May 2023

Improving Bridge Concrete Overlay Performance

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IMPROVING BRIDGE CONCRETE OVERLAY PERFORMANCE

by

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A Thesis Submitted in

Partial Fulfillment of the

Requirements for the Degree of

Master of Science

in Engineering

at

The University of Wisconsin-Milwaukee

May 2023

ABSTRACT

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by

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The University of Wisconsin-Milwaukee, 2023
Under the Supervision of Professor Habib Tabatabai

Low slump concrete overlays have been widely utilized in the midwestern United States, including Wisconsin, to mitigate bridge deck deterioration and extend service life. However, concerns regarding their performance have necessitated investigations into optimal mix designs, placement procedures, and curing practices. This study focuses on assessing the cracking potential of seven overlay mixtures, including: Current Wisconsin Grade E concrete with Type I and IL cement, latex modified concrete, fly-ash modified Grade E concrete, Grade E with reduced cement content, and fiber reinforced concrete. The various concrete mixtures were tested for compressive strength, slump, and air content. Seven 8ft x 8ft x 6 in test slabs were subjected to field conditions with 3- and 7-day curing periods. The salt ponding test was conducted on 21 small slab specimens fabricated based on the seven mix designs to assess their chloride penetration resistance. A new dog bone test was developed to assess the restraint stress response of Grade E mix (type IL cement) under different curing conditions. The 7-day wet curing (with wet burlap) is recommended (based on the dog bone test results) to control and limit restraint of shrinkage stresses. A 15% reduction in cement content and addition of PVA fibers to the Wisconsin Grade E mix can potentially improve the performance of overlays with respect to cracking. Latex modified mix exhibited the lowest chloride permeability.

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ACKNOWLEDGEMENTS

First, I want to express my deepest gratitude to my thesis advisor, Professor Habib Tabatabai, whose unwavering support, and expertise have been invaluable throughout this research. He has been a constant source of inspiration and motivated me to achieve my best. I am truly grateful for his mentorship and guidance, which have made a significant impact on my personal and academic growth.

I would also like to extend a tremendous thanks to Qian Lin, Rahim Reshadi, and Bob Breske, for their invaluable support with laboratory experiments and fabrication. Their expertise and knowledge have been instrumental in shaping my ideas and improving the quality of my work. I am incredibly grateful for their contributions and insights into my research.

Additionally, I am grateful to my colleagues and friends who have provided physical, academic, and emotional support throughout my research. Their friendship and unwavering support have been an essential source of motivation, and I am fortunate to have them in my life.

I am indebted to all those who have supported me throughout this journey. Thank you for your support, guidance, and encouragement, may you experience abundance of blessings.

1 INTRODUCTION

1.1 Background Information

Concrete overlays are commonly used on bridge decks when signs of distress in the form of cracking or delamination becomes evident. Long-term exposure to deicing salts and reinforcing bar corrosion can lead to significant distress after roughly 40 to 60 years of service. 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 midwestern United States. 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 Minnesota's 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]. This puzzling phenomenon occurs despite no apparent change in the mixed proportions or the process of mixing or placing concrete overlays. The problems observed in Wisconsin are not unique to Wisconsin and extend across state boundaries in the Midwest region and beyond. Therefore, a careful and thorough examination of the low slump overlay concrete mixtures, properties of the mixed ingredients, placement procedures, and curing practices is therefore needed to definitively address this problem. After identifying the relevant factors, options to extend crack-free service life of overlays may include addition of supplementary cementitious materials, reduction of Portland cement content, or the use of different materials such as latex modified overlays or synthetic fibers. Other factors may be related to the use of dual oscillating transverse screeds to achieve the desired finish for the overlay. Finally, there is interest in the long-term maintenance and protective measures for overlays that are needed to extend the life of the overlays (and the deck) and mitigate the long-term effects of any cracks that may appear over time and compromise the protective nature of a solid concrete overlay. The impact of these supplementary cementitious materials on the resistance of concrete to soluble chloride ions is also a durability concern for these overlay slabs.

1.2 Objective and Scope

The overall objective of this study is to evaluate alternate mixtures (with respect to cracking) of low-slump concrete overlays for bridge decks. An important goal is to identify solutions that could substantially reduce or eliminate the incidences of cracking while restoring the historically high-performing low-slump concrete overlays. Specific objectives and scope of this project are:

1. Investigate the cracking potential of various concrete overlay types such as latex-modified, pozzolans, fly ash-modified, and synthetic fiber-infused concrete, in addition to the current WisDOT Grade E mix.
2. Investigate the resistance of different concrete overlay mixes to penetration of chloride ions

To achieve the goals of this study, an experimental program was decided to evaluate the cracking potential of various overlay mixes and to study the impact of curing practices on the potential for cracking. Other tests were performed to assess the resistance of these overlay mixes to the penetration of chloride ion.

1.3 Thesis Organization

The thesis is organized into six chapters to present a comprehensive study on the performance of bridge overlay concrete. Chapter 1 introduces the research problem and objectives, while Chapter 2 offers a comprehensive literature review on the performance of low slump bridge deck overlays, cracking problems, and ways to mitigate cracking issues. Chapter 3 presents detailed information on the material, mix proportions, and mix procedures used in the study, while Chapter 4 describes the test methods employed, including compressive strength tests, field monitoring of concrete overlay slabs, dog bone tests, and salt ponding tests. The results and discussions of the field overlay slabs compressive strength tests, dog bone specimen, and salt ponding test are presented in Chapter 5. Finally, Chapter 6 summarizes the conclusions drawn from the study results and provides recommendations for future research. The Appendix includes experimental data on the rapid chloride test results for further reference.

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 the premature deterioration of concrete overlays, including 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], such as improving ride quality, reducing service interruption, extending service life, and improving public safety. The low-slump dense concrete (LSDC) 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 35+ years of proven performance, relatively simple mixing and placement procedures, and a reasonable cost of $6~$9 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 uses reduced cement content with up to 20% fly ash addition. Adding fly ash would slow down strength gain and reduce the heat of hydration. None of the states (in the currently available dataset) use slag, silica fume, or fiber in the mix.

Table 1 LSDC overlay from 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 low slump 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 delamination or 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 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 clearly illustrated in Fig. 1, the finer cement (fineness number of 380 m^2/kg) generated a higher peak temperature and a much higher heat release than the coarser cement. Fig. 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./$yard^3$). Therefore, high cement content coupled with gradually increased cement fineness over the years can inevitably lead to more frequent observation of early-age cracking in the field.

