Improving Bridge Concrete Overlay Performance

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16. Abstract
Concrete overlays are commonly used on bridge decks to extend the service life of the deck when signs of distress become evident. The concrete overlay approach restores the riding surface of the deck, provides a protective physical barrier, and delays the time required for a more drastic and costly bridge deck replacement. The concrete mix design and placement procedures for these low-slump concrete overlay systems have remained essentially unchanged over several decades. Despite its long history of satisfactory performance, extensive cracking of the overlays has been noted in recent years in several states including Wisconsin. The overall objective of this study was to evaluate, identify, and mitigate the cause(s) of cracking in low-slump concrete overlays for bridge decks. An experimental research program was initiated to study the causes of cracking in concrete overlays. Several changes are suggested including reduction of cement content by 15%, addition of PVA fibers, increasing the specified water-cement ratio to 0.38 (from the current 0.324), better curing procedures, and relaxing the slump requirements (from <2 in to < 4 in).

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EXECUTIVE SUMMARY

Long-term exposure to deicing salts and reinforcing bar corrosion can lead to significant distress in bridge deck slabs (end of service life) after roughly 40 to 60 years of service. Concrete overlays are commonly used on bridge decks to extend the service life of the deck when signs of distress become evident. The concrete overlay approach restores the riding surface of the deck, provides a protective physical barrier, and delays the time required for a more drastic and costly bridge deck replacement. Low-slump concrete overlays have long been used in many states, especially in the midwestern United States. The concrete mix design and placement procedures for these low-slump concrete overlay systems have remained essentially unchanged over several decades. Despite its long history of satisfactory performance, extensive cracking of the overlays has been noted in recent years in several states including Wisconsin.

The overall objective of this study was to evaluate, identify, and mitigate the cause(s) of cracking in low-slump concrete overlays for bridge decks. An important goal was to develop a recommended course of action that could substantially reduce or eliminate the incidences of cracking, while restoring the historically high-performing low-slump concrete overlays. In addition, this study reviewed experiences and best practices of other states' concrete overlays.

A survey of individuals with knowledge of concrete overlay systems in several states was initially performed. Then, an experimental research program was initiated to study the causes of cracking in concrete overlays. These included calorimetry tests to evaluate heat of hydration, ring tests to assess restrained shrinkage, field slab tests to evaluate cracking potential under realistic environmental conditions, salt ponding tests to evaluate chloride penetration, and dog bone restraint tests (a new test) to assess the effect of various curing procedures on cracking potential in concrete. Seven different mix designs (variants of the current WisDOT Grade E mix) were tested. These included a reduction in cement content, the addition of Polyvinyl Alcohol (PVA) fibers, partial replacement of cement with fly ash, latex modified concrete. Ordinary portland cement (Type I) and Type IL (limestone cement) were tested.

Wisconsin's Grade E overlay mix had been successfully utilized over several decades without early age cracking. However, its performance has declined in recent years due to extensive cracking typically observed within the first year following placement. What has changed over the years primarily relates to the fineness of portland cement particles, which has increased substantially over the years (Bentz et al. 2008), to meet the competitive need of manufacturers to claim higher strength concrete at earlier ages.

Based on this research, several recommendations are made that address changes to the mix design (including reduction of cement content and addition of PVA fibers) as well as improvement in curing practices. The current Wisconsin Grade E mixture is susceptible to cracking and should be modified.

The primary objective of a deck overlay system is to extend the service life of the bridge deck. The overlay cannot do that if the substrate (bridge deck) is highly contaminated with chlorides, and the reinforcing bars are corroding. Therefore, it is important to place the concrete overlay when the deck slab has not deteriorated significantly (i.e., not needing partial- or full-depth patch repairs). The Minnesota DOT has used an NBI deck rating of 6 as a benchmark for planning and installation of a concrete overlay. It is suggested that the same approach be adopted for Wisconsin bridge decks.

Test results have demonstrated the positive effect of reducing the cement content or partial replacement of cement with fly ash. A cement reduction of 15-20% is recommended. Alternatively, a 15-20% replacement of cement with fly ash can be considered. Iowa allows the incorporation of up to 20% fly ash in the concrete overlay mix. However, recent severe shortages of fly ash in the Wisconsin market, lack of bins to accommodate fly ash in existing mobile mixers, and the long-term trends in reducing coal-based power generation require alternate solutions. The reduction of Grade E cement content by 15-20% is therefore recommended. For the current Grade E cement content of 823 lbs./cy, a 15% reduction would result in a cement content of 700 lbs./cy.

Our tests indicate improved performance when PVA fibers are added to the overlay mix. Considering that the incorporation of PVA fibers introduces additional mix elements, procedures, and costs, it is recommended that PVA fiber be added when a higher performance level (longer service life of overlay) is required. Therefore, it is proposed that two Grade E mixes (E1 and E2) be considered. Both grades would include a 15% cement reduction. However, Grade E1 would not incorporate the PVA fiber while Grade E2 would include PVA fiber (1.5 lbs/cy) as well as enhanced curing procedures (described in Section 7.2.3).

The Grade E mix has traditionally incorporated a relatively low water-cement ratio of 0.324 in Wisconsin and several other states. While lower water-to-cement ratios are important in achieving higher strength and lower permeability of concrete, they can also increase autogenous shrinkage and increase the stiffness of concrete, especially at early ages. The current water-to-cement ratio (w/c) has been in effect for decades. However, it is important to note that today's portland cement is much finer than the cement used in 1970s. This would result in substantially higher hydration-induced temperature and stiffness at early ages. The problem of cracking of overlays is primarily related to the restraint of inelastic compressive strains due to shrinkage and thermal effects. The restraint stresses are tensile and can crack the overlay. The restraint stress is equal to the restraint strain times the modulus of elasticity. Higher concrete stiffness (modulus of elasticity) of the concrete overlay at early ages (due to low w/c ratio) results in higher tensile restraint stresses for a given restraint strain. It is therefore suggested that the water-to-cementitious material ratio for Grade E mixes (E1 and E2) be increased to 0.38 from 0.324. Our tests indicated that such a water-to-cement ratio would still provide a substantial compressive strength of 7800 psi at 28 days.

The concrete overlay systems discussed in this research have long been known as “low slump”. Many overlay mix designs (including Wisconsin Grade E mix) have limited the slump to less than 2 in. However, while the rationale for this requirement may be understandable (especially in decades past), the justification for its continued use in modern times is lacking. The availability of modern chemical admixtures makes it possible to achieve the goals of low-slump concrete without the significant workability and construction issues associated with low slump mixes. Therefore, it is proposed that the slump requirement for the Grade E (E1 and E2) be changed to less than 4 in. This could also potentially help with the limited availability of specialized double vibratory screed systems needed for low-slump mixes.

Proper curing procedures for concrete overlays are of utmost importance for reducing the cracking potential. The current WisDOT provisions require 3 days of curing. WisDOT procedures (Section 502.3.8) provide a few curing options including impervious coating, impervious sheathing, continuous wet cure, or alternative methods approved by the engineer. Several other states have higher duration curing requirements including 7 and 14 days of curing with wet burlap. The curing tests performed using the dog bone specimens in this research clearly show the benefits of at least 7 days of pre-soaked wet burlap covered with a polyethylene sheathing. Fourteen days is better than 7 days but may not be practical in all situations. Tests indicate that burlap curing causes expansive strains in the concrete, which would mitigate the subsequent shrinkage after the curing has stopped. Coverage with plastic sheathing alone is found to be ineffective as leaks invariably reduce humidity at the surface and the shrinkage would start even prior to removal of the cover. It is therefore suggested that Grade E1 overlays receive a minimum of 7 days of curing with a polyethylene coated pre-wetted burlap cover. The Grade E2 overlays should utilize a minimum of 14 days of curing using the same coated burlap procedure.

The placement of concrete overlay requires ensuring that the substrate is solid and not deteriorating. Therefore, sounding techniques are commonly used to identify deteriorating areas to be removed before the placement of overlays. It is suggested that all full- and partial-depth patch repairs be performed before placing the overlay. WisDOT currently performs full-depth deck repairs in advance of overlay placement while partial-depth patches are placed at the same time as the overlay. Although not tested in this research, it is anticipated that simultaneous casting of the patch areas and the overlay may increase restraint stresses due to apparent “shear key” effect. Therefore, partial-depth patches should also be performed in advance in the same way the full-depth repairs are done.

A crack-free concrete overlay offers a substantial thickness of additional protective cover (against chloride diffusion) unless this protection system is short-circuited with cracks. It is recommended that low-viscosity crack sealers be applied on the overlay surface beginning one year after the overlay placement and repeated as needed.

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INTRODUCTION

1.1 Background

Long-term exposure to deicing salts and reinforcing bar corrosion can lead to significant distress in deck slabs after roughly 40 to 60 years of service. Concrete overlays are commonly used on bridge decks to extend the service life of the deck when signs of distress become evident. The concrete overlay approach restores the riding surface of the deck, provides a protective physical barrier, and delays the time required for a more drastic and costly bridge deck replacement. The low-slump concrete overlays have long been used in many states [1], especially in the Midwest. For example, over approximately four decades [2], Minnesota has been using a low-slump concrete overlay mix, which is very similar to Wisconsin's Grade E mix. They have been applying the overlay [3] when the deck rating of 6 is reached to delay the arrival of the rating of 5. This practice has successfully extended the service life of the bridge deck and postponed the more costly but eventual deck replacement. Even though the concrete mix design and placement procedures have not changed over these decades, extensive cracking of the overlays has been noted in recent years [2] [4]. The problems observed are not unique to Wisconsin and extend across state boundaries in the Midwest region and beyond.

Low-slump concrete (LSC) overlays have long been used in many US states, especially Midwestern states. For example, since 1974, the Minnesota DOT (MnDOT) has placed LSC overlays on approximately 2,025 Bridges [2]. When the NBI deck rating reaches 6, the recommended approach in Minnesota has been to place concrete overlays. This approach has successfully extended the service life of bridge decks [3]. The mix design for LSC overlays has not changed significantly in the last 30 years [4], while cracks have been observed on some overlays in recent years [2]. This type of cracking has also been widely noted in Wisconsin, which has an LSC mix that is similar to the MnDOT mix. The phenomenon of increasing early cracks has been observed across a broad region.

As part of this study, a comprehensive online survey of bridge deck concrete overlay performance was performed. Twenty-four responses from eleven states (Wisconsin, South Dakota, Oklahoma, North Dakota, North Carolina, Nebraska, Minnesota, Michigan, Kansas, Iowa, and Illinois) were received. Results of this survey are presented and discussed in Section 3.0 and Appendix A.

1.2 Research Objectives

The overall objective of this study was to evaluate, identify, and mitigate the causes of cracking in low-slump concrete overlays for bridge decks. An important goal was to develop a recommended course of action that could substantially reduce or eliminate the incidences of cracking, while restoring the historically high-performing low-slump concrete overlays. In addition, this study reviewed experiences and best practices of other states' concrete overlays and conducted laboratory studies to evaluate and determine the appropriate concrete overlay systems for Wisconsin. Specific objectives of this project were to:

A. Evaluate WisDOT's current low-slump concrete overlay specifications, including method of application and cure, specifically addressing if any technique other than current specification requirements should be considered. Recommend changes to the WisDOT Bridge Manual and Standard Specifications.
B. Provide guidance for maintaining low-slump concrete overlays, such as silane sealers, epoxy crack-fill, methacrylate flood coats and thin-polymer overlays. Recommend changes to the WisDOT Bridge Manual and Standard Specifications updates.
C. Investigate alternative overlay types such as latex modified, silica fume, pozzolans, fly ash modified and synthetic fiber infused concrete, including method of application and cure. Recommend changes to the WisDOT Bridge Manual and Standard Specifications.

1.3 Research Scope

This research was conducted within the scope of the following seven tasks.

- Task 1: Literature Review
- Task 2: Contact Other Agencies for Information
- Task 3: Establishing Contacts with WisDOT and Site Visits
- Task 4: Evaluation of Maintenance/Protection Practices for Overlays
- Task 5: Laboratory Experiments
- Task 6: Develop Recommendations and Guidelines
- Task 7: Final Report

2 REVIEW OF LITERATURE

2.1 Low slump overlay Slab

Concrete overlays can extend the service life of existing concrete pavements and bridges. However, several factors can lead to their premature deterioration. Important considerations relate to mix design, placement practices, and curing procedures. To develop recommendations for changes to the Wisconsin specifications for concrete overlays, a literature review was first conducted. The literature review can help with understanding the current concrete overlay mix design and practices and the early cracking issues that are experienced in recent years.

a) Low-slump concrete overlay: Utilizing low-slump concrete overlays is a long-standing method for addressing bridge deck deterioration [1], which can provide benefits such as improving ride quality, reducing service interruption, extending service life, and improving public safety. The low-slump dense concrete (LSDC or LSC) overlay has historically been tremendously successful in the protection of bridge decks [1] [2] [5]. The LSDC overlay has had advantages over other overlay types with its decades of proven performance, relatively simple mixing and placement procedures, and a reasonable cost per square foot [2]. It is believed that the original mix was developed in the late 1960s [1] and later adopted by many states, including Wisconsin. Wisconsin uses low slump overlays to rehabilitate bridge decks, protect the deck from further chloride infiltration, and provide an improved riding surface. Table 1 shows data on LSDC mix designs currently used in several states. Most states listed use very similar cement content and water-to-cement ratios. However, Iowa allows up to 20% cement replacement with fly ash. Adding fly ash would slow down strength gain and reduce the initial heat of hydration. None of the states using LSDC (in the currently available dataset) use slag, silica fume, or fibers in the mix.

Table 1 LSDC overlay in different states.

State	Cement content (lb./yard^3)	w/c ratio	Supplementary cementitious material (lb./yard^3)			Fiber
			Fly ash	Slag	Silica Fume	
Wisconsin	823	0.324	-	-	-	-
Minnesota	836	0.323	-	-	-	-
Iowa	736	0.330	Up to 20% fly ash replacement permitted	-	-	-
North Dakota	823	0.324	-	-	-	-
South Dakota	823	0.324	-	-	-	-

The low-slump concrete overlay mix designs have suffered cracking issues in recent years. Minnesota has recently reported that newly cast LSDC overlays often exhibit high levels of early-age cracking (e.g., transverse cracking, map cracking, or alligator cracking) [2] [4]. Wisconsin has also reported similar overlay cracks. A preliminary review [1–19] indicated that other states, including north central states and national concrete consortium states, have reported similar observations. As a result, some states, such as Washington and Indiana [19], do not recommend using the LSDC overlay mix due to its perceived poor performance, while other states hesitate to reuse it because of the potential for cracks.

Although some reports [1], [5–9], [19] have attempted to correlate such cracks with shrinkage, curing conditions, high elastic modulus, or traffic-induced fatigue, these factors may not fully explain the underlying root cause(s) of poor performance for this otherwise long-proven overlay system. For instance, Minnesota Department of Transportation (MnDOT) [4] has reported that multiple trials of the LSDC overlays with different curing methods, including superior curing and ideal conditions, still exhibited cracking within a year, even though adequate curing is considered a crucial factor in reduced cracking. Considering that the general formulation of these LSDC overlays has remained unchanged over decades, it is suspected that individual materials that make up the mixture (principally the Portland cement) have evolved over the years resulting in a different performance when compared with earlier mix compositions.

In this regard, one potential cause of excessive cracks experienced in the LSDC mix design could result from a commercial demand for higher early-age strengths and fast-track construction by much of the construction industry [10]. This has led to the production of much finer cement and higher alkali clinker mineralogical composition over the past 50 years, and this trend is continuing [10–13]. Blaine fineness values for Type I Portland cement reached an average of 410 m^2/kg by 2020, compared to an average of roughly 340 m^2/kg in 1970. Considering that the LSDC mix design has not been significantly modified in the last 40 years, the change in the fineness of cement over the same period could lead to significant changes in early-age performance [10–14] (e.g., significantly increased heat release during cement hydration, increased apparent shrinkage, and development of residual/restraint tensile stresses that can cause early-age cracking). For instance, Bentz et al. [10] investigated two Type I Portland cements with different Blaine fineness numbers (311 and 380 m^2/kg). As illustrated in Figure 1, the finer cement (fineness of 380 m^2/kg) generated a higher peak temperature and a much higher heat release than the coarser cement. Figure 2 confirmed that the residual tensile stresses developed in the finer cement eventually led to early-age cracking. As the concrete initially sets at elevated temperatures, an apparent “shrinkage” develops due to thermal cooling strains. As shown in Table 1, the overlay concrete mixtures used in various states typically contain relatively high cement content (over 800 lb./cy). Therefore, high cement content coupled with progressively increasing cement fineness over the years could inevitably lead to more frequent early-age cracking in the field. The effect of cement fineness on the heat of hydration has been previously researched. However, its effect on cracking potential in concrete overlays should be established through testing. This may be an important factor in restoring the high-performance capabilities and competitive advantage of low slump concrete overlays by restoring its primary role in bridge preservation and service life extension of existing bridges.

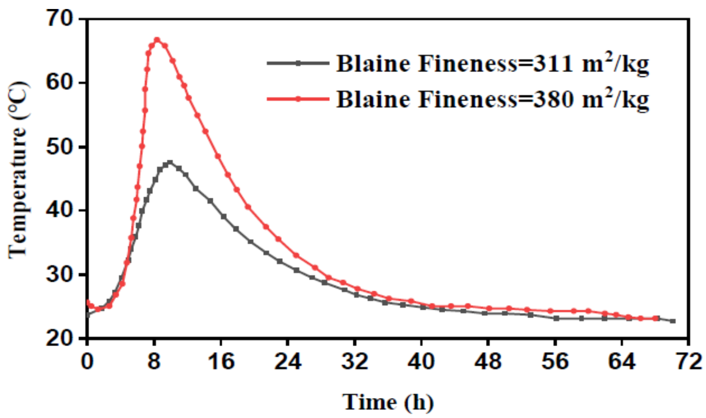


Figure 1. Semi-adiabatic temperature rise for two types of cement paste (adapted from Bentz et al., 2008 [10])

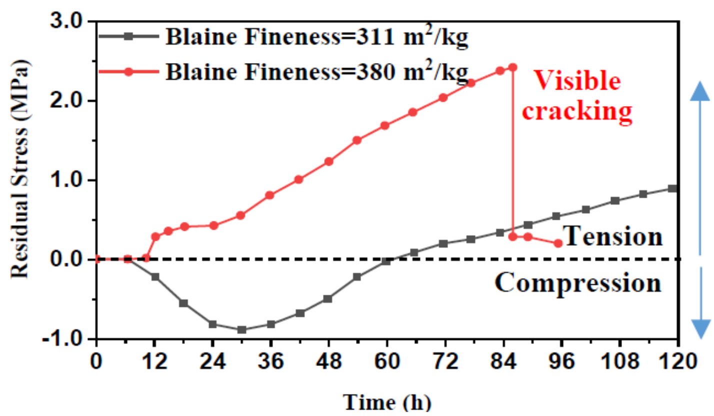


Figure 2 Residual stress development of two cement pastes (adapted from Bentz et al., 2008 [10])

b) Other bridge concrete overlays: Aside from the LSDC overlay, a variety of other concrete overlay types including Portland cement concrete (PCC), silica fume concrete (SFC), latex-modified concrete (LMC), very early strength latex-modified concrete (LMCVE)([1],[5]) and polymer concrete overlays (e.g., thin polymer concrete (TPC) [35] and premixed polymer concrete (PPC), have been developed and widely accepted in many states, as listed in Table 2. Different concrete overlays, as illustrated in Table 3, can exhibit varying service life benefits, costs, construction duration, curing, and maintenance requirements.

c) Incorporation of synthetic fiber and shrinkage reduction additives for bridge concrete overlays: Synthetic macro-fibers have also been used for fiber-reinforced concrete (FRC) bridge overlays to reduce cracking. FRC has been extensively studied in laboratory testing, and states such as South Dakota, Minnesota, and Georgia have implemented field trials since the 1990s [5], [20], [21]. Iowa conducted a study beginning in 1974 that included an FRC overlay on a bridge deck and concrete overlay [15], [20], [21]. Table 4 shows that some states have incorporated macro-fibers in the bridge concrete overlays.

Table 2 Various bridge concrete overlays used in state specifications [5]

State	Hydraulic cement concrete					Polymer concrete	
	LSDC	PCC	SFC	LMC	LMCVE	TPC	PPC
Wisconsin	X					X	X
Minnesota	X	X		X		X	X
Iowa	X		X				
Missouri	X		X	X	X	X	
North Dakota	X	X					
South Dakota	X			X			
Michigan			X	X			
Nebraska		X	X			X	
New York		X	X				
Ohio			X	X		X	
Virginia		X	X	X	X	X	
Illinois		X	X	X		X	
Indiana			X	X			X
Kansas		X				X	
California							X

Table 3 Comparison of concrete overlays [5].

Parameter		Hydraulic cement concrete					Polymer concrete	
		LSDC (35+ yrs.)	PCC (10-15 yrs.)	SFC (15+ yrs.)	LMC (10-20 yrs.)	LMCVE (10-20 yrs.)	TPC (7-15 yrs.)	PPC (15+ yrs.)
Proven Performance		√	√	√	√	x	√	√
Ride quality		√	√	√	√	√	√	√
Construction duration		x	x	x	x	√	√	√
Permeability		√	x	√	√	√	√	√
Added dead load		x	x	x	x	x	√	x
Inspection access to deck		√	√	√	√	√	x	x
Removal difficulty		√	√	√	√	√	√	√
Standard equipment		√	√	√	√	x	x	x
Sensitivity to ambient conditions	moisture	√	√	√	√	√	x	x
	Temperature	√	√	√	√	√	x	x

Notes: Symbol √ = favorable while **x** = unfavorable

Table 4 Bridge concrete overlays with macro-fibers in state specifications [21]

State	Year	Note
Delaware	2016	"For micro silica overlays: 1.5 lb./yd^3 fibers" (1046.02.2)
Idaho	2018	For silica fume concrete bridge deck overlays, fibers meeting ASTM C1116 with a minimum dosage rate of 1.5 lb./yd^3 (510.02(E))
Iowa	2018	For ultra-high performance concrete overlays: "Steel Fibers – ASTM A820, Type 1, Minimum steel fiber content will be 3.25% of the mix's dry volume."
Michigan	2012	For silica fume-modified concrete overlays: "Virgin polypropylene collated fibers at 2 lb./yd^3." (703.02D)
Missouri	2016	For bonded concrete overlays on asphalt (BCOA): "Fibrillated polypropylene fibers shall be added at a rate of 3.0 pounds per cubic yard." (506.10.2.1)

2.2 Service life of concrete overlays

From 1964 to 1978, the Iowa Department of Transportation overlaid 446 bridge decks with LSC, with generally satisfactory performance. Brown [39] studied the chloride content, electrical corrosion potential, delamination or debonding, and deck conditions of 19 LSC or latex modified concrete overlays (overlays were 5-13 years at the time of evaluation). It was reported that the overlays did not have signs of surface deterioration, and the chloride penetration was relatively low. The LSC overlay system had shown good performance, and its performance was equivalent to the latex-modified concrete system after six years of service [39].

Chamberlin [40] assessed 50 bridge decks covered with low-slump concrete overlay in the State of New York, with an average overlay age of 5 years. The average life of the LSC overlay built in New York was estimated to be 25 years, when about half of the deck surface was excavated beneath the reinforcement. When the entire surface were excavated, the service life would be estimated at 40 years. A study by Babaei and Hawkins [43] found that LSC and LMC overlays had a practical service life of 9-25 years based on a 10% deterioration area. Weyers et al. [42] conducted a study to estimate the service life of reinforced concrete bridge members exposed to chlorides. They developed a database of 308 overlays (156 LSCs and 152 LMCs) in 16 states and provincial agencies. The service lives of both LSC and LMCs were 15 to 25 years, with a 20-year average. Estimates of overlay service life were based on historical data related to 40% damage, defined as the cumulative percentage of deck area that was delaminated, spalled, or patched. For LMC and LSC bridge deck overlays, Chamberlin and Weyers [41] suggested that an average service life of 30 to 50 years was possible, when concrete removal standards were based on half-cell potential measurement (rather than observed damage), removal of chloride-contaminated concrete was extended below the rebar, and substrate sandblasting was used to remove concrete with microcracks before cleaning.

Hatami and Morcous [44] developed deterministic and stochastic deterioration models for bridge decks in Nebraska. Searching the 2009 National Bridge Inventory (NBI) database, 338 Bridges were found to have low-slump concrete overlays. Most bridge decks in Nebraska with LSC overlay had an average overlay life span of 15 to 30 years.

2.3 Cracking of LSC

Halverson Korfhage [45] described the restoration of the 42nd Street Bridge on I-35W in South Minneapolis, where a cathodic protection system was placed on the bridge deck, and a low-slump concrete overlay was used as the wearing surface. Tests indicated no delamination after the construction of the new overlay. After one harsh winter, some surface scalings were found without noticeable cracking.

Havens et al. [46] examined 119 experimental bridge deck overlays in 1987. There were 23 low-slump overlays, 87 latex concrete overlays, and nine membrane bridges. The low-slump overlays, constructed between 1975 and 1979, performed as well as the latex concrete overlays. Fourteen of the overlays received good ratings, and nine received excellent ratings.

