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Concrete Bridge Deck Crack Sealing: An Overview of Research

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16. Abstract

Cracking in concrete bridge decks is widely regarded as a long-term durability and maintenance problem that requires attention. It is a problem that occurs in most geographical locations and climates, and in many types of bridge superstructures. These cracks propagate through the deck allowing rapid ingress of moisture and chloride ions into concrete interior leading to excessive deterioration due to rebar corrosion. Popular measures to minimize rebar corrosion are to apply surface treatment sealers, which decrease the overall permeability of concrete, and/or to seal/fill the cracks to prevent the direct intrusion of chloride bearing water. In California, High Molecular Weight Methacrylate (HMWM) has been frequently used as crack sealers with millions of dollars spent annually on work involving Methacrylate applications on state owned bridges.

While focusing on HMWM as a crack sealer/filler, the objectives of this research include:

1- A thorough review of previous research regarding the effectiveness of concrete bridge deck sealers.
2- A nationwide survey investigating the effectiveness of using Methacrylate as a sealer.
3- Developing guidelines concerning the use of HMWM along with other potential successful sealers.

It was found that HMWM can be used as a crack sealer in conjunction with the use of silane as a surface sealer. A wide range of application temperature was reported in the literature. However, a range of application temperature between 7°C (45°F) and 29°C (85°F) is recommended. For new decks, it is recommended that HMWM be applied 3-6 months after construction to make sure that chloride concentration does not reach the corrosion threshold value. For old decks careful attention should be paid to the preparation method and the cleanness of both deck surface and cracks. It is recommended that HMWM sealer be applied every 4-5 years or as recommended by the bridge inspection team. For areas not subjected to deicing chemicals/chloride-laden environment, the use of HMWM as crack sealers can help restore the structural bond strength and the flexural strength, only if cracks are narrow and contaminants free. In the same areas and based on a parametric study employing Life-365 Model, the use of sealant to retard corrosion initiation in reinforcement steel is not significant. However, more laboratory/field investigations are recommended.

17. Key Words
High Molecular Weight Methacrylate, HMWM, Concrete Bridge Deck, Sealants, Deck Cracking

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Concrete bridge deck cracking is the most common type of deck distress observed throughout the U.S. including California. Cracking in concrete bridge decks can occur due to numerous reasons that include cement mortar shrinkage, freeze-thaw cycles, settlement, and traffic loading. According to a survey conducted in 1996 from respondents in several State Departments of Transportation, more than 100,000 bridge decks in the U.S. have suffered from early transverse cracking (Krauss and Rogalla, 1996). The presence of these cracks in concrete bridge decks often leads to eventual structural deficiency because these cracks permit the ingress of harmful substances into the decks. This in turn causes accelerated corrosion of reinforcing steel, deterioration of concrete, leakage onto structural members and components beneath the deck, and poor appearance.

Various modifications to standard bridge deck design have been incorporated in the past 30 years to mitigate deck cracking. However, these modifications have not been successful in reducing cracking and, in some cases, cracking has increased (Eppers et al., 1999). As awareness has grown since the 1960s regarding the severity of the cracking problem and the resulting reinforcement steel corrosion, the interest in and the use of sealers/repair systems have expanded exponentially. Therefore, a number of crack repair systems and surface sealers have been developed over the years and are used widely in treating and protecting concrete bridge decks (Tsiatas and Robinson, 2002). Table 1 presents a broad description of these repair systems.

Table 1. Generic classification of concrete crack repair systems.
(Tsiatas and Robinson, 2002)

Cementitious materials	Crack repair materials that use hydrated cement as the binding medium for aggregates and fillers. Aggregate size and water/cement ratios vary. Includes portland cement, drypack, and shotcrete.
Modified cementitious materials	Crack repair materials that use hydrated cement and includes additional materials to increase repair strength, durability, or effectiveness. Includes various polymer modifiers at various percentages.
Resinous materials	Crack repair materials that do not use cement but rather other materials that may or may not be added to aggregates to result in an effective repair material. Includes epoxies, polyurethanes, and methyl-methacrylates.

1.2 OBJECTIVES

In this research study, a thorough review of previous studies and the current state of practice regarding concrete bridge deck crack sealing was conducted. Case studies were drawn from across the U.S. through a nationwide survey. While focusing on HMWM, the effectiveness of different treatment methods was derived from published literature. Guidelines concerning the use of HMWM and other successful sealants based on the characteristics of sealants, cracks, and bridge decks were developed.

CHAPTER 2

CRACKING IN CONCRETE BRIDGE DECKS

2.1 BACKGROUND

Approximately 40 percent of the nearly 578,000 bridges throughout the U.S. are considered deficient. More than 130,000 bridges are posted with restricted weight limits and roughly 5,000 are closed (Tsiatas and Robinson, 2002). In California, Caltrans is performing inspection and maintenance under Federal regulations on more than 12,300 state highway bridges covering an estimated total deck area of 21,619,215 m^2 (www.ca.dot.gov, 2004). From Figure 1, two thirds of the bridge deck area is between 25 and 50 years old and efficient maintenance for these aging bridge decks is vital.

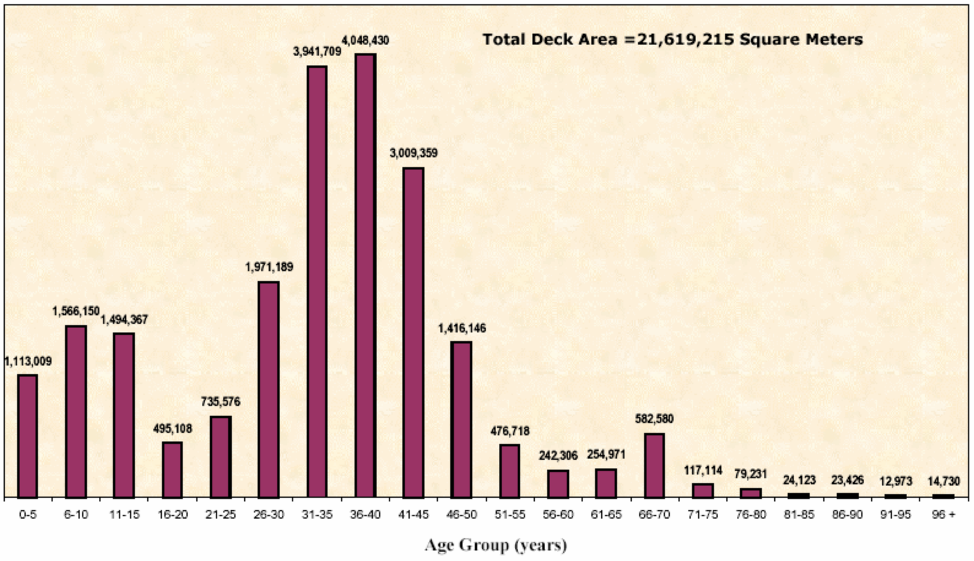

Figure 1. California State owned and maintained bridge deck area by age
(From http://www.dot.ca.gov, 2004)

One of the first signs of bridge deterioration is deck cracking and much of the deterioration is caused by the intrusion of water and chloride ion-bearing water into the concrete deck. In the presence of moisture and Oxygen, the chloride attacks the reinforcing steel within the bridge deck causing corrosion (Meggers and Kurt, 2002). Many highway agencies, including Caltrans, employ the use of epoxy-coated reinforcing steel (rebar) to combat the corrosion process. However, there are still concerns regarding the unabated ingress of chloride-bearing water into bridge decks, such as the reduction of freeze-thaw durability and crystalline growth pressure development (Soriano, 2002). Other popular measures to minimize corrosion activity are to apply some type of surface treatment (i.e., penetrating sealer, waterproofing coating/membrane, corrosion inhibitors, etc.) and/or perform crack sealing activities to prevent chloride-bearing water from contacting the rebar. Even in the absence of chloride-bearing water, bridge decks that initially experienced shrinkage/thermal cracking would continue to deteriorate due to traffic load and evolved loss n their structural integrity.

2.2 CRACKING AND DECK DETERIORATION

Most concrete bridge decks develop cracks that may be either transverse, longitudinal or random (ACI Committee 345, 1999). A cooperative study by the Portland Cement Association (PCA) and ten State DOTs found that transverse cracking was the predominant mode of deck cracking (Carden and Ramey, 1999). These transverse cracks develop when longitudinal tensile stresses in the deck exceed the tensile strength of the concrete. The tensile stresses are caused by temperature changes, concrete shrinkage, and bending from self-weight and traffic loads. A combination of shrinkage and thermal stresses causes most of the transverse cracking found in concrete bridge decks (Krauss and Rogalla, 1996). Deck cracking can cause accelerated corrosion of reinforcing steel, deterioration and leaching of concrete; accelerated damage to structural members and components beneath the deck; and appearance concerns.

Approximately, forty percent of the 578,000 bridges on the federal-aid system are classified as either “structurally deficient” or “functionally obsolete”, with approximately twenty percent of the current backlog of rehabilitation costs are caused by the corrosion of reinforcement steel in bridge decks (Zematt and Weyers, 1996). This problem is more dominant in the chloride-laden environments of coastal regions and in regions that use chloride salts in winter maintenance activities. Consequently, a large number of concrete bridge decks are exposed to contamination with chlorides that penetrate through surface pores and shrinkage induced cracks initiating corrosion of reinforcing steel. The presence of chlorides and loss of the alkaline environment causes the embedded steel to lose its surface passivity (Zematt and Weyers, 1996). Corrosion follows as water and Oxygen become available to the steel. The accumulation of corrosion products, which occupy more volume, causes cracking of the protective concrete cover. This, in turn, allows for the intrusion of chlorides and Oxygen at a much faster rate accelerating the corrosion process and the deterioration rate.

