North Carolina. **Figure 8** consolidates data from the specifications of these two state DOTs, presenting a unified sample specification for NCDOT to consider.

SAMPLE POLYURETHANE SPECIFICATIONS	
Tack Free Time, minutes	120 maximum
Non-Volatile Content, %	93 minimum
Viscosity, cps	110 - 130
Compressive Strength, psi (ASTM C39)	One Component: 600
	Two Component: 75
Tensile Strength, psi (ASTM D1623, ASTM 3574)	40
Cure Time	One Component: 400 psi within 30 minutes
	Two Component: 60 psi within 30 minutes
Density	4.7 - 6.5 lbs per cubic foot

Figure 8 *Polyurethane Sample Specification*

In addition to **Figure 8** sample specification for Polyurethane, we would also recommend NCDOT to reference their Epoxy resin and Silicone specifications when creating a future specification for this promising sealant. Epoxy resins and Polyurethanes are both topical sealants and therefore could have comparable qualities. In addition, Silicone and Polyurethane are both used to seal concrete joints and therefore could have comparable specification criteria. Compiling all the specification suggestions provided will allow NCDOT to have a very well-rounded base specification for future Polyurethane use.

3.2.2 Other Emerging Sealant Specifications

Poreshield emerges as a highly promising and innovative penetrating sealant, garnering support from numerous DOTs across the United States. Despite the absence of dedicated specifications for Poreshield in these states, we propose a strategic approach. To establish a specification, we recommend leveraging the specifications of supporting states for other penetrating sealants, such as Silicone and Silane. Noteworthy among these states are ArDOT, INDOT, Iowa DOT, South Dakota Department of Transportation (SDDOT), WisDOT, TxDOT, ODOT, Washington State Department of Transportation (WSDOT), and Nebraska Department of Transportation (NDOT). Given the geographical and climatic affinities, the specification titled "Penetrating Concrete Surface Treatment" from the TxDOT stands out as the most pertinent starting point for this purpose [70]. This specification provides comprehensive insights into crucial criteria, including temperature restrictions, water content, depth of penetration, accelerated weathering test results, and various other parameters.

Acrylics represent another viable sealant lacking a specification from the NCDOT. To address this gap, we recommend utilizing criteria established by the TxDOT as a foundational framework for developing an Acrylic Resin sealant specification in North Carolina[71]. **Figure 10** presents a sample specification for acrylics, derived from the TxDOT's Acrylic sealant specification. While the testing methods are primarily Texas-centric, NCDOT can leverage this as a starting point and adapt it to align with ASTM or AASHTO testing methodologies.

SAMPLE ACRYLIC SPECIFICATIONS	
Nonvoltile Content, % (ASTM C2369)	20% minimum solids by weight
Viscosity (ASTM D562)	Will not vary by more than 5 KU of the original Prequalification sample
Accelerated Weathering (Tex-814-B)	No yellowing, checking, cracking, or adhesion loss
Infrared Spectrum (Tex-888-B)	No tackiness before or after testing
	Must match spectrum on file with CST/M&P

Figure 9 Acrylic Sample Specification

Further, Acrylics are frequently compared to Epoxy Resins and various other penetrating sealants. Drawing inspiration from NCDOT's existing specifications for these penetrating and film-forming sealants could contribute to the development of a potential Acrylics specification in the future.

Concluding the emerging sealant recommendations, NCDOT stands to benefit significantly from the establishment of a Polysulfide sealant specification. Given the prevalence of areas in North Carolina susceptible to consistent rain or wet conditions, the implementation of a penetrating sealant resilient to such environmental challenges becomes paramount. A valuable resource in this regard is the documentation provided by the Caltrans for two-part Polysulfide concrete joint sealants [72]. In this document, Caltrans specifies that they utilize CT 206, ASTM C 192, ASTM C 719, ASTM D 217 and ASTM D 5329. In addition, they specify separate testing procedures at 25 degrees Celsius and 70 degrees Celsius. This testing includes procedure for mixing the components, cone penetration, cold flow, resilience, concrete bonding, non-volatile content, viscosity of components and pot life of the mixed joint sealant.

4 Data Synthesis & Recommendations

4.1 List of Sealants in US Market

While providing all of the sealants available on the market proves nearly impossible, we have compiled a list of sealants that are viable for usage by NCDOT. This list includes both film formers and penetrating sealers with a broad range of capabilities. In **Figure 11**, we included a list of the sealants, which is separated by whether the product is included in an NCDOT specification yet.

Sealants Within SEECS		
Utilized by NCDOT (Provisions Available)	**Additional Sealants for NCDOT Use**	
Oxime Neutral Cure Silicone	Polyurethane	Acrylics (Water - based)
Alkoxy Neutral Cure Silicone	Polyurethane Methyl Methacrylate (PUMMA)	Acrylics (Solvent - based)
Silane (Solvent - based)	Silane (40% Solids)	Sodium Silicates
Silane (100% Solids)	Silane (Water - based)	Potassium Silicates
Epoxy Resin (Two Part)	Silane (40%Solids)	Lithium Silicates
HMWM	Silane - Siloxane	Colloidal Silicates
	Siloxane	Polysulfide (One Part)
	Poreshield	Polysulfide (Two Part)
	Fluorinated Sealants	

Figure 10 SEECS List of Sealants

4.2 Optimum Use of Different Sealants in NCDOT Projects Given Different Scenarios

NCDOT currently utilizes Silane, HMWM, Epoxy, and Silicone sealants, all of which are considered excellent options. Nevertheless, certain alternative sealants emerge as contenders against these established options.

As an alternative to the powerhouse Silicone, we advocate for the primary use of Polyurethane, and Polysulfides. Polyurethane emerges as a strong competitor to Silicone, excelling in temperature resistance, durability, and time until reapplication. Meanwhile, Polysulfide proves to be an excellent option for sealing near water, offering high water resistance and flexibility.

Furthermore, we propose the consideration of Siloxane as a potential alternative to Silane, or for concurrent utilization. Whether used independently or in conjunction with Silane, Siloxane provides a cost-effective and hydrophobic alternative with enhanced surface-level protection.

To compete with the plethora of other penetrating sealants currently utilized, we recommend the implementation of Poreshield. This emerging sealant stands out for its speed of application, durability, and sustainable qualities. Noted by various Departments of Transportation, Poreshield could potentially become the next penetrating powerhouse in the sealant market.

These proposed alternatives aim to provide NCDOT with a diverse range of options, each catering to specific project requirements while maintaining or surpassing the performance of the currently employed sealants.

4.3 Explanation & Implementation of SEECS

To begin the comprehensive array of information associated with concrete sealants, we have meticulously devised a user-friendly table known as SEECS (Selection for Emerging and Explored Concrete Sealants). This extensive table encapsulates a plethora of material guidelines, facilitating the seamless selection of sealants tailored to the specific criteria of a given project. The encompassing criteria span diverse aspects, including temperature resistance, water and UV resistance, and installation methods.