Although the effect of cement fineness on heat of hydration has been previously researched, its effect on cracking potential in concrete overlays must be established through testing. If this is verified during the proposed research, the team would propose refinements of the current low slump concrete overlay mix design used by WisDOT such that the heat released from the refined mix is controlled and is comparable to the historically proven early mix, with the goal of dramatically reducing the incidences of cracking. 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.

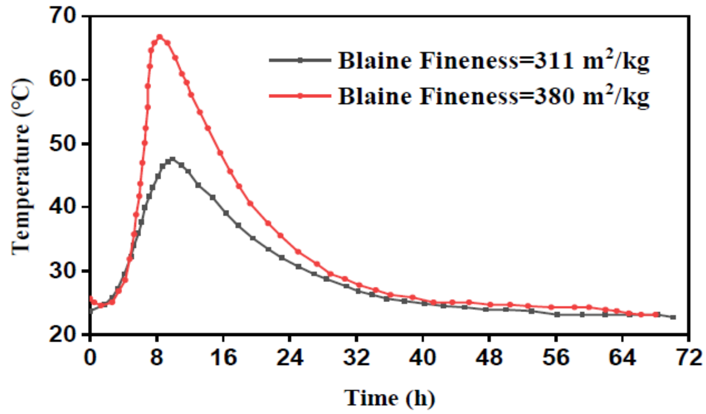

Figure 1: Semi-adiabatic temperature rise for two types of cement paste (re-plot from Bentz et al., 2008 [10])

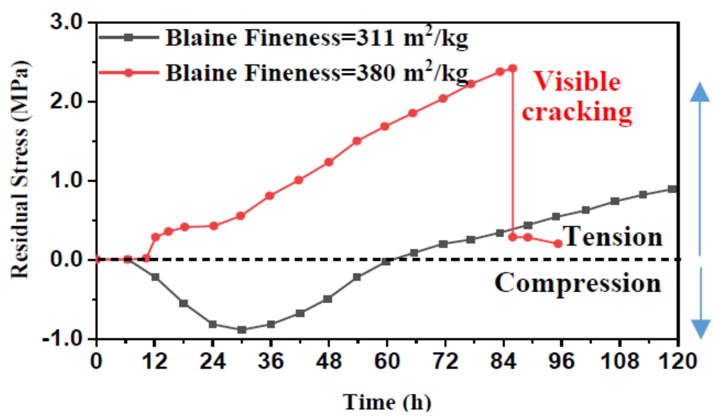

Figure 2 Residual stress development of two cement pastes (re-plot from Bentz et al., 2008 [10])

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

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].

No.		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)

3 MATERIALS AND MIX PROPORTIONS

3.1 Types of Mixtures

Concrete overlays are predominant in transportation infrastructure projects, with various types being developed and implemented across the United States. Low-slump concrete (LSDC) overlays are widely used in several US states, including Minnesota, North Dakota, and Iowa. While LSDC overlays are desirable due to their constructability and low cost, other types are also used.

In this study various types of concrete overlays are investigated, focusing on low-slump concrete overlays. These include the existing WisDOT Grade E-mix, Grade E mix with various changes, and other overlay types. Adjustments to the current Grade E mix include addition of PVA fibers, reduction of Portland cement by 15%, replacement of 15% of Portland cement with class C fly ash, and addition of PVA fiber. The Grade E mix was evaluated with two types of cement Type I and Type IL (limestone cement). A latex modified concrete mix was also tested. The performance of each mix type was evaluated in various laboratory tests. Table 5 summarizes the mixtures and types of Portland cement used in each mix.

This study's results can contribute to enhance the sustainability and durability of bridge decks. Improving concrete overlays for bridge decks can inform engineering decisions and promote adopting more effective and sustainable infrastructure solutions.

Table 5 Overlay slabs mix designation.

Concrete mix	Mix type
NC-IL	Grade E mix (Type IL cement)
FRC	Grade E (Type IL cement) + PVA fiber(1.5lb/yd^3)
CR-15	Grade E (Type IL cement, 15% cement reduction)
FRC-15	Grade E (Type IL cement, 15% cement reduction) + PVA fiber(1.5lb/yd^3)
FAMC	Grade E (Type IL cement) + 15% fly ash replacement
LMC	Grade E (Type IL cement), Latex modified mix
NC-I	Grade E (Type I cement)

3.2 Materials

3.2.1 Portland Cement

Portland cement (Type I & IL) was used in this study. The University of Wisconsin Milwaukee Structural Engineering Laboratory commercially obtained these types of cement. Both types of cement meet the ASTM C-595 [22] and ASTM C150 [23] standards.

Figure 3 Grade E Type I & IL Portland cement

3.2.2 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 is shown in Table 6 and 7. The sieve analysis values meet the WisDOT aggregates gradation limits in Table 8.

Table 6 Properties of fine aggregates

Sieve Size	Percent Passing (%)
3/8”	100
#4	97.9
#8	78.4
#16	63
#30	49.3
#50	28.5
#100	1.8
#200	1.2
Fineness Modulus	2.81

Table 7 Properties of Coarse aggregates

Sieve Size	Percent Passing (%)
1”	100
3/4”	98
1/2''	70.4
3/8”	45.8
#4	4.1
#8	0.7
#16	0.7

Table 8 Aggregate Master Gradation Limits [24].