In areas not subjected to deicing chemicals or chloride-laden environments, these cracks reduce the structural integrity of concrete decks in the presence of heavy traffic. The intrusion of water and Oxygen through these cracks will accelerate the deterioration rate.

2.3 FACTORS AFFECTING CRACKING

Cracking in concrete bridge decks is dominated by three factors: (1) degree of deck restraint; (2) concrete’s effective modulus of elasticity; and (3) concrete volume change due to shrinkage and thermal effects (Krauss and Rogalla, 1996).

It is the shrinkage and thermal induced tensile stresses that initiate the cracking process. Further deterioration in the concrete bridge decks will take place due to traffic loading and/or water intrusion through the cracks. Shrinkage of concrete is defined as the time-dependent strain measured in an unloaded and unrestrained specimen at constant temperature [Gilbert, 2001]. As the degree of deck restraint and the effective modulus of elasticity of concrete increase, the tendency of the concrete deck to develop transverse cracking increases. Concrete materials and mixture proportions have been found to be the most critical factors affecting shrinkage cracking. Three types of shrinkage (plastic, chemical and drying shrinkage) take place in concrete bridge decks. Plastic shrinkage occurs at the surface of fresh concrete soon after it is placed and while it is still plastic (http://www.prmconcrete.com/plastic.htm, 2004). Plastic shrinkage occurs mainly due to a rapid loss of water from the concrete surface before it has set. Chemical shrinkage results from various chemical reactions within the cement paste and includes hydration shrinkage (Gilbert, 2001). Drying shrinkage is the reduction in volume caused principally by the loss of water during the drying process. As concrete cures and dries, tensile stresses are created due to hydration and loss of moisture (Mokarem, et al., 2003). As concrete undergoes drying shrinkage, shrinkage induced tensile stresses develop due to restrained movement of the bridge deck. The tensile stresses may cause immediate cracking (when the developed tensile stresses exceed the concrete tensile strength) or linger as “residual stresses” that tend to limit the capacity of concrete material (Altoubat and Lange, 2001). Such premature deterioration affects the integrity, durability, and long-term service life of concrete structures.

The restraint of shrinkage leads to stress development, which in turn causes the material to creep (Altoubat and Lange, 2001). The tensile creep at early age forms a substantial portion of the time dependent deformation; its role in reducing the shrinkage strain and relaxing the shrinkage stresses can be expressed as the ratio of total creep to free shrinkage (Altoubat and Lange, 2001). Altoubat and Lange (2001) concluded that the tensile creep relaxes shrinkage stresses by at least 50% for normal and high performance concrete. This in turn extends the time to fracture by two to three times than that which would be predicted based on free shrinkage alone. Folliard et al. (2003) stated that if a potential concrete mixture has a high creep capacity, shrinkage stress can be greatly reduced. To prevent drying shrinkage cracking, therefore, a concrete mixture with a low elastic modulus, small shrinkage potential, and a high creep capacity is desired.

Curing has a pronounced effect on the properties of hardened concrete such as durability and strength. Adequate and timely curing is a key factor in reducing cracking. The importance of curing is emphasized by a vast majority of studies. Initial fogging, early curing, sprinkling water on concrete surface, applying wet burlaps, and applying curing compounds are among the recommendations proposed in literature (Hadidi and Saadighvaziri, 2003). In their comprehensive review, Krauss and Rogalla (1996) stated that ineffective curing was the most common reason suggested by the transportation agencies for excessive transverse deck cracking.

2.4 ACCEPTABLE CRACK WIDTHS

In their report (NCHRP 380), Krauss and Rogalla (1996) presented the findings of a survey and literature search they conducted regarding the acceptable crack widths. There was disagreement among researchers and highway agencies about how wide a crack in a bridge deck can be without significantly affecting performance. Some agencies have limited acceptable crack widths to 0.3 mm or less for aesthetic reasons, however, this value is subjective (Krauss and Rogalla, 1996). Countries like Denmark, Japan, and

Switzerland typically limit crack widths on conventionally reinforced decks to 0.2 mm. Krauss and Rogalla stated that only two state DOTs limit crack widths; one limits crack width to 0.18 mm and the other limits it to 0.5 mm (for 15.2 m of cracks per 46.5 m^2 of deck).

For structures subjected to deicing chemicals, the ACI Committee 224 limits crack width to 0.18 mm, while for structures subjected to sea water and wetting and drying the same committee limits crack width to 0.15 mm (Soriano, 2002). However, Krauss and Rogalla (1996) stated that many other researchers and agencies have recommended smaller crack widths. Many cracked decks with crack widths as narrow as 0.05 mm experienced water leakage through with accelerated corrosion of embedded reinforcing steel and supporting girders at the crack. In the same reference it was mentioned that, while the corrosion resistance of reinforcing steel is greatly enhanced by epoxy coating, corrosion can occur where breaks or other defects in the coating are present. In a harsh environment where concrete bridge decks are subjected to deicers and/or sea spray/splash, cracks of widths as small as 0.05 mm could be significantly detrimental and they must be sealed to maintain durability.

2.5 HOW TO SLOW DOWN CONCRETE DECK DETERIORATION

Deterioration of concrete bridge decks usually results from, or dependent on, the ingress of substances through the deck surface and on the traffic volume. Cracks in concrete bridge deck mainly initiate due to shrinkage and thermal movement. Water, penetrating through these cracks, is the most important substance that is involved in virtually every form of concrete deterioration—freezing-thawing damage, reinforcement corrosion, alkali-aggregate reactions, dissolution, sulfate attack, and carbonation (Cody, 1994).

However, in the absence of the aforementioned conditions such as areas in benign environments, traffic loads would have a significant effect on deck deterioration. One way to slow down the deterioration process is to provide a protective system by the use of overlay (ACI 345R-91). Three different types of overlays are common to use for this purpose. Type I overlays are composed of multi-component polymer resins that are flooded onto bridge decks, then sprayed with aggregate for traction. Because of the low viscosity of the system, shrinkage and flexural cracks in the existing bridge deck are also filled during the application (ACI 345R-91). Type II overlays are always of high-performance Portland cement concrete that is 32-76 mm thick atop the existing deck. Type III is a combined system involving asphalt concrete (Sharooz et al. 2000). Type I overlays are the most economical and practical option (cost is low and lane closure is minimum). The focus in this review will be on type I overlays including the different sealers used, their performance and effectiveness, and application conditions.

CHAPTER 3

SURFACE AND CRACK SEALERS

3.1 INTRODUCTION

The ingress of water, chloride ions, and other aggressive substances into concrete bridge decks through surface cracks accelerates the deterioration of the deck. The most notable type of deterioration is the chloride-induced corrosion of reinforcing steel (Cady, 1994). One way to prevent reinforcement corrosion is to prevent the ingress of chloride ions, which initiate the corrosion. This can be achieved by sealing the concrete deck surface, potentially retarding the movement of Oxygen, which in turn prevents the carbonation process. Hundreds of concrete sealer products produced by different manufacturing firms are available. Several products have been used in sealing decks/cracks with different performance results reported even within the same sealer's group. The success of sealants in treating concrete bridge decks depends on a number of parameters such as the type and viscosity of sealant, degree of polymerization, width of crack, injection pressure, moisture content of concrete surface, and temperature. Several research studies have been conducted investigating the efficiency of using different approaches to treat/repair cracking in concrete bridge decks. The findings of these studies are highlighted in this chapter.

3.2 CONCRETE DECK SEALERS

3.2.1 Penetrating Sealants

The primary objective of a surface treatment sealer is to prevent capillary action at the surface, thus preventing the ingress of water and chloride ions into the concrete deck (Zematt and Weyers, 1996). Application of surface sealers can be used for both new and older decks that have not yet been critically contaminated with chlorides (Weyers et al., 1993). The effectiveness of a sealer is based on its ability to: reduce ingress of chlorides into the concrete, penetrate the concrete to a depth sufficient to avoid corrosion under traffic, and last long enough so that the number of application is minimized (Witting et al., 1992).

Several concrete surface sealers were identified during the course of this literature search. The most common in classifying concrete sealers is to use two classes—penetrants and coatings. Penetrants are generally considered to be vapor transmissible while coatings are not, or are very much less (Cady, 1994). Penetrants can be divided into water-repellent and pore-blocking types. Water-repellent refers to those materials that penetrate concrete pores to some degree and coat pore wall that it may contain from penetrating concrete pores, but allows gases and vapors to transmit through. Pore blockers are sealers of sufficiently low viscosity that allow the sealers to penetrate the concrete pores and seal them while leaving little or no measurable coating on the exterior surface of concrete (Cady, 1994).