In the following sections, we will delve into a detailed exploration of each category presented in SEECS, progressing through the table from left to right. This structured approach aims to provide an understanding of the multitude of considerations encapsulated within the table, offering a valuable resource for informed decision-making in concrete sealant selection.

The initial four sections of the table are dedicated to Minimum and Maximum Application/Service Temperatures. Given that many sealants lack comprehensive information for both temperature categories, our primary objective is to present all available data in a comprehensible format. It is essential to note that all temperature references are in ambient air temperatures measured in Fahrenheit, as opposed to concrete temperatures. The Application temperature signifies the temperature at which the sealant can be applied. Minimum Application Temperature denotes the lowest temperature at which the sealant can be applied without compromising strength or adhesion. Maximum Application Temperature represents the highest air temperature permissible for the application of the sealant without compromising strength or adhesion properties. Service Temperature relates to the temperature range within which the sealant can maintain its strength and adhesion properties during the period between initial application and subsequent reapplication. Within the SEECS framework, both Minimum and Maximum Service Temperatures are incorporated, as illustrated in **Figure 12** below.

NCDOT Provision Available?	Sealant	Minimum Service Temperature (F)	Minimum Application Temperature (F)	Maximum Service Temperature (F)	Maximum Application Temperature (F)
No	Polyurethane (Urethane)	(-40) - (-20)	20	170	100
No	PUMMA	Unspecified **	14 - 40	90	110
Yes	HMWM	40 - 50	50	Unspecified **	100
Yes	Oxime Neutral Cure Silicone	(-180) - (-30)	40	300	100
Yes	Alkoxy Neutral Cure Silicone	(-70) - (-40)	Unspecified **	400	Unspecified **
No	Water-based Silane	Unspecified **	40	Unspecified **	95
Yes	Solvent-based Silane	Unspecified **	40	Unspecified **	95
No	40% Solids Silane	Unspecified **	32 - 40	Unspecified **	95
Yes	100% Solids Silane	20	20 - 40	Unspecified **	100
No	Silane-Siloxane	Unspecified **	40	Unspecified **	95
No	Siloxane	Unspecified **	40	Unspecified **	95
Yes	Two Part Epoxy Resin	(-60) - (-4)	40 - 60	300 - 500	90
No	PoreShield	Unspecified **	20 - 40	Unspecified **	120
No	Water-based Acrylics	(- 30) - (-25)	32	180	Unspecified **
No	Solvent-based Acrylics	-25	32 - 55	180	85
No	Sodium Silicates	40 - 50	40	Unspecified **	95
No	Potassium Silicates	Unspecified **	40	Unspecified **	95
No	Lithium Silicates	Unspecified **	40	Unspecified **	95
No	Colloidal Silicates	Unspecified **	40	Unspecified **	95
No	Fluorinated Sealers	Unspecified **	40	Unspecified **	95
No	One Part Polysulfide	(-40) - (-4)	40	176	Unspecified **
No	Two Part Polysulfide	(-40) - (-4)	40	176	110

Definition	Definition	Definition	Definition
The lowest (air) temperature that the sealant can operate in at full strength from application until the time of reapplication	The lowest (air) temperature that the sealant can be applied in without losing strength	The maximum (air) temperature that the sealant can operate in at full strength from application until the time of reapplication	The highest (air) temperature that the sealant can be applied in without losing strength

Figure 11 Temperature Resistance Portion of SEECS Guidelines

In the case of HMWM, a red triangle is positioned in the upper right-hand corner of the Minimum Service Temperature category. This emblem signifies that the sealant possesses the capability to function under conditions where temperatures may sink below the values stipulated in SEECS. To facilitate operation in sub-zero Fahrenheit temperatures, it is imperative to incorporate a Cold Temperature Accelerator into the sealant mixture prior to the initial application. The specific brand or type of Accelerator required is likely to vary among different sealant providers. **Figure 13** below offers an enhanced view of the chart, providing additional clarity on the precise location and corresponding annotation.

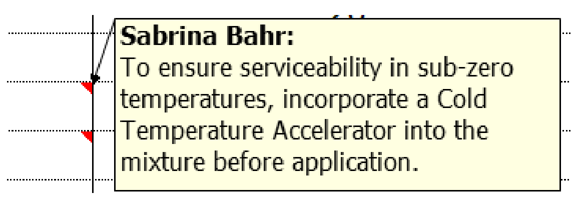

Figure 12 Cold Temperature Accelerator Note

For criteria lacking numerical values, the descriptor 'Unspecified' is employed, followed by a corresponding number of asterisks. A single asterisk ("Unspecified*") denotes that the Time Until Reapplication for the sealant is directly correlated to the lifespan of the underlying concrete. This particularly applies to Silicates, which function as densifiers and undergo chemical reactions with the concrete to which they are applied. In instances where the label includes "Unspecified**" with two asterisks, it signifies a lack of available information for the specific category. Unfortunately, not all pertinent details for the sealants are accessible online, necessitating adaptive measures in our representation. The use of three asterisks denotes situations where the criteria range is excessively broad, with insufficient accompanying explanation. In the context of SEECS, this notation is employed with HMWM, where sources indicate a Time Until Reapplication within a wide range of up to 30 years, without further elucidation on the rationale behind this extensive time frame. Lastly, N/A is utilized for sealants where there may not be enough specific evidence to draw conclusions in certain categories but research still proves it to be a viable sealant.

Proceeding within the SEECS guidelines, our focus now shifts towards the section that delves into the fundamental qualities of both the crack and the sealant itself. This encompasses critical considerations such as Crack Orientation, Crack Width, Joint Width, Sealant Location, and the classification of the sealant as either a Film Former or a Penetrating sealant. The intricate details of these categories are shown in **Figure 14**, establishing a foundational framework for the systematic selection of sealants. This section serves as a primary feature in the overall sealant selection process, laying the groundwork for informed decision-making based on the intrinsic characteristics of both the cracks being addressed and the sealants under consideration.