Concerning the high incidence of cracking, especially plastic shrinkage cracking of LSC overlay, Chamberlin [40] recommended changing the New York state overlay specifications by 1) requiring that the free moisture content of sand and stone be less than 7 percent, 2) proposing a minimum slump of 0.5 inches. When the slab reconstruction concrete and the LSC overlay are placed separately, the maximum slump of LSC can be 4 in.; 3) not allowing additional superficial water in the finishing operation; 4) requiring a minimum density; 5) extending wet curing time to 96 hours; 6) Pre-wetting structural slab surfaces, but keeping the surface free of standing water before placing bonding grout; 7) Covering with wet burlap within 10 minutes.

The low-slump concrete overlay mix designs that were clearly successful in the past have suffered cracking issues in recent years. This perplexing phenomenon occurs even though there is no apparent change in the mix proportions or the process of mixing or placing the concrete overlays. It has recently been reported that newly cast LSC overlays often exhibit high levels of early-age cracking (e.g., transverse cracking, map cracking, or alligator cracking) ([2][4]). Wisconsin has also reported low slump overlay cracks. Some references (Sun 2004 [1], Ray et al. 2008 [17], Distlehorst 2009 [16], Balakumaran et al. 2017, Virginia Department of Transportation manual 2017, Hunsucker et al.2018 El Batanouny et al. 2020) indicated that other states, including north central states and national concrete consortium states, have reported similar observations.

In a study for the Pennsylvania DOT, Hopper et al. [37] studied causes and mitigation of early age cracking in bridge decks. Although their observations were related to decks and not overlays, their conclusions are relevant to this study on concrete overlays for bridge decks. Some of their recommendations that may also be applicable to overlays are shown below:

- Reduce total cementitious materials content.
- Prevent excessive compressive strength (e.g., >5000psi at 28 days). Excessively strong mixtures have high elastic modulus and low creep, and result in higher restraint shrinkage stresses and higher risk of cracking.
- Limit slump (e.g., to 4.0”) to minimize the risk of settlement cracking.
- Avoid too low or too high water-to cementitious material (w/cm) ratios. Too low w/cm is prone to high autogenous shrinkage, high heat of hydration and high stiffness. Too high w/cm can result in high drying shrinkage and high risk of plastic shrinkage cracking.
- Use proper cement types. Type III and other cements with high heat of hydration, fine particle size, and rapid hardening/stiffening result in higher risk of cracking.

- Use of supplementary cementitious materials (SCMs) such as fly ash and slag (but not silica fume) reduces cracking by reducing the heat of hydration and reducing concrete stiffness. SCMs increase the electrical resistivity of concrete, which is very beneficial in lowering the rate of rebar corrosion.
- Optimizing and blending aggregate gradations to minimize the cement paste content.
- Air content maintained per ASTM C94 in the range (6% - 8%)
- Proper and timely wet curing (i.e., starting no later than 15 minutes after finishing and lasting for 14 days - 7 days is widely recognized as minimum)
- Prevent excessive water evaporation from the surface of fresh concrete by using foggers.
- Avoid extreme ambient temperatures; concrete should not be placed at air temperatures below 45F (high risk of thermal cracking) or above 90F (high risk of plastic shrinkage cracking).
- Concrete temperature and girder temperature at deck placement should be maintained between 55 to 75F. Heat girders within 20F of deck and/or chill concrete to manage differential between deck and girders.
- Total cementitious materials (CM) content should be limited to 620 lbs/cy.
- Use SCM to reduce concrete resistivity and heat of hydration.
- Do not use silica fume in bridge decks.
- A max compressive strength limit is advised: 4000psi at 7 days or 5000 psi at 28 days.
- Discourage half-width construction of bridge decks, where possible.
- Consider use of shrinkage reducing admixtures (SRA) or fibers to reduce cracking and crack widths.
- Deck remediation (sealing, overlay, …) must be employed before significant salt penetration and start of active corrosion.

2.4 Fibers, Latex Modified Concrete, and Supplementary Cementitious Materials

Fibers have a generally positive effect on improving crack resistance and reducing drying shrinkage in bridge deck overlays. However, attention should be paid to ensuring a uniform distribution of fibers in the concrete mixture, ensuring the workability of concrete, and controlling the initial cost of the concrete overlay.

Latex-modified concrete has better adhesion to the substrate and improves aggregate adhesion (Joseph et al. 2017). LMC has been widely applied and studied for overlay applications. Several studies have been conducted on shrinkage deformation ([49][50]), compressive strength, bond strength, flexural strength, permeability, and freeze-thaw resistance of LMC overlays ([50] [51] [52] [53] [54] [55]).

LMC overlays have been used in Virginia for bridge rehabilitation since the mid-1970s [52]. With the introduction of fibers, the LMC overlay can achieve enhanced cracking and bending resistance. However, the above studies also found that the cost, joint treatment issues, timely curing, and environmental conditions during construction (such as humidity and air temperature) need special consideration.

Alhassan et al. [57] studied a potential overlay system consisting of fiber-reinforced fly ash concrete (using two types of synthetic fiber, polyolefin and polypropylene). Results showed that the properties of this overlay were comparable to those of fiber reinforced LMC overlays in terms of compressive strength, flexural strength, shrinkage, bond strength, and toughness. The fiber additive could significantly improve the overlay performance concerning crack reduction.

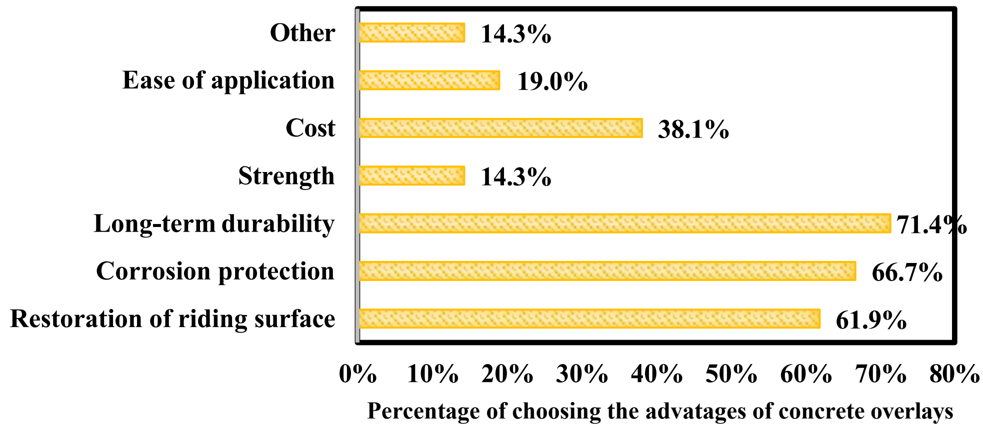
Sprinkel et al. [57] studied sixteen high-performance concrete overlays placed on two 28-span bridges on Rte.60 over Lynnhaven Inlet in Virginia Beach, Virginia. There were thirteen different concrete mixtures, including a high-performance concrete mixture with 5% silica fume and 35% slag (as % replacement of cement). It was found that high-performance concrete overlays with high bond strength and low permeability could be constructed with different mixtures of materials, including silica fume, fly ash, slag, latex, corrosion-inhibiting admixtures, shrinkage-reducing admixtures, and fibers.

In general, with the addition of fly ash, the strength of concrete would be lower at early ages, but the strength would catch up after 90 days. Fiber-reinforced fly ash concrete overlays have comparable compressive strength, flexural strength, shrinkage, bond strength, and toughness to those of fiber-reinforced LMC overlays.

3 SURVEY

In this study, a survey questionnaire was sent to 65 professionals in eighteen U.S. states and three Canadian institutions. Twenty-four responses were received from the following eleven states: Wisconsin, South Dakota, Oklahoma, North Dakota, North Carolina, Nebraska, Minnesota, Michigan, Kansas, Iowa, and Illinois. Survey questions covered the following: (1) advantages, disadvantages, life expectancy, and cost of low-slump concrete overlays compared to other bridge deck overlays; (2) service life of concrete overlays; (3) mix design, casting, and curing problems; (4) influential factors and solutions for low-slump concrete overlays cracking; and (5) applications of sealers and coatings on the overlay. Detailed results of the survey are presented in Appendix A. Highlights are summarized below:

On the advantages of concrete overlay over other overlays, most respondents believed that long-term durability (71.4%), corrosion protection (66.7%), and restoration of riding surface (61.9%) were the primary advantages, followed by cost (38.1%) and ease of application (19.0%). The main disadvantages were cracking (76.2%) and traffic disruptions (76.2%), followed by increased deadload (28.6%) (Figure 3).



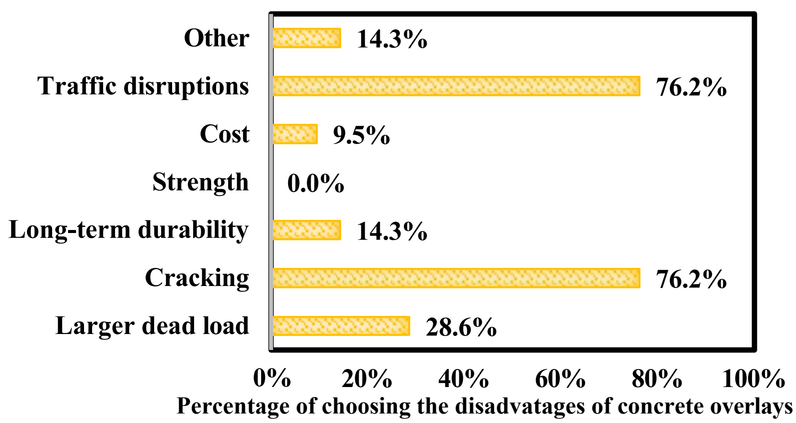


Figure 3. Advantages and disadvantages of concrete overlays.

On the average cost (per square ft) of a complete low-slump concrete overlay system, including surface preparation, labor, materials, and maintenance, 25% of the respondents chose ($20-25), 20% picked ($10-$15), and 10% opted for ($15 -$20) and ($25-30), and 65% selected "other" (Figure 4). On the thickness of the overlay, 57% of the respondents indicated a 2-in thickness, 24% chose 1.5 in, and 5% picked 3 in. (Figure 5).

On the timing of the placement of LSC overlays, most respondents believed that reaching a National Bridge Inventory (NBI) deck rating of 6 or 5 (27.3% each) was suitable for LSC overlay placement (Figure 6). As for the life expectancy of LSC, one-third of respondents chose 20-25 years, followed by 25-30 years (28.6%). The expected traffic impact time (length of construction) for a typical LSC overlay project (including deck preparation, concrete placement, and curing, but excluding any expansion joint work or staging) was considered to be 10 to 15 days by 35%, and 7-10 days by 20% of the respondents (Figure 7).

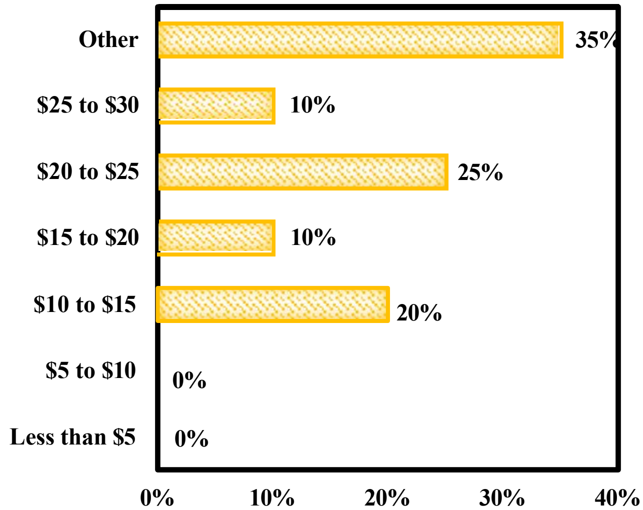


Figure 4. Average cost ($/S.F.) of a complete low-slump concrete overlay system.

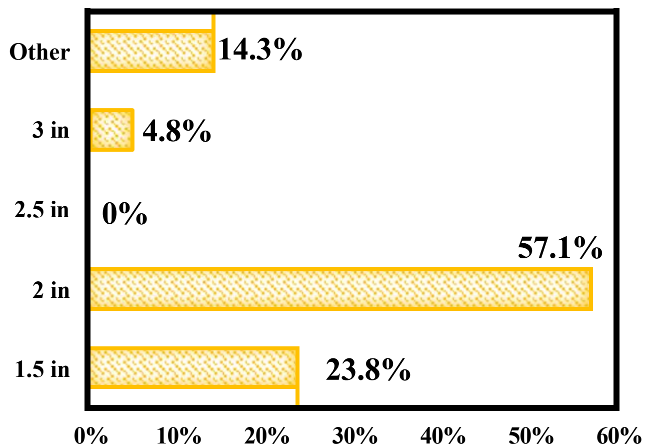


Figure 5. Typical thickness of a low-slump concrete overlay

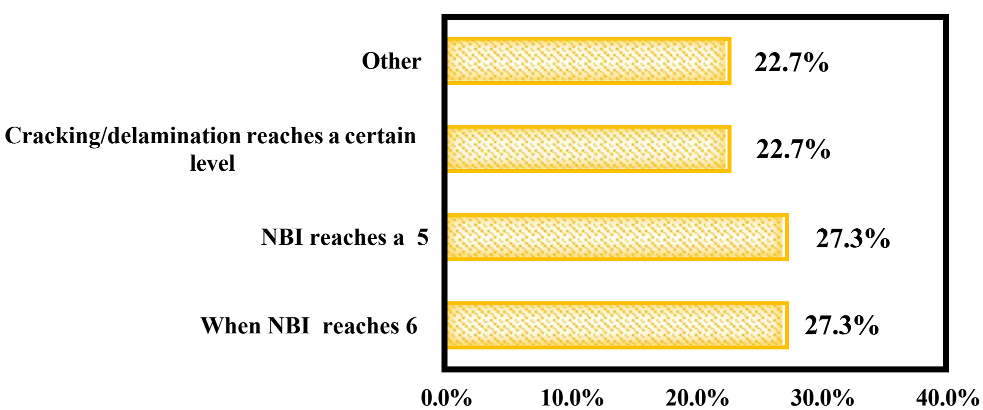


Figure 6. Timing of placement of concrete overlay.

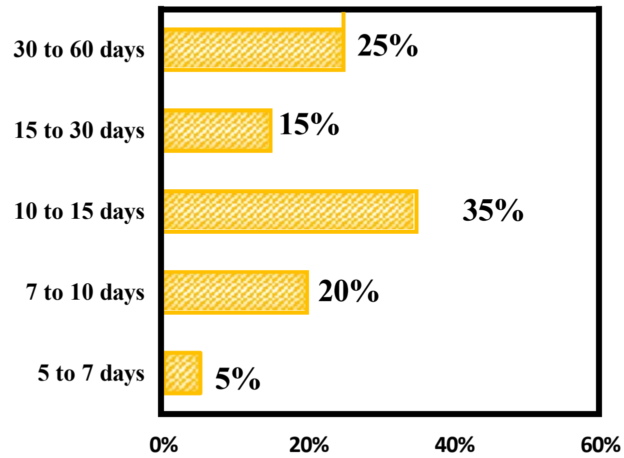


Figure 7. Expected traffic impact (length of construction in days) for a typical concrete overlay project.

More than 70% of the respondents agreed that more instances of overlay cracking had been noted in recent years despite the fact that the same mix design had been used successfully in the past (Figure 8). Regarding factors that lead to overlay cracking, the top three responses were shrinkage (81%), improper curing (71.4%), and temperature at the time of construction (61.9%). Others were high cement content (47.6%), high heat of hydration and subsequent cooling (33.3%), and humidity at the time of construction (28.6%) (Figure 9). Those who selected the "Other" option suggested additional factors such as w/c ratio, vibration, and traffic on the bridge during pouring and curing.

A survey question asked about the typical post-construction issues associated with the placement of concrete overlays on bridge decks. Early cracking (within one year) was selected by 90% of the respondents, while 45% chose cracking (1-3 years after construction). Cracking after 3-5 years after construction was chosen by 20% of the respondents (Figure 10). Only 15% of the respondents chose delamination.

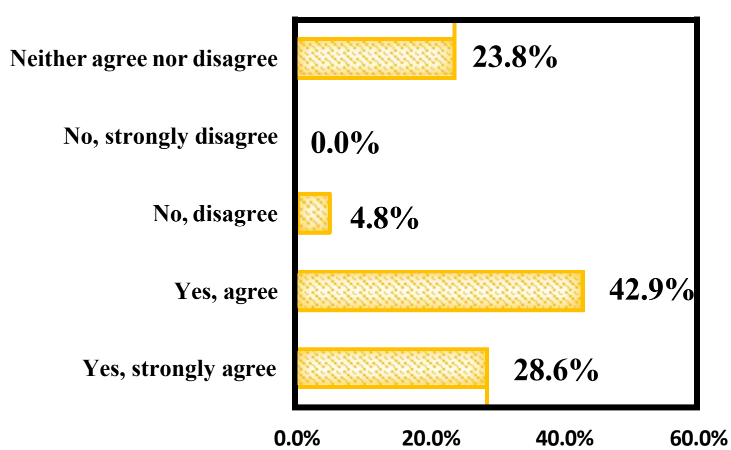


Figure 8. Do you agree that more instances of overlay cracking have been noted in recent years?

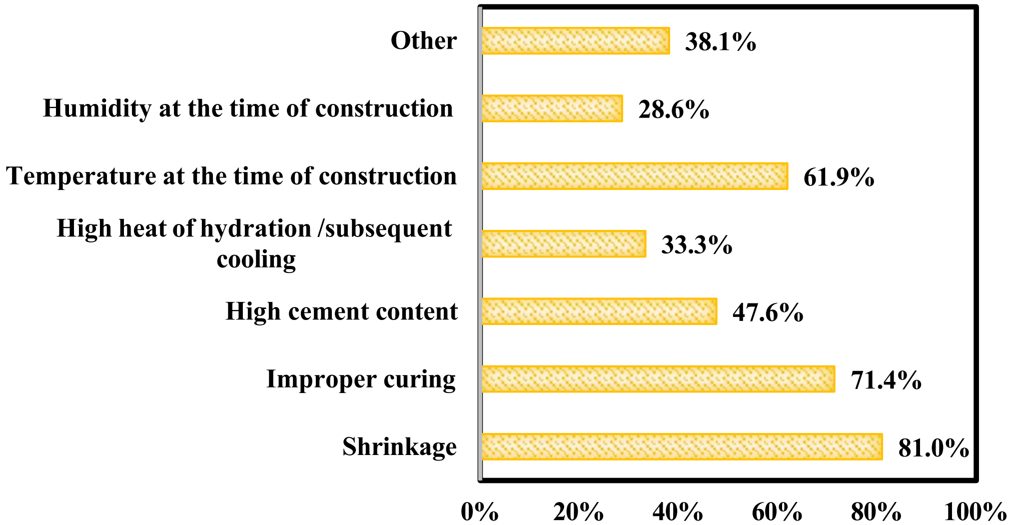


Figure 9. Factors that contribute to the concrete overlay cracking.

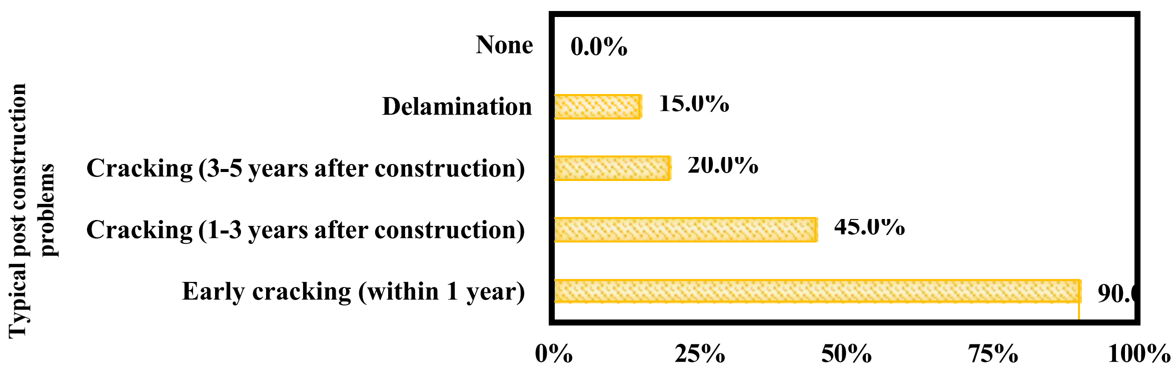


Figure 10. Typical post-construction problems.

A question on measures to improve cracking performance resulted in 65% of the respondents choosing better curing practices, while adding synthetic fibers and adding shrinkage-reducing admixtures were each selected by 60% of the respondents. Other options selected by 30% of the respondents were the addition of supplementary cementitious materials (cement replacement), reducing cement content, and improved placement procedures. (Figure 11).

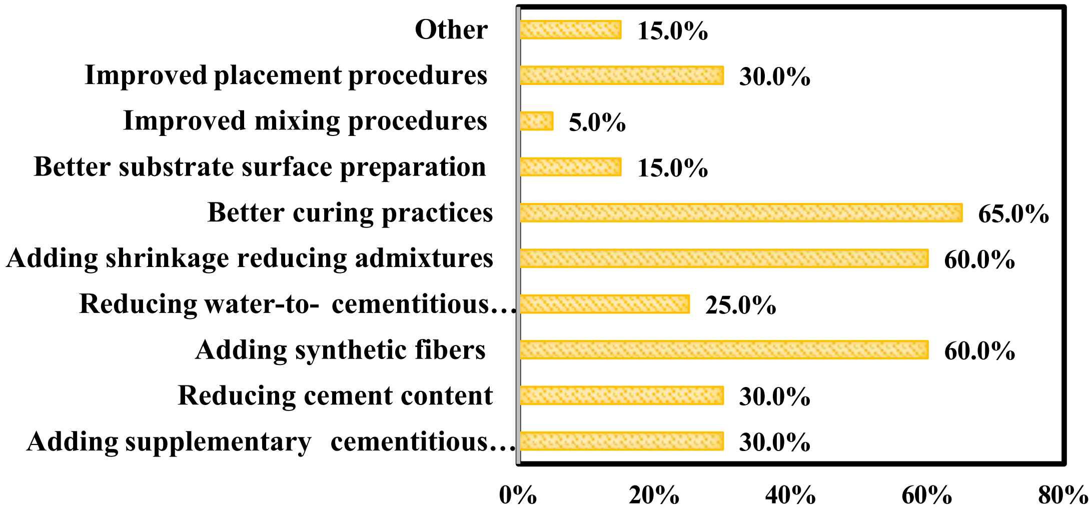


Figure 11. Adjustments to the concrete overlay to improve the cracking performance.

A survey question asked whether sealers and coating were needed to extend the service life of concrete overlays. The answer "Yes, penetrating sealers after overlay placement with subsequent reapplication" accounted for 31.6% of the respondents, while 15.8% answered, "Yes, penetrating sealers after overlay placement without subsequent reapplication." The answer "No" accounted for 31.6% of the respondents (Figure 12).

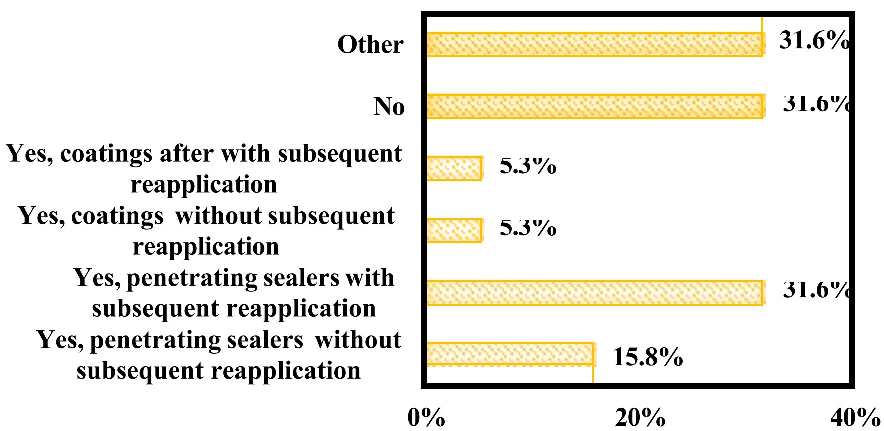


Figure 12. Are sealers and coating needed to extend the service life of concrete overlays?

4 FIELD OBSERVATIONS

Two bridges with previously placed concrete overlays were inspected in the Milwaukee metro area. In addition, the removal and replacement of concrete overlay on one of the bridges was observed and crack developed was visually ascertained.

4.1 Bridge No B67-099

Bridge No. B67-099 is located on Madison Street over Fox River in Waukesha County, Wisconsin. A concrete overlay had been placed on the deck in spring of 2022 and cracking was reported a few months later. The research team performed a crack map on September 8, 2022. Figures 13 and 14 show crack map and picture from Bridge B67-99. In addition to the cracks shown in Figure 13, there was also evidence of random (map cracking) in some locations.