SIEVE	FINE AGGREGATE	COARSE AGGREGATE		COMBINED AGGREGATE GRADATION		OPTIMIZED AGGREGATE GRADATION (OAG)
		SIZE NO. 1 AASHTO No. 67[1]	SIZE NO. 2 AASHTO No. 4[1]	STANDARD	100 % PASSING 1-inch sieve	TARANTULA CURVE GRADATION BAND
	(% passing by weight)					(volumetric % retained)
2-inch	__	__	100	100	100	0
1 1/2-inch	__	__	90 - 100	96 - 100	100	<= 5
1-inch	__	100	20 - 55	70 - 99	100	<= 16
3/4-inch	__	90 - 100	0 - 15	55 - 96	95 - 100	<= 20
1/2-inch	__	__	__	48 - 86	75 - 91	4-20
3/8-inch	100	20 - 55	0 - 5	38 - 77	56 - 80	4-20
No. 4	90 - 100	0 - 10	__	30 - 60	42 - 60	4-20
No. 8	__	0 - 5	__	25 - 53	36 - 55	<= 12
No. 16	45 - 85	__	__	20 - 44	27 - 45	<= 12
No. 30	__	__	__	10 - 32	15 - 32	4-20
No. 50	5 - 30	__	__	2 - 14	3 - 14	4-20
No. 100	0 - 10	__	__	0 - 6	0 - 6	<= 10
No. 200	<= 3.5[2]	<= 1.5		0 - 2.3	0 - 2.3	<= 5
ADDITIONAL REQUIREMENTS - OPTIMIZED AGGREGATE GRADATION						
Percent by weight passing the 200 sieve <= 2.3						
OAG sum of volumetric percentages retained on No. 8, No. 16, and No. 30 >= 15						
OAG sum of volumetric percentages retained on No. 30, No. 50, No. 100, and No. 200 24-34[3]						

[1] Size No. according to AASHTO M43.

[2] Reduce to 2.3 percent if used in grade E concrete.

[3] Increase to 40 percent if the concrete will be placed by a pump or by hand.

3.2.3 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 Power Plant operated by We Energies in Wisconsin. The fly ash met the requirements of ASTM C618 [25] the standard specification for fly ash and raw or calcined natural pozzolan for use in concrete. Table 9 below shows the chemical composition of this fly ash.

Table 9 Chemical composition of fly ash for the mix

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

3.2.4 PVA Fiber

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

Figure 4 PVA fiber

3.2.5 Admixtures

The high range water reducing admixture used for the mixes was Sika Viscocrete-1000, which meets the ASTM C494 [26] Type A and F admixtures requirements. The specific gravity of this admixture is approximately 1.06.

The air-entraining admixture used for the mixes was Sika Air-360, which meets the requirements of ASTM C260 [27]. This is an aqueous solution used to improve workability and freeze-thaw resistance. The Specific Gravity of this admixture is approximately 1.01.

3.2.6 Latex

SBR latex, a carboxylate styrene-butadiene copolymer from Euclid Chemical, was used during the study as it complies with ASTM C1059 [28]. 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 10.

Table 10 Properties of latex (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

3.2.7 Water

The water used for the mixes was tap water from the City of Milwaukee water supply system with an approximate density of 62.4 lbs/ft^3. This water is free of any impurities that can affect the concrete batches.

3.3 Mixture Proportions

The overlay mixtures were based on seven mix designs: NC-IL, FRC, CR-15, FRC-15, FAMC, LMC, and NC-I. The mixture proportions shown in Table 11 are based on one cubic yard of concrete. For this mix design, the measured moisture content and absorption are 4.35% and 1.05% for sand and 0.19% and 1.51% for gravel, respectively.

Table 11 Mixture Proportions for Overlay Concrete (per one cubic yard of concrete)

Mixture	NC-IL	FRC	CR-15	FRC-15	FAMC	LMC	NC-I
Sand (lbs)	653	653	653	653	653	653	653
Gravel (lbs)	626	626	626	626	626	626	626
Cement	366	366	312	312	312	294	366
Water (lbs)	106	106	88	90	106	45	106
Water reducer (oz)	59	79	50	50	48		59
Air Entrainment (oz)	30	30	25	30	30		30
PVA fiber (lbs)		0.66		0.66			
Fly Ash (lbs)					55		
Latex (lbs)						62	

3.4 Mixing Procedure

Seven different mixes were prepared using a standard laboratory rotary drum mixer. The first six mixes used the basic Wisconsin Grade E mix type IL cement and with some adjustments such as 15% cement reduction, the addition of PVA fiber, 15% replacement of cement with fly ash latex modified mix, and a combination of these modifications. The mixing procedures for each mix are shown below:

Grade E Type IL mix (NC-IL)

1. Measure the specified amount of mixing water required for the mix. Divide the water into two halves.
2. Add the air-entraining chemical (Sika Air-360) to half the water and mix well. The water reducer is then added to the remaining half and mixed well.

3. The coarse and fine aggregate are placed in the rotary mixer and uniformly mixed while adding half of the water containing the air entraining solution. Mix for about 2-3 minutes or until the aggregates are uniform.
4. Add half of the cement to the mix and the remaining air-entraining solution and mix for an additional 2 minutes.
5. Add the remaining cement to the mixture while gradually adding the water-reducer solution. Mix until a consistent mix is achieved.

Latex Modified Concrete (LMC)

1. Measure the specified amount of mixing water required for the mix.
2. The coarse aggregate and fine aggregate a placed in the rotary mixer and uniformly mixed while adding half of the water containing the air entraining solution. Mix for about 2-3 minutes or until the aggregates are uniform.
3. Add half of the cement to the mix and the remaining water and mix for an additional 2 minutes.
4. Add the remaining cement to the mix while gradually adding the latex solution. Mix until a consistent mix is achieved.

Other concrete mixes used in this study include the 15% Cement Reduction mix (CR-15), Fly Ash Modified Concrete (FAMC), and Grade E Type I mix (NC-I), each of which follow the same mix procedures as the Grade E Type IL mix, with the appropriate proportion of materials provided for the mix design. The fiber reinforced mixes, both FRC and FRC-15, also follow the same mix procedures as the Grade E Type IL mix, with the addition of PVA fibers at the end of the mix until the required consistency is achieved.

The air content, and slump were measured at the end of each mix based on the ASTM and AASHTO standards. Three cylinder samples (4in x 8in) were taken for each of the seven mixes stored and tested for compressive strength at 28 days.

4 EXPERIMENTAL METHODS

4.1 Overview

Concrete is a widely used construction material due to its strength and durability. To ensure the long-term performance of concrete structures, it is essential to understand the properties that affect their service life. This research conducted experimental tests on seven different concrete mixes for bridge deck overlays to investigate their potential for cracking. This section presents an overview of the various tests conducted in this study. The tests performed were field evaluation of concrete overlay slabs, compressive strength test, dog bone restraint stress test, and salt ponding test.

The compressive strength of the concrete mixes was tested using 4 x 8 in cylinder samples. These tests were conducted to assess the mechanical properties of concrete mixes. The results of these tests provide valuable information on the strength and durability of concrete mixes.