Surface sealers, when applied to a concrete deck surface, react in two fashions. One group (silanes, siloxanes, and siliconates) “wets” the surface and limits the penetration of chlorides and water into the concrete. The second group (silicates) reacts chemically with concrete components and forms precipitates to seal the pores at or below the surface of the concrete (Soriano, 20022). Silanes, siloxanes, and silicones produce the same end product-a hydrophobic silica gel (Hagen, 1995). The basic difference between these products is their molecule size, silanes being the smaller of the two. This gives silanes the advantage of penetrating deeper into concrete than siloxanes and silicones. Silanes require some humidity in the concrete for the chemical reaction to form silica gel, but too much moisture retards penetration (Hagen, 1995). Siloxanes are less volatile than silanes and can provide similar initial surface protection.

3.2.1.1 Sealant Penetration Depth

Sealer's penetration depth is an important property for both hydrophobic and pore-blocking sealer types. The penetration needs to be deep enough to provide adequate protection of the sealer against wear, weathering, and ultraviolet radiation. The desirable penetration depth is about 6 mm with a minimum of about 3 mm as recommended by Cady (1994). In fact, the quality of concrete is a major factor that affects the penetration depth where it may be greater with poor quality concrete. Also, different sealer generic types result in different penetration depths: 2.5 mm to 6.4 mm for silanes and 1.5 mm to 3.8 mm for siloxanes (Cady, 1994).

3.2.1.2 Water Vapor Transmission

A successful concrete surface sealer should permit passage of water vapor. This property will help promote additional drying of the concrete. A minimum vapor transmission of 35 percent (relative to untreated concrete surface) is recommended (Weyers, et al., 1993).

3.2.1.3 Sealant Service Life

The service life of a concrete sealer relative to chloride ingress is a function of three categories of factors: (1) sealer materials properties, (2) service conditions related to sealer durability, and (3) chloride diffusion related factors (Cady, 1994).

A field trial was conducted in the Fall of 1991 by the Minnesota Department of Transportation (Mn/DOT) to evaluate the effectiveness of various concrete sealers at reducing chloride penetration into concrete bridge decks (Hagen, 1994). Sixteen different concrete penetrating sealers were tested on sixteen test sections, in addition to an untreated control section. Drill dust samples were collected annually for three years following the application to analyze chloride content. The effectiveness of sealants was determined based on the chloride content of treated sections versus that for the control section. Results from this study indicated that silanes and siloxanes, as a group, resulted in the best performance with considerable variability among products. Also, it was reported that the best penetrating sealers appeared to provide protection for about three years while epoxy-based surface sealers appeared generally ineffective after one year (Hagen, 1994). Based on field evaluation, Sprinkel et al., (1993) reported different service lives for solvent-based epoxy, water-based epoxy and silanes to be 10, 8, and 7 years, respectively.

Zemajatis and Weyers (1996) investigated the effect of using surface sealers on extending bridge deck service life in chloride-laden areas. Four sealers were investigated: water-based epoxy and solvent-based epoxy (as pore blockers), and silane and siloxane (as hydrophobic agents). A total of 15 horizontal slabs (910 x 910 x 100 mm) were cast; three slabs were sealed using each of the four sealers while the remaining three were not sealed (control slabs). The slabs were exposed to full direct sunlight and cyclic ponding with three percent (by weight) sodium chloride solution for three days, followed by four days of air drying (Zemajtis and Weyers, 1996). Based on the diffusion characteristics, chloride exposure condition, and sealer characteristics, the extended service life for decks treated with the aforementioned sealers under exposure conditions occurring in New York, Pennsylvania, and Virginia were determined (see Table 2).

Table 2. Service life extension based on diffusion characteristics for investigated sealers. (Zemajtis and Weyers, 1996)

Surface treatment	**Service life extension, years**		
	Virginia	**Pennsylvania**	**New York**
Water-based epoxy	39.5	42.9	17.3
Solvent-based epoxy	39.5	27.3	11.6
Silane	39.5	53.8	49.7
Siloxane	39.5	53.8	39.5

3.2.2 Crack Sealers

Different types of crack sealing materials were cited in the literature as most frequently used in sealing/repairing deck cracks: High Molecular Weight Methacrylate (HMWM), epoxy-based, and urethane-based (Soriano, 2002, and Sprinkel and DeMars, 1995). These materials are low viscosity materials that depend on gravity in filling the cracks and are called gravity-fill sealers. The ACI 224.1R-93 (1998) states: "low viscosity monomers and resins can be used to seal cracks with surface widths of 0.001 to 0.08 in. (0.03 to 2 mm) by gravity filling. High-molecular-weight methacrylates, urethanes, and some low viscosity epoxies have been used successfully." Gravity-fill crack sealers consist of two or more low-viscosity liquid monomer or polymer components that can be mixed and poured directly over a cracked surface. The monomer or polymer fills the cracks and hardens into polymers that seals the cracks, bonds to the crack walls, and restores a percentage of the flexural strength of the original concrete (Sprinkel and DeMars, 1995).

HMWM is an adhesive composed of methacrylate monomers. It is a three-component system (monomer resin, initiator, and promoter) that requires extra precaution during mixing because a violent reaction may occur if the initiator and promoter are mixed first or improperly (Soriano, 2002). An alternative product was developed, which is a two-part ultra low viscosity, low odor modified HMWM system. The manufacturers claim the new product minimizes safety hazard (www.wbacorp.com, 2005).

Epoxies are adhesives based on a reaction between biphenol A and epichlorohydrin (Meggers, 1998). They are highly viscous and generally diluted with solvents or prepared in emulsion form with water to facilitate their use as concrete sealers (Cady, 1994).

Urethanes are reactive resins that are provided as the conventional two-component (resin-hardener) system or as a one-component system where curing is initiated by atmospheric vapor (Cady, 1994). In application and properties, urethanes are similar to epoxies, except they are more flexible.

3.3 HMWM AS A GRAVITY-FILL SEALER

Several research studies have been conducted investigating the effectiveness of gravity-filling sealers in penetrating, sealing and repairing cracks in concrete bridge decks (Meggers and Kurt 2002, Soriano, 2002, Sprinkel and DeMares, 1995, Shahrooz et al., 2000, Tsiatas and Robinson, 2002, Attanayaka, et al., 2003, Rodler, et al., 1989, and Kessler et al., 1990). In the following sections, the use of HMWM as a gravity-fill sealer in sealing deck cracks is discussed. With the focus being on HMWM, other successful crack sealers will be mentioned as part of case studies referenced in this review.

3.3.1 Field and Laboratory Case Studies

Meggers and Kurt (2002) conducted both field and laboratory studies investigating the use of HMWM and epoxy sealers for crack sealing and repair of bridge decks. In the field application, two HMWM (A, B) materials and one epoxy were applied (poured and flooded) to eight bridge decks throughout Kansas in 1992. The sealers' physical properties are presented in Table 3.

Table 3. Significant material properties.
(Meggers and Kurt, 2002)

Sealer	**Viscosity,** pa's (cps)	**Tensile Strength,** MPa	**Tensile Elongation,** %
Epoxy	0.3-0.5 (300-500)	29.3	9.9
HMWM A	0.01-0.025 (10-25)	2.8	30
HMWM B	0.07-0.l5 (70-150)	8.3	10
HMWM C	0.025 (25)	2.8	1.9

Samples were taken from each deck prior to the application and in 1995 for chloride content determination. Also, cores were extracted immediately after the application of sealers and over the subsequent three years to evaluate the penetration and durability of sealers. Meggers and Kurt (2002) reported variability in the penetration and chloride concentration. Even though the penetration results were inconsistent, the HMWM A material penetrated slightly better than the others. In terms of chloride concentration, the results indicated that the sealers were not effective in preventing chloride ions from penetrating into the concrete. Therefore, laboratory tests of concrete beams treated with the same sealers and an additional HMWM C (see Table 3) were initiated. Specimens were subjected to tests that included wet/dry, freeze/thaw, and salt ponding. Laboratory results suggested that both epoxy and HMWM B sealers performed the best. This was probably due to the relatively high tensile strengths and elongation of the two sealers.

In October 2001, various concrete deck surface and crack sealers were applied to three different bridge decks in South Dakota (Soriano, 2003). The bridge decks received three different surface preparations, namely sandblasting, power broom/forced, and do nothing The sealers used in this study are listed in Table 4. Three cores were extracted from each test section to be tested for sealer penetration. It was reported that crack sealers exhibited good penetration and appeared to be well-bonded to the crack walls (Soriano, 2003). It was also noticed that even though cracks were sealed, water ingress occurred around the cracks through unsealed concrete surface. On bridge decks that received sandblasting, it was noticed that water ingress measurements were significantly worse than those decks that received power-brooming/forced air or no preparation. This could be due to the opening and widening of the surface pore structure (Soriano, 2003). Silane products were reported as an excellent choice for surface penetration, with MMA and MPU being the best choice for sealing cracks larger than 1.02 mm (0.04 in.) while MMA, MPU, and epoxy products could be used to seal cracks smaller than 1.02 mm (0.04 in.). Note that these products should be low viscosity sealers (less than 15 cp).

Table 4. Selected crack and surface sealers.
(Soriano, 2003)

Sealer	**Application**
100% Silane	Surface sealer
40% Silane	Surface sealer
Reactive Methyl Methacrylate (MMA)	Crack sealer
Modified Ployurethane (MPU)	Crack sealer
Two-component Epoxy	Crack/Surface sealer
Dow 888 Silicone	Crack sealer

Sprinkel and DeMars (1995) conducted a laboratory evaluation of three two-component epoxies, a three-component HMWM, and a two-component polyurethane that have the properties shown in Table 5.