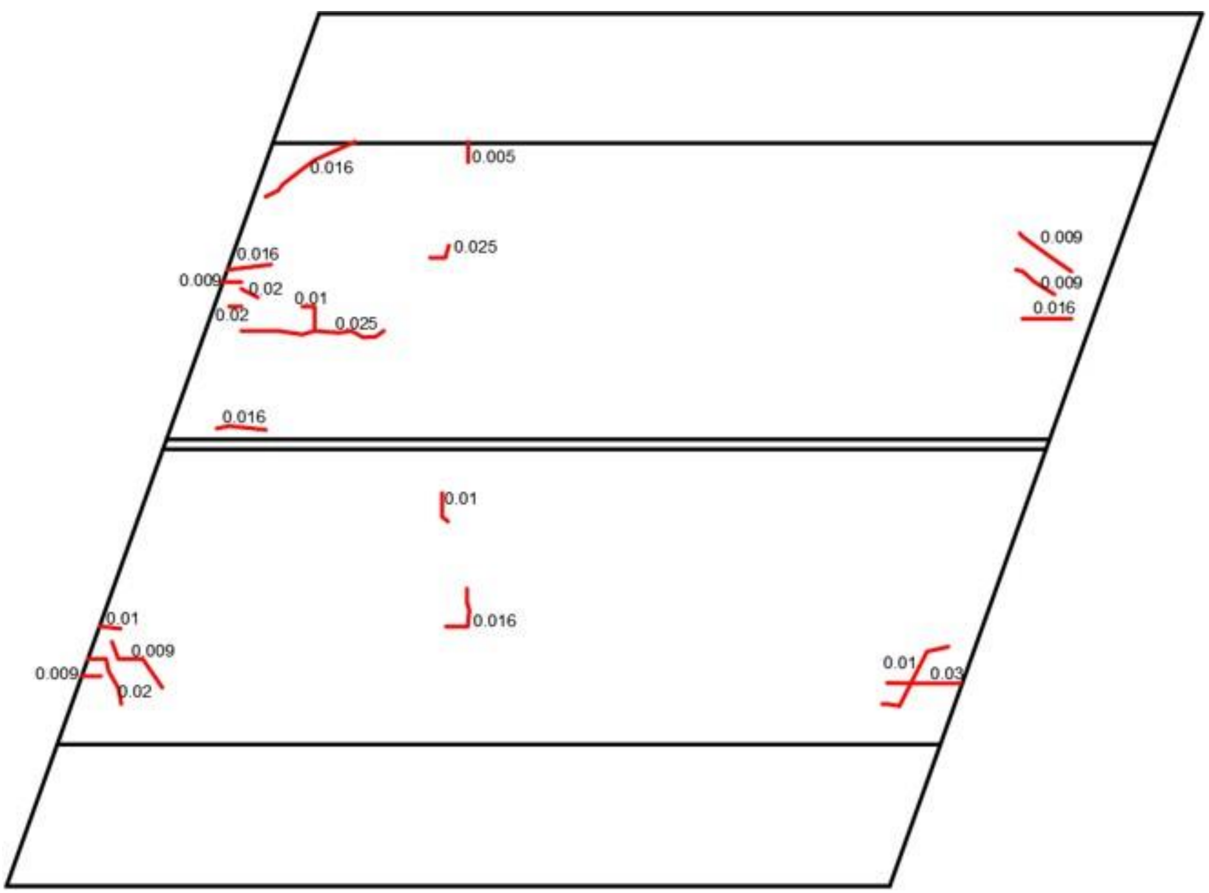


Figure 13. Bridge B67-099 crack map (crack widths in inches noted next to each crack).

Figure 14. Large crack in B67-099 (epoxy sealed).

4.2 Bridge No B40-336

Bridge No B40-336 is located on Capitol Drive (STH 190 EB) over the Menomonee River Parkway in Milwaukee County. The concrete overlay was initially placed in 2003. However, the overlay was experiencing cracking. Bridge B40-336 was scheduled for overlay removal and replacement in October 2022. Therefore, the research team inspected and crack-mapped the deck surface shortly before overlay removal operations. Figure 15 shows the crack map before removal operations.

The removal of overlay (milling), deck surface preparation, deck repairs and subsequent overlay placement was observed by the research team. The original overlay and any loose deck surface were removed. Figure 16 shows the deck surface before placement of the new overlay. The parts of the deck where full-depth deck repairs were needed (far section of the bridge in the photograph) were filled-in with concrete prior to the overlay placement. However, partial depth repairs (seen in Figure 16) were done at the same time as the overlay placement. The new overlay was placed overnight. The overlay mix design (with Type IL cement) used by the contractor is shown in Figure 17. The process started by the application of a cement-water slurry (1.5-gallon water with one bag of cement) using a broom (Figure 18). This mix was prepared onsite using a mobile mixing system and placed using a double vibrating screed (Figure 19). The surface was then finished, and a broom finish was applied (Figures 20 and 21).

This bridge was then monitored to observe cracking after placement of the new overlay. The research team noted several (mainly transverse) cracks that were apparent on the new overlay in April 2023. The inspection was performed from the sidewalk because of heavy traffic on the bridge. Additional cracks (mainly transverse and some map cracks) had appeared during a June 2023 visit by the research team. Figure 22 shows the June 2023 partial crack map (obtained from the sidewalk due to traffic) with extensive transverse cracks noted. Figures 23 and 24 show a few cracks and localized map cracks.

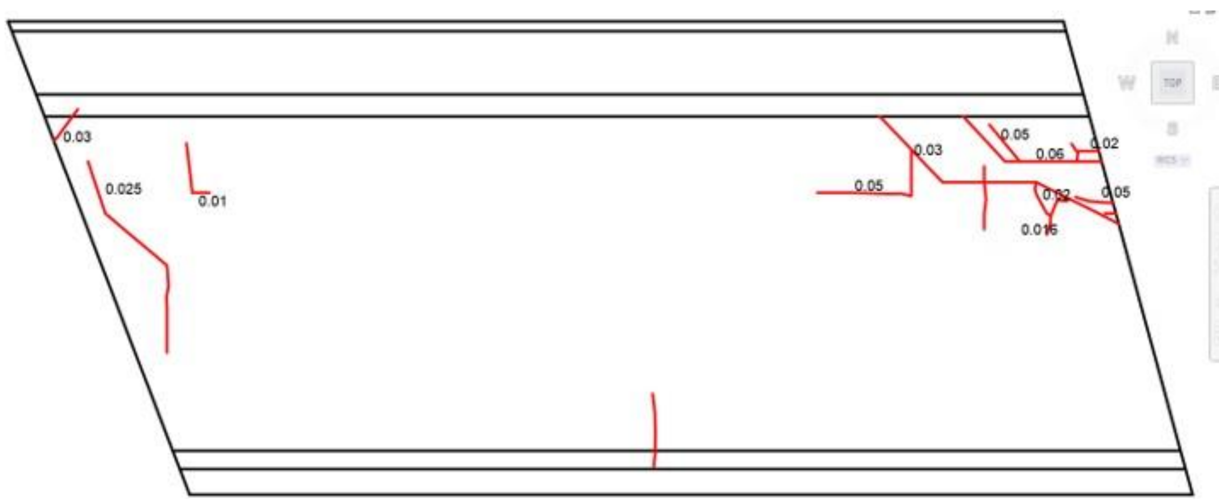


Figure 15. Bridge B40-336 crack map before overlay replacement (crack widths in inches noted next to each crack).

Figure 16. Bridge B40-336 before placement of new overlay.

Project Info

State Project No.	2025-20-70
County:	Milwaukee
Roadway:	STH 190
ZTI Project No.	504896
Structure(s) No.	B-40-335, B-40-336
Specification:	Concrete Overlays: 509.2500 / Deck Repairs: 509.XXXX
Mix Type:	Grade E - Overlays: 6% air +/- 1%; < 2" slump / Repairs: 6% air +/- 1%; < 3" slump

Fine Aggregate Source:	Lannon Lisbon 0-225-93-2020			
% Moisture	1.4%			
Dry Design Weight	1405	#/CY		
Moisture Content	1405	x % Moisture =	19.7	#/CY
Total Fine Aggregate	**1405**	**#/CY + MC =**	**1424.7**	**#/CY**

Coarse Aggregate Source:	Lannon Lisbon 0-225-93-2020			
% Moisture	2.1%			
Dry Design Weight	1405	#/CY		
Moisture Content	1405	x % Moisture =	29.5	#/CY
Total Fine Aggregate	**1405**	**#/CY + MC =**	**1434.5**	**#/CY**

Cement Content:	**Holcim - Ste. Genevieve Plant Type IL = 823#/CY***

Water Source/Content:	**Hydrant**	**Design = 32 gallons/CY****

Admixtures		
Air Entrainment:	**Polychem VR**	**Dose = 1 oz / (94 lbs. cement) x (823 # cement) = 8.75 oz**
Water Reducer:	**Polychem 400 NC**	**Dose = 4 oz / (94 lbs. cement) x (823 # cement) = 35 oz**

*= Per spec 501.3.2.2.2 (3) ZTI is requesting that the minimum SCM content be waived.

**= Actual design water may vary based on actual aggregate moisture contents and slump tests completed during placement

Figure 17. Overlay mix design information used on Bridge B40-336 (based on WisDOT Grade E mixture).

Figure 18. Application of cement-water slurry before overlay placement.

Figure 19. Placement of overlay using double vibrating screed.

Figure 20. Finishing after passage of double vibrating screed.

Figure 21. Broom finish.

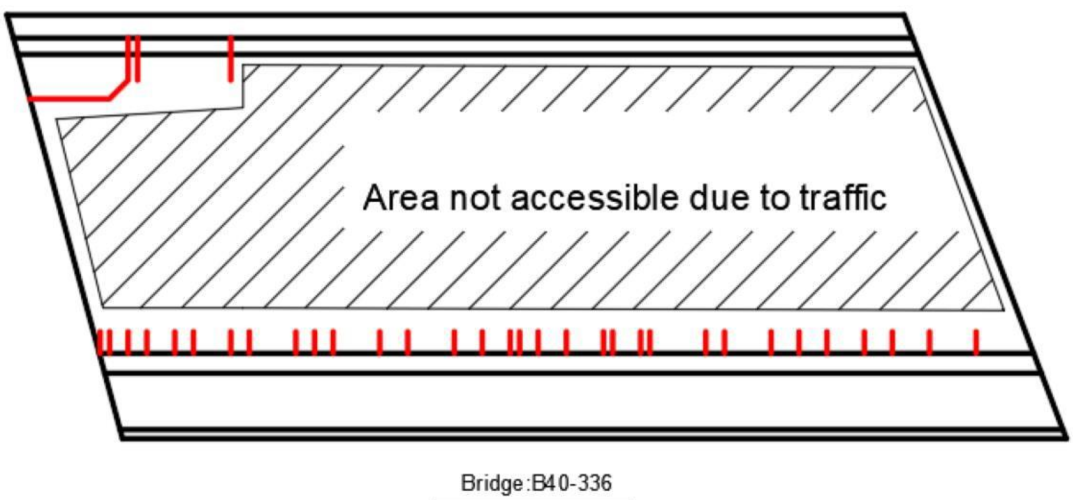


Figure 22. Crack map of Bridge B40-336 eight months after placement of overlay.

Figure 23 Overlay cracking observed on Bridge B40-336 eight months after placement.

Figure 24 Localized overlay map cracking observed on Bridge B40-336 eight months after placement.

5 EXPERIMENTAL PROGRAM

The experimental program was designed to evaluate various concrete overlay mix designs with respect to potential for early age cracking. Seven different overlay mixtures (Mix 1 to Mix 7) were examined and tested. These included the current Grade E Wisconsin mix with Type I and Type IL cements as well as Grade E mix modified by reducing cement content, partially replacing cement with Class C fly ash (15%), adding PVA fibers (1.5 lb./cy), and latex modified concrete. The current WisDOT Grade E mix has a specified water to cement ratio of 0.324, air content of approximately 6%, and a slump of less than 2 in. Table 5 describes the seven mixes tested.

Three categories of tests were performed: 1) Material tests on Portland cement Type I and Type IL (limestone cement); 2) Standard tests on concrete specimens for Mix 1 through Mix 7; and 3) Outdoor tests on 2-in overlays placed on concrete slabs with Mix 1 through Mix 7 overlays applied on them. In Category 1 tests, the chemistry and fineness of the Portland cement sources were evaluated. Cement sources were characterized using x-ray diffraction, Blaine fineness, and particle size analysis. Calorimetry tests (ASTM C1702) were performed to measure heat generation in different mixes. For Category 2 tests, the research team conducted the ring test (restrained shrinkage test - ASTM C1581) to measure early age cracking tendencies due to shrinkage, 90-day salt pond test (AASHTO T259) to assess chloride penetration, compressive strength test (ASTM C39), and a new dog-bone test to evaluate curing conditions. For Category 3 tests, 2-in-thick overlay mixtures were placed on existing concrete slabs that were 8 ft x 8 ft x 4 in. The slabs were placed outdoors (at the UWM USR facility).

Table 5. Mixture Designations and Proportions for Overlay Concrete (per one cubic yard of concrete)

Mixture	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7
Designation	E-IL	FRC	CR-15	FRC-15	FA	LMC	E-I
Description	Grade E	Grade E, PVA Fibers	Grade E Reduced Cement	Grade E Reduced Cement PVA Fiber	Grade E 15% Fly Ash	Latex Modified Mix	Grade E
Cement Type	IL	IL	IL	IL	IL	IL	I
Sand, dry (lbs)	1405	1405	1405	1405	1405	1405	1405
Gravel, dry (lbs)	1405	1405	1405	1405	1405	1405	1405
Cement	823	823	700	700	700	659	823
Water-Cement Ratio	0.324	0.324	0.324	0.324	0.324	0.324	0.324
Water reducer (oz)	To meet slump requirement						
Air Entrainment (oz)	To meet air content requirement						
PVA fiber (lbs)		1.5		1.5			
Fly Ash (lbs)					123		
Latex (lbs.)						139	

5.1 Materials

5.1.1 Portland Cement

Two types of portland cement were used in this study. Manufacturers have switched to producing Type IL cement (limestone cement or ILC) instead of the conventional Type I cement (ordinary portland cement or OPC). Type IL cement incorporates limestone powder (up to 15%) to reduce the carbon footprint of cement. Particle size analyses performed on both types of cement indicate that Type IL cement is much finer than the Type I cement (Figure 25 and Table 6). In Table 6, SSA refers to specific surface area in m^2/kg, and D10, D50, and D90 to particle size in microns corresponding to 10, 50, and 90 percentile levels. This is meant to compensate for the addition of limestone by increasing the reactivity of cement particles. The chemistry of Type IL cement is provided by St Marys Cement as shown in Appendix B.

Table 6. Particle size analysis for OPC and ILC.

Materials	Particle size analysis			
	SSA(m^2/kg)	D10(μm)	D50(μm)	D90(μm)
OPC	801.9	3.79	14.9	37.0
ILC	1161	2.33	10.0	25.4

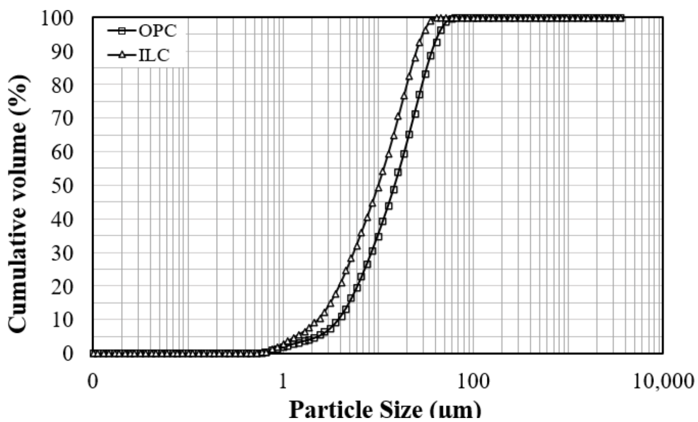


Figure 25. Particle size distribution curves for OPC and ILC

5.1.2 Aggregates

The fine and coarse aggregates used for this study were obtained from Payne and Dolan (a Walbec Company) locally from Waukesha, WI. The sieve analysis results are shown in Table 7. The sieve analysis values meet the WisDOT aggregates gradation limits.

Table 7. Properties of fine and coarse aggregates.

Sieve Size	Fine Aggregate Percent Passing (%)	Sieve Size	Coarse Aggregates Percent Passing (%)
3/8’’	100	1’’	100
#4	97.9	3/4’’	98
#8	78.4	1/2’’	70.4
#16	63	3/8’’	45.8
#30	49.3	#4	4.1
#50	28.5	#8	0.7
#100	1.8	#16	0.7
#200	1.2		
Fineness Modulus	2.81		

5.1.3 Fly ash

Fly ash is a byproduct of coal combustion electric power plants. Class C fly ash typically has a higher calcium oxide content than Class F fly ash, which makes it more reactive and allows it to develop strength more quickly. The Class C fly ash used in this study was obtained from the Oak Creek, WI Power Plant operated by We Energies. The fly ash met the requirements of ASTM C618 [25]. Table 8 shows the chemical composition of this fly ash.

Table 8 Chemical composition of Class C fly ash

Element	Proportion (%)
SiO_2	37.47
Al_2O_3	19.18
Fe_2O_3	5.95
CaO	25.22
MgO	5.33
Na_2O	1.72
K_2O	0.63
TiO_2	1.41
P_2O_5	1.33
CO_2	0.53
LOI	0.53

5.1.4 PVA Fiber

Commercially acquired Polyvinyl alcohol short-cut fibers were used in some of the mixes. These fibers were made up of short-cut fiber about ½ in length and obtained from Kuraray Co. Ltd.

5.1.5 Admixtures

The high range water reducing admixture used for the mixes was Sika Viscocrete-1000, which met the ASTM C494 Type A and F admixtures requirements. The air-entraining admixture used for the mixes was Sika Air-360, which met the requirements of ASTM C260.

5.1.6 Latex

SBR latex, a carboxylate styrene-butadiene copolymer from Euclid Chemical, was used during the study as it complies with ASTM C1059. This is designed to improve bond strength, durability during freeze-thaw cycles, and the chemical resistance of concrete. The properties of this latex are shown in Table 9.

Table 9. Properties of latex (from Euclid Chemicals)

Property	Value
Solids Content (by weight)	48%
Unit weight, Specific Gravity	8.4 lbs/gal, 1.01
VOC Content	<5 g/L
Appearance	White
pH	10-11

5.2 Test Methods

5.2.1 Heat of Hydration (Calorimetry)

The first set of calorimetry tests were performed on cement pastes with varying water-cement ratios. Table 10 shows the paste mixture information. Ordinary Type I portland cement (OPC) and type IL (limestone cement) (ILC) were each mixed with water at three different w/c ratios of 0.36, 0.43, and 0.5, respectively. Pastes were prepared by manual mixing for about 4-5 minutes. Approximately 25 grams of the fresh paste was poured into a plastic ampoule (HDPE) and placed inside the isothermal calorimeter (TAM Air) to measure the heat of hydration (Figure 26). The test was performed for 48 h at a controlled temperature of 23 °C.

For the second set of tests, the effect of the replacement of each type of cement with Class C fly ash (FA) at different w/c ratios was evaluated. Each type of cement (ILC and OPC) was replaced with fly ash at 10%, 15%, and 20% cement replacement and mixed with three different w/c ratios of 0.36, 0.43, and 0.5, respectively. Tables 10 and 11 show the mixture information for the second experiment and the mixing time and weight of paste in ampules, respectively. Pastes were prepared by manual mixing for about 4-6 minutes (Figure 27).

Table *10*. Paste mixture data for the first set of experiments.

w/c	Cement (g)	Water (mL)	Total wt. (g)
0.36	18.38	6.62	25
0.43	17.48	7.52	25
0.50	16.67	8.33	25

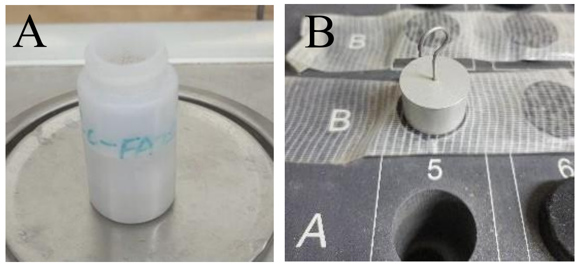


Figure *26*. (A) Calorimeter plastic ampoule with 25 grams of the fresh paste and (B) weight balance

Figure 27. The sequence of HOH sample preparation from left to right.

Table 11. Mixture designation for the second set of experiments.

Designation	Materials					
	ILC (g)	OPC (g)	FA (g)	Water (ml)	W/C	Total wt. (g)
ILC-FA0-0.36	18.38	0	0	6.62	0.36	25
ILC-FA10-0.36	16.54	0	1.84	6.62	0.36	25
ILC-FA15-0.36	15.62	0	2.76	6.62	0.36	25
ILC-FA20-0.36	14.70	0	3.68	6.62	0.36	25
OPC-FA0-0.36	0	18.38	0	6.62	0.36	25
OPC-FA10-0.36	0	16.54	1.84	6.62	0.36	25
OPC-FA15-0.36	0	15.62	2.76	6.62	0.36	25
OPC-FA20-0.36	0	14.70	3.68	6.62	0.36	25
ILC-FA0-0.43	17.48	0	0	7.52	0.43	25
ILC-FA10-0.43	15.73	0	1.75	7.52	0.43	25
ILC-FA15-0.43	14.86	0	2.62	7.52	0.43	25
ILC-FA20-0.43	13.98	0	3.50	7.52	0.43	25
OPC-FA0-0.43	0	17.48	0	7.52	0.43	25
OPC-FA10-0.43	0	15.73	1.75	7.52	0.43	25
OPC-FA15-0.43	0	14.86	2.62	7.52	0.43	25
OPC-FA20-0.43	0	13.98	3.50	7.52	0.43	25
ILC-FA0-0.50	16.67	0	0	8.33	0.5	25
ILC-FA10-0.50	15.00	0	1.67	8.33	0.5	25
ILC-FA15-0.50	14.17	0	2.50	8.33	0.5	25
ILC-FA20-0.50	13.34	0	3.33	8.33	0.5	25
OPC-FA0-0.50	0	16.67	0	8.33	0.5	25
OPC-FA10-0.50	0	15.00	1.67	8.33	0.5	25
OPC-FA15-0.50	0	14.17	2.50	8.33	0.5	25
OPC-FA20-0.50	0	13.34	3.33	8.33	0.5	25

5.2.2 Ring Tests (Restrained Shrinkage)

The mixtures used in this study were identified as Mix 1 through Mix 7. Table 12 presents the detailed mixture proportions for the concrete used in each mix. The face slab concretes were designed to achieve a compressive strength range of 35.0-45.0 MPa at 28 days, which is commonly employed in practical engineering of Concrete-Faced Rockfill Dams (CFRDs).

Slabs 1, 2, 3, 4, and 6 were prepared using Grade E cement (type IL), whereas slab 7 utilized Grade E cement (type I). Slab 1 represents the baseline mixture proportion. In slab 2, 1.5 lb/yd³ of Polyvinyl Alcohol (PVA) fibers were added to the mixture. Slab 3 involved a 15% reduction in cement content. Slab 4 combined both the addition of 1.5 lb/yd³ PVA and a 15% reduction in cement content. Slab 5 employed a 15% replacement of cement with fly ash, which is known to minimize shrinkage in thin concrete face slabs. Lastly, slab 6 incorporated latex into the mixture.

Table 5 mixture proportions of concrete mixes (per cubic foot).

Mix	Sand (kg)	Gravel (kg)	Cement (kg)	Water (kg)*	Water Reducer (ml)	Air Entrainment (ml)	PVA fiber (kg)	Fly Ash (kg)	Latex (kg)
Mix 1	24.63	23.65	13.83	4.00	144.2	72.1			
Mix 2	24.63	23.65	13.83	4.00	194.2	72.1	0.025		
Mix 3	24.63	23.65	11.76	3.30	122.5	61.3			
Mix 4	24.63	23.65	11.76	3.40	122.5	72.1	0.025		
Mix 5	24.63	23.65	11.76	4.00	119	72.1		2.07	
Mix 6	24.63	23.65	11.10	1.70	0	0			2.31
Mix 7	24.63	23.65	13.83	4.00	144.2	72.1			

*Adjusted based on aggregate moisture content.

The test procedure was based on ASTM C1581 and involved determining the age at cracking under restrained shrinkage. Concrete ring specimens were prepared in two layers and subjected to external vibration after each layer. The instrumented rings (with strain gages) were then placed in a moist curing environment for 24 hours before stripping as shown in Figure . Subsequently, the specimens were stored in a room maintained at a temperature of 73°F and a relative humidity of 50%. The strain in the steel ring was carefully monitored and recorded throughout the testing process.