4.2 Overlay Concrete Slabs

As part of this research, seven overlay slabs were fabricated to evaluate the cracking potential and response of the various overlays to different curing conditions. Seven 8 ft x 8 ft x 4in concrete slabs were fabricated for outdoor testing. The surfaces of the slabs had a broom finish. A few months after casting the slabs, 2-in-thick overlays were placed on the top surfaces of the slabs (seven overlay types). The overlays also received a broom finish. The slabs were located outdoors in an open field in Milwaukee, WI, and the overlays were placed in October 2022. Mechanical points were embedded in the overlay as shown in Figure 5 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. The strains and temperatures were also recorded. This test provides valuable information on the performance of various overlay mixes exposed to field environmental conditions.

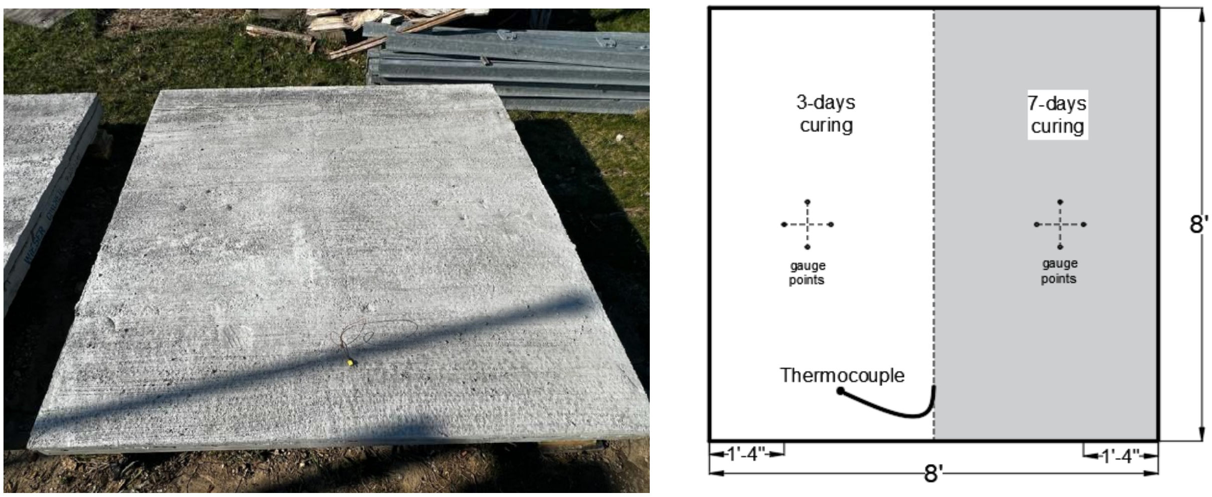

Figure 5 Schematic of overlay slabs

4.3 Dog Bone Test

The custom-designed dog bone specimens are designed to evaluate the restraint stresses developing in concrete due to inelastic strains (shrinkage and temperature). This test is an alternative method to the ring test, a standard method for assessing cracking potential of concrete due to restraint of shrinkage strains. This new test is an easier and more flexible approach by utilizing smaller samples and includes a 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 6. For each mix design, two types of dog-bone specimens were cast, one unrestrained and the other restrained. The restrained specimens were sandwiched between two steel tubes as shown in Figure 7. Two different curing conditions (plastic covering and wet burlap) 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 specimen shrinks or expands due to shrinkage, moisture 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:

$$2\varepsilon_s A_s E_s = \sigma_c A_c \tag{1}$$

$$\sigma_c = \frac{2\varepsilon_s A_s E_s}{A_c} \tag{2}$$

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. width and length 6 in inches length, with a round fillet at the ends. 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 connected to the top middle portion of the steel and connected to a Vishay P3500 Strain Indicator system.

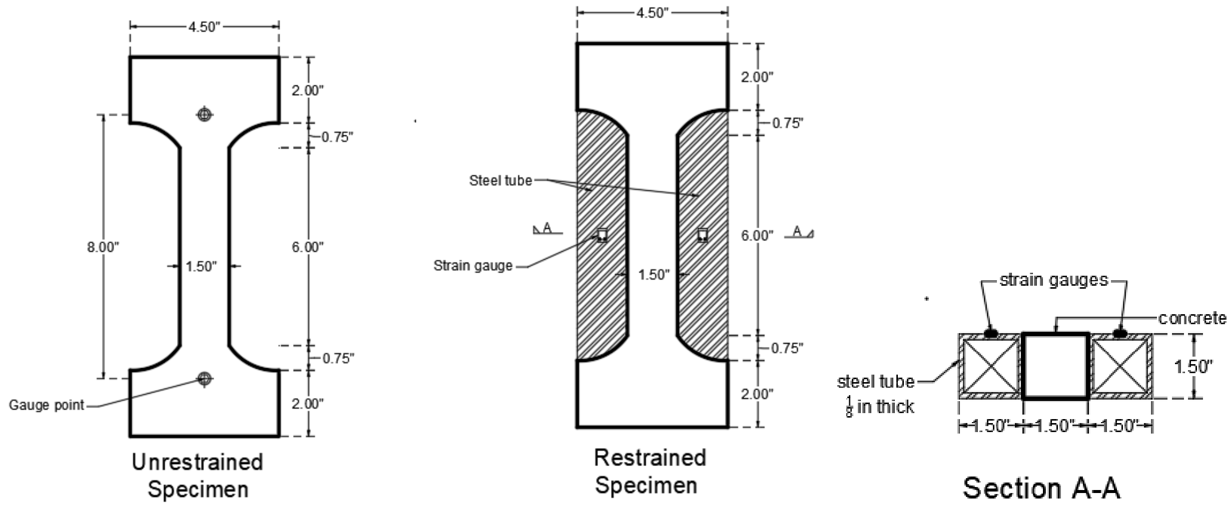

Figure 6 Geometry of dog bone specimens

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. These specimens were cured for 3, 7, and 14 days with plastic sheathing or wet burlap (and plastic sheathing) in a room with stable temperature (20 ± 1°C). The samples were demolded, 24 hours after casting and their strains were measured. Two sets of samples were fabricated for the test. Set 1 specimens were restrained with steel tubes, and the strains were measured daily. Set 2 specimens were without restraint and strain readings were made daily using mechanical strain gauge with a gauge length of 8 in. The sides of Set 2 specimens were covered with duct tape after their curing period to restrict the moisture movement to the top and bottom faces of the specimen (as was the case with the restrained specimens). All samples were placed on their side during the entire monitoring period.