Table 5. Properties of crack sealers.
(Sprinkel and DeMars, 1995)

Product	**Cost,** $/liter ($/gallon)	**Viscosity at 23^{o}C, cps**	**Tensile strength,** MPa (Psi)	**Elong-ation,%**	**Odor**
Polyurethane	18-24 (67-90)	Ave. 14	31 (4500)	<10	Almost none
Epoxy (E1)	5 (18)	175-250	48 (7000)	1.9	Stinky
Epoxy (E2)	21 (80)	200-230	22 (3250)	37.5	Mild
Epoxy (E3)	9 -13 (33-50)	300-500	29 (4247)	9.9	Stinky
HMWM	11 (40)	< 100	>10 (>1500)	>30	Ext. pungent

Testing included measurements of the flexural and freeze-thaw durability of repaired beams and the gel time and the penetration abilities of the sealers, as well as the effects of temperature and crack width on the quality of the repair. Results of these tests indicated that all the sealers tested can seal cracks in concrete bridge decks and under ideal conditions. These sealers restored 100 percent or more of the original flexural strength, were reasonably durable in freeze-thaw testing, and had gel times that decreased as temperature increased (Sprinkel and DeMars, 1995). HMWM, along with two epoxies (E1 and E3), demonstrated the best behavior, where most of the failure during flexure test occurred in the concrete with a very small number of samples with bond or polymer failure (see Figure 2). Table 6 presents the flexural test results before and after sealing cracks with HWMW. (Note that this test was conducted at the room temperature/humidity with no deicing chemicals were applied). Based on the performance ranking, Sprinkel and DeMars stated that HMWM outperformed the other products tested in terms of flexural strength, gel time and penetration (1995). HMWM was cited as an effective sealer for all types of projects where budget, time of repair, and durability are all critical factors. HMWM is effective when used at temperatures between 4 and 38^{o}C (40 and 100^{o}F) and is excellent for hairline cracks.

Table 6. Flexural test results for beams before and after sealing with HMWM.
(Sprinkel and DeMars, 1995)

Crack width, mm	**Flexure strength,** MPa		**Flexure ratio, %**	**Failure type, %**		
	Initial[a]	**Final**[b]		**Bond**	**Concrete**	**Polymer**
0.2	4.7	6.0	131.0%	2	98	0
0.5	6.1	6.2	102.0%	0	97	3
0.8	5.3	6.6	128.0%	0	97	3
1.0	5.7	6.1	108.0%	0	100	0

Although the polyurethane sealer's ability to penetrate narrow cracks, seal large cracks effectively, and withstand freeze-thaw is less than those of the other sealers, its fast curing, no-odor characteristic and ease of application makes it appropriate for hasty repairs and for small cracked areas where leaking may be a problem and sealing the underside of the crack is not practical (Sprinkel and DeMars, 1995).

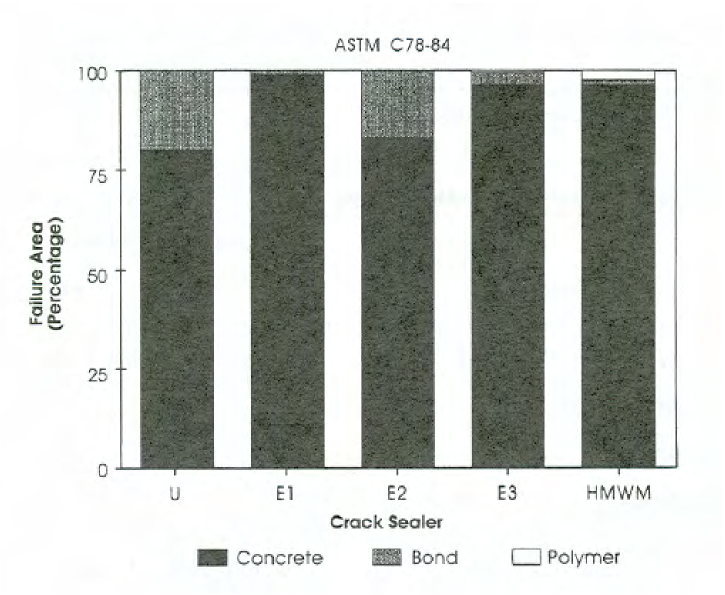

Figure 2. Failure mode of new cracks sealed with different gravity-fill sealers.
(Sprinkel and DeMars, 1995)

Tsiatas and Robinson (2002) conducted a laboratory study investigating the effect of using different concrete crack repair systems on the durability of concrete. In this study six repair materials were evaluated that included two cementitious systems, two epoxy based systems, and two HMWM repair products. Concrete beams were cast and crack inserts were placed to create cracks of widths 0.51 mm (0.02 in.), 6.35 mm (0.25 in.), and 12.7 mm (0.5 in.) while the crack depth was one-half of the beam depth. The beams were subjected to freezing and thawing testing in accordance with ASTM C666, followed by fatigue testing in accordance with ASTM C78. It was reported that among the six repair groups investigated, epoxies and HMWM performed the best with significant variation between individual products within the same group (Tsiatas and Robinson, 2002). In terms of crack width, epoxies seemed to be efficient in repairing cracks of 0.51 mm (0.02 in.) and 6.35 mm (0.25in.), and HMWM seemed efficient for crack widths of 6.35 mm (0.25 in.) and 12.7 mm (0.5 in.).

The concrete deck of the Seven Mile Bridge in Florida, which experienced extensive longitudinal cracks shortly after construction, was sealed in 1989 using High Molecular Weight Methacrylate (HMWM) (Kessler, et al., 1990). The total treated area was calculated at 120,006 m^2 (1,291,068 ft^2). The HMWM was applied over the bridge deck using specially designed mixing equipment and airless spray bars mounted on pneumatic tires and pulled by a truck (Kessler, et al., 1990). Brooms were used to sweep the excess material toward the cracks in order to fill them up as much as possible. Silica sand cover was spread over the treated areas while still curing in order to provide additional skid resistance to the deck surface. The treated deck was opened to traffic within four hours after sealant application. Approximately, one year after the completion of the project cores were extracted from both the cracked and un-cracked areas. The extracted cores were examined for penetration depth and the results are shown in Table 7.

Table 7. Penetration depth for different crack widths.

(Kessler et al. 1990)

Crack width, mm (in.)	Penetration depth, mm (in.)	
	Range	Average
< 0.127 (0.005)	4.52-36.65 (0.178-1.443)	19.3 (0.76)
0.127-0.254 (0.005 – 0.01)	14.22-43.89 (0.56-1.728)	23.72 (0.95)
> 0.254 (0.01)	-----*	24.13 (0.95)*

* Only one core in this category was tested

To evaluate bonding strength of HMWM, the top one inch of cores was cut and subjected to indirect tensile testing. The same test was conducted on cracked and un-cracked cores for comparison (see Table 8).

Table 8. Load at failure in indirect tensile test.

(Kessler, et al. 1990)

	Sealed cracks	Un-cracked cores	Ratio of Restored bond
Range, , kN (Ib)	0.605-8.37 (136-1880)	------	-------
Average, , kN (Ib)	4.33 (972.67)	4.78 (1074.95)	90.48%

The friction coefficient of treated deck was measured and the test values ranged from 42.3 to 52.8 with an average of 45.5. Note that the friction coefficient of the concrete deck before sealing was 52.8. Based on the results of this project, it was found that the HMWM was able to penetrate through cracks 0.127 mm (0.005) easily. However, for wider cracks the HMWM was able to penetrate even deeper. The HMWM was able to restore the cracked concrete strength up to 90% of its original (un-cracked) strength. The skid resistance of the concrete was not significantly affected.

Between 1991 and 1998, the Montana Department of Transportation used a different formulation of HMWM to repair cracks in many bridge decks throughout the state. The typical crack width ranged from 0.01 mm to 0.8 mm with an average of 0.2 mm. In 1999, twenty six of these bridges were examined by extracting two to four cores from each deck to determine the effectiveness of the HMWM resins in penetrating and bonding cracks (Krauss, 2000). Crack contamination was observed in almost all of the cores, making structural bonding of the cracks by HMWM unlikely. The results of this study revealed no correlation between crack widths and penetration depth. However, the deepest resin penetration was typically achieved in narrow cracks (less than 0.4 mm) (Krauss, 2000). There was no significant difference in the penetration depth of high versus low elongation HMWM resins. From the twenty six bridges surveyed in this study, only a very few had evidence of new cracking after the HMWM treatments. In addition, the HMWM treatments appeared to have stopped leakage through most through-deck cracks. In the same reference it was stated that HMWM may penetrate and achieve better structural bond to cracks in newly constructed bridges that contain cracks without significant contamination. It was also noted that HMWM in the cracks has not affected by time, however, surface abrasion and weathering removed the resin HMWM from the surface after 3 to 4 years (Krauss, 2000).