Sealant	Crack Orientation	Crack Width Range (Inch)	Joint Width Range (Inch)	Film Former or Penetrating?	Sealant Location
Polyurethane (Urethane)	H, V	0.001 - 2	0.25 - 1.5	F	C, J
PUMMA	H	0.0625 - 0.25	0.25 - 2	F	J, D
HMWM	H	0.001 - 0.08	N/A	F	D
Oxime Neutral Cure Silicone	H, V	0.125 - 0.787	0.125 - 0.787	F	C, J
Alkoxy Neutral Cure Silicone	H, V	0.125 - 0.5	0.125 - 0.787	F	C, J
Water-based Silane	H, V	<0.08	N/A	P	C, D
Solvent-based Silane	H, V	<0.08	N/A	P	C, D
40% Solids Silane	H, V	<0.08	N/A	P	C, D
100% Solids Silane	H, V	<0.08	N/A	P	C, D
Silane-Siloxane	H, V	<0.002	N/A	P	C, D
Siloxane	H, V	<0.002	N/A	P	C, D
Two Part Epoxy Resin	H, V, O	0.001 - 2	< 1	F	C, D
PoreShield	H, V, O	Unspecified **	Unspecified **	P	C, J, D
Water-based Acrylics	H, V, O	< 0.5	N/A	F	C, D
Solvent-based Acrylics	H, V, O	< 0.5	N/A	F	C, D
Sodium Silicates	H	N/A	N/A	P	D
Potassium Silicates	H	N/A	N/A	P	D
Lithium Silicates	H	N/A	N/A	P	D
Colloidal Silicates	H	N/A	N/A	P	D
Fluorinated Sealers	H, V	Unspecified **	N/A	P	D
One Part Polysulfide	H, V, O	0.25 - 1	0.25 - 1	F	J
Two Part Polysulfide	H, V, O	0.236 - 2	0.236 - 2	F	J

Orientation Indicator
H = Horizontal V = Vertical O = Overhead

Film Former	Location Indicator
Extend sealing capabilities only into surface pores of the concrete	C = Crack J = Joint D = Bridge Deck

Penetrating Sealants
Move into concrete surface's top layer to repel water & stains

Figure 13 Crack & Sealant Fundamental Data for SEECS Guidelines

The categorization of Crack Orientation contains three distinct classifications: Horizontal (H), Vertical (V), and Overhead (O). While many sealants demonstrate applicability to Horizontal surfaces, it is noteworthy that not all are equally suitable for Vertical or Overhead orientations. This limitation stems from various factors, with viscosity as a primary determinant. Sealants characterized by excessive viscosity risk ineffective application on Vertical or Overhead surfaces, as they may exhibit a tendency to slip. Sealants denoted by the label "H,V,O" indicate versatility across a broad spectrum of orientations.

Take Epoxy, for instance, which exhibits a wide range of viscosity values, enabling its application in diverse orientations. Conversely, sealants marked with "H" exclusively suggest either explicit instructions for Horizontal application or a demonstrated tendency to be employed solely in that orientation. Silicate-based sealants, designated for Horizontal orientation, possess a distinctive characteristic. Their application involves a chemical reaction with the concrete post-application, differentiating their behavior from other "H" sealants such as HMWM. This chemical reactivity sets Silicate-based sealants apart in terms of performance and behavior post-application.

The Crack Width Range serves as a crucial parameter, delineating the minimum and maximum crack sizes that various sealants can effectively address. This capacity is contingent upon intrinsic properties such as viscosity and durability unique to each sealant. Hairline cracks characterized by their small dimensions of approximately 0.003 inches in width and variable depth, e.g., plastic shrinkage cracks. Sealants with potentially lower viscosities exhibit the capability to penetrate these hairline cracks, exemplifying the significance of this category. It is imperative to underscore that not all sealants are equally proven to address larger cracks, particularly those reaching dimensions of 2 inches. The ability to fulfill this task is influenced by factors such as higher viscosity or the inherent nature of the sealant. Consideration of these factors becomes paramount when determining the most suitable sealant for a given application.

The Joint Width Range functions analogously to the Crack Width Range parameters. Joints manifest between two adjacent concrete slabs and are subject to natural expansions and contractions derived from environmental influences such as temperature fluctuations. While certain sealants capable of sealing both joints and cracks specify only one width range, others delineate distinct ranges for general cracking versus joints specifically. This distinction was considered in the SEECS guidelines.

The distinction between Film Forming and Penetrating sealants is identified in SEECS. Film Formers represent topical sealants that envelop the entire concrete surface without permeating into its pores. In contrast, Penetrating sealants protect the concrete by infiltrating its capillaries, establishing a formidable barrier against external contaminants. The incorporation of this criterion is pivotal as it illustrates the anticipated interaction of the sealant with the concrete and its subsequent behavior.

Concluding our SEECS guidelines, the Sealant Location category is intricately divided into three distinct groups: Crack (C), Joint (J), and Bridge Deck (D). Concrete joints, encompassing various types, are defined by their necessity to permit displacements and facilitate stress transfer [73]. Notably, for a sealant to be deemed suitable for Joint sealing within the Sealant Location category, criterion is the flexibility post-application. This underscores the importance of accommodating displacements and stress transfer in these structural elements. While the Bridge Deck category is inherently self-explanatory, the Crack category assumes a broader scope. The selection of the 'Crack' Sealant Location is appropriate when the specific location requiring sealing does not align with the defined parameters of either the Joint or Bridge Deck categories.

Sealant	Time Until Reapplication (Years)	Durability	VOC (g/l)	Water Resistant?	UV Resistant?
Polyurethane	5 - 10	9	0 - 50	Yes	Yes
PUMMA	Unspecified **	5	0 - 50	Yes	Yes
HMWM	Short to 30 ***	7	0 - 50	Yes	Yes
Oxime Neutral Cure Silicone	20	8	0 - 50	Yes	Yes
Alkoxy Neutral Cure Silicone	20	8	0 - 50	Yes	Yes
Water-based Silane	7 - 10	4	100 - 250	Yes	Yes
Solvent-based Silane	7 - 10	4	100 - 250	Yes	Yes
40% Solids Silane	7 - 10	4	100 - 250	Yes	Yes
100% Solids Silane	7 - 10	4	100 - 250	Yes	Yes
Silane-Siloxane	7 - 10	3	50 - 100	Yes	Yes
Siloxane	3 - 5	3	50 - 100	Yes	Yes
Two Part Epoxy Resin	5 - 10	7	0 - 50	Yes	No
PoreShield	10	8	0 - 50	Yes	Yes
Water-based Acrylics	1 - 4	7	0 - 50	Yes	Yes
Solvent-based Acrylics	1 - 4	7	0 - 50	Yes	Yes
Sodium Silicates	Unspecified *	1	0 - 50	No	Yes
Potassium Silicates	Unspecified *	1	0 - 50	No	Yes
Lithium Silicates	Unspecified *	2	0 - 50	No	Yes
Colloidal Silicates	Unspecified *	2	0 - 50	No	Yes
Fluorinated Sealers	Unspecified **	2	0 - 50	Yes	Yes
One Part Polysulfide	10 - 20	6	0 - 50	Yes	Yes
Two Part Polysulfide	10 - 20	6	50 - 100	Yes	Yes

Definition	DURABILITY INDICATOR	VOC CONTENT INDICATOR (g/l)	Definition	Definition
The number of years that it will take for the sealant to lose strength and serviceability given standard conditions. (Correlates to 'Service Life')	Low Strength	0 - 50	Is the sealant able to maintain full strength when coming in contact with water? (Does not pertain to the sealant being fully submerged)	Is the sealant able to maintain full strength without discoloring when having constant contact with the sun's rays?
	Moderate Strength / Resistance to Abrasion	50 - 100		
	High Resistance to Abrasion	100 - 250		
	Not Known Yet	250 - 600		
		600 - 700		
		Not Known Yet		

Figure 14 SEECS Guidelines Continued

The midsection of the SEECS guidelines includes several criteria as shown in **Figure 15**, namely Durability, Volatile Organic Compounds (VOC), Time Until Reapplication, Water Resistance, and UV Resistance. Notably, Durability and VOC stand out as the sole categories featuring colored indicators. The rationale behind introducing color-coded indicators stems from the relative nature of these criteria, facilitating easier comparisons among different sealants within the same category.