A total of 24 specimens were fabricated (12 each for Set 1 and Set 2 specimens) for the first group of samples. For the restrained specimens, 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). The same curing conditions were used for Set 2 specimens. Designations for unrestrained specimens with plastic sheathing for 3, 7, and 14 days of curing were UP3, UP7, and UP14, respectively. The unrestrained specimens with wet burlap plus outer plastic sheathing were designated UPB3, UPB7, and UPB14, 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 0.382 instead of the original w/c ratio of 0.324. Two restrained and two unrestrained specimens were prepared and subjected to the 7-day wet burlap curing. These specimens are designated as NPB7 and NUPB7 for restrained and unrestrained specimens, respectively.

Figure 7 Restrained and Unrestrained dog bone specimens

4.4 Salt Ponding Test

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 modified AASHTO T259 [29], "Standard Method for Testing Resistance of Concrete to Chloride

Ion Penetration," and ASTM C1543 [30], "Standard Test Method for Determining the Penetration of Chloride Ions into Concrete by Ponding." Before the salt ponding tests, 21 concrete slabs were cast based on the mix designs shown in Table 11, 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 $20°C$ and $50 \pm 5\%$ humidity until 28 days. Cylinder samples (2 x 4 in.) were obtained from the concrete mix, cured, and similarly stored as background samples for the original concrete during the chloride test.

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 adhesives, as shown in Figure 8. The slabs were ponded and exposed to a 3% (by weight) NaCl solution to a height of 0.5 in. The dikes are covered with plastic sheets to reduce evaporation. The level of NaCl solution was restored if a decrease in level was observed.

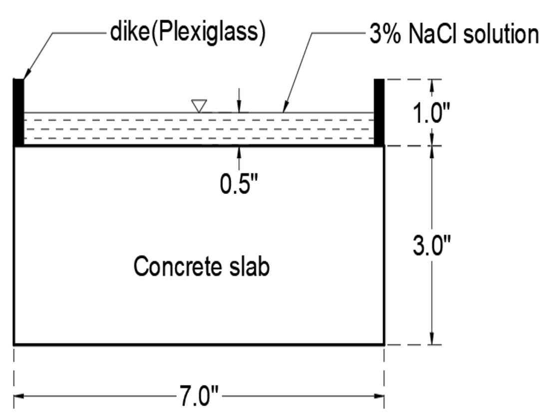

Figure 8 Schematic of Salt Ponding Test

After the ponding process, the slabs were left undisturbed for 28 days instead of the usual 90 days to allow the chloride ions to penetrate the concrete. 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 on their surface.

4.4.1 Determination of Chloride Content (Rapid Chloride Test)

Concrete powder samples were collected from the top surface of the slabs and background samples (uncontaminated original concrete) using an 18mm hammer drill as shown in Figure 9. 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

Figure 9 Sampling of Concrete powder from salt ponding slabs with hammer drill

Figure 10 Storage of samples and measuring sampling depths

After collecting and tagging all powder samples, the Rapid Chloride Test (RCT 1029) was conducted 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 [31]. The samples were tested using the RCT-500 test kits in Figure 11 from Germann Instruments Inc. The hardware include 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. The test process based on this RCT kit is described below:

1. The electrodes are calibrated with four calibration liquids (each for 0.005%, 0.020%, 0.050%, and 0.500% chloride ions) before and after the test to obtain a stable reference curve for chloride calculations.
2. 1.5 grams of concrete powder from each sample is measured based on a volumetric procedure where it is poured into plastic ampoule tubes and compacted to a red reference line.
3. The measured samples are poured into vial bottles containing 10 ml of extraction liquids.

4. The vial bottles are covered and shaken for 5 minutes to facilitate the chloride extraction.
5. The tip of the calibrated electrode already connected to the electrometer is placed into the liquid until the millivolt (mV) readings on the electrometer are stable.
6. The chloride content was read directly from the calibration curve by tracing the millivolt values.
7. A similar process is repeated after 24 hours to obtain about 100% accuracy of the chloride ion content.

Figure 11 Rapid Chloride test setup and measurement

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, which provides a comprehensive analysis of the data obtained from the experimental tests.

5 RESULTS AND DISCUSSION

5.1 Compressive strength test

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 values of these compressive strengths are shown in Table 12 alongside the standard deviation to show variations in the measured strengths for each set of samples. It should be noted that all concrete mixes for slab 1 to 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.

Table 12 Compressive strength values for the overlay slabs

Slab No	Concrete mix	Average Compressive Strength (psi)	Standard deviation (psi)	Number of Samples
1	NC-IL	8770	45	3
2	FRC	11020	386	3
3	CR-15	9300	340	3
4	FRC-15	9940	267	3
5	FAMC	8890	213	3
6	LMC	7730	69	3
7	NC-I	8390	475	3
New mix (dog bone test)	15% cement reduction w/c = 0.381	7800	220	3

Results are shown in Figure 12. It can be observed that the addition of PVA fibers to the Grade E mix in Slab 2 (FRC) resulted in a significant increase in compressive strength compared to the reference mix Slab 1 (NC-IL). Slab 4 (FRC-15), which had both PVA fibers and a 15%

reduction in cement content, also had higher compressive strength than NC-IL. In Slab 3 (CR-15), the 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 Slab 5 (FAMC) resulted in a slight increase in compressive strength compared to NC-IL, while the latex-modified mix in slab 6 (LMC) had the lowest compressive strength among all the mixes tested. The Grade E mix with Type I cement (NC-I) and Grade E mix with 15% Type IL cement reduction (for dog bone test) had lower compressive strength than all the Type IL mixes except the Latex modified mix (LMC).