In December 2004, the Louisiana Department of Transportation conducted a field trial in an attempt to determine the feasibility of using HMWM in sealing deck cracks. The Amite River/190 bridge deck (a badly deteriorated bridge deck that may be replaced within five years) was selected for this trial where HMWM based sealer (DEGADECK Crack Sealer) was applied (telephone and e-mail contacts, June 2005). Three cores were extracted with not one of them survived the coring process intact. It was noticed that only the top one inch was sealed. Different hypothesis could be given to the inconclusive performance; the cold temperature at which the sealer was applied (below 40^oF), unclean cracks (since the deck was badly deteriorating), high sealer viscosity, and the advancement of deck deterioration stage.

A 4-inch Portland cement deck overlay on the new Loop 1604 bridge over IH 10 in San Antonio had serious shrinkage cracking and received an HMWM application in the 1980s (Rodler et al., 1989). The deck was prepared by high pressure water blasting followed by a drying period of seven days. On the day of application, the cracks were blown clean using dry-filtered air before being sealed. The HMWM monomer (in which the initiator was cumene hydroperoxide) was applied on the entire deck surface (Rodler, et al., 1989). Cores extracted from the treated deck showed only 60-80 percent of each crack filled with the monomer. Nevertheless, the top of the crack was always filled and water penetration from the top was prevented. The splitting tension test was conducted on disks trimmed from the extracted cores to evaluate the bond strength. Results indicated the strength of all repaired crack specimens were at least 80 percent of those of the un-cracked specimens (Rodler, et. al., 1989).

In 1988, two HMWM monomers were used to treat the cracks and seal the surfaces on two bridges over the New River in Virginia (Sprinkel, 1991). The deck surface and the cracks were blasted with oil-free compressed air to remove dirt, dust, and other loose material. The cracks were sealed by HMWM monomer that was applied between sunrise and 11:00 am at a deck surface temperature between 10.5^{o}C and 21 ^{o}C (51^{o}F and 70 ^{o}F). The HMWM monomer was then applied to seal the entire deck surface. Cores were extracted in 1988 and 1989 from the cracked and un-cracked concrete and were tested for permeability, penetration depth, flexure, and tensile strength. It was reported that, on the average, the HMWM monomers filled 95 percent of the crack width at the surface (Sprinkel, 1991). However, for narrow cracks (<0.2 mm), the HMWM did not penetrate and fill the cracks completely. Due to the partial filling of cracks and the presence of dust and contaminants inside the cracks, HMWM did not seem to restore load transfer across the cracks. However, it was indicated that the polymer in many cracks was cracked after one year in service due to traffic-induced and temperature-induced strains across the cracks.

A single HMWM application was applied to the U.S. 136 bridge deck over the Mississippi River at Keokuk, Iowa at a temperature close to 7^{o}C (45^{o}F) (Marks, 1988). Leakage through cracks treated using HMWM was reduced, but not completely prevented. Cores of 2-in diameter were drilled 2 in. deep, to avoid damaging the epoxy coating, and were subjected to split test. It was noted that HMWM had penetrated at least 2 in. deep at all cracks. Marks (1988) mentioned the split did not always follow the crack, however, in some instances the concrete fractured instead of the crack, indicative of the bonding capabilities of the HMWM.

3.3.2 HMWM and Crack Width

Different crack width criteria were found in the literature. These different criteria along with the references that cited them are listed in Table 9.

Table 9. Crack width when applying HMWM[a].

Reference	Crack width, mm (in.)	Notes
Attanayaka et al. (2003)	< 2.03 (0.08)	- New decks (6 months old)[b] - For older decks, adequate surface preparation is needed
Tsiatas and Robinson (2002)	6.35-12.7 (0.25-0.5)	- Durability is the concern
Soriano (2002)	<1.02 (0.04)	-Crack frequency < 3 m (10 ft.) -Used in conjunction with silanes.
	> 1.02 (0.04)	-Any crack frequency -Used in conjunction with silanes.
Meggers (1998)	Ave. 0.31 (0.012)	-Crack contamination is a problem -Decks should be sealed when 1-2 yrs old
Sprinkel et al. (1993)	0.2-2.0 (0.008-0.08)	-Viscosity less than 25 cps
Krauss (1996)	< 0.25 (0.01 in.)	
Xi et al. (2004)	0.05-2.0 (0.002-0.08)	-HMWM following silane application

a HMWM was applied successfully on cracks less than 0.15 mm (0.006in.). (ACI RAP Bulletin 2, 2003)
b Silane may be applied first as surface treatment followed by HMWM as crack filler.

3.3.3 Temperature of Application

The effect of temperature on gel time was investigated by Speinkel and DeMars (1995). It is reported that as the temperature increases the gel time decreases and, therefore, Sprinkel and DeMars recommended a temperature range between 4 and 38^{o}C (40 and 100^{o}F) at which HMWM would be effective. Krauss (2000) recommends using HMWM resins when the deck and air temperatures are between 13 and 32^{o}C (55 and 90^{o}F). The Iowa Department of Transportation Special Provision for HMWM requires a temperature range from 4 to 38^{o}C (40 and 100^{o}F) (Marks, 1988). Marks (1988) indicated a minimum temperature of 10^{o}C (50^{o}F) was strongly recommended by the manufacturer during the second application of HMWM. Krauss (1996) stated that HMWM resin performs well if it is applied when the concrete and air temperature are between 7°C (45°F) and 32°C (90°F). Sprinkel (2001) states that HMWM does not cure satisfactory when temperatures are below 13°C (55°F) and best results can be obtained by filling cracks when they are open the widest at the surface (temperature between 13°C (55°F) and 21°C (70°F)). Montana Department of Transportation requires HMWM applied when deck surface temperature is between 10°C (50°F) and 32°C (90°F) (www.mdt.state.mt.us, 2005). It is noteworthy to mention that special formulations are currently available in the market to help improve curing during cold and hot weather.

3.3.4 Deck Surface and Crack preparation

One of the most important steps in deck/crack sealing is the preparation of the surface or cracks to be sealed. The sealing will be only as good as the surface/crack preparation, regardless of the nature, sophistication, or type of the sealing material. Many surface and crack preparation methods have been included in the literature. These methods include; grinding, pressurized water, power broom, sand blasting, and forced air among others (Soriano, 2003 and ACI 546). According to manufacturers' recommendations as well as data published in the literature, concrete must be at least 28 days old, surface must be clean, dry, and free of curing compounds and pore blocking contaminants (Attanayaka et al., 2003). Should water blasting be used to clear the cracks, the deck should undergo a drying period of at least seven days and cracks should be blown clean with dry-filtered air on the day of the application (Rodler et al., 1989). The ACI E-706 recommends considering sand- or shot-blasting in preparing large areas (2003). For cleaning and preparing individual cracks, the ACI E-707 recommends beginning with wire brushes and wheels, followed by high pressure, oil-free compressed air to remove dust from the surface of the crack. If the crack surface is packed solid with dirt and/or debris, they must be removed by routing the crack surface and following up with compressed air to remove fines. Cracks may be air blasted or vacuumed to ensure they are free of water and dirt/dust. After surface and crack cleaning, the deck should be allowed to dry for at least 24 hours prior to sealant application. However, field trials where high pressure washers and sand blasting were used resulted in inconclusive results in terms of penetration depth (Soriano, 2003 and Meggers, 1998). Note that decks included in these trials were 1 to 29 years old and cracks had been severely contaminated. Therefore, early treatment (approximately 3 to 6 months after construction), where the developed cracks are not severely contaminated with dust and debris, is recommended.

Atanayaka et al. (2003) reported the compatibility of silane with HMWM and the possibility of treating cracks with HMWM after applying silane sealers. However, Soriano (2003) mentioned the application of crack sealers (for example HMWM) before applying a penetrant sealers (for example silane).

3.4 APPLICATION CYCLES

The literature search revealed no consensus among agencies/researchers on how frequent concrete bridge decks should be sealed. Soriano (2003) recommended 5 years application intervals based on the Taber abrasion test and taking into account application, concrete permeability, and traffic variability. Alberta Department of Transportation generally seals bridges on a 4-year cycle, which varies from region to region (http://www.trans.gov.ab.ca/Content/doctype253/production/BrSealerGdln.pdf, 2005).

Cady (1996) reported service life range of 5-15 years, based on the exposure conditions, for acrylic based sealers (note that HMWM belongs to this broad group).

3.5 NATIONWIDE SURVEY RESULTS

As part of this project, a nationwide questionnaire was sent to each of the 50 state DOTs including the District of Columbia. The questionnaire form used is provided in Appendix A. The objective of the questionnaire was to learn the current state-of-the-practice in sealing bridge decks and the guidelines for using High Molecular Weight Methacrylate (HMWM) in crack/deck sealing.

Forty one transportation agencies responded to the survey including Caltrans. However, response was not included in the analysis and was kept for comparison to other DOTs. Eight-five percent of the transportation agencies responding to the survey reported experiencing transverse cracking, sixty-five percent experiencing random cracking, and 1fifteen percent experiencing other types of cracking including longitudinal and diagonal cracking in their concrete bridge decks.

Of the transportation agencies responding, 42.5 percent stated using HMWM, 52.5 percent using Epoxy, 7.5 percent using Polyesters, and 37.5 percent employing other types of sealants including urethanes, silanes, siloxanes, linseed oil and bituminous membranes. It is noteworthy to mention that some DOTs reported using more than one sealant in sealing their bridge decks.

Fifty-nine percent of the transportation agencies that reported using HMWM are using it solely as a crack sealer, six percent solely as surface sealer, and thirty-five percent have dual use as both crack and surface sealer.