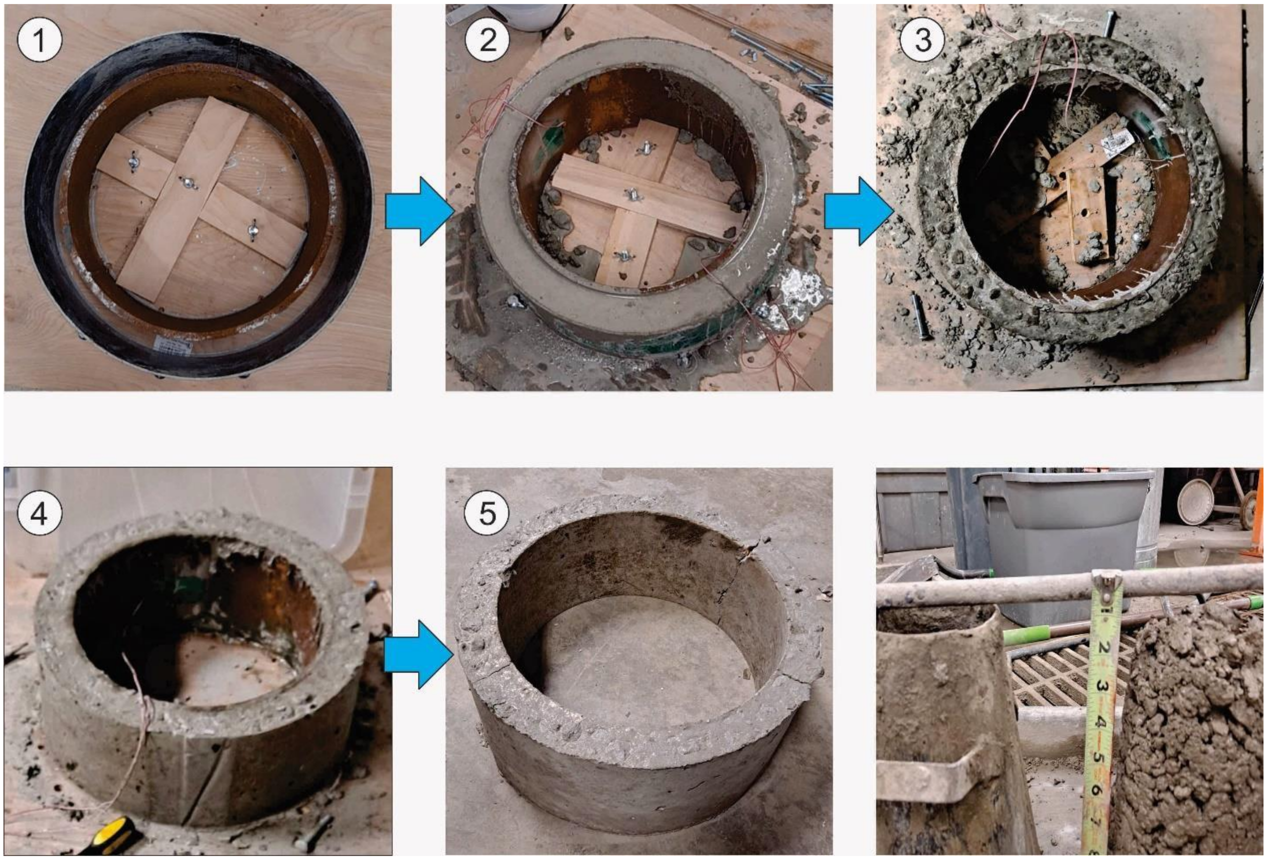


Figure *28.* The ring testing process and samples.

In this experimental study, the effects of modifications in Grade E mix on restrained shrinkage were examined. Mix 1 and Mix 7 served as the control group (Type IL and Type I cement). To assess the influence of cement type on shrinkage, Grade E cement (type IL) was used for Mix 1 through Mix 6, while Mix 7 utilized Type I cement.

5.2.3 Salt Ponding Test (Chloride Penetration)

The salt ponding test was conducted to evaluate the susceptibility of different concrete mixes to chloride exposure and penetration of chloride ions into concrete. This test is based on a AASHTO T259, "Standard Method for Testing Resistance of Concrete to Chloride Ion Penetration," and ASTM C1543, "Standard Test Method for Determining the Penetration of Chloride Ions into Concrete by Ponding." Twenty-one concrete slabs were cast based on the seven mix designs described, with three samples prepared for each mix design. The salt ponding slabs had dimensions of 7 x 7 x 3 in. and were cured in 100% humidity for the first 14 days. Afterwards, they were moved to a room with a temperature of 20℃ and 50 $\pm$ 5% humidity until 28 days. Cylinder samples (2 x 4 in.) were obtained from each concrete mix, cured, and similarly stored.

Once the curing process was complete, the sides of the slabs were coated with polyurethane paint (vapor barrier) and left to dry for 24 hours. This was done to reduce the lateral moisture migration. The top and bottom of the slabs were left uncoated. Plexiglass dikes of height 1 in. were placed around the top of each slab and sealed with silicon caulk, as shown in Figure 29. The slabs were then exposed to a 3% (by weight) NaCl solution to a height of 0.5 in. The dikes were covered with plastic sheets to reduce evaporation. The level of the NaCl solution was restored if a decrease in level was observed.

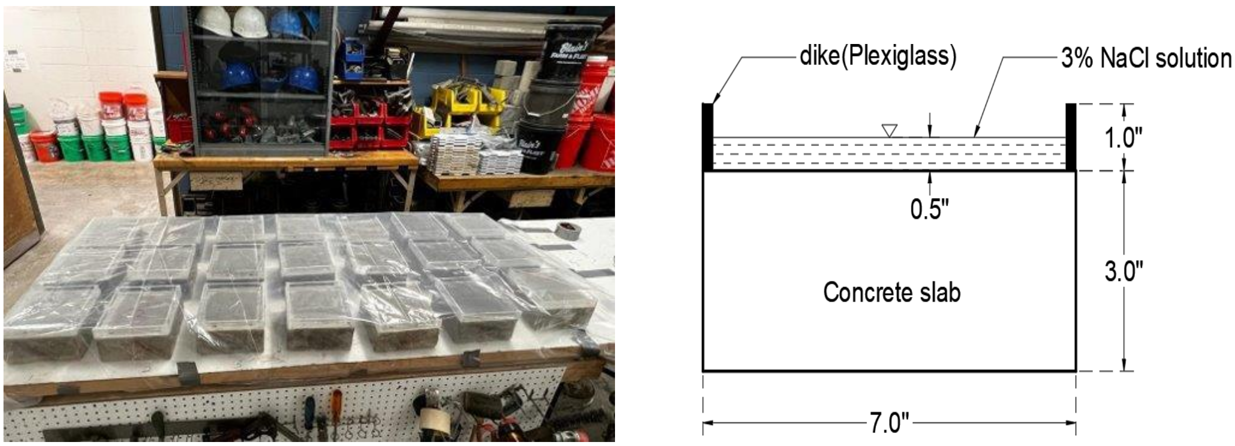


Figure 29. Schematic of salt ponding test.

After the ponding process, the covered specimens were exposed to chlorides for 90 days. The slabs were removed, and water was removed at the end of the 28-day exposure period. The surfaces of the samples were allowed to dry and were cleaned to remove crystallized salt particles and debris from their surface.

Concrete powder samples were collected from the top surface of the slabs and background samples (uncontaminated original concrete) using an 18mm hammer drill. The sampling process was done per the ASTM C1152 (Standard Test Method for Acid-Soluble Chloride in Mortar and Concrete) while maintaining all drill bits and sampling papers clean to avoid contamination of the samples. A total of 14 powder samples were collected from the background specimen, consisting of two samples each for every mix. A total of 42 concrete powder samples were also taken from the ponded slabs, with samples taken at depth ranges 0-0.25 in. and 0.25-0.5 in. for each slab.

After collecting and tagging all powder samples, the Rapid Chloride Test (RCT 1029) was performed on these samples. The RCT 1029 method has shown good agreement with the standard laboratory titration tests provided by AASHTO T-260, ASTM C114, NT BUILD 208, and DS 423.28. The samples were tested using the RCT-500 test kits from Germann Instruments Inc. The hardware included a high impedance electrometer, electrode with a wetting agent, calibration liquids, plastic ampoules for measuring test samples, and RCT-1023 vials with extraction liquids for chloride extraction (Figure 30).

Figure 30. Rapid Chloride test setup and measurement

5.2.4 Dog Bone Tests

The custom-designed dog bone specimens were designed to evaluate restraint stresses due to inelastic strains (shrinkage and temperature). This test, which was developed as part of this study, is an alternative method to the ring test. This new test is an easier and more flexible approach by utilizing smaller samples and includes a relatively simple instrumentation plan.

In this research, dog bone specimens were used to assess the effectiveness of various curing conditions. The geometry of the dog bone specimens is shown in Figure 31. The specimens were sandwiched between two steel tubes as shown in Figure 32. Two different curing conditions (plastic covering and wet burlap with plastic covering) and three different curing times (3, 7, and 14 days) were tested. Two specimen sets were prepared for each curing condition and curing time for a total of 28 sets of specimens. One strain gauge was installed on each steel tube in the restrained specimens. As the restrained concrete specimens shrink or expand due to shrinkage, moisture movements, and thermal changes, restraint stresses are developed since the steel tubes resist those concrete movements. Periodic measurements of strain gages allow determination of restraint stresses in steel. The restraint stress in concrete can be determined based on equilibrium of forces as shown in Equations 1 and 2:

$$2\varepsilon_s A_s E_s = \sigma_c A_c \quad (1)$$

$$\sigma_c = \frac{2\varepsilon_s A_s E_s}{A_c} \quad (2)$$

Where ε_s, A_s, E_s and A_c are the measured steel strain, area of one steel tube, modulus of elasticity of steel (29,000 ksi), and the cross-sectional area of concrete, respectively. σ_c is the restraint stress in concrete.

The test sample is a dog bone-shaped specimen with a width of 4.5 in., length of 11.5 in., and thickness of 1.5 in. The reduced width of the middle section is 1.5 in. with a length 6 inches. The steel tubes were *HSS 1.5 x 1.5 x 1/8* steel sections machined to fit the curved fillets of the concrete specimen. Strain gauges were attached at the top middle portion of the steel and connected to a Vishay P3500 Strain Indicator system.

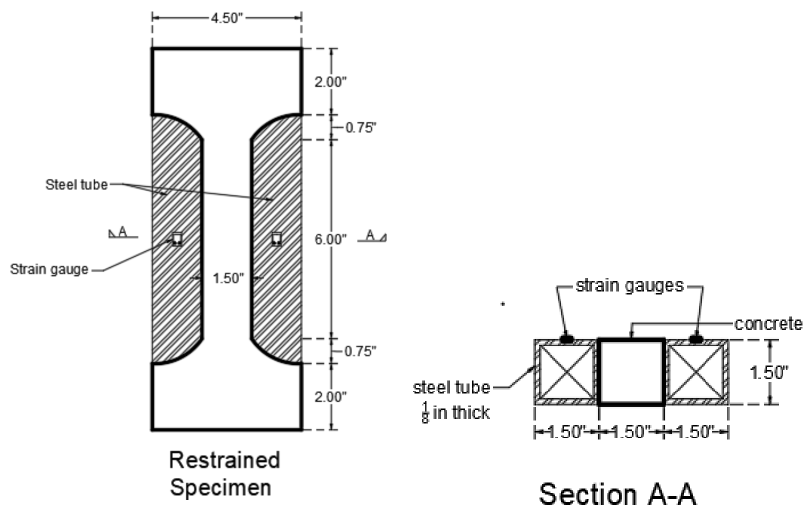


Figure 31. Geometry of dog bone specimens.

The dog bone test was designed to investigate the effect of curing conditions on the strain response in concrete over time. The WisDOT Grade E mix with Type IL cement was used in all specimens (the test variable was the curing condition). These specimens were cured for 3, 7, and 14 days with either plastic sheathing (P) or wet burlap with plastic cover (PB) in a room with a temperature of (20 ± 1°C). The samples were demolded 24 hours after casting and their strains were measured daily. All samples were placed on their side during the entire monitoring period.

A total of 12 specimens were fabricated. Six were cured with only plastic sheathing for 3, 7, and 14 days (2 for each curing period and designated as P3, P7, and P14, respectively). The six remaining samples were cured with wet burlap plus outer plastic sheathing (2 for each curing period and designated PB3, PB7, and PB14, respectively).

An additional set of tests was performed on a similar dog bone specimen considering a 15% reduction in cement, with a new w/c ratio of 0.381 instead of the original w/c ratio of 0.324. Two restrained specimens were prepared and subjected to the 7-day wet burlap (PB) curing. These specimens are designated as NPB7.

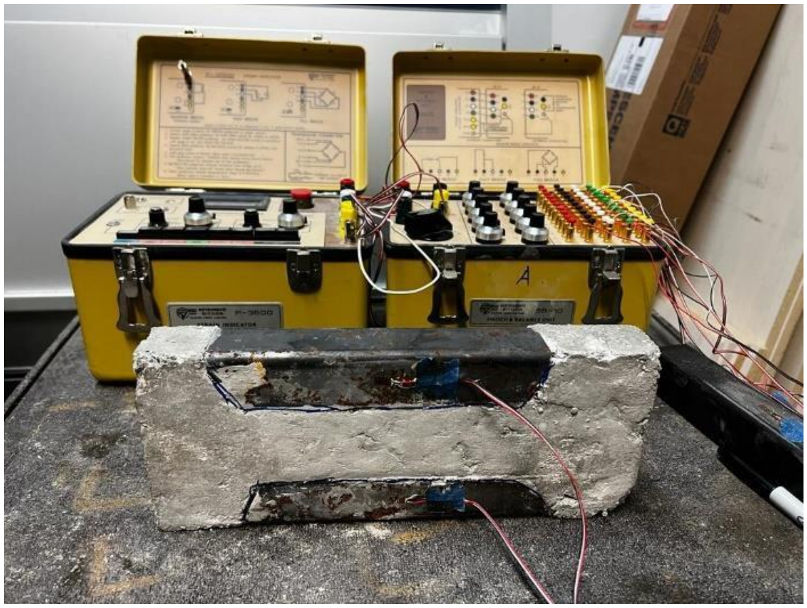


Figure 32. Restrained dog bone specimens.

5.2.5 Field Slab Tests

As part of this research, seven slabs with overlays were fabricated to evaluate the cracking potential and response of the various overlays to different curing conditions. Seven 8 ft x 8 ft x 4 in concrete slabs were fabricated (by a precast company) for outdoor testing. The surfaces of the substrate slabs had a broom finish. A few months after casting the substrate slabs, 2-in-thick overlays were placed on the top surfaces of the slabs (seven overlay types corresponding to Mixes 1 through 7 described earlier). A cement-water slurry was first applied to the surface before placement of overlays. Figure 33 shows the process of mixing and casting the overlays. The overlays also received a broom finish. The slabs were located outdoors in an open field in Milwaukee, WI, and the overlays were placed over one week in October 2022. Mechanical points were embedded to the overlay as shown in Figure 34 to allow periodic measurements of strain using mechanical strain gages. A thermocouple was also embedded in the overlay to measure concrete temperatures. The slabs were covered with plastic sheathing for curing. The covering was removed from one-half of the surface of each slab after three days (3-day curing) and the covering was removed from the second half after 7 days (7-day curing). The slabs were monitored on a weekly basis for any evidence of cracking. This test was intended to provide information on the performance of various overlay mixes exposed to field environmental conditions on a relatively large scale.

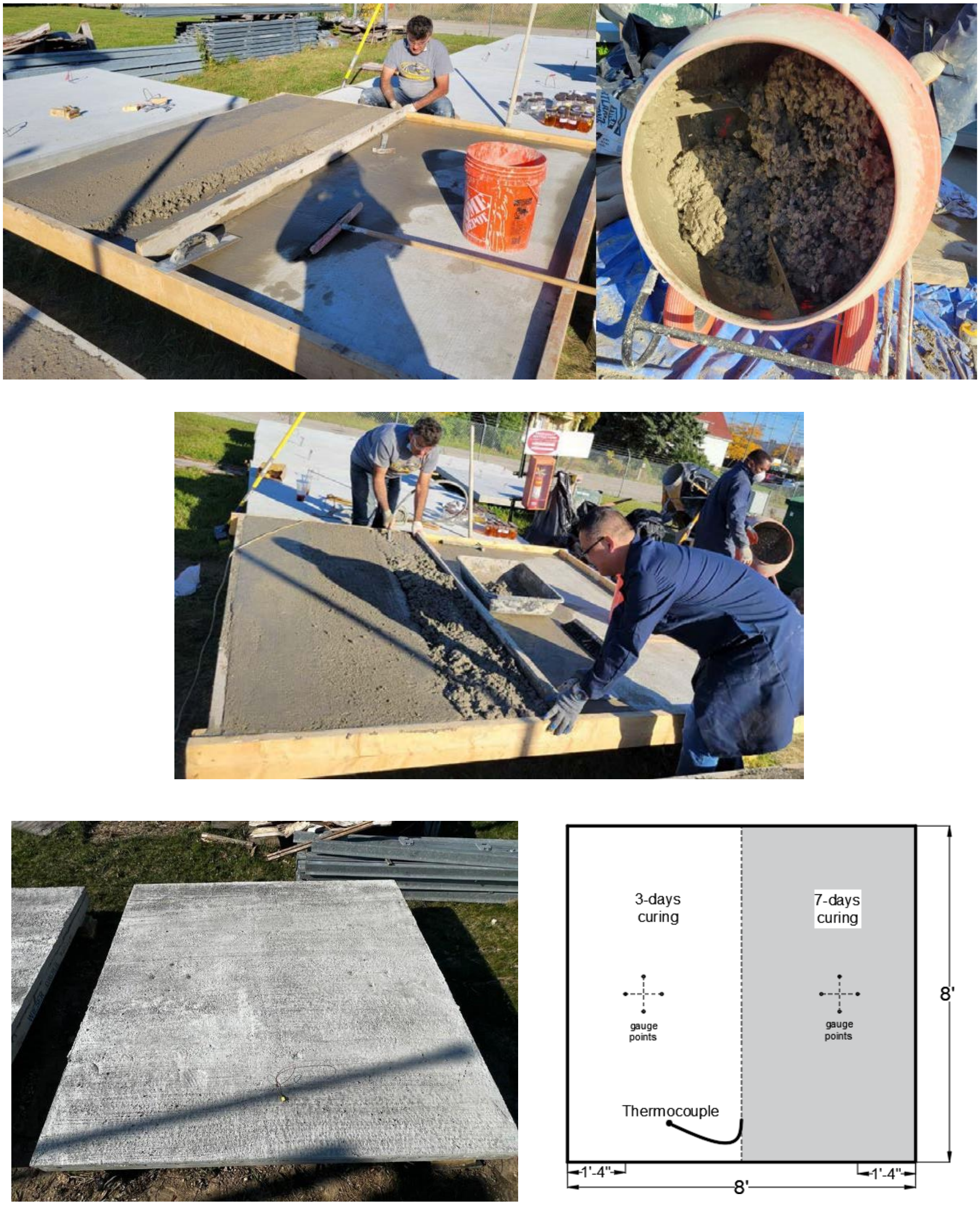


Figure 33. Mixing and placing overlays on field slab specimens.

The experimental tests described above were designed to provide insights into the cracking potential of concrete overlays subjected to environment and curing conditions. The results of these tests will be discussed in the subsequent section.

6 EXPERIMENTAL RESULTS

6.1 Compressive Strength Results

The 28-day compressive strength of concrete used in various slabs was obtained from testing sets of three 4 x 8 in. cylinders for each mix type according to ASTM C9. The average compressive strength values, standard deviations, and a graph of the results are shown in Table 6. It should be noted that all concrete mixes (Mixes 1 through 7) had the same water to cementitious materials ratio of 0.324. The alternate mix used for the 7-day wet cured dog bone samples had a 15% cement reduction and a w/c ratio of 0.381.

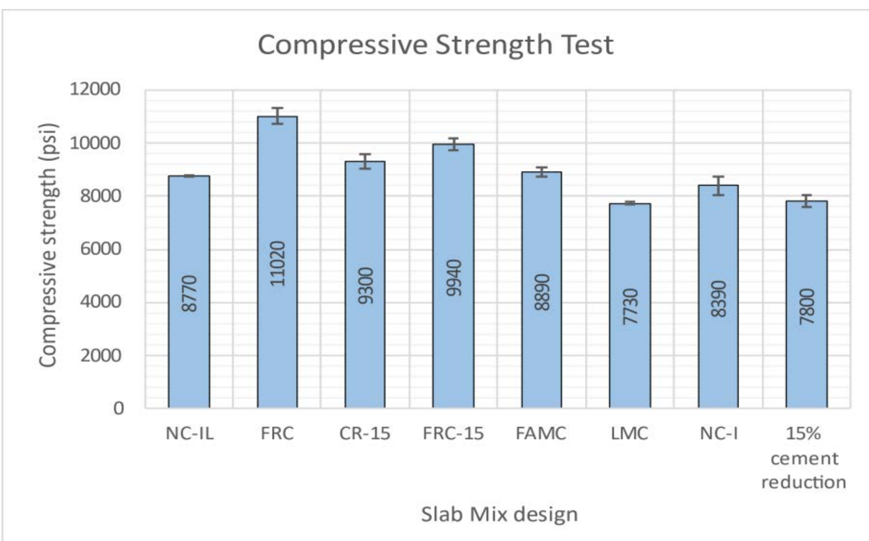
It can be observed that the addition of PVA fibers to the Grade E mix in Mix 2 (FRC) resulted in a significant increase in compressive strength compared to the reference Mix 1 (E-IL). Slab 4 (FRC-15), which had both PVA fibers and a 15% reduction in cement content, also had higher compressive strength than E-IL. In Mix 3 (CR-15), a 15% cement reduction (while maintaining the water/cement ratio) increased compressive strength compared to the reference mix. Adding fly ash (15% replacement of cement) in Mix 5 (FAC) resulted in a slight increase in compressive strength compared to E-IL, while the latex-modified mix in Mix 6 (LMC) had the lowest compressive strength among all the mixes tested. The Grade E mix with Type I cement (E-I) and Grade E mix with 15% Type IL cement reduction (and w/c ratio of 0.38) had lower compressive strength than all the Type IL mixes except the Latex modified mix (LMC).

The variation in compressive strength within each set of three samples is represented by the standard deviation, which measures the spread of the data. A lower standard deviation indicates that the values are more consistent and reliable. In this case, the standard deviations range from 45 to 475 psi, indicating some variability in the compressive strength values for the different mixes.

The results demonstrate the impact of different mix components on compressive strength. The addition of PVA fibers led to increased compressive strength, while the addition of latex modification resulted in a decrease in compressive strength. Reduction of cement by 15% while increasing the w/c ratio to 0.38 resulted in a compressive strength of 7800 psi. This indicates that such a reduction in cement content can still provide a substantial compressive strength.

Table 6 Compressive strength values for the overlay mixes

Mix No	Designation	Average Compressive Strength (psi)	Standard Deviation (psi)	Number of Samples
1	E-IL	8770	45	3
2	FRC	11020	386	3
3	CR-15	9300	340	3
4	FRC-15	9940	267	3
5	FAC	8890	213	3
6	LMC	7730	69	3
7	E-I	8390	475	3
New mix (dog bone test)	15% cement reduction (Type IL) w/c = 0.38	7800	220	3



Mix No	Description
1	Grade E (Type IL cement)
2	PVA fiber (Type IL cement)
3	15% cement reduction (Type IL cement)
4	15% cement reduction + PVA fiber (Type IL cement)
5	15% fly ash replacement of cement (Type IL cement)
6	Latex modified concrete (Type IL cement)
7	Grade E (Type I cement)

Figure 34. Compressive strength test results

6.2 Heat of Hydration (Calorimetry)

The heat of hydration was measured for 48 hours. Figure 35 shows the heat of hydration per gram of the paste (25 g) of the six samples, including ordinary OPC and ILC, with three different w/c ratios. Results show that the heat of hydration of the OPC sample is lower than the corresponding ILC sample. The contribution to heat evolution is governed by C_3S (alite), a main cement clinker phase (Thongsanitgarn, Watcharapong Wongkeo, and Chaipanich 2014).

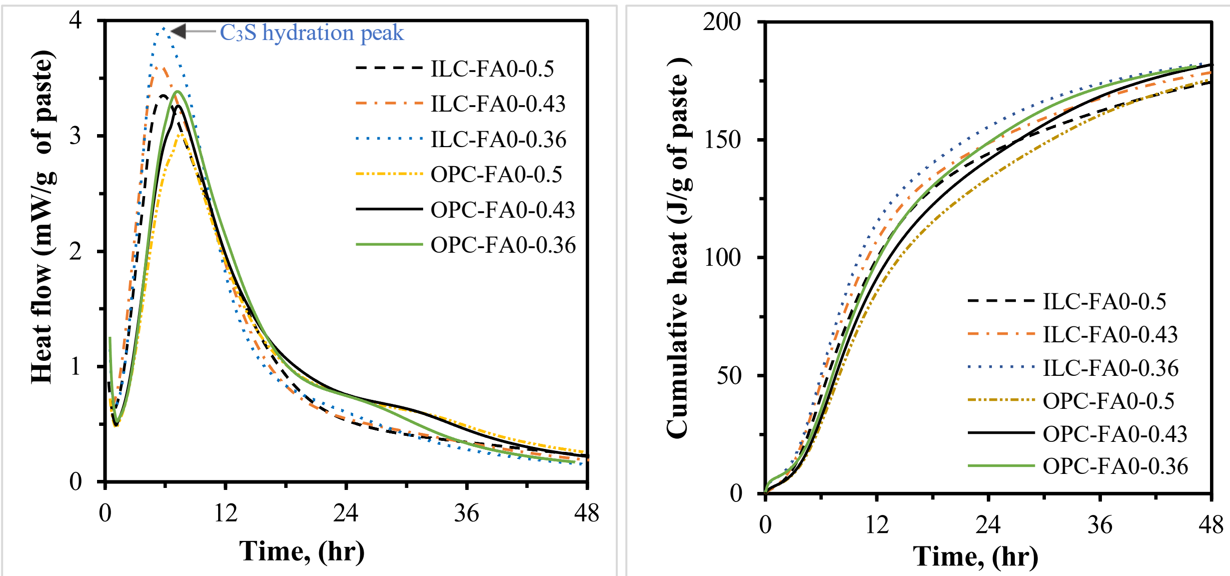


Figure *35*. Heat of hydration of ILC and OPC with three different w/c ratios

Figures 36 through 38 show the heat of hydration of the 24 prepared samples of OPC and ILC with three different w/c ratios and FA-replacement after 48 hours. It is observed that the heat of hydration of both types of cement decreased with an increase in the w/c ratio and fly ash content. Therefore, the higher FA replacement level provides lower heat release per unit weight of paste, which is consistent with the lower hydration rate peak.