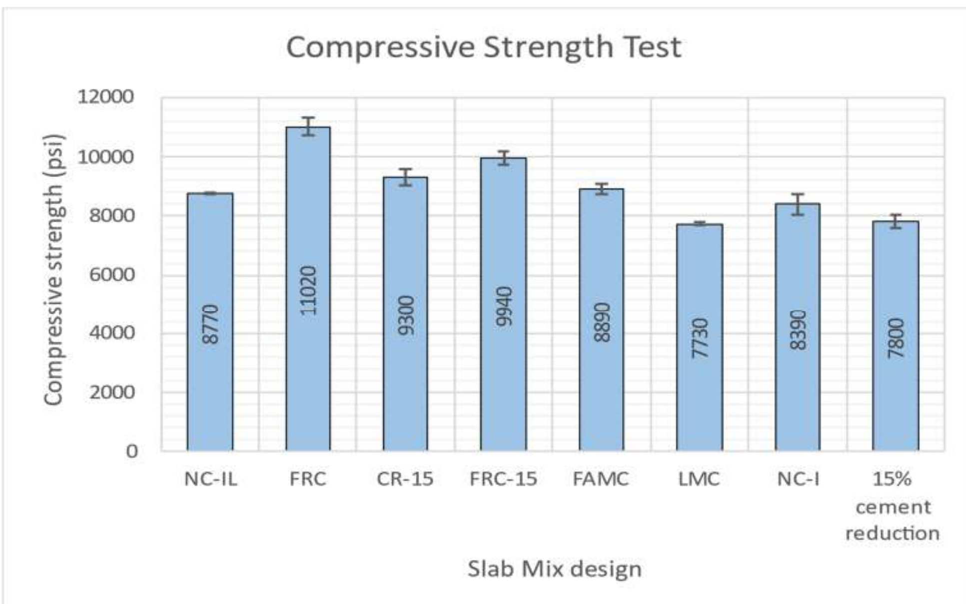

Figure 12 Compressive strength test

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, fly ash and a reduction in cement content (while keeping the same w/c ratio) led to increased compressive strength, while the addition of latex modification resulted in a decrease in compressive strength.

5.2 Slump and Air Content

The slump and air content test results for different concrete mixes provide valuable information on the workability and durability of the concrete. The slump for the mixes was measured per ASTM C143.

Table 13 Slump and Air content for overlays slab mixes

Concrete mix	Slump (in)	Air Content (%)
NC-IL	3	7
FRC	2.25	5
CR-15	3.5	7
FRC-15	1.5	4
FAMC	4	5.5
LMC	2	3
NC-I	2.75	5.5

5.3 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. The results were obtained through weekly gauge readings for 26 weeks. The gauge readings for all slabs are shown in Figures 13 to 19. These results include the impact of changing temperature and weather conditions in the field on the gauge readings. Temperature and moisture movements create substantial variability in the measured strain values. The fluctuations in strains correspond to fluctuations in slab temperature. Research by [32] noted shrinkage recovery in winter months due to availability of significant moisture in winter months. Therefore, a typical shrinkage pattern is not observed during the monitoring time covered in this thesis.

There is no clear discernable pattern in the strain data as the slabs are subjected to a variety of environmental conditions. Slab 7, the current Grade E overlay mix 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 20.