With regard to the time for HMWM application, eighty-two percent reported applying the sealer after cracks are initiated/cracks are prominent, and eighteen percent using it right after decks are constructed. Note that the three state DOTs that reported early application apply HMWM as both surface and crack sealer.

In preparing bridge decks, twenty-nine percent of transportation agencies that reported using HMWM as deck sealer use power broom, sixty-five percent employ forced air, twelve percent use pressurized water, and twenty-nine percent employ other preparation techniques including sand blasting, shot blasting, or simply follow manufacturer instructions. Note that some respondents reported using more than one preparation technique.

Of the transportation agencies that reported using HMWM, 71 percent apply the sealer to cracks that are narrower than 1.6 mm (0.0625 in), 35 percent apply it to cracks that are in the range of 1.6mm-3.2mm (0.0625in-0.125in), and 6 percent reported that cracks have to be visible to the inspector. In responding to this question, some agencies reported more than one criterion in applying HMWM.

In tables 10 through 16, the survey results are summarized with comparisons to CalTrans practices.

Table 10. Deicing chemicals used by different DOTs.

Chemical	**Caltrans**	**# of DOTs**[1]	**Percent,**[2] **%**
NaCl	x	29	72.5
CaCl		14	35.0
MgCl	x	16	40.0
Other[3]		7	17.5

1 Other than Caltrans
2 Some DOTs reported using more than one deicing chemical
3 Include sand, salt, acetate magnesium, …

.

Table 11. Type of cracking experienced by different DOTs.

Type of Cracks	Caltrans	# of DOTs[1]	Percent,[2] %
Transverse	x	34	85.0
Random	x	26	65.0
Other[3]	x	6	15.0

1 Other than Caltrans

2 Some DOTs reported experiencing more than one crack type

3 Include longitudinal and diagonal

Table 12. Type of sealant used by different DOTs.

Type of Sealant	Caltrans	# of DOTs[1]	Percent,[2] %
HMWM	x	17	42.5
Epoxy		21	52.5
Polyester		3	7.5
Other[3]		15	37.5

1 Other than Caltrans

2 Some DOTs reported using more than one sealer

3 Include Urethanes, Silanes, Siloxanes, Linseed Oils and Bituminous membrane.

Table 13. Type of HMWM application.

HMWM Appl.	Caltrans	# of DOTs[1]	Percent,[2] %
Surface Sealer		7	41.0
Crack Sealer	x	16	94.0

1 Other than Caltrans

Table 14. Time of HMWM application.

Appl. Time	Caltrans	# of DOTs[1]	Percent,[2] %
After Crack Initiation	x	14	82.0
Right after Constr.		3	18.0

1 Other than Caltrans

Table 15. Surface preparation technique.

Surface Prep.	Caltrans	# of DOTs[1]	Percent,[2] %
Bower Broom		6	15.0
Forced Air		11	65.0
Pressurized Water		2	12.0
Other[3]	x (sand blasting)	5	12.5

1 Other than Caltrans

2 Some DOTs reported employing more than one technique

3 Include sand blasting, shot blasting, and follow manufacturer instruction

Table 16. Crack width criteria for using HMWM.

Width Criterion	Caltrans	# of DOTs[1]	Percent,[2] %
<1.6 mm (<0.0625 in)	x	12	70.0
1.6-3.2 mm (0.0625-0.125in)	x	6	35.0
Other[3]		1	6.0

1 Other than Caltrans

2 Some DOTs reported adopting more than one criterion

3 Follow manufacturer's instruction

3.6 CONCLUSIONS

Several types of surface penetrating sealers and gravity-fill crack sealers have been applied successfully on concrete bridge decks. Based on their performance, silanes and siloxanes are considered the most popular penetrating sealers. In the gravity-fill group, HMWM and low viscosity epoxy are used favorably. HMWM can be used successfully to seal cracks wider than 1.0 mm (0.04 in.). However, results from the nationwide survey revealed HMWM is applied to cracks narrower than 1.6 mm (0.0625 in). For cracks narrower than 1.0 mm (0.04 in.) HMWM can be used following an application of Silane. A wide range of application temperature was reported in the literature. However, a range of application temperature between 7^{o}C (45^{o}F) and 29^{o}C (85^{o}F) is recommended. For new decks, it is recommended that HMWM be applied 3-6 months after construction to make sure that chloride concentration did not reach the corrosion threshold value. For old decks, careful attention should be paid to the preparation method and the cleanliness of both deck surface and cracks. It is recommended that HMWM sealer (when used as a surface penetrating sealer) be applied every 4-5 years or as recommended by the bridge inspection team. For areas not subjected to deicing chemicals/chloride-laden environments, the use of HMWM as crack sealers can effectively restore the structural bond strength and the flexural strength but only if cracks are contaminants free. The compatibility of silane with HMWM was cited in the literature.

CHAPTER 4

BRIDGE DECK SERVICE LIFE

4.1 INTRODUCTION

Bridge deck service life is based on the concrete deterioration and the corrosion of reinforcing bars. The latter is controlled by the penetration of chlorides through the concrete cover. Deicing salts and seawater are the main source for the chloride concentration on the concrete bridge decks.

A number of Service Life Models to predict the service life for concrete exposed to chloride environment have been recently developed. The objective of developing these models is to simplify the complexity of the chlorides diffusion process in concrete members with and without different corrosion protection strategies. The approaches adopted by these models vary considerably, therefore, significant variance in the results of the service life models is expected. The inconsistency in the estimated service life triggered researchers to develop a standard service life model for concrete members.

4.2 LIFE-365 MODEL

The National Institute of Standards and Technology (NIST), The American Concrete Institute (ACI), and the American Society for Testing and Materials (ASTM) recognized the need to develop a “standard” model to predict service life. The first phase of the standard model has been developed under the jurisdiction of the ACI Committee 365 “Service Life Prediction.” The model has some limitations since a number of assumptions and simplifications have been made to overcome such a complex phenomena or areas where there is insufficient knowledge to permit a more thorough analysis.

The following sections include description, assumptions, parameters, and limitations of the 365-Model.

4.2.1 Prediction of the Initiation Period

The initiation period, t_i, is the time taken by the chlorides to penetrate the concrete cover and accumulate in sufficient quantity (threshold concentration, C_t) at the depth of the embedded steel to initiate corrosion. The initiation period is based on the concrete quality, the cover thickness, and the exposure conditions including the level of chloride at the surface and the temperature of the environment. To simplify the process, the ionic diffusion is assumed to be the only mechanism of chloride transport. Also, the concrete is assumed to be completely saturated in chlorides (Boddy et al., 1999).

The governing differential equation is as follows (Fick’s second law):

$$\frac{dC}{dt} = D \cdot \frac{d^2C}{dx^2} \qquad \text{……………………………………} \quad \text{Equation 4.1}$$

where: C = chloride content

D = apparent diffusion coefficient

x = depth (from the exposed surface)

t = time

The model adopts the following relationship to account for time-dependent changes in diffusion:

$$D(t) = D_{ref} \cdot \left(\frac{t_{ref}}{t} \right)^m \qquad \text{…………………………………….. Equation 4.2}$$

where: $D(t)$ = diffusion coefficient at time t

D_{ref} = diffusion coefficient at reference time (28days)

m = constant (depending on mix proportions)

The model considers values of D_{ref} and m based on the mix design (i.e., water-cement ratio, the material type and proportions). The equation is set for up to 30 years and therefore, the diffusion coefficient is assumed to be constant after time, t, equals to 30 years. The following relationship is used to account for temperature-dependent changes in diffusion:

$$D(T) = D_{ref} \cdot \exp\left[\frac{U}{R} \cdot \left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right] \quad \text{……………………..Equation 4.3}$$

where:

$D(T)$ = diffusion coefficient at time t and temperature T

D_{ref} = diffusion coefficient at some reference time t_{ref}

U = activation energy of the diffusion (35000 J/mol)

R = gas constant

T = absolute temperature

In the model t_{ref} = 28 days and T_{ref} = 293K (20°C). The temperature T of the concrete varies with time according to the geographic location. The chloride exposure condition which is the rate of chloride build up at the surface and maximum chloride content, are based on the type of structure (e.g., bridge deck, parking structure), the type of exposure (e.g., marine or deicing salts), and the geographic location. The solution is performed using a finite difference implementation of Fick's second law where the value of D is modified at every time step using Equations 4.2 and 4.3.

4.2.2 Model Parameters

The following parameters are considered to estimate the initiation period:

1- Geographic location.

2- Type of structure and nature of exposure; one-dimensional (e.g., marine pile) or two-dimensional (e.g., parking or bridge deck).

3- Thickness of clear concrete cover to the reinforcing steel (x_d).

4- Details of protection method such as water-cement ratio, type and quantity of mineral admixtures or corrosion inhibitors, type of steel, and presence of membranes or sealers.

4.2.2.1 Effect of Silica Fume

Adding the silica fume reduces significantly the permeability and the diffusivity of concrete. The model reduces the value calculated for Portland cement, D_{PC}, based on the level of silica fume (*%SF*) in the concrete. The following equation is adopted:

$$D_{SF} = D_{PC} \cdot e^{-0.165 \cdot SF} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{Equation 4.4}$$

The relationship is only valid up to replacement levels of 15% silica fume. The model does not consider diffusion values for higher levels of silica fume.