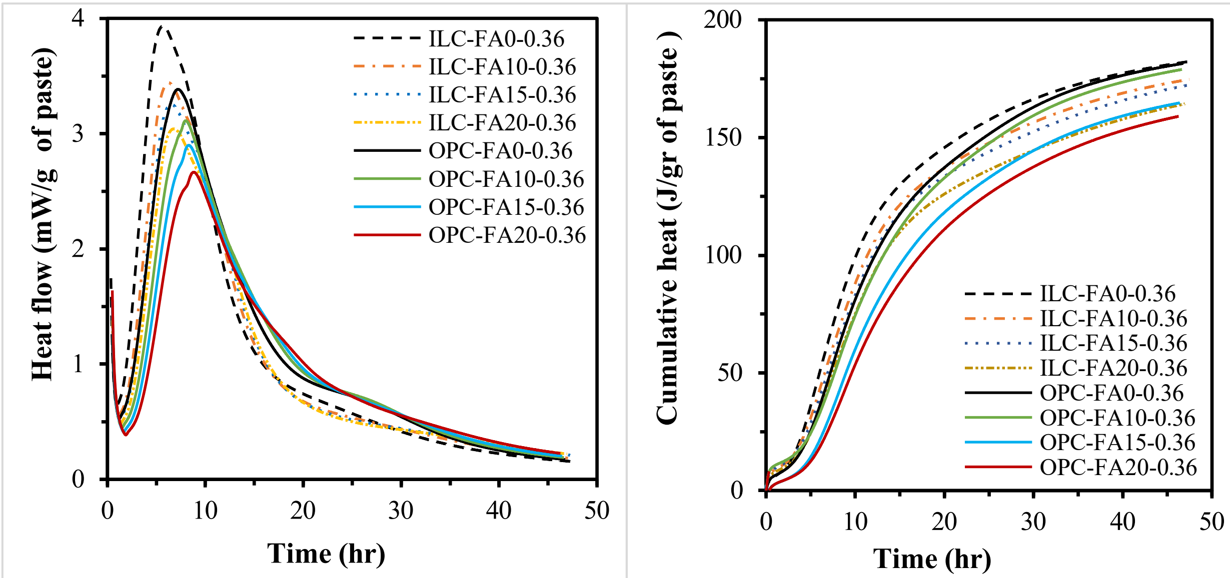


Figure *36*. Heat of hydration after 48 hours with a w/c ratio of 0.36.

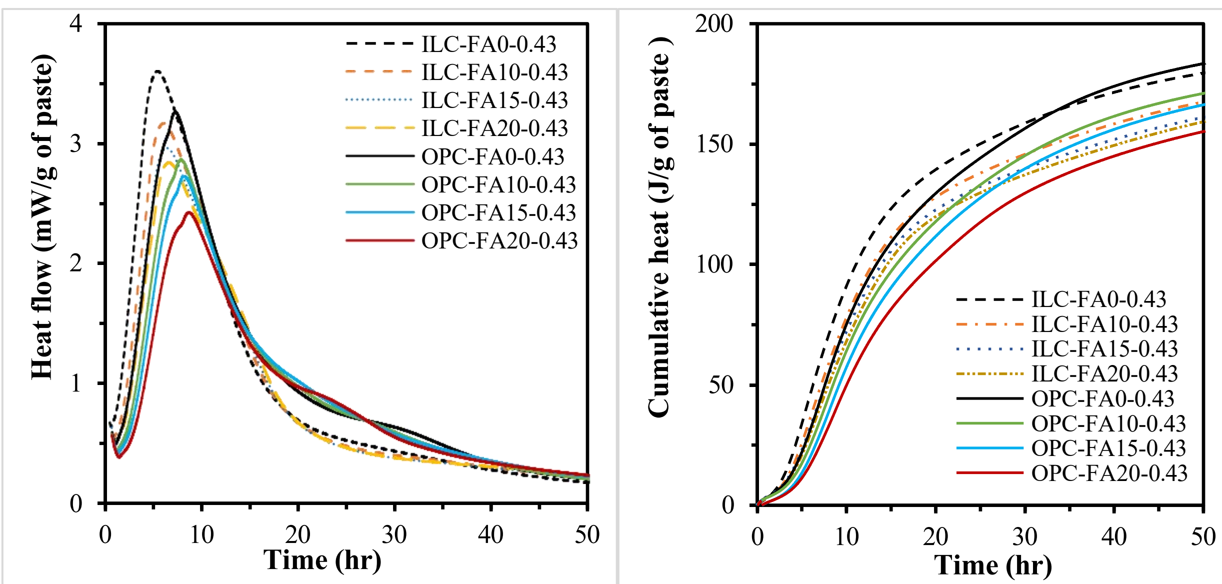


Figure *37*. Heat of hydration after 48 hours with a w/c ratio of 0.43

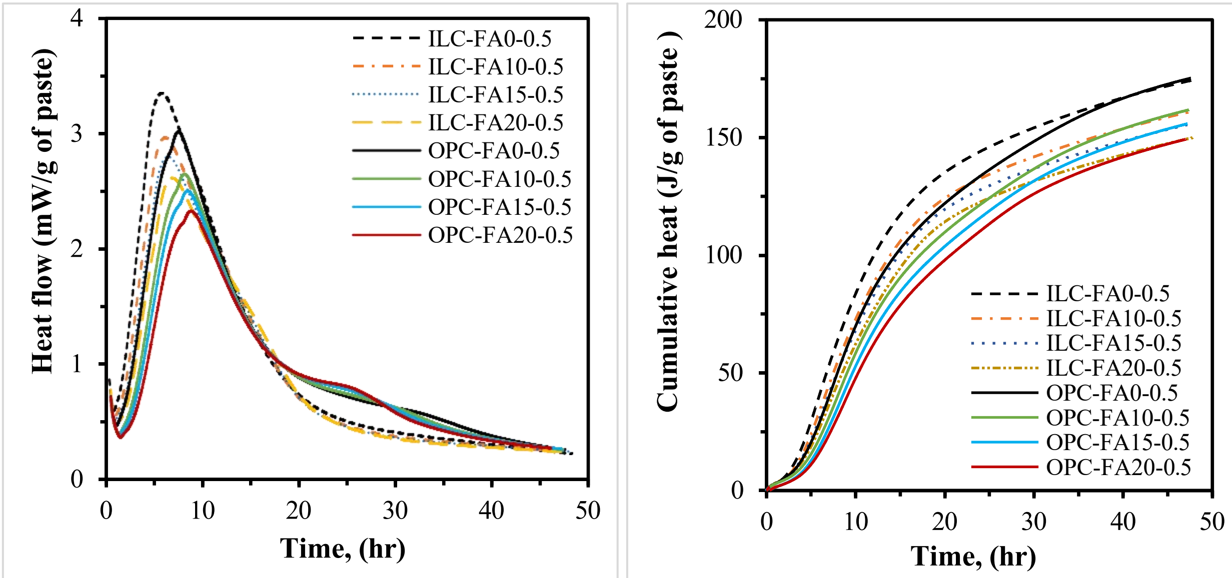


Figure *38*. Heat of hydration after 48 hours with a w/c ratio of 0.5

6.3 Ring Tests (Restrained Shrinkage)

As of the time of writing this report, none of the ring specimens had cracked. However, the measured strain values provide valuable information of the restraint stresses developed in each ring specimen. The experimental results (strain measurements) indicated that all modifications based on the baseline group (Mix 1) reduced restrained shrinkage strains (Figure 39). Additionally, the type of cement had a minor impact on shrinkage. Notably, Mix 7, which used cement Grade E (Type I), exhibited slightly lower restrained shrinkage strain when compared to Mix 1, which used cement Grade E (Type IL). Although the calorimetry test results showed higher temperature in Type IL mix, it appears that the filler effect from the limestone powder mitigates the higher temperature effects resulting in comparable (but slightly smaller) strains between Mix 1 and Mix 7 at 60 days.

Among the single modification methods, both Mix 2 (adding PVA fiber) and Mix 3 (reducing cement by 15%) successfully decreased restrained shrinkage strains, with Mix 2 (PVA fiber addition) demonstrating superior performance compared to cement reduction. Mix 4 (concrete with added fiber and reduced cement) exhibited lower restraint strains when compared to Mix 5 (15% fly ash) and Mix 6 (LMC).

Overall, the results indicated that Mix 4 displayed the best overall performance in terms of reducing restrained shrinkage. Based on these findings, it is clear that adding PVA fibers and reducing the cement content are the most effective methods for minimizing restrained shrinkage based on the ring tests.

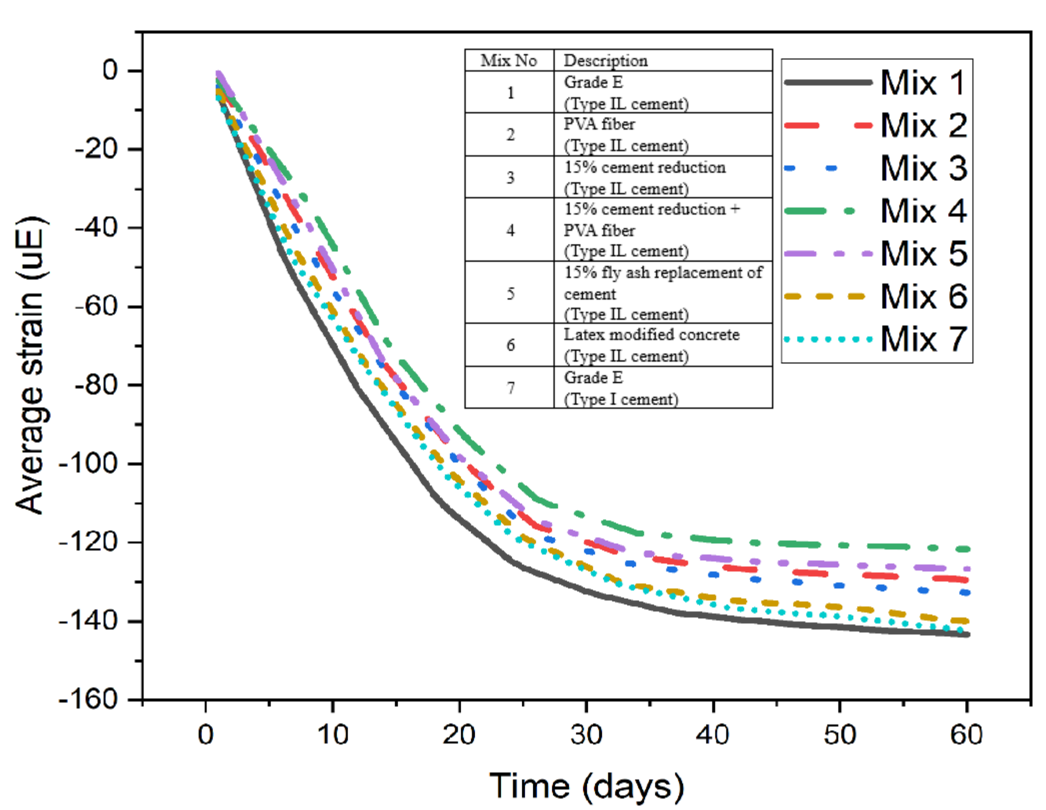


Figure *39*. Restrained shrinkage strains of various mixtures in ring tests.

6.4 Salt Ponding (Chloride Tests)

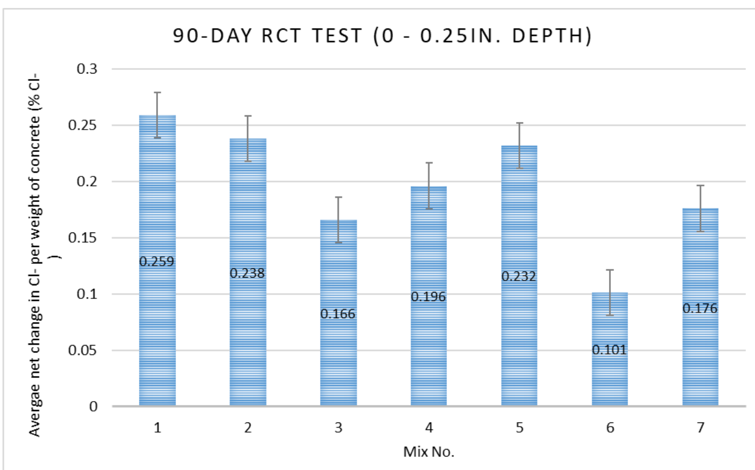
The 90-day rapid chloride test results are shown in Table 14. The test results showed the original chloride content of the concrete samples and the change in chloride ion content after exposure to 3% NaCl solution for 28 days. The net change in chloride ion content at depth 0-0.25in. are shown in Figure 40.

The 24-hr test for the ponded samples showed some changes in the chloride content. For concrete samples taken at a depth of 0-0.25 inches, the latex-modified mix had the least change in chloride ions. The fiber-reinforced mix (FRC), fly ash-modified mix (FAMC), and the original Grade E mix (NC-IL) showed the highest change in chloride ions. Samples taken at a depth of 0.25-0.5 inches showed smaller changes in chloride ions, as not enough chloride ions had traveled to this depth. The latex-modified mix showed the lowest change in chloride ions, while the fiber-reinforced mix (FRC) and Type I cement mix (NC-I) showed higher changes in chloride ions.

Table 14. Summary of **90-day** Rapid Chloride test

Mix No	Mix ID	Average Chloride content Original concrete (%) *	Average net change in Cl- (%) * (Depth: 0-0.25in)	Average net change in Cl- (%) * (Depth: 0.25-0.5in)
		24 hr. test	24 hr. test	24 hr. test
Mix 1	E-IL	0.052	0.259	0.052
Mix 2	FRC	0.050	0.238	0.042
Mix 3	CR-15	0.084	0.166	0.019
Mix 4	FRC-15	0.077	0.196	0.023
Mix 5	FAC	0.070	0.232	0.058
Mix 6	LMC	0.073	0.101	0.034
Mix 7	E-I	0.091	0.176	0.011

*All values are percent chloride by concrete weight



Mix No	Description
1	Grade E (Type IL cement)
2	PVA fiber (Type IL cement)
3	15% cement reduction (Type IL cement)
4	15% cement reduction + PVA fiber (Type IL cement)
5	15% fly ash replacement of cement (Type IL cement)
6	Latex modified concrete (Type IL cement)
7	Grade E (Type I cement)

Figure 40. Net change of chloride ions at 0-0.25in. depth after 90 days

6.5 Dog Bone Tests (Assessment of Curing Procedures)

The strains in the restrained samples were recorded as restraint strains developed in the steel because of the strains generated in concrete. Shrinkage in concrete is restrained by steel tubes which, in effect, generate tensile stresses in concrete. Alternatively, expansion in concrete is also restrained by the steel tubes, which can cause compressive restraint stress in the concrete.

In the following figures, measured strain readings are shown either with respect to the condition at day 1 (i.e., zeroed out at concrete age of 1 day) (shown in blue color), or with respect to the condition at the day when the covering (curing) was removed (i.e., zeroed out at the time curing ended, either day 3, 7, or 14) (shown in orange color). The strain profiles of the samples at different stages of the curing process were analyzed. The results showed that moisture that is present in the wet burlap in the early stages causes concrete to expand slightly. However, the concrete shrinks as the moisture is lost, resulting in tensile stresses in concrete (higher negative strains). With an initial expansion, the effect of subsequent contraction (shrinkage) can be mitigated.

Results of the plastic only (P3, P7 and P14) are shown in Figures 41 through 43. The strain values referenced to day 1 (blue) showed roughly similar values for all samples, although slightly higher negative strains were recorded for the 14-day cured specimens as shown in Figure 43. For strain in Figures 41 and 42 referenced to day 1, maximum strains of about 78 µstrains were recorded for the 3-day and 7-day cured specimens, compared to about 98 µstrains for the 14-day cured samples. Strains referenced to the end of the curing periods showed significant differences in the samples. The strain change for the 3-day cured specimens showed larger negative strains (max of 88 µstrains) than for the 7-day curing (max of 72 µstrains) and 14-day curing (max of 56 µstrains).

Based on these observations, we can conclude that plastic curing for 3- and 7-day periods have similar strain responses on the specimen. However, plastic curing for 14 days generates higher shrinkage strains likely due to moisture leaking out of the plastic covering.

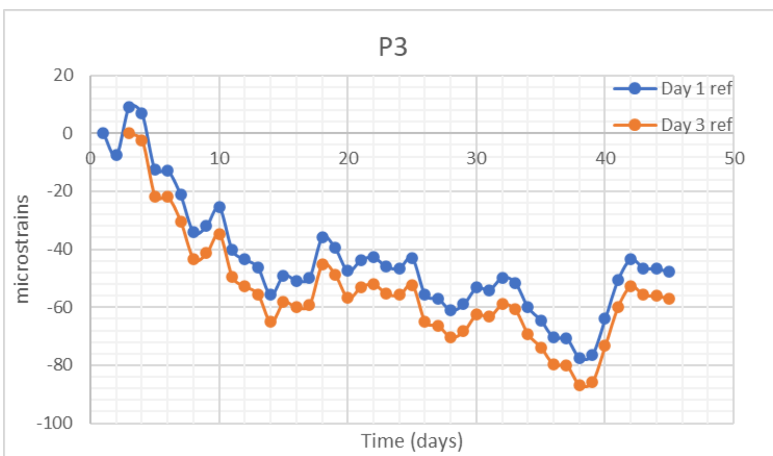


Figure 41. Strain results - 3-day curing with plastic sheathing.

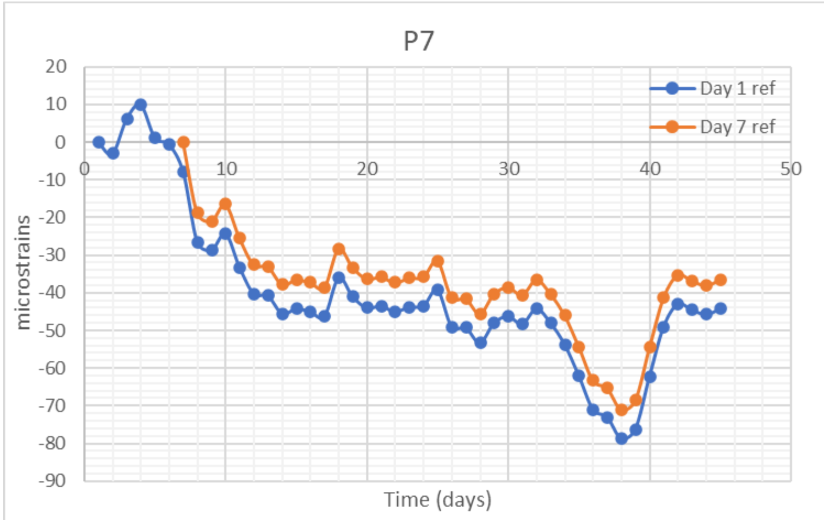


Figure 42. Strain results - 7-day curing with plastic sheathing.

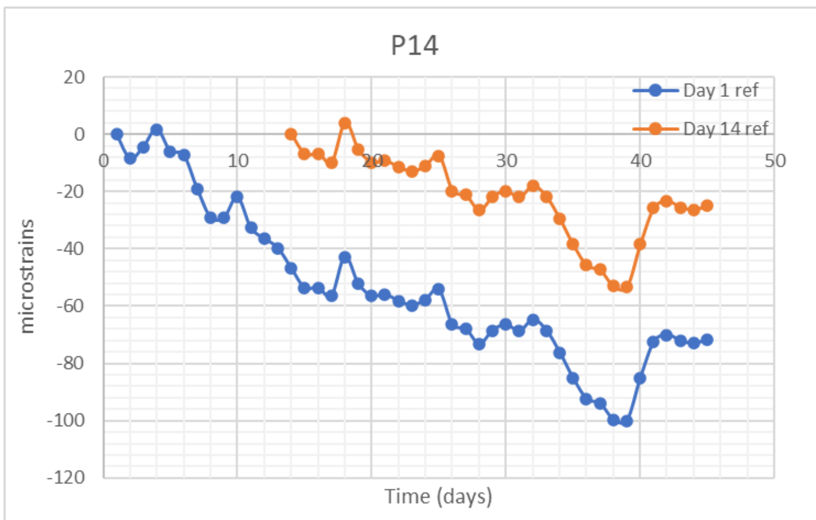


Figure 43. Strain results - 14-day curing with plastic sheathing.

The strain profiles of dog bone specimens cured with burlap and plastic covering (PB) for 3, 7, and 14 days are shown in Figures 44 through 46. The results show that wet-cured samples exhibited much higher initial positive strains (expansion of concrete) than the plastic-covered samples discussed earlier, when considering the strain profiles referenced to Day 1. This initial positive strain resulted from a large source of available moisture from wet burlap.

With a short, wet curing period, rapid moisture loss after removal of curing resulted in a sharp increase in shrinkage strains. For a longer wet curing period, lower overall shrinkage is observed. In Figure 44, the 3-day wet cured specimen exhibited a strain drop of about 80 µstrains, while the 7-day cured specimen (Figure 45) showed a strain drop of about 60 µstrain. Figure 47 shows that the 14-day cured specimen exhibited a high positive strain before and after the shrinkage due to the availability of more moisture during the curing period, and an expansion of concrete before removal of curing, which increased the initial strain (positive).

Figure 47 shows the strain result for the 7-day wet cured specimen with 15% cement reduction (NPB7). These specimens (NPB7) showed a higher early positive strain (compression) than the specimen without cement reduction (PB7). Specifically, NPB7 exhibited an early strain reading of about 400 µstrains, followed by a reduction of about 100 µstrain at the end of the curing period as compared to 60 µstrain for PB7 in Figure 45. NPB7 performed similarly to the 14-day curing specimens but with lower strains. This clearly shows the benefits of extended wet curing.

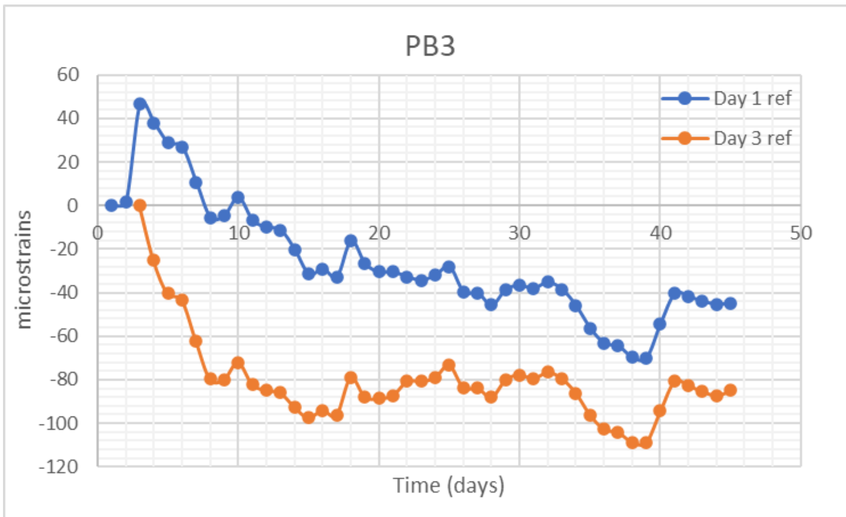


Figure 44. Strain results - 3-day curing with wet burlap and plastic sheathing.