In the Durability category, a lighter color (or associated lower numerical ranking) denotes lower strength or diminished resistance to abrasion. Conversely, a darker color (higher numerical ranking) signifies heightened sealant strength. The VOC category follows a similar trend, albeit in the opposite direction. Here, the optimal choice involves aiming for a lighter color and a lower numerical value (comparative VOC content), indicative of reduced organic compound content. The utilization of both relative color and numerical values in these categories enhances the discernibility and comparative assessment of sealants, contributing to a more comprehensive understanding of their performance attributes.

Durability, within the context of concrete sealants, denotes the sealant's ability to sustain strength and adhesion over its service life, coupled with its resistance to abrasion. This criterion assumes heightened significance, yet its interpretation is inherently relative. While diverse sealants may individually exhibit commendable strength and durability, the relative comparison among them is essential for discerning the optimal choice. It is imperative to emphasize that, despite its important role, the Durability category should not be used as the sole criterion for sealant selection. Rather, it is recommended that Durability be considered in conjunction with other criteria within SEECS. This approach ensures a comprehensive evaluation, enabling a decision-making process that accounts for various factors beyond durability alone.

Volatile Organic Compounds (VOCs), as defined by the EPA, include compounds characterized by lower water solubility and higher vapor pressures [74]. These chemical properties, with human-made origin, significantly influence the safety of a product's impact on both human health and the surrounding environment. Opting for a sealant with lower VOC content becomes instrumental in aligning with environmentally safe practices. Given the escalating emphasis on eco-friendly approaches, the inclusion of this category assumes significance in evaluating the safety of various sealant options.

Time Until Reapplication presents the service life of the sealant, signifying the duration during which it maintains optimal strength and functionality before necessitating reapplication or repair. SEECS provides a diverse spectrum of service lives, ranging from as brief as one year of serviceability to an extended thirty years of sustained strength before reapplication. This criterion assumes substantial significance in the selection of sealants, considering the potential cost implications associated with recurrent reapplications or the need for consistent labor for the reapplication process. The variability in service lives underscores the economic and practical considerations in choosing a sealant that aligns with the desired longevity and cost-effectiveness for a given application.

The ‘Water Resistant?’ and ‘UV Resistant?’ categories are important for sealants exposed to external environmental conditions. Given North Carolina's susceptibility to hotter summers, rainy climates, and proximity to bodies of water, these criteria become particularly relevant. An affirmative response in these categories signifies the sealant's capacity to maintain strength when exposed to water or prolonged sunlight. It is crucial to note that the Water Resistance category does not inherently address the sealant's ability to retain strength when fully submerged in water for extended durations. In cases where UV resistance is denoted as 'No,' as observed with Epoxy, it could imply susceptibility to discoloration upon UV exposure. As these considerations play a pivotal role in the sealant's performance within the varied environmental conditions of North Carolina, meticulous attention to Water and UV resistance categories is warranted.

Sealant	Shortest Time Until Traffic Reopens (Hours)	Longest Time Until Traffic Reopens (Hours)	Installation Notes
Polyurethane	72	72	POLYURETHANE PREP/ INSTALLATION TIPS
PUMMA	1	1	POLYURETHANE MMA PREP/ INSTALLATION TIPS
HMWM	3	16	HMWM PREP/ INSTALLATION TIPS
Oxime Neutral Cure Silicone	3	168	OXIME NEUTRAL CURE SILICONE PREP/ INSTALLATION TIPS
Alkoxy Neutral Cure Silicone	72	168	ALKOXY NEUTRAL CURE SILICONE PREP/ INSTALLATION TIPS
Water-based Silane	2	4	WATER BASED SILANE PREP/ INSTALLATION TIPS
Solvent-based Silane	24	48	SOLVENT BASED SILANE PREP/ INSTALLATION TIPS
40% Solids Silane	5	168	40% SOLIDS SILANE PREP/ INSTALLATION TIPS
100% Solids Silane	24	48	100% SOLIDS SILANE PREP/ INSTALLATION TIPS
Silane-Siloxane	2	12	SILANE-SILOXANE PREP/ INSTALLATION TIPS
Siloxane	8	48	SILOXANE PREP/ INSTALLATION TIPS
Two Part Epoxy Resin	4	168	TWO PART EPOXY PREP/ INSTALLATION TIPS
PoreShield	24	48	PORESHIELD PREP/ INSTALLATION TIPS
Water-based Acrylics	4	72	WATER BASED ACRYLIC PREP/ INSTALLATION TIPS
Solvent-based Acrylics	24	72	SOLVENT BASED ACRYLIC PREP/ INSTALLATION TIPS
Sodium Silicates	1	12	SODIUM SILICATE PREP/ INSTALLATION TIPS
Potassium Silicates	1	1	POTASSIUM SILICATE PREP/ INSTALLATION TIPS
Lithium Silicates	1	12	LITHIUM SILICATE PREP/ INSTALLATION TIPS
Colloidal Silicates	1	2	COLLOIDAL SILICATE PREP/ INSTALLATION TIPS
Fluorinated Sealers	24	72	FLUORINATED SEALANT PREP/ INSTALLATION TIPS
One Part Polysulfide	120	672	ONE PART POLYSULFIDE PREP/ INSTALLATION TIPS
Two Part Polysulfide	24	192	TWO PART POLYSULFIDE PREP/ INSTALLATION TIPS

Definition	Definition
The **shortest** time it will take for the sealant to fully cure and vehicular traffic will be allowed to resume	The **longest** time it will take for the sealant to fully cure and vehicular traffic will be allowed to resume

Figure 15 Time Until Traffic Reopens & Installation Notes from SEECS

Concluding our exploration of the SEECS guidelines, the last categories include Time Until Traffic Reopens and Installation Notes, as illustrated in **Figure 16**. Time Until Traffic Reopens is directly correlated to the duration required for the sealant to achieve full cure (enabling the resumption of vehicular traffic). To enhance user-friendliness, we have organized two columns to delineate the respective ranges for each sealant. Additionally, Installation Notes within SEECS are accessible by clicking on the 'Prep/Installation Tips' for individual sealants. This action shows a dedicated page containing key insights and recommendations agreed upon by many manufacturers of the respective sealant. These tips serve as valuable guidelines for preparation and installation, providing a starting point for users navigating the intricacies of concrete sealant selection and application.