4.2.2.2 Effect of Membranes or Sealers

Membranes and sealers are assumed to only impact the rate of chloride build-up. Membranes start with an efficiency of 100%. The efficiency deteriorates over the membrane lifetime, which is assumed to be 20 years. Consequently, the rate of build-up starts at zero and increases linearly to the same rate as that for unprotected concrete at 20 years. The efficiency of sealers is assumed to be 90% with a lifetime of seven years.

4.2.3 Prediction of the Propagation Period

The propagation period, t_p, is the time for corrosion to reach an unacceptable level. The propagation period is assumed to be at 6 years (Weyers, 1998; Weyers et al., 1993). The time to first repair, t_r, is the sum of the initiation and propagation periods: i.e. $t_r = t_i + t_p$.

The only protection strategy that influences the duration of the propagation period is the use of different steels such as epoxy-coated steel, stainless steel, or MMFX Steel.

4.2.4 Case Studies

The study parameters in these case studies include: the concrete deck thickness, concrete cover thickness, water-cement ratio, fly ash percentage, type and percentage of the deck reinforcing steel, bridge location, type of exposure, and protection technique. Table 4.1 presents the study parameters and the values used in the analyses.

Table 17. Case study parameters

Parameter	**Symbol**	**Values**
Water-cement ratio (Ratio)	w/c	0.4 and 0.5
Bridge location Exposure type		San Diego and Sacramento, California
Protection technique		None, sealer and membrane

The slab thickness, h_s, was considered as 8 inches, while the concrete cover, C_{CLR}, was assumed as 2 inches. The amount of the fly ash was assumed to be 15%. This value was considered since it represents the minimum typical used fly ash in concrete mixtures. Black steel is considered for all study cases, as epoxy coated steel, stainless steel, and MMFX steel impact the propagation period and not the initiation period. The reinforcement ratio was assumed 1%. This value represents an upper limit for reinforcement ratios in bridge concrete decks. Sealers and membrane characteristics are presented in Section *4.2.2.2*. Table 4.2 includes details of the case studies.

4.2.5 Case Study Results

Figures 4.1 through 4.6 show the initiation period and chloride concentration for the cases. The average initiation period for concrete bridge decks located in Sacramento is nearly two and half times that of San Diego concrete bridge decks, while the average initiation period of Fresno bridge decks was nearly 3 times that of San Diego concrete bridge decks. Note that the chloride exposure in the San Diego area is much more sever compared to that in both Sacramento and Fresno.

Increasing the water-cement ratio from 0.4 to 0.5 resulted in reducing the initiation period by an average of 15%. Adding the sealer to concrete bridge decks increased the initiation period by nearly 8%, while adding membrane resulted in an increase with an average of 32%.

The effect of applying concrete deck protection on the initiation period is based on the bridge location and exposure type. Table 4.3 presents the expected extension in the initiation period for concrete bridge decks based on the protection method used for three different locations in the state of California. The extension percentage helps in making decisions on the use of the protection technique based on the exposure. The results show that the effect of sealers added to concrete bridge decks in Fresno was negligible due to the low chloride content, while it was significant in San Diego because of the higher chloride content. However, the effect of using sealers (for example, HMWM) on structural bond at crack surface needs to be investigated.

Table 4.18. Details of the case studies

Case	*w/c*	*Location*	*Protection*
C-1	0.4	San Diego	None
C-2	0.4	San Diego	Sealer
C-3	0.4	San Diego	Membrane
C-4	0.5	San Diego	None
C-5	0.5	San Diego	Sealer
C-6	0.5	San Diego	Membrane
C-7	0.4	Sacramento	None
C-8	0.4	Sacramento	Sealer
C-9	0.4	Sacramento	Membrane
C-10	0.5	Sacramento	None
C-11	0.5	Sacramento	Sealer
C-12	0.5	Sacramento	Membrane
C-13	0.4	Fresno	None
C-14	0.4	Fresno	Sealer
C-15	0.4	Fresno	Membrane
C-16	0.5	Fresno	None
C-17	0.5	Fresno	Sealer
C-18	0.5	Fresno	Membrane

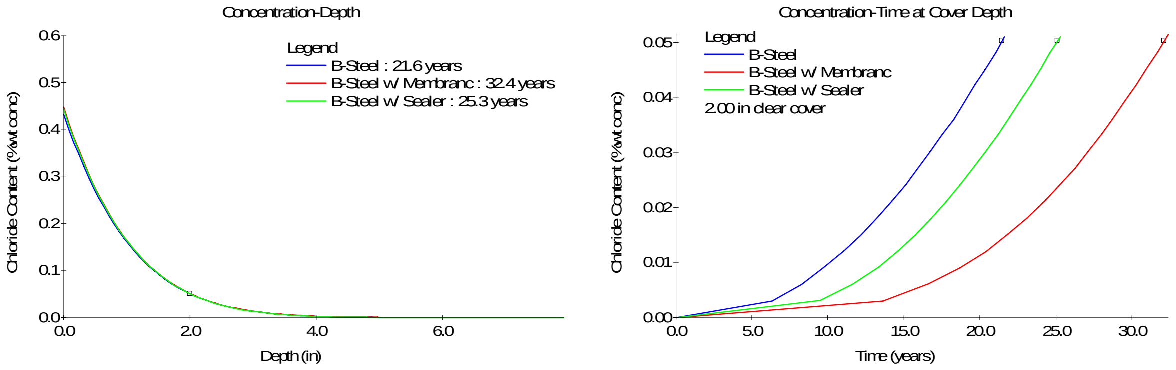

Figure 3. Initiation period and chloride concentration for cases “C1 to C3”

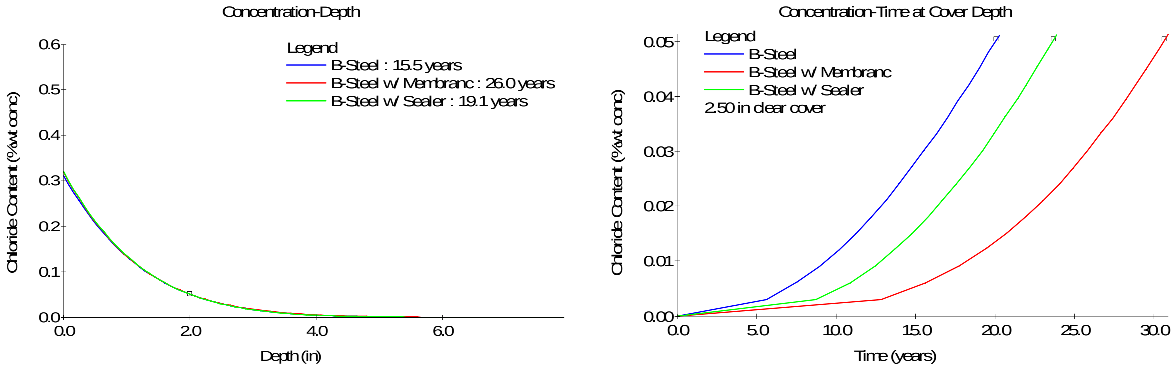

Figure 4. Initiation period and chloride concentration for cases “C4 to C6”

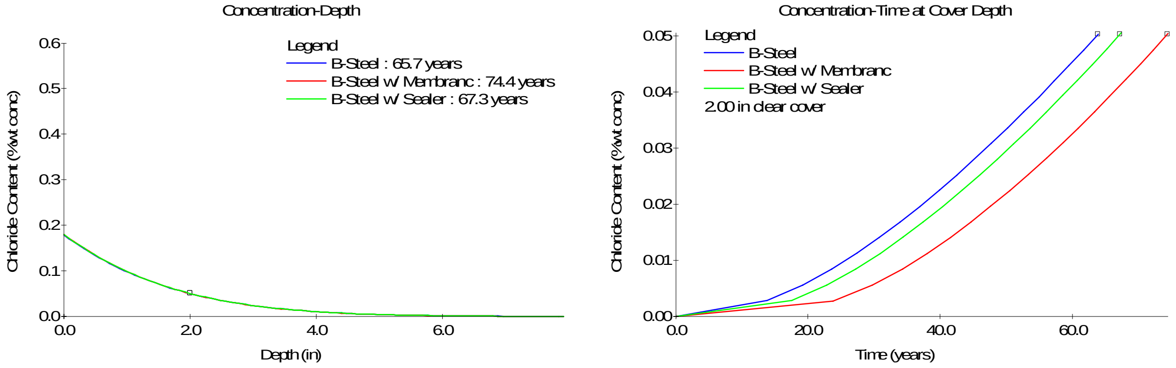

Figure 5. Initiation period and chloride concentration for cases “C7 to C9”