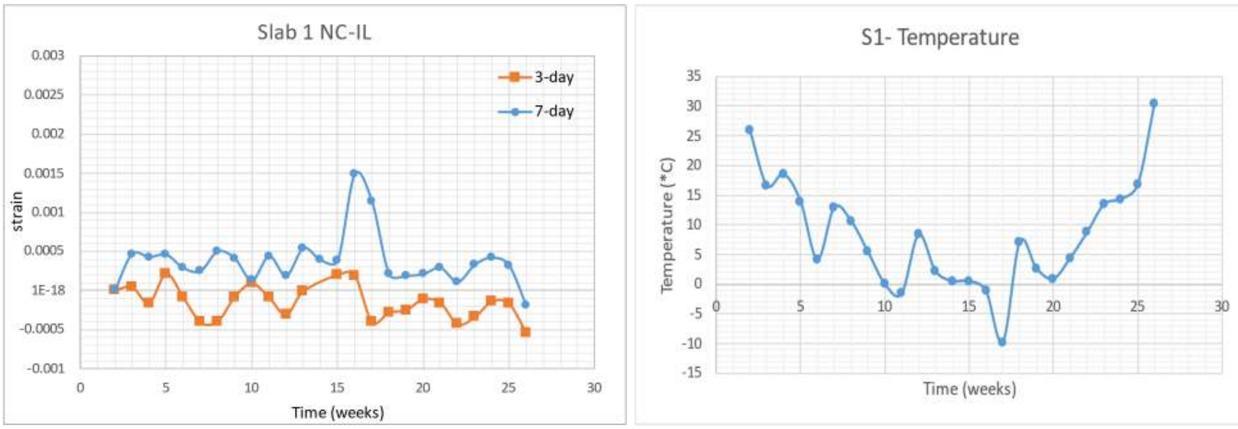

Figure 13 Strain variation for Overlay Slab 1 and its core temperature variation

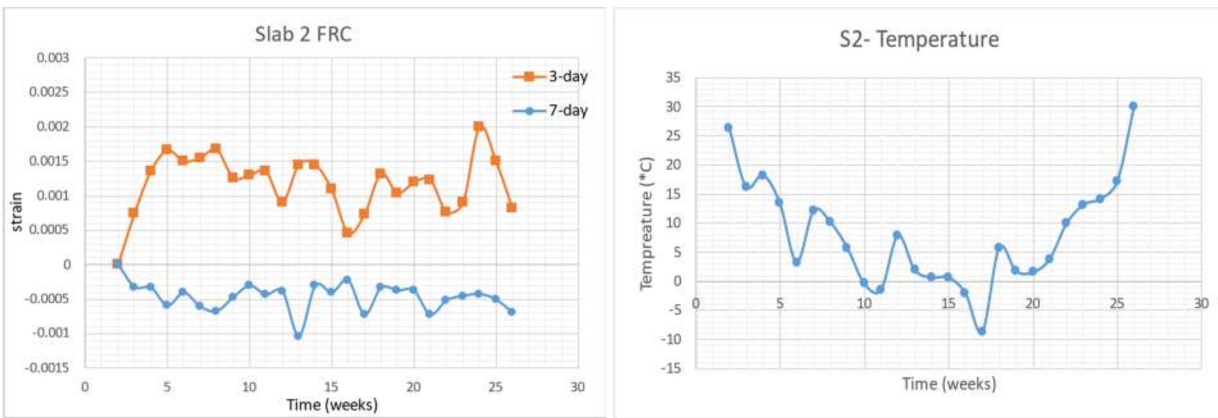

Figure 14 Strain variation for Overlay Slab 2 and its core temperature variation

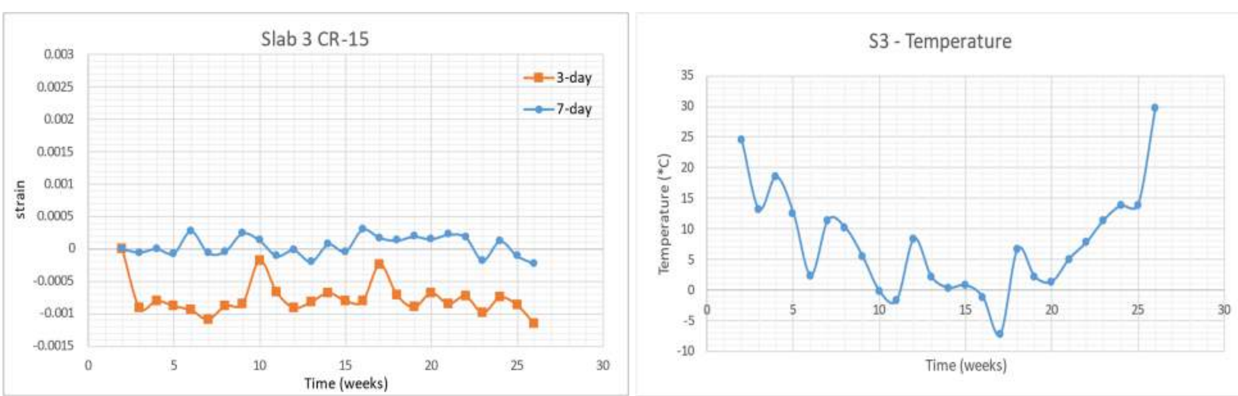

Figure 15 Strain variation for Overlay Slab 3 and its core temperature variation

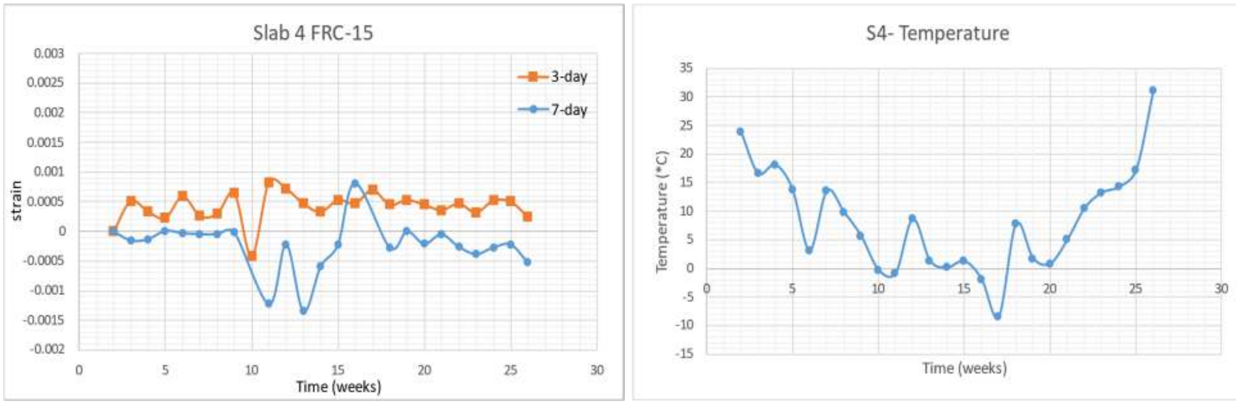

Figure 16 Strain variation for Overlay Slab 4 and its core temperature variation

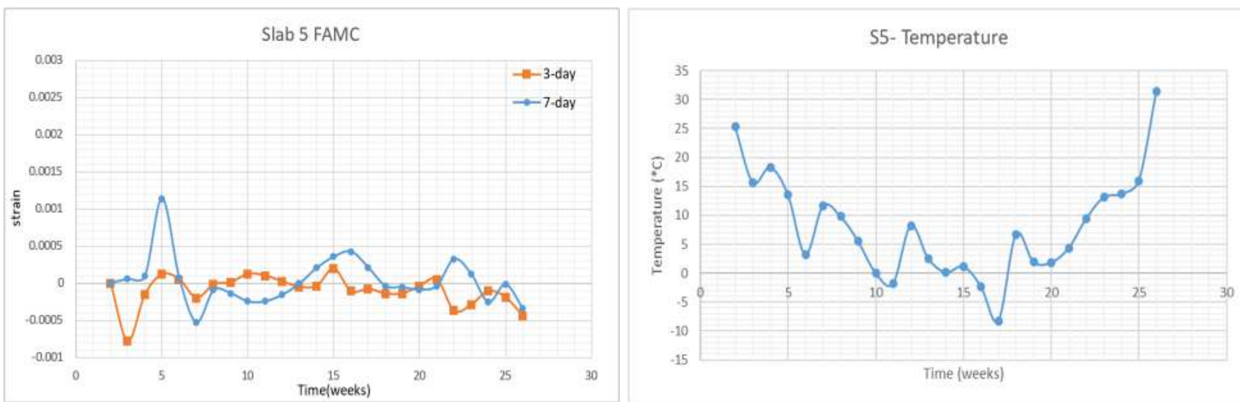

Figure 17 Strain variation for Overlay Slab 5 and its core temperature variation

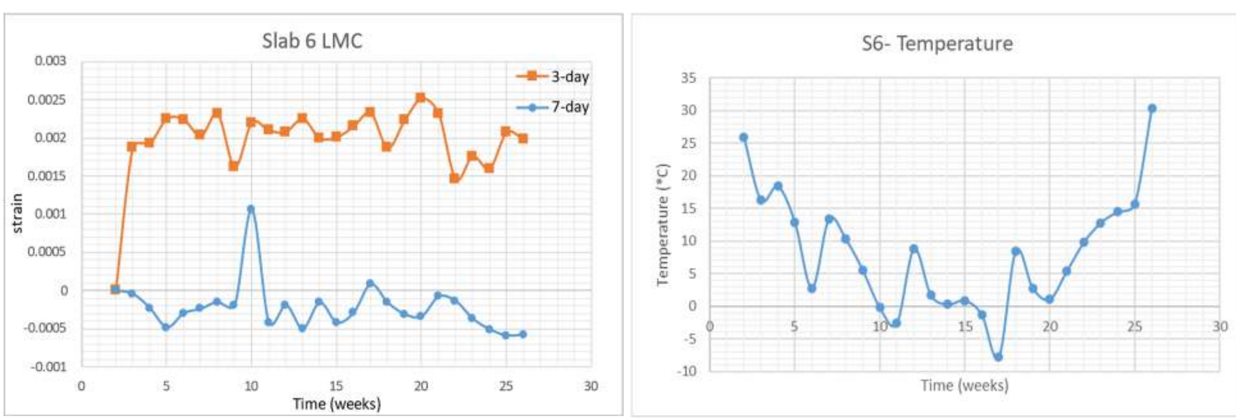

Figure 18 Strain variation for Overlay Slab 6 and its core temperature variation

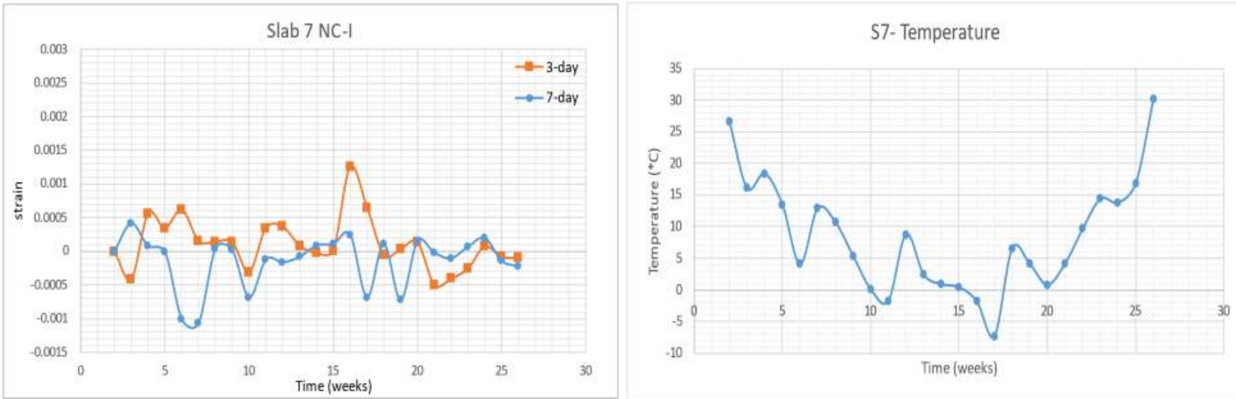

Figure 19 Strain variation for Overlay Slab 7 and its core temperature variation

Figure 20 Cracks on Overlay Slab 7 (NC-I)

5.4 Dog bone Specimens

The curing process is an essential step in the production of high-quality concrete structures. The concrete gains strength, durability, and resistance to external stresses during this process. However, shrinkage is an inherent problem that can be aggravated with insufficient curing, which can lead to cracks in the concrete structure. In this study, we investigated the strain profiles of