Navigating through SEECS involves two primary methods. The first approach is straightforward, requiring users to identify specific sealants for comparison. By clicking the arrow beside the 'Sealant' column and selecting sealants with check marks, users can streamline their search based on known project requirements. This method, while simple, relies on prior knowledge of the necessary sealants.

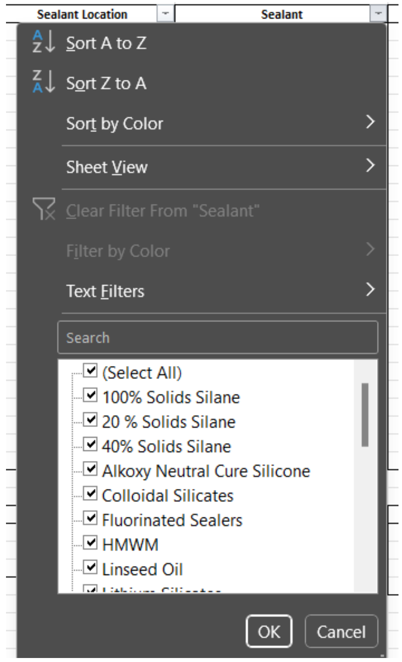

Figure 16 SEECS Navigation by Sealant

The second method is more intricate and preferable when the required sealants are unknown. Consider a scenario where the task is to seal the Blue Ridge Parkway Bridge Deck in Asheville, North Carolina, during October, facing heavy traffic patterns and varying temperatures. Commencing with Step one, users must select criteria within the 'Sealant Location' section. For a bridge deck, entering "D" in the search bar narrows down the options to sealants commonly used for such structures.

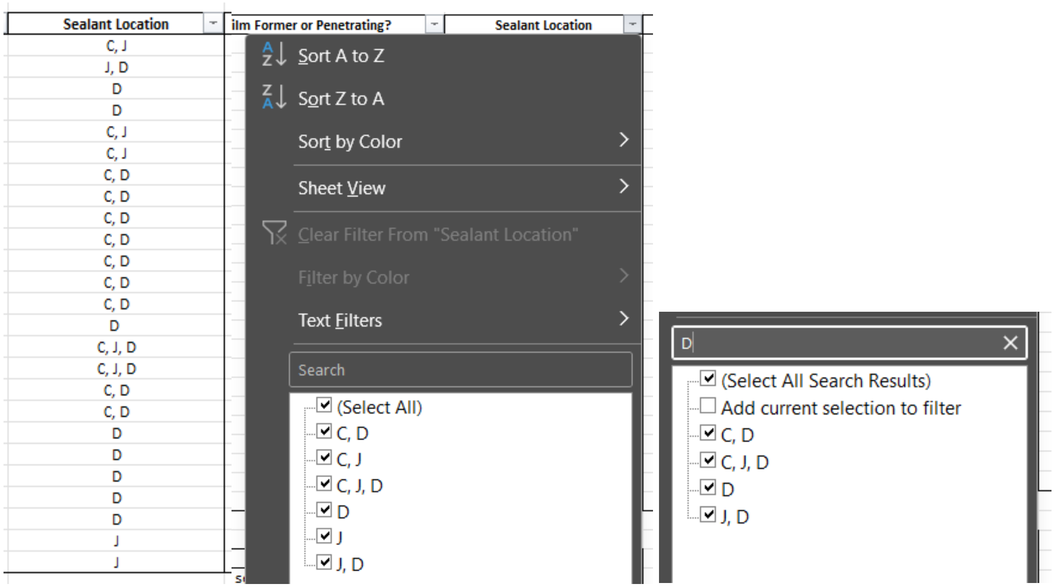

Figure 17 SEECS Example - Sealant Location

Proceeding to Step two, criteria such as 'Water Resistant?' and 'UV Resistant?' are crucial for an outdoor bridge. Only sealants marked "Yes" for both categories should be considered. This is because the location that will be sealed is constantly in contact with the elements (such as sunlight and rain) and the sealant should be able to withstand these conditions with ease.

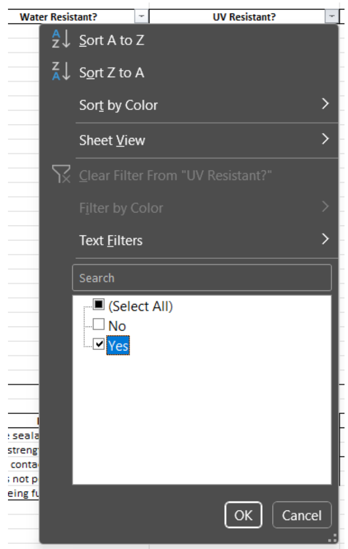

Figure 18 SEECS Example - Water & UV Resistance

In Step 3, considering the high traffic volume of America's most visited park, limiting closure time is imperative. Utilizing the 'Longest Time Until Traffic Reopens (hours)' filter, users can set a maximum allowable cure time. For instance, assuming a 24-hour closure is acceptable, users would select "Less Than Or Equal To" in the drop-down menu and input 24.