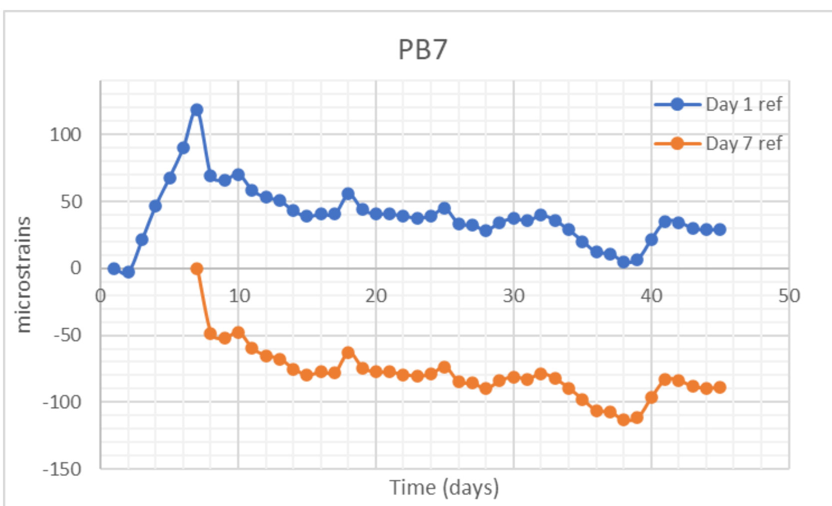


Figure 45. Strain results - 7-day curing with wet burlap and plastic sheathing.

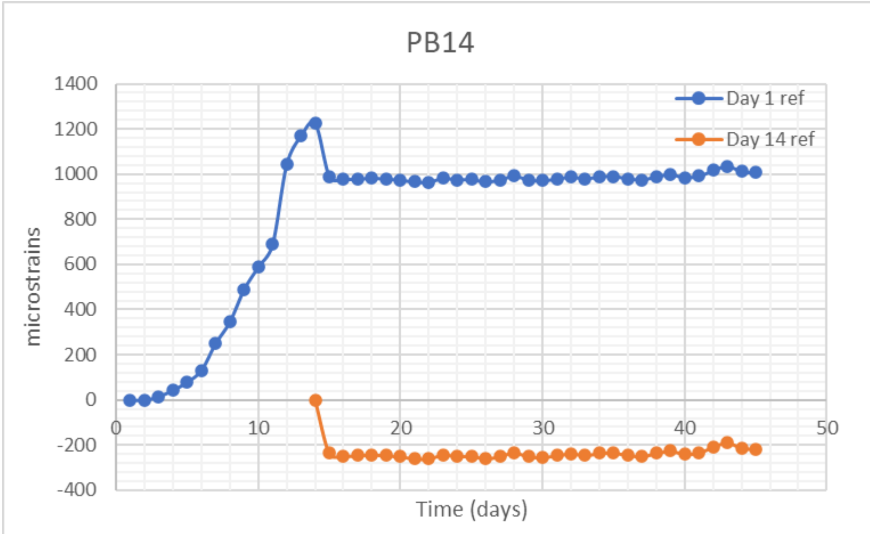


Figure 46. Strain results - 14-day curing with wet burlap and plastic sheathing.

A crack developed on the 3-day wet cured restrained specimen. This indicates that the length of wet curing period is critical, and a 3-day curing is not sufficient. Based on the results and observations, the 14-day wet curing method is ideal for the overlay concrete, as it exhibits lower overall shrinkage strains and leaves the specimen in compression after the end of curing. However, the 14-day period may be too long when the bridge must be opened to traffic as soon as possible. Overall, the 7-day wet curing with a 15% cement reduction (NPB7) is recommended. However, a 14-day wet burlap curing provides superior performance.

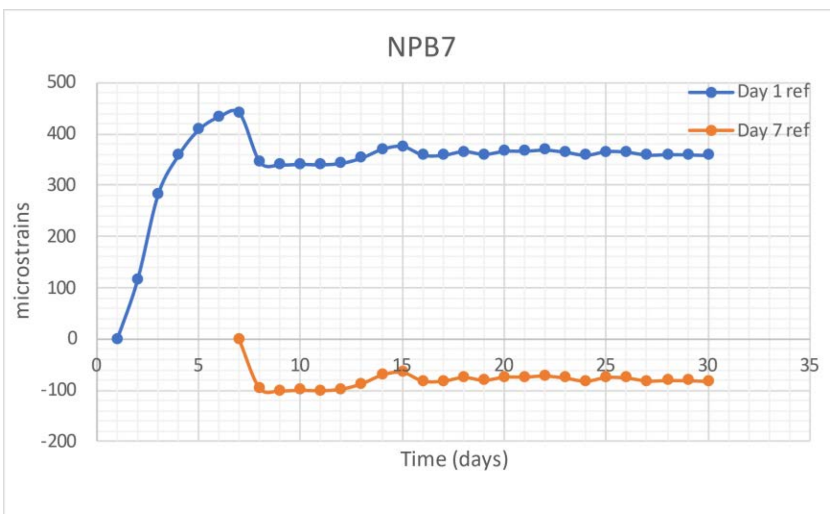


Figure 47. Strain results 7-day wet burlap and plastic curing (15% cement reduction)

6.6 Field Slab Monitoring

The overlay slabs for this study were cured using plastic sheathing, with half of slab (west side) covered for three days and the east side covered for seven days. This experiment investigated the performance of overlay slabs in the field and their susceptibility to cracking as well as the effect of plastic cover curing duration on the performance. Crack conditions were monitored on a weekly basis and mechanical strain gage and temperature measurements were also made at the same time. The slabs are subjected to changing temperature and moisture conditions in the field. Temperature and moisture movements create substantial variability in the measured strain values. Strain measurements were not consistent and did not provide a discernable pattern due to substantial moisture and temperature fluctuations.

Slab 7, the current Grade E overlay mix (with Type I cement) developed a short visible crack on the west side shortly after casting (1-2 weeks). Later, this crack grew to the entire width of the slab as shown in Figure 48. A few short-length hairline cracks have also been noted on Slabs 5 and 6. Other slabs did not show any cracking during this study.

Figure 48. Cracks on Overlay Slab 7 (E-I)

7 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

7.1 Summary of Test Results

The performance and adequacy of various mix designs for deck slab overlays were assessed through a series of laboratory and field tests. The 28-day compressive strength results showed that all seven mix designs (Mix 1 through Mix 7) exhibited very high strengths with values ranging from 7700 to 11000 psi. Addition of 1.5 lb/cy of PVA fiber to the mixes (FRC & FRC-15) with or without the reduction of cement content (while maintaining the water-to-cement ratio at 0.324) resulted in higher compressive strengths. The latex modified concrete had the lowest compressive strength of all mixes, but still exhibited a high strength. Although high strength may imply better performance, that is not the case when deck cracking due to inelastic restraint strains (such as shrinkage) is an issue. Higher early strength means higher stiffness, which results in higher tensile restraint stresses that can contribute to overlay cracking. The structural purposes of the overlay can be met with substantially reduced compressive strengths. The reduction of cement content by 15% while maintaining the same water content (i.e., increasing the water-cement ratio to 0.381 from 0.324) reduced the compressive strength to 7800 psi.

The heat-of-hydration (calorimetry) tests indicated that the new Type IL cement can generate higher peaks of heat flow compared to the OPC (Type I). This is due to the substantially smaller particle sizes in Type IL cements. The Type IL cement is ground to a finer size to compensate for the substitution of up to 15% of the cement with limestone powder. Finer cement particles are more reactive and can increase the heat of hydration, which can enhance the early compressive strength and (along with the filler effect of limestone) compensate for the reduction of cement. The compressive strength of the Mix 1 (with Type IL cement) and Mix 7 (with Type I cement) were 8770 and 8390 psi, respectively.

The reduction of cement content (i.e., increasing the water-cement ratio from 0.36 to 0.5) resulted in reduced heat flow for both IL and OPC samples. Finally, replacing cement with fly ash (0, 10%, 15%, and 20% replacement) resulted in progressively smaller heat flow peaks. These results indicate that reductions in cement content and addition of fly ash can mitigate the early rise in temperature, thus reducing the potential for early cracking.

The salt ponding test results indicated that the latex modified concrete had the lowest chloride content. The reduction in cement content or addition of fly ash did not increase the chloride content. Considering that the overlay does not include any steel reinforcement, the diffusion of chlorides through the entire thickness of the overlay and the deck cover would take a substantial amount of time. It is the cracking, however, that can short-circuit this protective system and allow chlorides to reach the deck reinforcement faster. Therefore, crack control and mitigation is an essential part of preserving the bridge deck. If the overlay is cracked, low-viscosity crack sealers should be applied and reapplied periodically to maintain protection against chlorides.

The restrained shrinkage tests (ring tests) reveal trends in the development of restraint strains in various mixes, including the current WisDOT Grade E mix. Although none of the restrained shrinkage tests (ring tests) experienced cracking at the time of writing of this report, the measured restraint strains (on the steel rings) clearly show differences in stresses developed in the concrete over time. The lowest restraint strains were associated with the addition of PVA fibers and 15% reduction in cement (Mix 4) followed by the mix with 15% replacement of cement with fly ash (Mix 5). Mix 2 (Grade E mix with PVA fiber) and Mix 3 (15% reduction in cement) exhibited slightly higher restraint strains. The worst sample was Mix 7 (current

Grade E mix with Type I cement). The second worst was Mix 1 (Grade E mix with Type IL cement). The results of calorimetry tests alone would have suggested a worse performance for Mix 1. However, the limestone powder in Type IL cement acts as a filler, which can potentially mitigate shrinkage strains (Madani et al. 2011, and Ahmad et al. 2021). In general, findings from both calorimetry and ring tests suggest that the current WisDOT Grade E mixture (Mixes 1 and 7) can lead to higher cracking potentials, thus supporting the field observations and the current experience in Wisconsin.

The dog-bone restraint test is a new test that was designed in this study to examine various curing procedures. This test is somewhat similar to the ring test in that the concrete specimen is restrained against movement with two steel tubes with strain gages attached to them. This is meant to measure the restraint strains developed because of shrinkage or expansion of concrete in the test specimen (both during and after curing). The dog bone tests clearly established that wet curing (wet burlap) with presoaked burlap and covered with polyethylene sheathing is by far a better curing procedure when compared with covering the concrete with plastic sheathing alone (or similar). The 14-day curing results with plastic covering alone was not effective in keeping the specimens moist during the curing and this resulted in higher shrinkage during curing. The dog bone strain results show that wet curing induces an expansive strain in concrete, which can substantially mitigate the subsequent drying shrinkage. With respect to timing (duration of curing), the best results are achieved with a 14-day wet curing. However, it is realized that project requirements and the need to open the bridge to traffic may not allow a 2-week curing period. In such cases, no less than 7-days of wet curing should be maintained. It is important that a project's curing requirements (duration) are not waived based on achievement of specific compressive strength results from cylinder testing. Attainment of strength levels is not a valid measure of sufficient resistance to early cracking of overlays.

The field slab tests indicate that Mix 7 (current Grade E mix with Type I cement) developed an early crack which grew with time. Slabs with Mix 5 (Grade E with 15% cement replacement with fly ash) and Mix 6 (latex modified) have developed a couple of short hairline cracks. Other slabs (including the slab with Mix 1 – Grade E with Type IL cement) were uncracked as of the time of writing of this report. As stated earlier, this may change in the upcoming months. The current WisDOT Grade E overlay mix must be improved to reduce the potential for cracking. The slabs with PVA fibers performed well in both the field test and the ring test.

Although the Wisconsin Grade E overlay mix had been successfully utilized over several decades, its performance has declined in recent years due to extensive observed cracking, typically within the first year after placement. What has changed over the years primarily relates to the fineness of portland cement, which has increased substantially over the years [10]. Based on this research, a number of recommendations are made based on changes to the mix design (including addition of PVA fibers) and improvement of curing practices. The current Wisconsin Grade E mixture is susceptible to cracking and should be modified.

7.2 Recommendations

The following recommendations are made to help reduce or eliminate the phenomenon of early cracking in concrete overlays.

7.2.1 Timing of Overlay Placement

The primary objective of a deck overlay system is to extend the service life of the bridge deck. The overlay cannot do that if the substrate (bridge deck) is highly contaminated with chlorides, and the reinforcing bars are corroding. Therefore, it is important to place the concrete overlay when the deck slab has not deteriorated significantly. The Minnesota DOT has used an NBI deck rating of 6 as a benchmark for planning and installation of a concrete overlay (Tabatabai et al. 2016). The research team recommends the same approach for Wisconsin bridge decks.

7.2.2 Overlay Mix Design

Test results have demonstrated the positive effect of reducing the cement content or partial replacement of cement with fly ash. A cement reduction of 15-20% is recommended. Alternatively, a 15-20% replacement of cement with fly ash can be considered. Iowa allows incorporation of up to 20% fly ash in the concrete overlay mix. However, recent severe shortages of fly ash in the Wisconsin market and the long-term trends in reducing coal-based power generation require alternate solutions. The reduction of Grade E cement content by 15-20% is therefore recommended. For the current Grade E cement content of 823 lbs./cy, a 15% reduction would result in a cement content of 700 lbs./cy.

Our tests indicate improved performance when PVA fibers are added to the overlay mix. Considering that the incorporation of PVA fibers introduces additional mix elements, procedures, and costs, it is recommended that PVA fiber be added when a higher performance level is required. Therefore, it is proposed that two Grade E mixes (E1 and E2) be considered. Both grades would include a 15% cement reduction. However, Grade E1 would not incorporate the PVA fiber while Grade E2 would include PVA fiber (1.5 lbs/cy) as well as enhanced curing procedures (described in Section 7.2.3).

The Grade E mix has traditionally incorporated a relatively low water-cement ratio of 0.324 in Wisconsin and several other states. While lower water-to-cement ratios are important in achieving higher strength and lower permeability of concrete, they can also increase autogenous shrinkage and increase the stiffness of concrete, especially at early ages. The current w/c ratio has been in effect for decades. However, it is important to note that today's portland cement is much finer than the cement used in the early days. This would result in substantially higher temperature and stiffness at early ages. The problem of cracking of overlays is primarily related to restraint of inelastic compressive strains due to shrinkage and thermal effects. The restraint stresses are tensile and can crack the overlay. The restraint stress is equal to the restraint strain times the modulus of elasticity. Higher concrete stiffness (modulus of elasticity) of overlay concrete at early ages (due to low w/c ratio) results in higher tensile restraint stresses for a given restraint strain. As also noted by Hopper et al. (2015), to address early age cracking, it is important to not have too high or too low w/c ratios. It is therefore suggested that the water to cementitious material ratio for Grade E mixes (E1 and E2) be increased to 0.38 from 0.324. Our tests indicated that such a w/c ratio would still provide a substantial compressive strength of 7800 psi at 28 days.

The concrete overlay systems discussed in this research have long been known as “low slump” concrete overlays. Many overlay mix designs (including Wisconsin Grade E mix) have limited the slump to less than 2 inches. However, while the rationale for this requirement may be understandable (especially in decades past), the justification for its continued use in modern times is lacking. The availability of modern chemical admixtures (superplasticizers) makes it possible to achieve the goals of low-slump concrete without the significant workability and construction issues associated with low slump requirements. Therefore, it is proposed that the slump requirement for the Grade E (E1 and E2) be changed to less than 4 inches. This change could also potentially help with the limited availability of specialized equipment (such as double vibratory screed systems) needed for low-slump mixes.

7.2.3 Construction Requirements

Proper curing Procedures for concrete overlays are of utmost importance to reduce cracking. The current WisDOT provision for curing of overlay concrete is based on 3 days of curing and the curing procedures are based on the provisions in Section 502.3.8 which provides a few options including impervious coating, impervious sheathing, continuous wet cure, and alternative methods approved by the engineer. Several other states have higher duration curing requirements including 7 and 14 days of curing with wet burlap.

The curing tests performed using the dog bone specimens clearly show the benefits of at least 7 days of curing with pre-soaked wet burlap covered with a polyethylene sheathing. Fourteen days is better than 7 days but may not be practical in all situations. Wet burlap curing causes expansive strains in the concrete, which would mitigate the subsequent shrinkage after the curing has stopped. Coverage with plastic sheathing is found to be ineffective as leaks invariably reduce the humidity at the surface and the shrinkage would start even prior to removal of the cover. It is therefore suggested that Grade E1 overlays receive a minimum of 7 days of curing with a polyethylene coated pre-wetted burlap cover. The Grade E2 overlays should utilize a minimum of 14 days of curing using the same coated burlap procedure.

It is suggested that all full- and partial-depth patch repairs be performed before placing the overlay. Although not tested in this research, it is anticipated that simultaneous casting of the patch areas and the overlay may increase restraint stresses due to apparent “shear key” effect.

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APPENDIX A – SURVEY QUESTIONS AND RESULTS

Survey questions:

Q1 - Please select the role that best describes your background and experience.

Q2 – Which state or province (Canada) are you from (50 States, D.C. and Puerto Rico)

Q3 - Have you been involved in the design or construction of concrete overlays for protection of bridge decks, or have knowledge of the performance of such systems?

Q4 - In your view, at what point in the life of a bridge deck should a low-slump concrete overlay be considered?

Q5 - In your view, what is the expected service life (life span) of a low-slump concrete overlay?

Q6 - What is the expected traffic impact (length of construction in days) for a typical low-slump concrete overlay project (include deck preparation, concrete placement, and curing but do not include any expansion joint work or staging)?

Q7 - Based on your agency's experience or past research, what are the main advantages of concrete overlays over other overlay types (choose all that apply)?

Q8 - In your view, what are the main disadvantages of concrete overlays over other overlay types (choose all that apply)?

Q9 - In your view, under what circumstances other overlay types would be preferred over concrete overlays (please specify)?

Q10 - What is the average cost ($/SF) of a complete low-slump concrete overlay system (including surface prep, labor, materials, and curing)?

Q11 - Do you agree that more instances of overlay cracking have been noted in recent years even though the same mix design was successfully used in the past?

Q12 - What are the factors that contribute to the concrete overlay cracking on bridge decks (choose all that apply)?

Q13 - What is the typical thickness of a low-slump concrete overlay?

Q14 - In your view, what adjustments to the concrete overlay mix design or construction are likely to improve the cracking performance (check all that apply)?

Q15 - Has your agency made recent policy changes regarding concrete overlay mix design or construction practices to improve the cracking performance (check all that apply)?

Q16 - Are sealers and coating needed to extend the service life of concrete overlays (check all that apply)?

Q17 - What are the typical post-construction problems associated with recent placements of concrete overlays on bridge decks (check all that apply)?

Q18 - What mitigation/repair procedures are used to address concrete overlay cracking (check all that apply)?

Q19 - What are the typical surface preparation steps taken when placing concrete overlays on cracked and/or spalled bridge decks (check all that apply)?

Q20 - Based on your experience, what is the anticipated service life of a concrete overlay if constructed using current practices and without protection measures such as sealers and coatings?

Q21 - How much additional service life can be achieved with protection measures such as sealers and coatings?

Q22 - In addition to Portland cement, sand, gravel, and water, what other ingredients are added to the low-slump concrete overlay mix in your state?

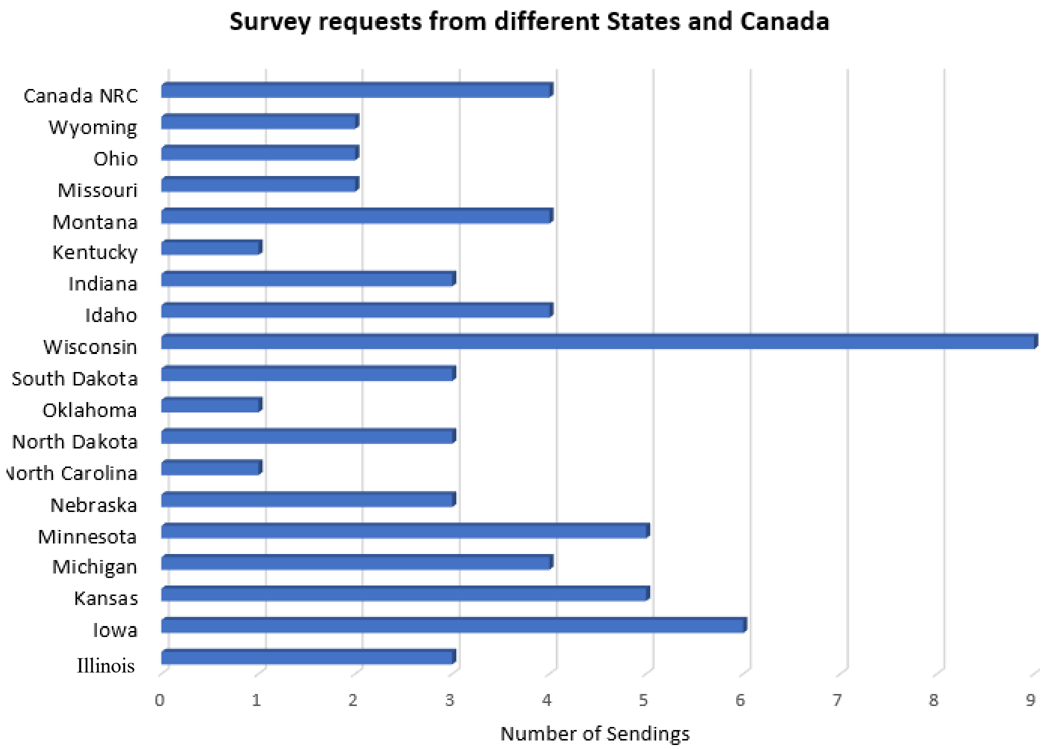
Q23 - What is the primary placement equipment used for low slump concrete overlays?

Q24 - Have you experienced issues associated with the supply or maintenance of equipment needed for low-slump concrete overlay construction?

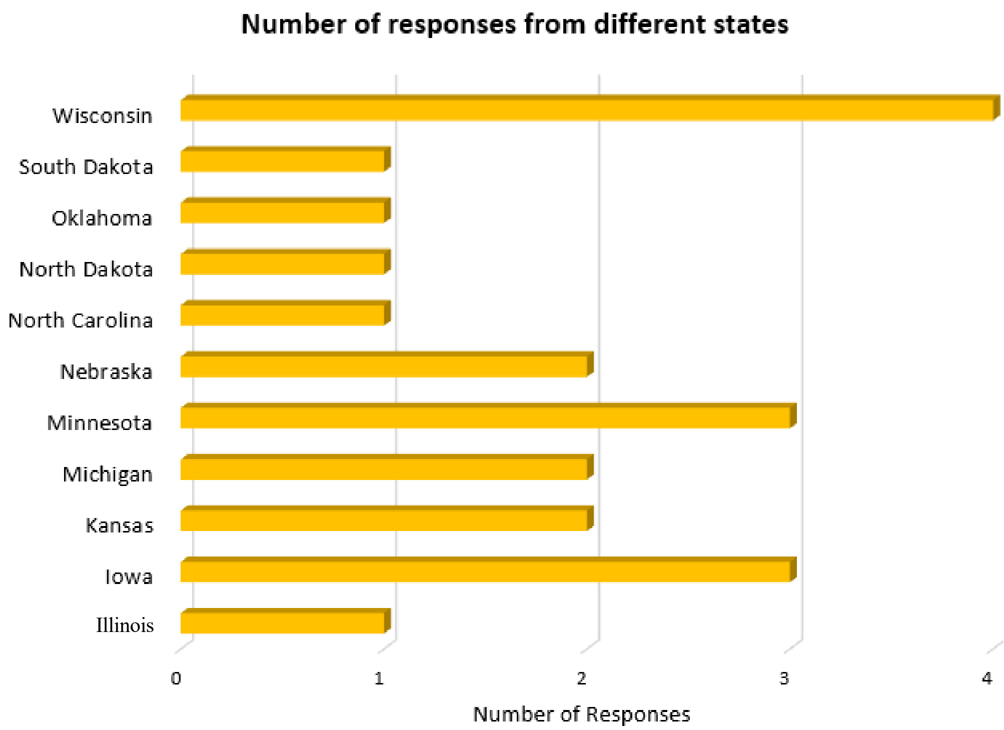
Q25 - In your view, what aspects of the low-slump concrete overlay should be improved?

Q26 - Would you be interested in participating in a follow-up phone survey?