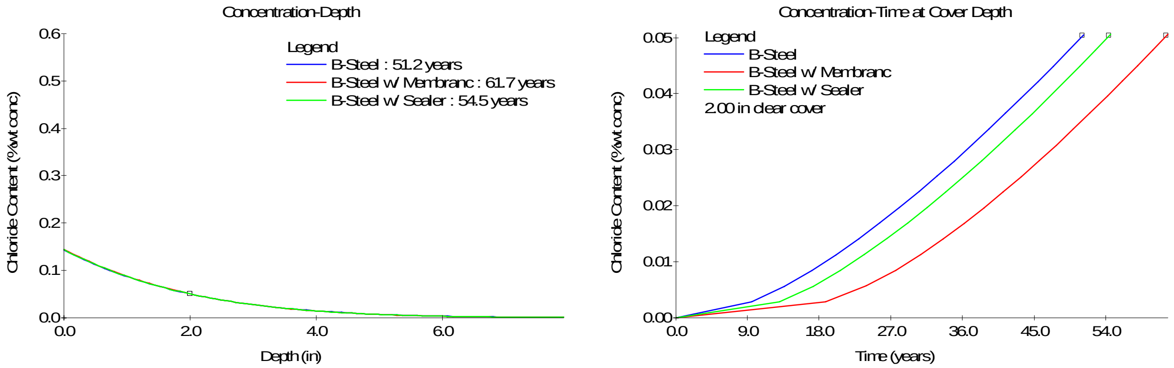

Figure 6. Initiation period and chloride concentration for cases “C10 to C12”

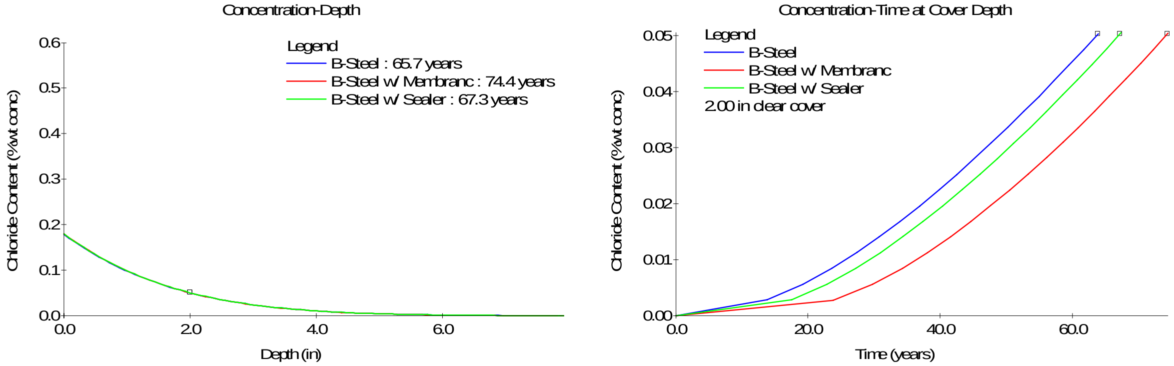

Figure 7. Initiation period and chloride concentration for cases “C13 to C15”

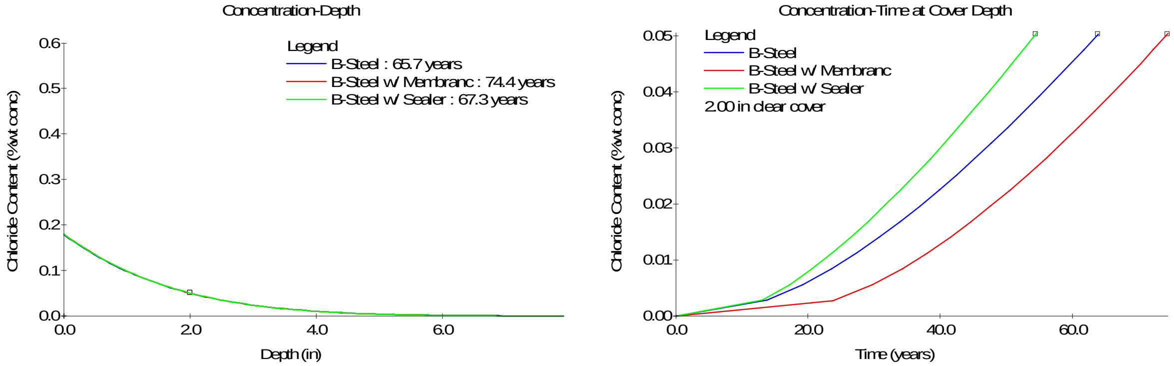

Figure 8. Initiation period and chloride concentration for cases “C16 to C18”

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 INTRODUCTION

Concrete bridge deck cracking is considered the most common type of deck distress observed throughout the U.S., including California. The presence of these cracks in concrete bridge decks often leads to eventual structural deficiency because these cracks permit the ingress of harmful substances into the decks. The current research included: a thorough review of previous research regarding the effectiveness of concrete bridge deck sealers, a nationwide survey investigating the effectiveness of using Methacrylate as a sealer, and development guidelines concerning the use of HMWM along with other potential successful sealers. The following are the main outcomes of this research.

5.2 CONCLUSIONS

1- For new decks, it is recommended that HMWM be applied 3-6 months after construction (while cracks are not badly contaminated). This will also ensure that chloride concentration does not reach the corrosion threshold value.

2- For old decks, careful attention should be paid to the preparation method and to the cleanness of both deck surface and cracks.

3- A range of application temperature between 7°C (45°F) and 29°C (85°F) is recommended.

4- HMWM is recommended to be applied every 4-5 years or as recommended by the bridge inspection team.

5- For decks not subjected to deicing chemicals or chloride-laden environments, the use of HMWM as crack sealers can help restore the structural bond strength and the flexural strength only if cracks are narrow and contaminants free.

6- Results from the nationwide survey revealed HMWM alone is applied to cracks narrower than 1.6 mm (0.0625 in).

7- Based on a parametric study employing Life-365 Model, the use of sealant to extend corrosion initiation period of reinforcement steel in decks not located in chloride-laden environment or subject to deicing chemicals is not significantly effective.

5.3 RECOMMENDATIONS

1- Due to the significant variation in the data collected from literature and a nationwide survey, further research is recommended to investigate the effectiveness of using HMWM in sealing decks with wide cracks (up to 5 mm) in benign areas.

2- The use of other sealers that were deemed successful (for example, silane) based on the literature review can be investigated.

3- The compatibility of silane sealers with HMWM and the order of application need to be investigated through a laboratory/field application considering California materials/climatic conditions. Would crack width be a factor in governing the compatibility needs to be investigated as well.

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ATTACHMENT A

Name: ____

Agency: ____

Division: ____ **Tel:** ________________

Please complete this survey form to the best of your knowledge. The information submitted in this form will be used in a research study. The identity of submitting agency will remain confidential.

1. Does your agency require epoxy-coated rebar in its bridge deck design specifications?

- ☐ Yes
- ☐ No

2. What deicing technology does your agency use? (Check all that are used)

- ☐ NaCl
- ☐ CaCl
- ☐ MgCl
- ☐ Other: ______________________________

3. Which crack pattern does your bridge decks experience? (Check all that apply)

- ☐ Transverse
- ☐ Random
- ☐ Other: ______________________________

4. Rank the following criteria in order of importance with regards to your decision whether to seal bridge decks (Rank 1-6 with 1 being highest or most important) :

____Width of bridge ____Traffic load

____Type of crack ____Cost

____Importance of bridge ____Other (specify): ______________________

5. Which bridge deck sealant does your agency apply? (check all that are used)

- ☐ Methacrylate
- ☐ Epoxy
- ☐ Polyesters
- ☐ Others: ________________________________

6. If your agency uses Methacrylate, what applications is it used for? (check all that apply)

- ☐ Surface sealer
- ☐ Crack sealer

7. If your agency uses Methacrylate for sealing bridge decks, how early is it applied?

- ☐ Right after construction
- ☐ After cracks are initiated
- ☐ Other: __________________________________

8. If your agency uses Methacrylate for sealing bridge decks, what surface preparation methods are used?

- ☐ Bower broom
- ☐ Forced air
- ☐ Pressurized water
- ☐ Other: _________________________

9. What range of crack widths do you use Methacrylate for crack repair?

- ☐ 0-1/16”
- ☐ 1/16”-1/8”
- ☐ Other (please specify):____________________________

10. What is the approximate total unit cost of applied sealant?

Methacrylate _________
Epoxy _______________
Polyesters ____________
Other sealants (specify) ____

11. If your agency uses Methacrylate, what is the expected lifespan of the bridge deck if sealant is **not** applied: ______ Years

12. If your agency uses Methacrylate, the expected added life if sealant is used: ______ Years

13. If your agency uses Methacrylate, please give some examples of bridge type/location:

Please, fill in the following table with the appropriate Cods selected from the following tables.

Example #	**1**	**2**	**3**	**4**
Bridge Construction Type*				
Exposure Type #				
Type of Reinforcing Bars ☐				
Bridge Location				
Concrete Slab Thickness				
Deicing Technology Used				

Please select the appropriate Code

*** Bridge Construction Type**		**# Exposure Type**		**☐ Type of Reinforcing Bar**	
Code	Type	Code	Type	Code	Type
1	Steel Girder	1	Marine splash zone[1]	1	Conventional
2	Pre-stressed Beam	2	Marine spray zone[2]	2	Epoxy Coated
3	Reinforced Concrete Box Girder	3	Within 1 mi. of the ocean	3	MMFX or Stainless
4	Others. (Please specify)	4	Others. (Please specify)	4	Others. (Please specify)

1. Marine splash zone (Defined as being in the tidal range or within 1 m of the high-tide level)

2. Marine spray zone (Defined as being more than 1 m above the tidal range but occasionally exposed to salt water spray)