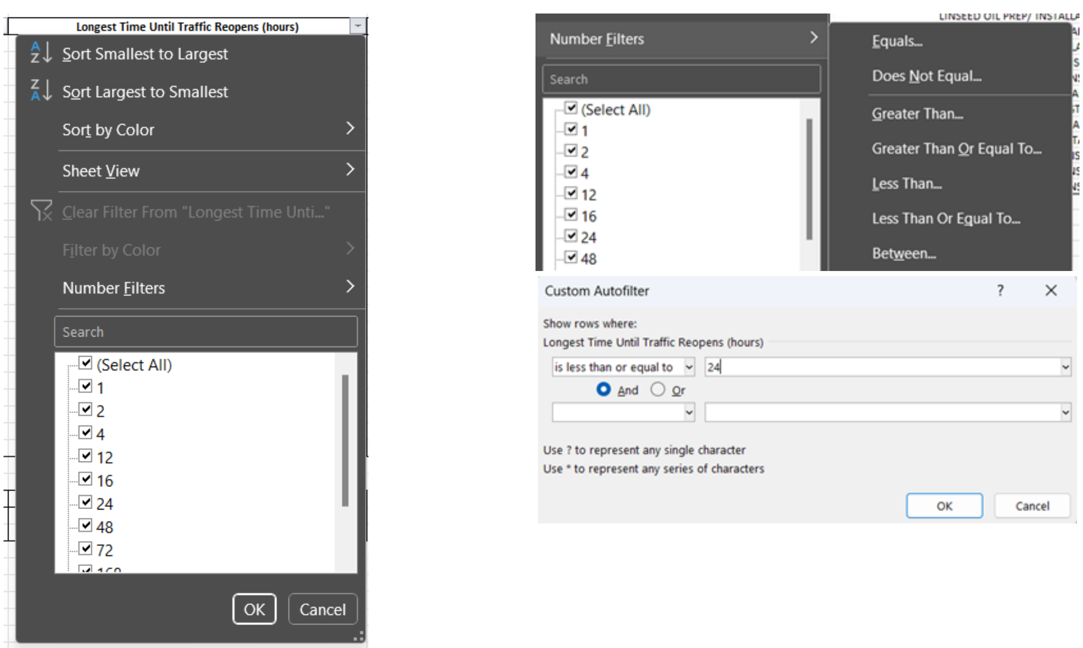

Figure 19 SEECS Example - Time Until Traffic Reopens

Further refinement is possible based on additional criteria, such as strength retention in negative temperatures, reapplication intervals, installation ease, or other relevant qualities. Currently, NCDOT employs HMWM and Silane, both with specific specifications, aligning with SEECS recommendations. However, for this project, branching out beyond the standard selection is an option. SEECS suggests Silane-Siloxane products, providing NCDOT with an alternative for consideration. In conclusion, the navigation methods within SEECS cater to both informed sealant choices and scenario-specific criteria, facilitating a comprehensive and tailored approach to sealant selection for diverse projects.

5 Conclusion

The durability of concrete structures is intricately tied to their capacity to resist the ingress of water and corrosive agents, such as chlorides. Cracks, acting as conduits, present susceptible pathways for the penetration of water and aggressive agents, posing a significant threat to the extended service life of concrete structures. The presence of cracks is a major concern for infrastructure owners and operators.

To mitigate the detrimental impact of cracks on the longevity of concrete structures, a commonly employed strategy is the application of sealants. Sealants act as a barrier to impede or minimize the intrusion of water and corrosive elements into the concrete. Various sealants, commercially available for decades, serve the purpose of protecting and preserving infrastructure. Despite the abundant options, comprehensive studies comparing the performance of different sealants remain limited.

This study examines the multitude of concrete sealants currently accessible in the United States market. The primary focus is to explore and discuss diverse ways in which various sealants can contribute to addressing concrete failures, providing valuable insights for the NCDOT in their efforts to enhance concrete protection in the future.

The study started with an extensive literature review encompassing over 20 sources, categorizing them into three distinct sections: Deck Sealant Comparisons, Joint Sealant Comparisons, and Generalized Crack Sealant Comparisons. In each category, a diverse array of film-formers and penetrating sealants were meticulously presented and compared. Film-forming sealants, known for creating a protective barrier over the concrete's surface, were compared with penetrating sealants, which act by filling the concrete's capillaries to repel contaminants. The comprehensive review delves into over 20 different sealants, accompanied by individual descriptions and scholarly sources providing insights into their respective characteristics.

Subsequently, an in-depth analysis of the current NCDOT specifications and corresponding recommendations was conducted. The existing repertoire comprises four sealant specifications: Silane, HMWM, Epoxy Resin, and Silicone. Following our evaluation, it was determined that no alterations were necessary for the HMWM and Silicone sealant specifications. However, for Silane and Epoxy Resin, adjustments to the criteria were proposed to enhance alignment with counterparts across the United States. Specifically, for Silane, a reduction in NCHRP 244 Series II values to 80-85% reduction minimums and a simultaneous reduction in NCHRP 244 Series IV (Southern) values to 90% reduction minimums may be considered. Regarding Epoxy Resins, two changes may be considered: a decrease in Compressive Yield Strength standards to a range of 5,000 to 8,000 psi minimum and a lowering of Tensile Strength criteria to approximately 5,000 psi minimum. These proposed modifications aim to foster greater consistency between North Carolina DOT specifications and those of other states.

Despite having only four established sealant specifications, the NCDOT faces a plethora of available options for concrete protection. To address this gap, this study presents starting points for the development of additional sealant specifications. Polyurethane, while already in use by other state DOTs, is illuminated with its respective specifications tabulated. Furthermore, for Poreshield, Acrylics, and Polysulfide—sealants with limited implementation across states—information is provided to guide the initiation of the specification creation process. This comprehensive approach seeks to offer valuable insights to NCDOT, providing a foundation for the formulation of additional sealant specifications beyond the existing four, and aligning with industry standards and practices.

Finally, the study explores the rationale and implementation of SEECS – Selection for Emerging and Explored Concrete Sealants. SEECS is a meticulously tabulated set of guidelines, presented in Excel format, designed to facilitate the systematic selection of concrete sealants based on a multitude of factors. The ensuing section provides a detailed description of each criterion within SEECS and elucidates their significance in the selection process. Furthermore, a step-by-step walkthrough is provided, exemplifying the practical application of SEECS guidelines.

References

1. Understanding the Different Types of Sealers for Concrete, https://concretecoloursystems.com.au/product-information/understanding-the-different-types-of-sealers-for-concrete

2. What Are Different Types of Penetrating Concrete Sealers?, https://www.concretesealersusa.com/blog/what-are-the-different-types-of-penetrating-concrete-sealers/

3. Vargas, V.V.: Bridge Deck Cracking Investigation and Repair, https://digitalcommons.unf.edu/cgi/viewcontent.cgi?article=1470&context=etd, (2012)

4. Hayes, A.R.: The Evaluation of High Molecular Weight Methacrylate as a Treatment Option for Shrinkage Cracks in Airfield Pavement, https://scholar.afit.edu/etd/2336, (2019)

5. National Cooperative Highway Research Program: Concrete Sealers for Protection of Bridge Structures, https://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_244.pdf, (1982)

6. Rahim, A., Jansen, D., Abo-Shadi, N., Simek, J.: Overview of High-Molecular-Weight Methacrylate for Sealing Cracks in Concrete Bridge Decks, https://journals.sagepub.com/doi/abs/10.3141/2202-10?casa_token=d9clg46pGEAAAAAA%3AYxq0T_Jzx8vJ4Wnk38nZ709vmQsqjeGtRayNi6IvDrxKTHDf0tjNnmmJFqiQ8a9ZLToGWglcyWZh&journalCode=trra, (2010)

7. Johnson, K., Schultz, A.E., French, C., Reneson, J.: Crack and Concrete Deck Sealant Performance, https://conservancy.umn.edu/bitstream/handle/11299/150969/Mn_DOT2009-13.pdf?sequence=1&isAllowed=y, (2009)

8. Ni, X., Leon-Miquel, M., Greiner, Q.R., Paul, A., Jin, Q.: Crack Sealers for the Preservation of Concrete Bridge Decks: A Synthesis of a National Survey and Literature Review, https://jipr.springeropen.com/articles/10.1186/s43065-023-00091-8, (2023)

9. New York State Department of Transportation: Bridge Manual, https://www.dot.ny.gov/divisions/engineering/structures/repository/manuals/brman-usc/NYSDOT_Bridge_Manual_2021_12-2023.pdf, (2021)