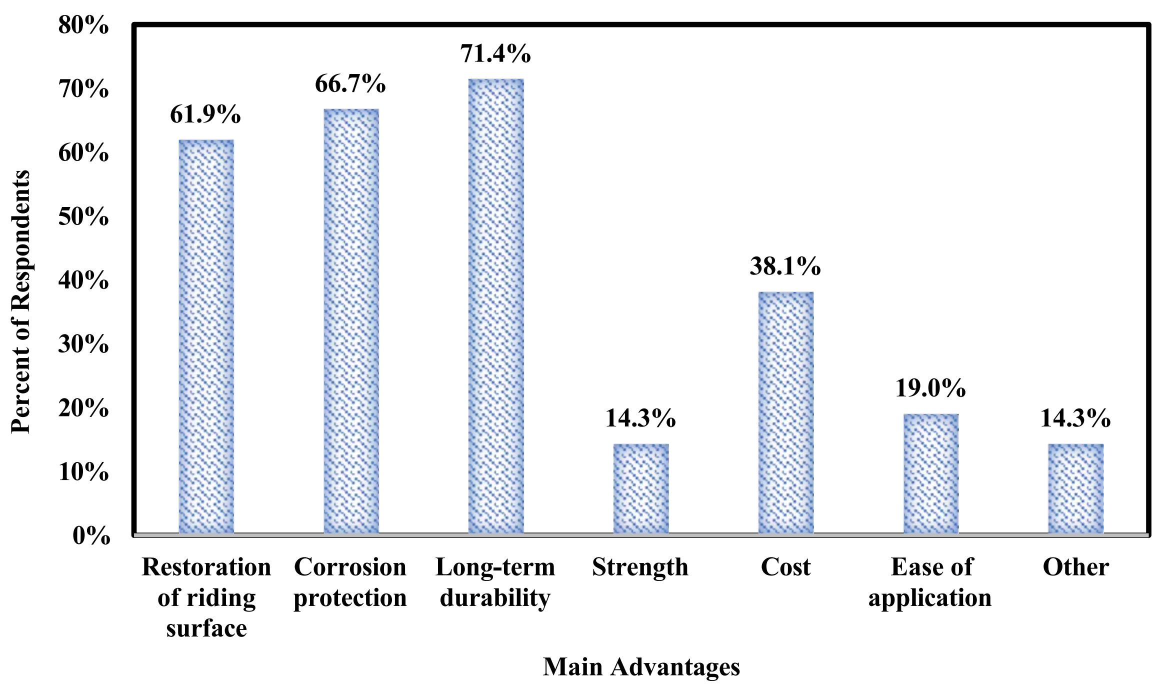
SURVEY RESULTS



Requests: 65

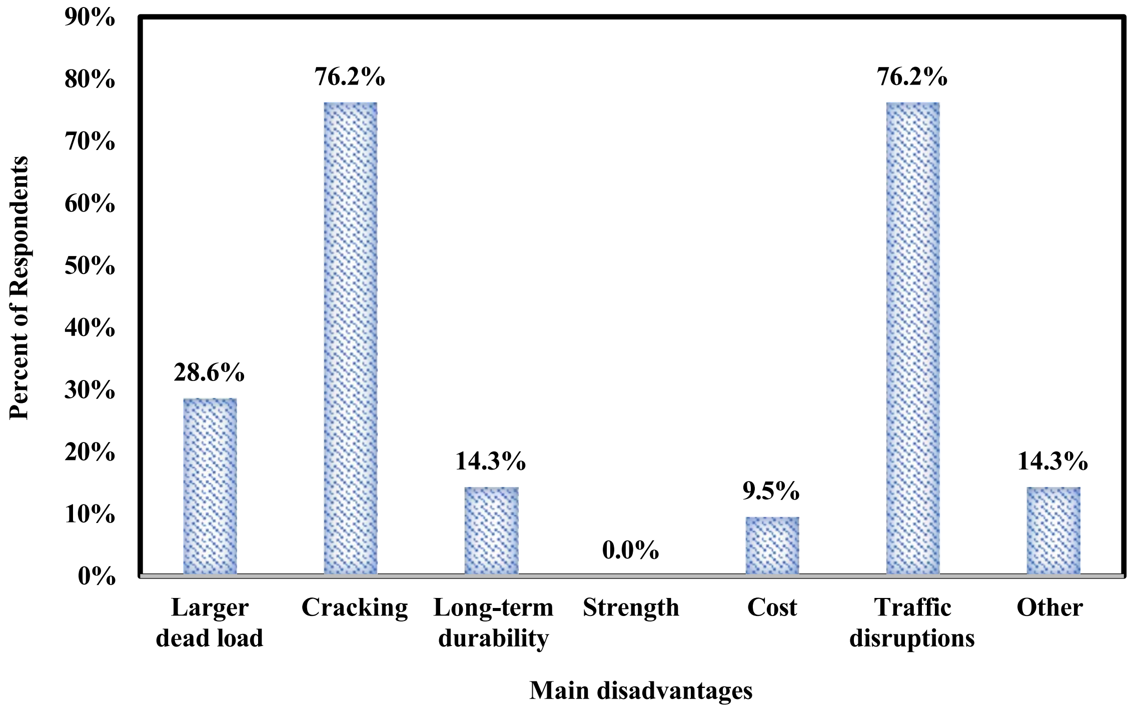


Reponses: 22



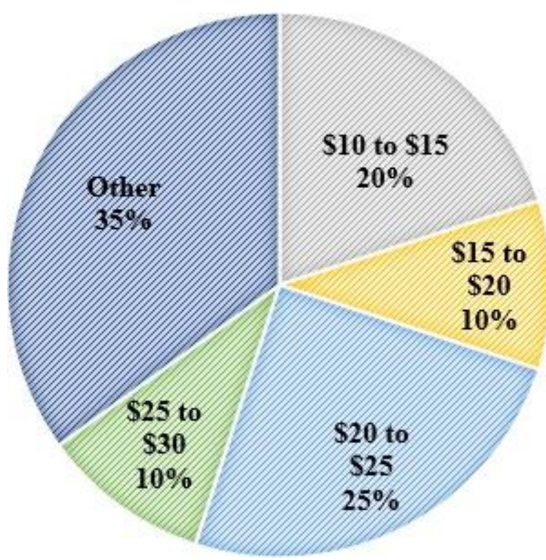
Response to Question on main advantages of concrete overlays

Respondents who chose “Other” provided the following specific comments: “life expectancy of overlay”, “Familiarity and setups of local contractors”, “Long-Term durability is an advantage provided the good bond and curing”, and “Compatible as deck patching material with overlay operation.”

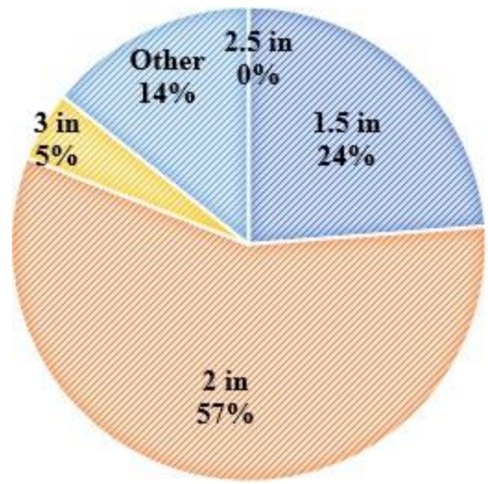


Response to Question on main disadvantages of concrete overlays.

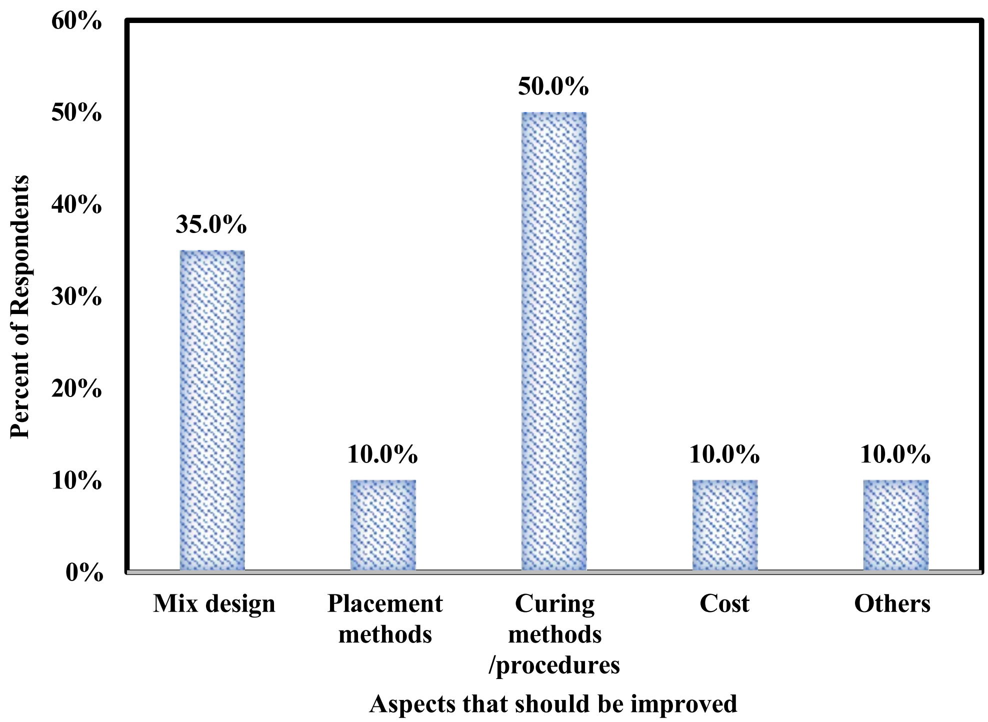
Respondents who chose “Other” provided the following specific comments: "Poor deck protection performance compared to alternatives" and "Construction duration."



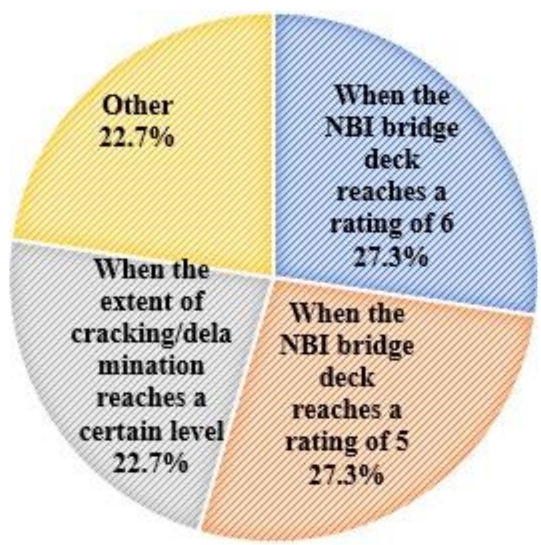
Response to question on cost per sq ft



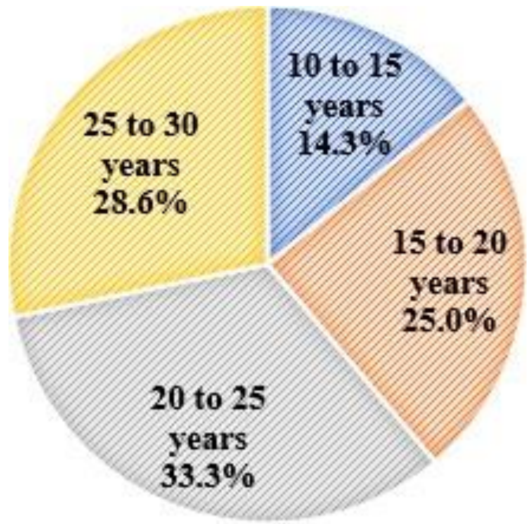
Response to question on thickness of concrete overlay.



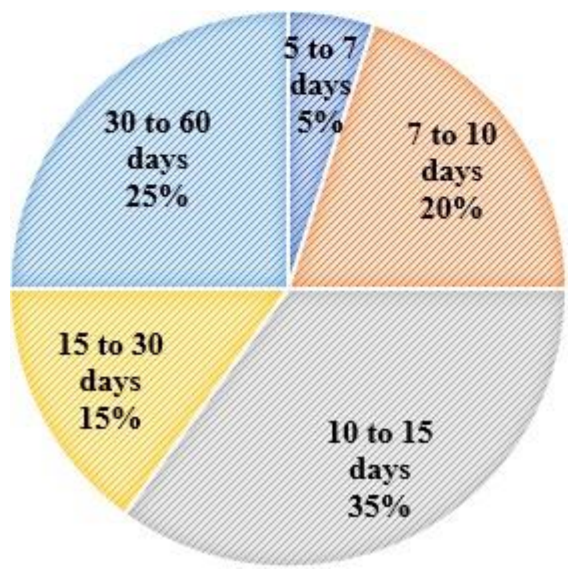
Response to question on aspects that should be improved.



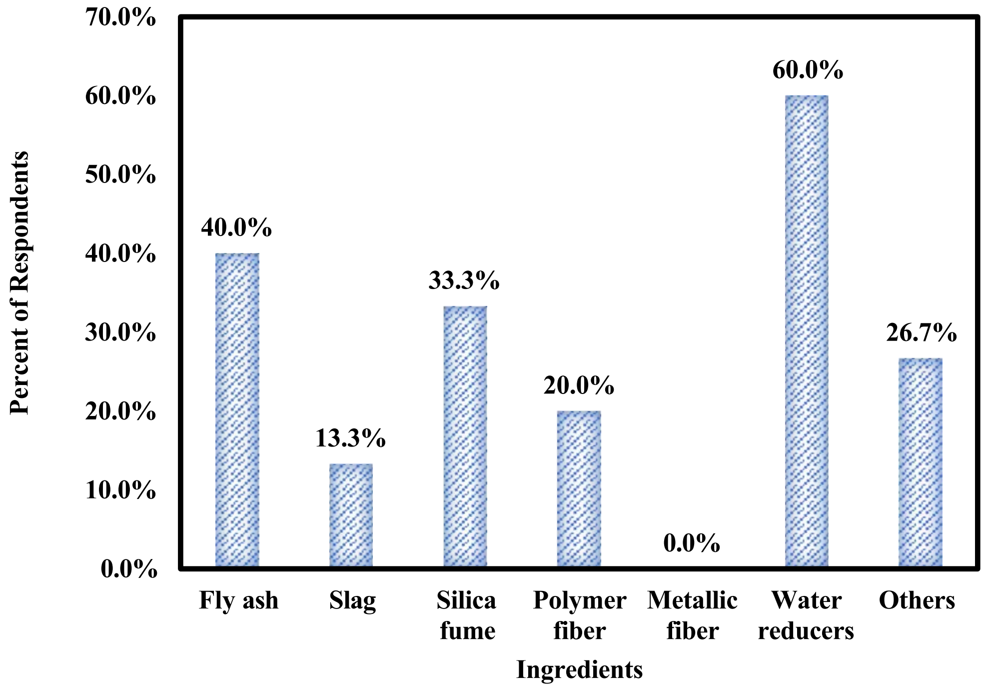
Response to question on when a concrete overlay should be considered.



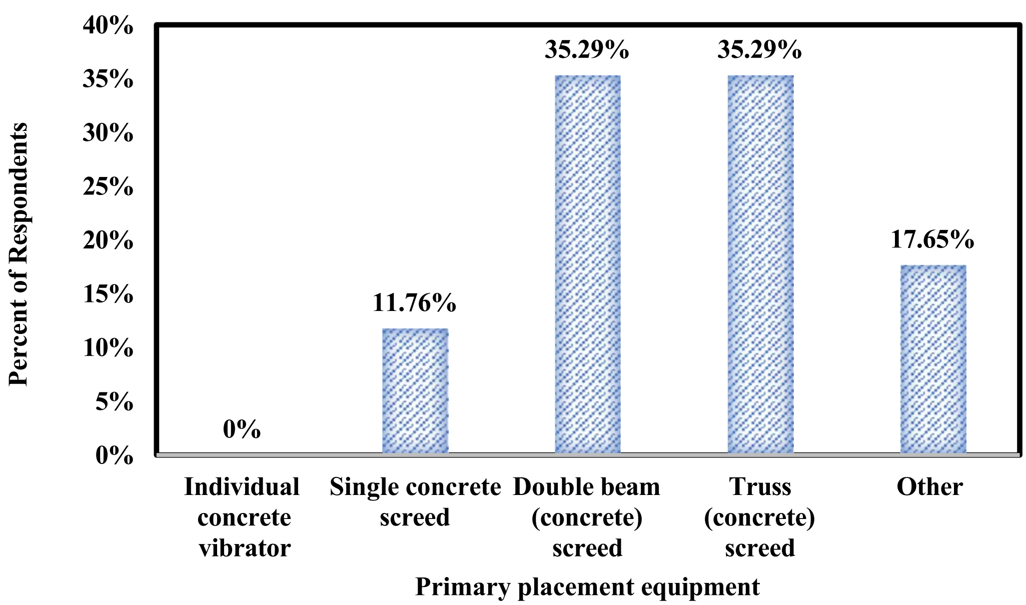
Response to question on expected service life of concrete overlay.



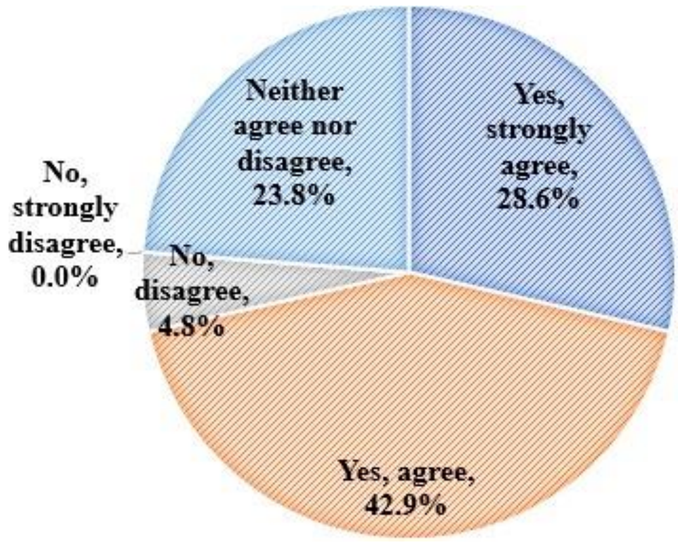
Response to question on expected traffic impact.



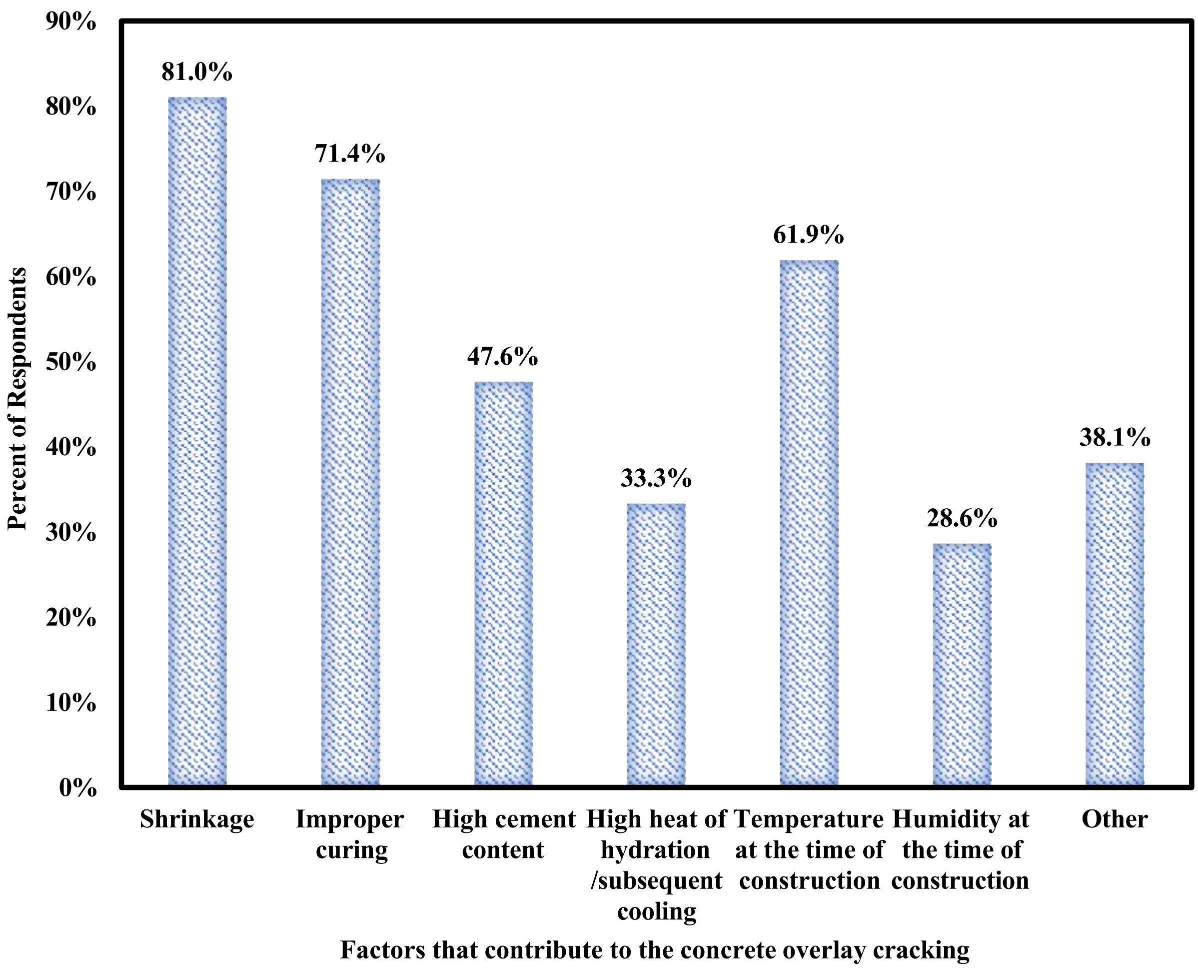
Response to question on other ingredients in concrete overlay mix.



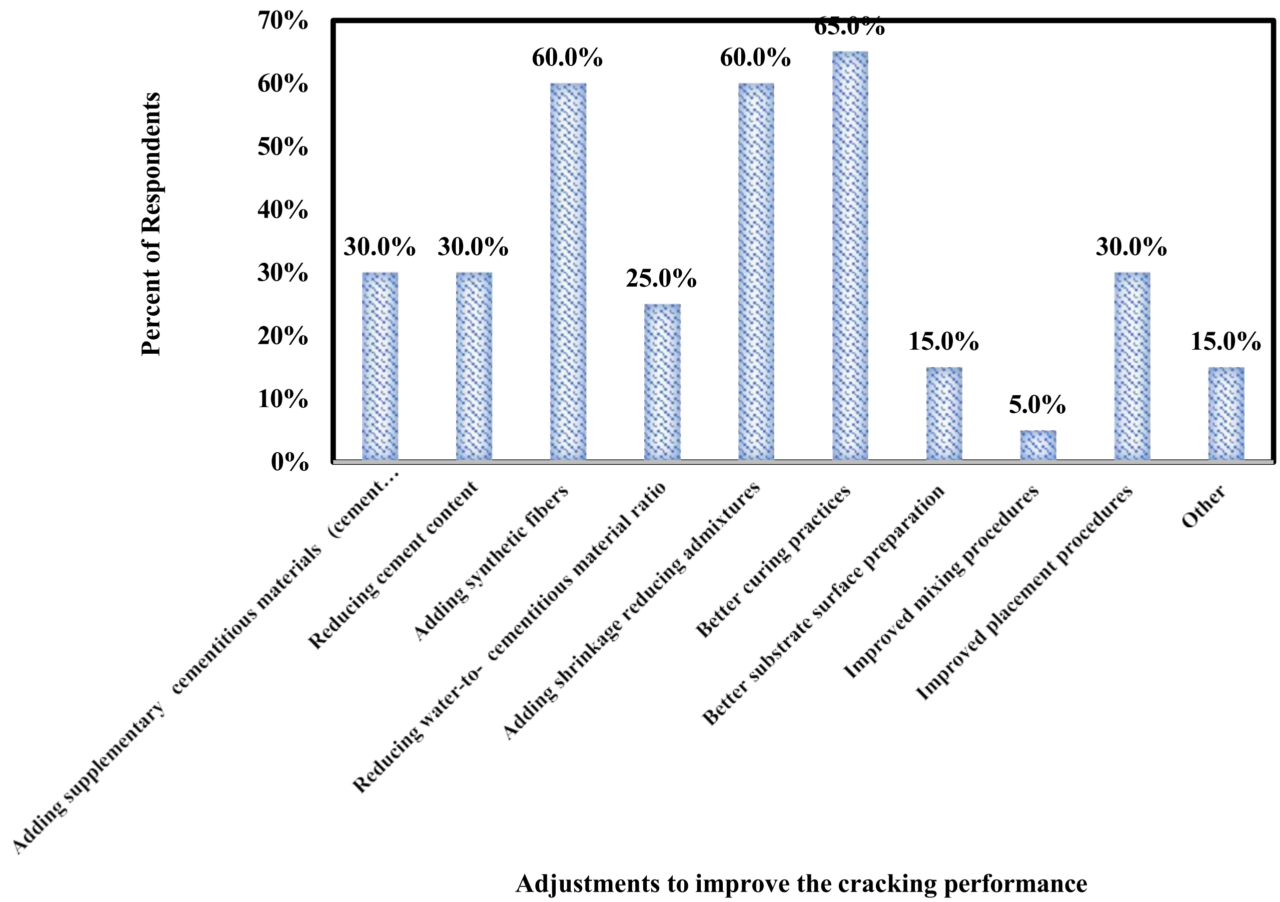
Response to question on primary overlay placement equipment.