10. Silane vs Siloxane: A Primer, https://www.monjuglobal.com/materials/silanes-vs-siloxanes-a-primer#:~:text=Silanes%20form%20a%20permanent%20chemical,reliable%20over%20the%20long%2Dterm.&text=Very%20low%20water%20absorption%20coefficient%2C%20about%200.07kg%2Fm2%20h0

11. Everything You Need To Know About Concrete Sealers, https://snugsservices.com/everything-you-need-to-know-about-concrete-sealers/

12. SpecSilane 20 WB Technical Data, https://www.buildsite.com/pdf/specchem/SpecSilane-20-WB-Product-Data-2194320.pdf

13. PowerSeal 20 Product Data, https://www.chemmasters.net/TDS/PowerSeal20.pdf

14. PS109 Silane Water Repellent SB-100 Penetrating Sealer, https://www.concretesealersusa.com/ps109-silane-water-repellent-sb-100-penetrating-sealer-5-gal/

15. Aquanil Plus 100 Cl Product Data, https://www.chemmasters.net/TDS/AquanilPlus100_CI.pdf

16. Wright, J., Shen, Z., Rizkalla, S.: A Three-Year Field and Laboratory Evaluation of Linseed Oil as a Concrete Sealer, https://cdnsciencepub-com.prox.lib.ncsu.edu/doi/pdf/10.1139/l93-110, (1993)

17. Kubie, W.L., Gast, L.E., Cowan, J.C.: Linseed Oil for the Preventative Maintenance of Concrete , https://onlinepubs.trb.org/Onlinepubs/hrr/1968/254/254-005.pdf

18. Sawmill Creek Forum: Linseed Oil For Concrete Sealer, https://sawmillcreek.org/showthread.php?24638-crazy-idea-linseed-oil-for-concrete-sealer#:~:text=Linseed%20oil%20has%20been%20used,outside%20every%20year%20or%20two

19. Mirza, J., Abesque, C.: Evaluation of Surface Sealers for Concrete Hydraulic Structures Exposed to Low Temperatures, https://link.springer.com/article/10.1617/s11527-010-9604-x, (2010)

20. Wilson, C.A., Drozdz, S.A.: Demonstration and Validation of a High-Performance Floor-Sealant System to Reduce Concrete Degradation, https://erdc-library.erdc.dren.mil/jspui/handle/11681/19953, (2015)

21. What Should You Know Before You Seal Your Joints In Exterior Concrete?, https://indconinc.com/2020/01/08/what-should-you-know-before-you-seal-your-joints-in-exterior-concrete/

22. Lynch, L., Chehovits, J., Luders, D.: Joint Sealant Field Performance - Ten Year Evaluation, https://www.sealnoseal.org/PDF/TenYear/joint sealant field performance 10 year eval.pdf

23. What Are Different Types of Topical Concrete Sealers and Coatings?, https://www.concretesealersusa.com/blog/what-are-the-different-types-of-topical-concrete-sealers-and-coatings/#:~:text=Epoxies%20form%20a%20thicker%20and,better%20than%20one%20component%20systems.

24. Nečasová, B., Liška, P., Šlanhof, J.: Performance of Selected Polyurethane Joint Sealants in Concrete Structures, https://www.proquest.com/docview/2039570712/fulltextPDF/287CD4A5E7874459PQ/1, (2018)

25. Deck-O-Seal Product Data, https://www.wrmeadows.com/data/787.pdf

26. Pecora Corporation - Polysulfide Sealants, https://www.pecora.com/polysulfide-sealants/

27. Poly-Jet Lox Product Data, https://www.wrmeadows.com/poly-jet-lox-low-modulus-joint-sealant/

28. Know Your Sealants, https://omcon-om.com/know-your-sealants/#:~:text=Two%2Dpart%20system%20Polysulphide%20sealant,is%20used%20for%20horizontal%20joints.&text=One%2Dpart%20system%20contains%20premixed,directly%20used%20without%20any%20mixing

29. Whole Life Costing: Sealants, https://www.greenspec.co.uk/building-design/sealants-costs/

30. Sealant Types and Uses, https://www.labcwarranty.co.uk/technical-blog/sealant-types-and-uses

31. North Dakota Department of Transportation: Evaluation of Polysulfide Joint Sealant in Concrete Joints, https://www.dot.nd.gov/divisions/materials/research_project/mr9602final.pdf

32. FHWA: Joint Sealing Tech Brief, https://www.fhwa.dot.gov/pavement/pubs/hif18019.pdf, (2019)

33. How Long Do Concrete Sealers Last?, https://www.foundationarmor.com/how-long-do-concrete-sealers-last/

34. Guang-Yao Leng, Wei Yan, Guang-Yao Leng, Hai-Mu Ye, Er-Dong Yao, Ji-Bin Duan, Zheng-Xian Xu, Ke-Pei Li, Jing-Ru Zhang, Zhong Li: Evaluation of the Injection and Plugging Ability of a Novel Epoxy Resin in Cement Cracks, https://www.sciencedirect.com/science/article/pii/S1995822623002893?ref=pdf_download&fr=RR-2&rr=82db5e0b6f7c53ee, (2023)

35. Kim Tae-Kyun, Park Jong-Sup: Performance Evaluation of Concrete Structures Using Crack Repair Methods, https://www.mdpi.com/2071-1050/13/6/3217, (2021)

36. Lu Lu, Zhao, D., Fan, J., Li, G.: A Brief Review of Sealants for Cement Concrete Pavement Joints and Cracks, https://par.nsf.gov/servlets/purl/10403775

37. Poreshield, https://poreshield.com/

38. Crafco: PORESHIELD™ MAXIMIZES ROI FOR WABASH COUNTY BRIDGES: PoreShield Surface Application Extends Life of Bridges, https://poreshield.com/wp-content/uploads/2023/06/PoreShield-Case-Study-Wabash-bridges.pdf, (2020)

39. Crafco: I-65 NEAR SEYMOUR RECEIVES PORESHIELD™ TREATMENT: Lower Application Costs and Enhanced Durability are a Win for this Roadway, https://poreshield.com/wp-content/uploads/2023/06/PoreShield-Case-Study-I65-Seymour.pdf, (2020)

40. Crafco: PROTECTING CONCRETE FROM CHLORIDE ION DIFFUSION: WisDOT proves that PoreShield™ provides long-term protection from chloride ion diffusion, https://poreshield.com/wp-content/uploads/2023/06/PoreShield-Case-Study-WisDOT-chlorides.pdf, (2020)

41. He, Farnam: MITIGATING THE EFFECTS OF CAOXY FORMATION IN CONCRETE USING PORESHIELD, https://poreshield.com/wp-content/uploads/2023/07/PoreShield-CAOXY-Summary_R02.pdf, (2021)

42. Flexible Polyurethane Methyl Methacrylate, https://www.epoxy.com/Polyurethane_Methyl_Methacrylate_Flexible.aspx

43. Sadati, S., Taylor, P., Kevern, J.T., Wang, K., Freeseman, K.: Evaluation of Penetrating Sealers for Concrete, https://intrans.iastate.edu/app/uploads/2022/05/concrete_penetrating_sealers_eval_lit_rvw_w_cvr.pdf, (2019)

44. Wells, D., Palle, S., Hopwood II, T.: Developing Material Specification and Application Criteria for Sealing Concrete Bridge Decks, https://uknowledge.uky.edu/cgi/viewcontent.cgi?article=2655&context=ktc_researchreports, (2019)

45. Idaho Transportation Department: Standard Specifications for Highway Construction, https://apps.itd.idaho.gov/apps/manuals/specbook/specbook18.pdf, (2018)

46. Florida Department of Transportation: Section 413- Sealing Cracks and Concrete Structure Surfaces, https://www.fdot.gov/docs/default-source/programmanagement/Implemented/SpecBooks/July2016/Files/413-716.pdf

47. The State of Delaware Department of Transportation: Standard Specifications for Road and Bridge Construction, https://deldot.gov/Publications/manuals/standard_specifications/pdfs/2016/2016_standard_specifications_08-2016.pdf, (2016)

48. Colorado Department of Transportation: Revision of Section 515 - Concrete Sealer (HMWM Resin), https://www.codot.gov/programs/bridge/bridge-manuals/specifications/psp_word/515_concrete_sealer_high_molecular_weight_methacrylate.docx

49. Arkansas Department of Transportation: Division 800 - Structures, https://www.ardot.gov/wp-content/uploads/2020/10/Division-800.pdf

50. Texas Department of Transportation: Special Specification 4038 - Gravity Feed Crack Repair for Concrete, https://ftp.txdot.gov/pub/txdot-info/cmd/cserve/specs/2004/spec/ss4038(04).pdf, (2004)

51. Ohio Department of Transportation: Section 705 - Concrete Incidentals, https://www.dot.state.oh.us/Divisions/ConstructionMgt/OnlineDocs/Specifications/2005CMS/700/705.htm#a_705_15__High_Molecular_Weight_Methacry

52. Tennessee Department of Transportation: Special Provision Regarding Repair of Bridge Deck Cracks, https://www.tn.gov/content/dam/tn/tdot/construction/special-provisions/Const-604CR.pdf, (2021)

53. Krauss, P.D., Lawler, J.S., Steiner, K.A.: Guidelines for Selection of Bridge Deck Overlays, Sealers and Treatments, https://deldot.gov/Business/drc/pdfs/bridge/relatedLinks/nchrp_report_20_07_task_234.pdf, (2008)

54. Georgia Department of Transportation: Section 833 - Joint Fillers and Sealers, https://www.dot.ga.gov/PartnerSmart/Business/Source/specs/ss833.pdf

55. South Carolina Department of Transportation: Standard Specifications for Highway Construction, https://www.scdot.org/business/pdf/2007_full_specbook.pdf, (2007)

56. Caltrans Division of Maintenance: Chapter 4 - Joint Resealing and Crack Sealing, https://www.csuchico.edu/cp2c/_assets/documents/caltrans/rpmtag-chapter-4---joint-resealing-and-crack-sealing.pdf, (2007)

57. Virginia Department of Transportation: Road and Bridge Specifications, https://www.vdot.virginia.gov/media/vdotvirginiagov/doing-business/technical-guidance-and-support/technical-guidance-documents/construction/VDOT_2020_RB_Specs_acc071522.pdf, (2020)

58. National Transportation Product Evaluation Program, AASHTO: User Guide for the Epoxy Resin Based Adhesive Bonding Systems, https://transportation.org/product-evaluation-and-audit-solutions/wp-content/uploads/sites/49/2023/03/ERB-User-Guide-2022-11.pdf

59. Massachusetts Department of Transportation Highway Division: QCML Criteria Epoxy-Resin Crack Sealers, https://www.mass.gov/doc/criteria-for-epoxy-resin-crack-sealers/download, (2023)

60. South Carolina Department of Transportation: Bridge Rehabilitation Requirements, https://scdot.org/business/TPA%20Files/700-8_Bridge%20Rehab%20Requirements.pdf

61. Tennessee Department of Transportation: Unit Cost Analysis, https://www.tn.gov/content/dam/tn/tdot/aeronautics/engineering/TDOT_UnitCostAnalysisFinal_111619.pdf, (2019)

62. New Mexico Department of Transportation: Standard Specifications for Public Works Construction, https://www.fmtn.org/DocumentCenter/View/23320/2006-NM-APWA-Specifications?bidId=, (2006)

63. Maryland Department of Transportation State Highway Administration: Standard Specifications for Construction and Materials, https://www.roads.maryland.gov/ohd2/2018_Standard_Specifications.pdf, (2018)

64. Missouri Highways and Transportation Commision: Standard Specifications for Highway Construction, https://www.modot.org/sites/default/files/documents/2022%20Missouri%20Standard%20Specific%20-%20MHTC%20%28Oct%202022%29_notsigned.pdf, (2022)

65. Kentucky Department of Transportation: Division 800 - Materials Details, https://transportation.ky.gov/Construction/Standard%20amd%20Supplemental%20Specifications/800%20Materials%20Details%202019.pdf

66. Georgia Department of Transportation: Section 886 - Epoxy Resin Adhesives, https://www.dot.ga.gov/PartnerSmart/Business/Source/specs/ss886.pdf

67. MnDOT: Bridge Deck Crack Sealer Qualification Procedure, https://www.dot.state.mn.us/products/bridge/pdf/bridgedeckcracksealerqualification.pdf

68. Hawaii Department of Transportation: Section 712 - Miscellaneous, https://hidot.hawaii.gov/highways/files/2013/01/712_Print.pdf

69. Oklahoma Department of Transportation: Special Provisions for Concrete Surface Repair by Sealing, https://www.odot.org/c_manuals/specprov1999/oe_sp_1999-523-1.pdf

70. Texas Department of Transportation: DMS - 8140 Penetrating Concrete Surface Treatment, https://ftp.dot.state.tx.us/pub/txdot-info/cst/DMS/8000_series/pdfs/8140.pdf, (2014)

71. Texas Department of Transportation: DMS - 8110 Coatings for Concrete, https://ftp.txdot.gov/pub/txdot-info/cst/DMS/8000_series/archives/8110-0804.pdf

72. State of California Department of Transportation: Method of Testing Cold Applied Two-Component Polysulfide Polymer Type Joint Sealing Compound, https://dot.ca.gov/-/media/dot-media/programs/engineering/documents/californiatestmethods-ctm/ctm-413-a11y.pdf, (2012)

73. Types of Joints in Concrete Construction, https://theconstructor.org/concrete/joints-in-concrete-structures/970/

74. What are volatile organic compounds (VOCs)?, https://www.epa.gov/indoor-air-quality-iaq/what-are-volatile-organic-compounds-vocs

Appendix

To supplement the written explanation and implementation involving SEECS, we have also included a video. The link to the video will be provided down below.