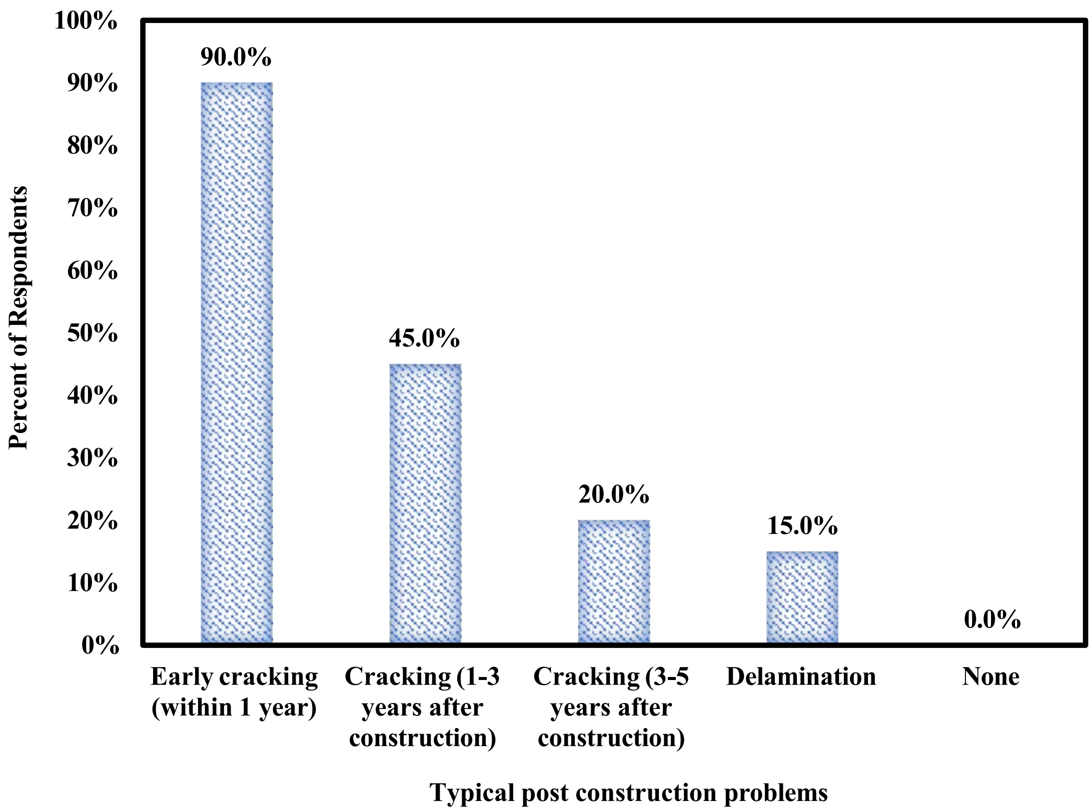
Response to question on recent increases in cracking.



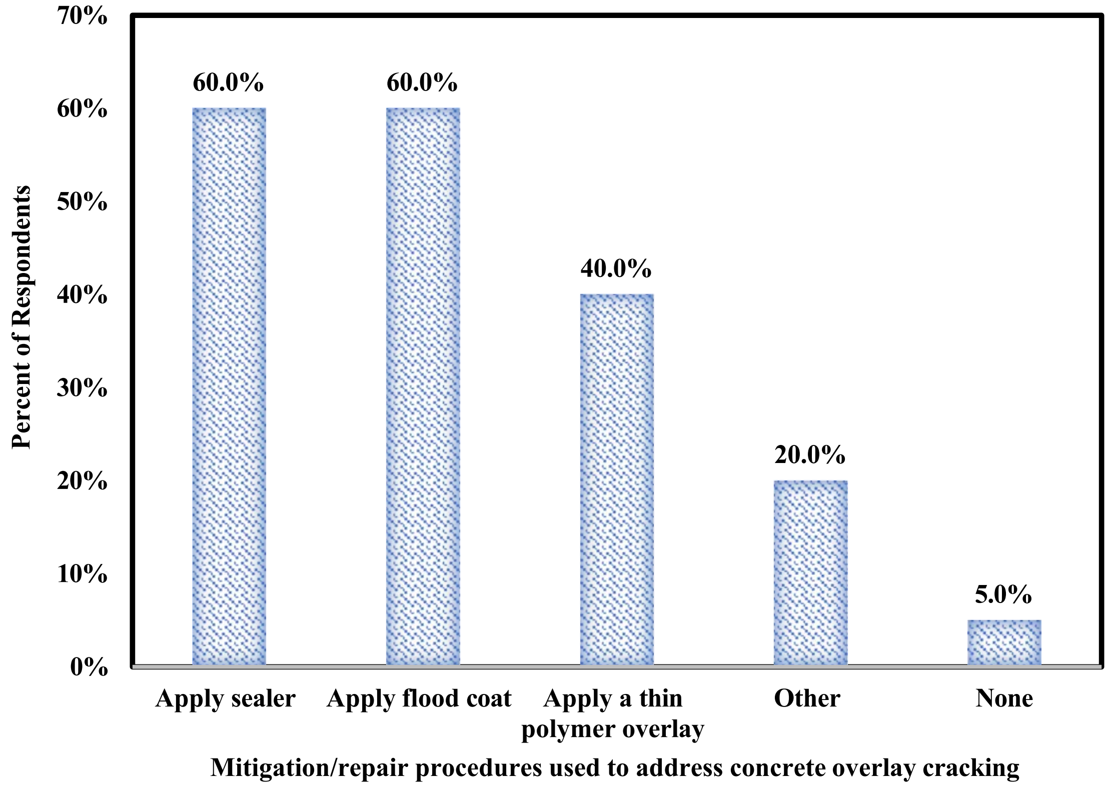
Response to question on factors that contribute to concrete overlay cracking.



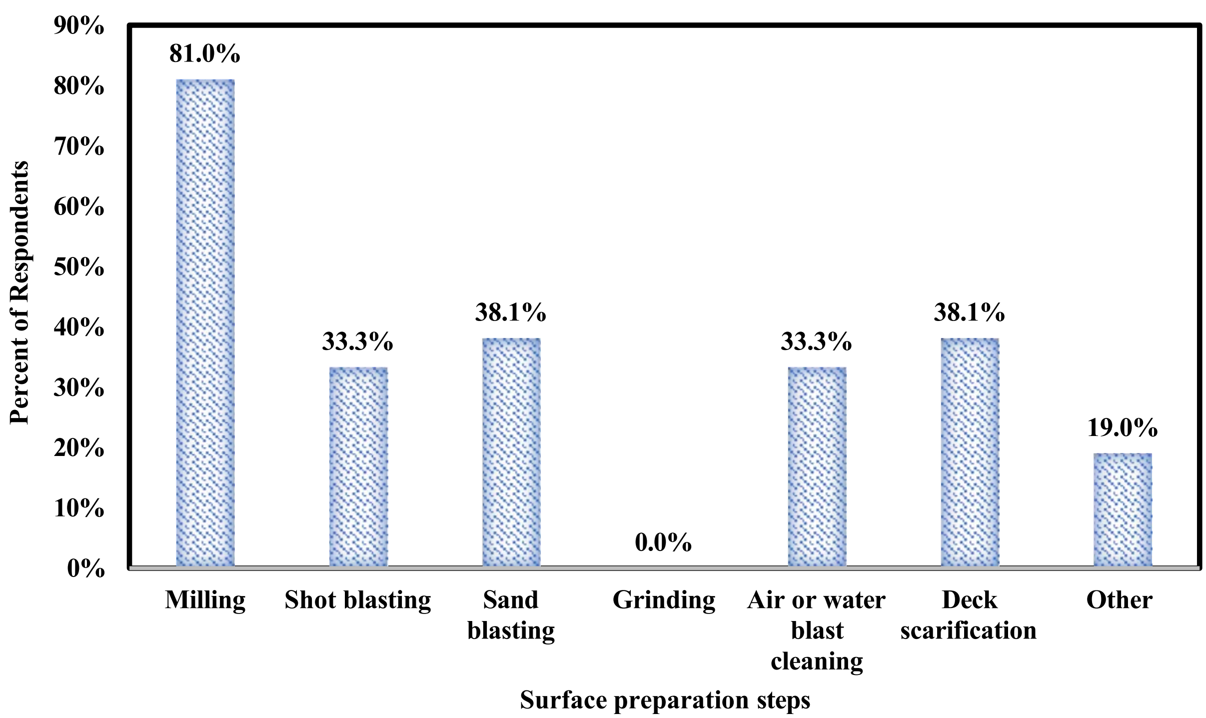
Response to question on adjustments to improve the cracking performance.



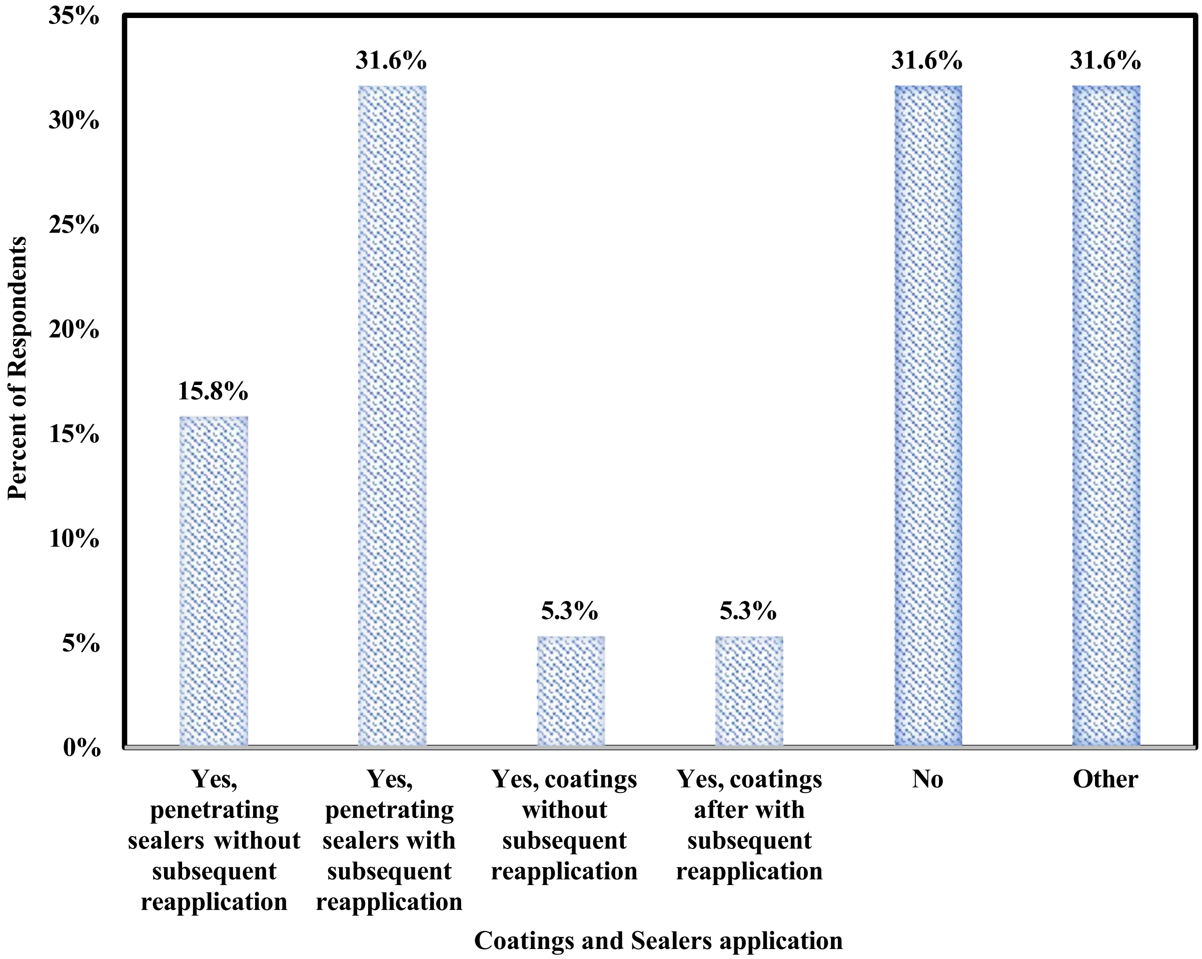
Response to question on post-construction problems.



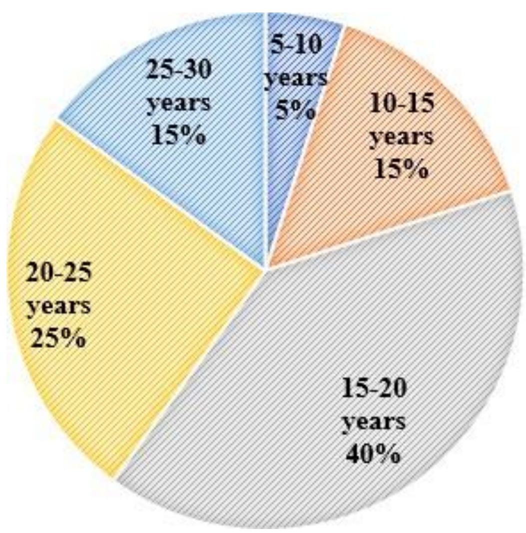
Response to question on mitigation/repair procedures used to address existing overlay cracking.



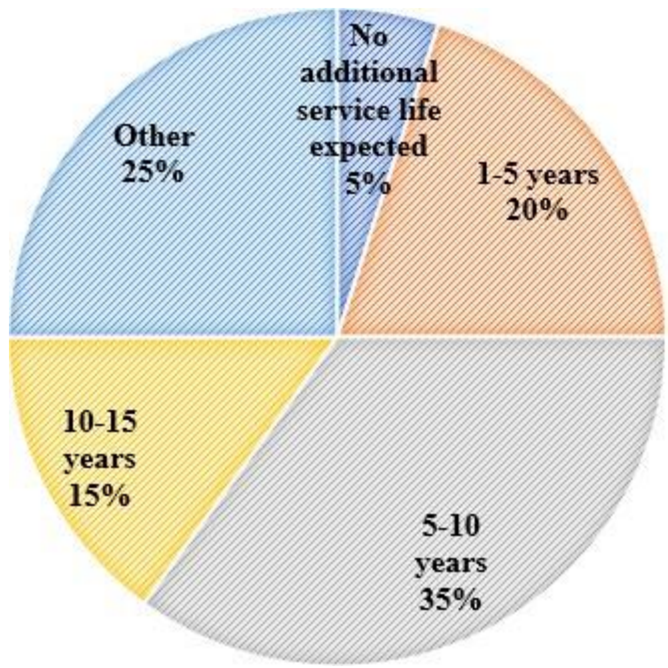
Response to question on surface preparation steps.



Response to question on coating and sealer application.



Response to question on anticipated service life of a concrete overlay without the protection of sealers and coatings.



Response to question on additional service life with protection of sealers and coatings.

APPENDIX B – PORTLAND CEMENT DATA

Votorantim Cimentos — St Marys Cement

Portland Cement Type I/II

Production Period : 1/1/2022 To 1/31/2022

STANDARD REQUIREMENTS

Chemical Data

Item	Spec. Limit	Results
SiO_2 (%)		19.4
Al_2O_3 (%)	*6.0 max*	4.8
Fe_2O_3 (%)		2.8
CaO (%)		61.2
MgO (%)	*6.0 max*	3.3
SO_3 (%)*		4.2
Loss of ignition (%)	*3.5 max*	1.9
Na_2O (%)		0.11
K_2O (%)		0.87
Insoluble residue (%)	*1.5 max*	0.44
CO_2 (%)		1.5
Limestone (%)	*5.0 max*	3.7
$CaCO_3$ in limestone (%)	*70 min*	95
Inorganic process addition(%)	*5.0 max*	0.0
Potential phase composition		
C_3S (%)		49
C_2S (%)		20
C_3A (%)	*8 max*	8
C_4AF (%)		9

Physical Data

Item	Spec. Limit	Results
Air Content of mortar (volume %)	*12 max*	8
Blaine fineness (m^2/kg)	*260 min*	391
Autoclave expansion (%)	*0.80 max*	0.13
Compressive strength (MPa/psi):		
1 day		16.9 [2460]
3 days	*12.0[1740] min*	27.2 [3940]
7 days	*19.0[2760] min*	33.5 [4860]
28 days *(previous month)*	*28.0[4060] min*	44 [6370]
Time of setting (minutes)		
(Vicat) Initial	*45 - 375*	105
(Vicat) Final		210
Mortar Bar Expansion (ASTM C1038) (%)*	*0.02 max*	0.011
Base Cement Phase Composition		
C_3S (%)		50
C_2S (%)		20
C_3A (%)		8
C_4AF (%)		9

OPTIONAL REQUIREMENTS

Item	Spec. Limit	Results	Item	Spec. Limit	Results
Equiv. Alkalies (%)	*A*	0.68	False Set (%)	*50 min*	69
			Retained 325 (%)		2.6

Additional Data

Type	Limestone	Inorganic Processing Addition
Amount (%)	3.7	0.0
SiO_2 (%)	2.7	
Al_2O_3 (%)	0.7	
Fe_2O_3 (%)	0.7	
CaO (%)	46.6	
SO_3 (%)	0.4	

This cement meets ASTM C150 and AASHTO M 85 Specification for Type I-II Portland Cement. The testing methods performed were in accordance with ASTM C109, C114, C151, C155, C185, C191, C204, C430, C451 and C1038

*It is permissible to exceed the max value for SO3 content, provided it is demonstrated by C1038 that the cement will not develop expansion exceeding 0.02% in 14 Days

Votorantim Cimentos

St Marys Cement

Blended Hydraulic Cement Type IL(13)

Production Period : 4/1/2022 To 4/30/2022

STANDARD REQUIREMENTS

Chemical Data			Physical Data		
Item	Spec. Limit	Results	Item	Spec. Limit	Results
SiO_2 (%)		18.9	Air Content of mortar (volume %)	*12 max*	9
Al_2O_3 (%)		4.5	Blaine fineness (m^2/kg)		486
Fe_2O_3 (%)		2.9	Retained 325 (%)		1.4
CaO (%)		63.7	Autoclave expansion (%)	*0.80 max*	0.32
MgO (%)		3.3	Compressive strength (MPa/psi):		
SO_3 (%)*	*3.0 max*	3.8	1 day		18.6 [2690]
Loss of ignition (%)	*10.0 max*	6.3	3 days	*13.0[1890] min*	26.7 [3870]
Na_2O (%)		0.10	7 days	*20.0[2900] min*	31.8 [4610]
K_2O (%)		0.95	28 days	*25.0[3620] min*	40.4 [5860]
CO_2 (%)		5.6	Time of setting (minutes)		
Limestone (%)	*15.0 max*	13.0	(Vicat) Initial	*45 - 420*	102
$CaCO_3$ in limestone (%)	*70 min*	95	(Vicat) Final		210
Inorganic process addition(%)	*5.0 max*	0.0			
			Mortar Bar Expansion (ASTM C1038) (%)*	*0.02 max*	0.005

OPTIONAL REQUIREMENTS

Item	Spec. Limit	Results
Equiv. Alkalies (%)	*A*	0.73

Additional Data

Type	Limestone	Inorganic Processing Addition	Item	Result
Amount (%)	13.0	0.0	Specific Gravity (g/cm3)	3.10
SiO_2 (%)	2.7			
Al_2O_3 (%)	0.7			
Fe_2O_3 (%)	0.7			
CaO (%)	46.6			
SO_3 (%)	0.4			

This cement meets ASTM C595 and AASHTO M 240 Specification for Blended Hydraulic Type IL(10) Cements. The testing methods performed were in accordance with ASTM C109, C114, C151, C155, C185, C191, C204, C430, C451 and C1038

*It is permissible to exceed the max value for SO3 content, provided it is demonstrated by C1038 that the cement will not develop expansion exceeding 0.02% in 14 Days

APPENDIX C – PROPOSED CHANGES TO WISDOT SPECIFICATIONS

Current	Proposed
509.3.9.3 Curing Concrete Overlays (1) Cure concrete overlays as specified for curing concrete in floors, wearing surfaces, and sidewalks in 502.3.8, including fogging, and allow to cure for 3 days.	509.3.9.3 Curing Concrete Overlays (1) Cure concrete overlays as specified ~~for curing concrete in floors, wearing surfaces, and sidewalks~~ in 502.3.8.1.2 within 15 minutes after finishing using pre-wetted polyethylene-coated burlap ~~including fogging~~, and allow to cure for ~~3~~ a minimum of 7 days (Grade E1) and 14 days (Grade E2). Overlap coated burlap at least 12 in. Secure the coated burlap covering in place. Ensure adequate moisture is present on the surface of the overlay beneath the curing material for a minimum 7-day and 14-day curing period for Grade E1 and E2, respectively. Attainment of a particular compressive strength (based on cylinder tests) is not a valid basis for waiving the minimum required curing duration.
509.2 Materials (3) Furnish grade C or E concrete conforming to 501 for surface repairs. The contractor may increase the slump for grade E concrete to a maximum of 4 inches. The contractor may apply an engineerapproved commercial grout or surface coating to surfaces being repaired instead of the grades of concrete designated above if the engineer approves in writing. (4) Furnish grade C or E concrete conforming to 501 for joint repairs, curb repairs, and full-depth deck repairs; except as follows: 1. The contractor may increase slump of grade E concrete to 3 inches.	509.2 Materials (3) Furnish grade C or E concrete conforming to 501 for surface repairs. ~~The contractor may increase t~~The slump for grade E concrete (both E1 and E2) must be a maximum of 4 inches. The contractor may apply an engineer approved commercial grout or surface coating to surfaces being repaired instead of the grades of concrete designated above if the engineer approves in writing. (4) Furnish grade C or E concrete conforming to 501 for joint repairs, curb repairs, and full-depth deck repairs; except as follows: 1. ~~The contractor may increase slump of grade E concrete to 3 inches.~~
502.3.13.1 Crack Sealing (1) For newly constructed bridge decks, seal cracks visible during dry weather conditions with low viscosity crack sealer. Conduct an initial crack survey with the engineer within 7 days after wet curing is complete, or when the deck dries enough to expose cracks requiring sealing. Seal the cracks identified in the survey. Seal crack areas only. Do not flood seal the deck unless the engineer allows as a part of overseeding with aggregate. (2) Prepare the deck by water blasting and apply crack sealer as the sealer manufacturer recommends except as follows: 1. The	502.3.13.1 Crack Sealing (1) For newly constructed bridge decks or deck overlays, seal cracks visible during dry weather conditions with low viscosity crack sealer. Conduct an initial crack survey with the engineer within 7 days after wet curing is complete, or when the deck dries enough to expose cracks requiring sealing. Seal the cracks identified in the survey. Seal crack areas only. Do not flood seal the deck unless the engineer allows as a part of overseeding with aggregate. (2) Prepare the deck by water blasting and apply crack sealer as the sealer manufacturer recommends except as follows:

contractor need only wait 7 days after completing moist curing before sealing. 2. Seal only if drying conditions have existed for the preceding 48 hours. 3. Immediately before applying sealer, direct an air blast over the surface to remove dust and any loose particles. 4. Seal before opening to public traffic.	1. The contractor need only wait 7 days after completing moist curing before sealing. 2. Seal only if drying conditions have existed for the preceding 48 hours. 3. Immediately before applying sealer, direct an air blast over the surface to remove dust and any loose particles. 4. Seal before opening to public traffic.
501.3.7.1 Slump (1) Use a 1-inch to 4-inch slump for concrete used in structures or placed in forms, except as follows: Do not exceed a slump of 2 inches for grade E concrete.	501.3.7.1 Slump (1) Use a 1-inch to 4-inch slump for concrete used in structures or placed in forms, except as follows: Do not exceed a slump of ~~2~~ 4 inches for grade E concrete (both E1 and E2).
TABLE 501-5 CONCRETE GRADES Grade E MINIMUM CEMENTITIOUS CONTENT FOR A NOMINAL CUBIC YARD (lb/cy) 823 MAXIMUM W/CM 0.36	**TABLE 501-5 CONCRETE GRADES** Grade E (both E1 and E2) MINIMUM CEMENTITIOUS CONTENT FOR A NOMINAL CUBIC YARD (lb/cy) ~~823~~ 700 MAXIMUM W/CM ~~0.36~~ 0.38
501.3.7.1 Slump Do not exceed a slump of 2 inches for grade E concrete.	**501.3.7.1 Slump** Do not exceed a slump of ~~2~~ 4 inches for grade E concrete.
528.3.5.1 Grade E Concrete Grade E concrete overlay must receive a tined finish. However, the turf drag or the alternative broom finish that is normally required before tining may be omitted. The curing period for Grade E concrete overlay is 3 days. Traffic may travel over a Grade E overlay or joint repair work 72 hours after completion unless the engineer extends the time period. Exception to this would be construction loadings on previously placed concrete overlay stages as indicated in standard spec 509.3.9.4(2). The intention is that all the concrete placed in previous overlay stages has cured a minimum of 12 hours (i.e., the last of the placed concrete on a previous pour has cured a minimum of 12 hours, and the remaining concrete has cured for longer). In addition to this curing requirement, the expectation is that the contractor maintains their curing process on all areas of the previously placed concrete overlay stages for the required 3 days; even throughout the set-up, placement, and finishing operations of an adjacent overlay.	528.3.5.1 Grade E Concrete Grade E concrete overlay must receive a tined finish. However, the turf drag or the alternative broom finish that is normally required before tining may be omitted. The curing period for Grade E concrete overlay is ~~3~~ a minimum of 7 days (Grade E1) and 14 days (Grade E2). Traffic may not travel over a Grade E overlay ~~or joint repair~~ unless the minimum curing period is completed. ~~work 72 hours after completion unless the engineer extends the time period~~. Exception to this would be construction loadings on previously placed concrete overlay stages as indicated in standard spec 509.3.9.4(2). The intention is that all the concrete placed in previous overlay stages has cured a minimum of 12 hours (i.e., the last of the placed concrete on a previous pour has cured a minimum of 12 hours, and the remaining concrete has cured for longer). In addition to this curing requirement, the expectation is that the contractor maintains their curing process on all areas of the previously placed concrete overlay stages for the required ~~3~~ 7 days; even throughout the set-up, placement, and finishing operations of an adjacent overlay.