dog bone specimens for different curing conditions and curing periods to determine the curing regime that would produce the least shrinkage strains (or restraint strains). All these specimens were made from the Grade E Type IL cement mix (NC-IL).

5.4.1 Restrained dog bone specimens

1. Curing with plastic sheathing

The strains in the restrained samples were recorded as restraint strains developed in the steel as a result 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 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 test was conducted by curing the restrained dog bone specimens with plastic covering for 3, 7, and 14 days. 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.

The strain values referenced to day 1 showed similar values for all samples, although slightly higher negative strains were recorded for the 14-day cured specimens as shown in Figure 23. For strain in Figures 21 and 22 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, making it a less recommended plastic curing method. This may be due to the fact that it is difficult to maintain coverage (without air leak) in plastic covered specimens.

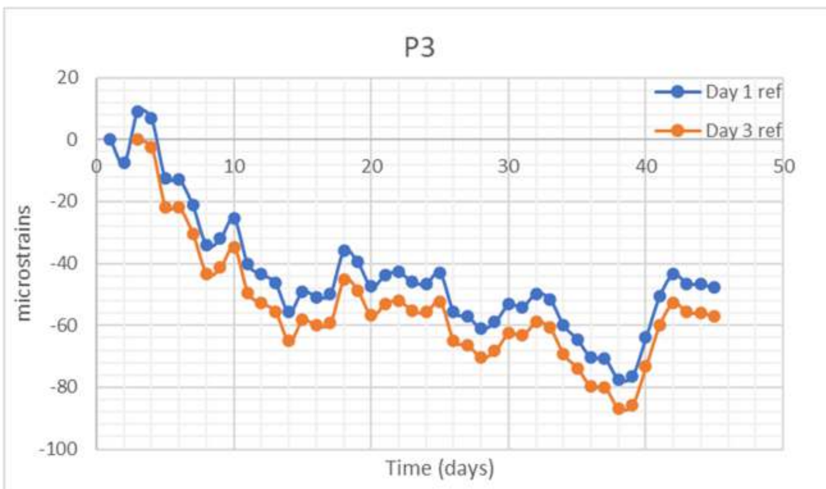

Figure 21 Strain results 3-day plastic curing

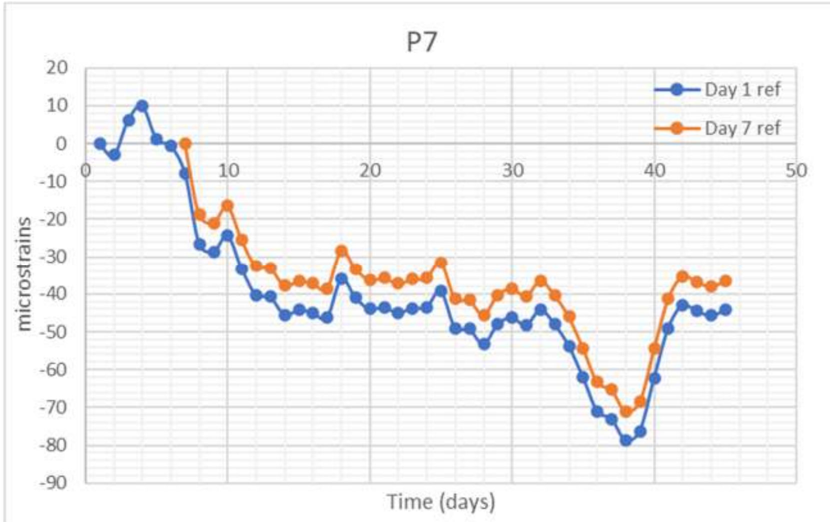

Figure 22 Strain results 7-day plastic curing

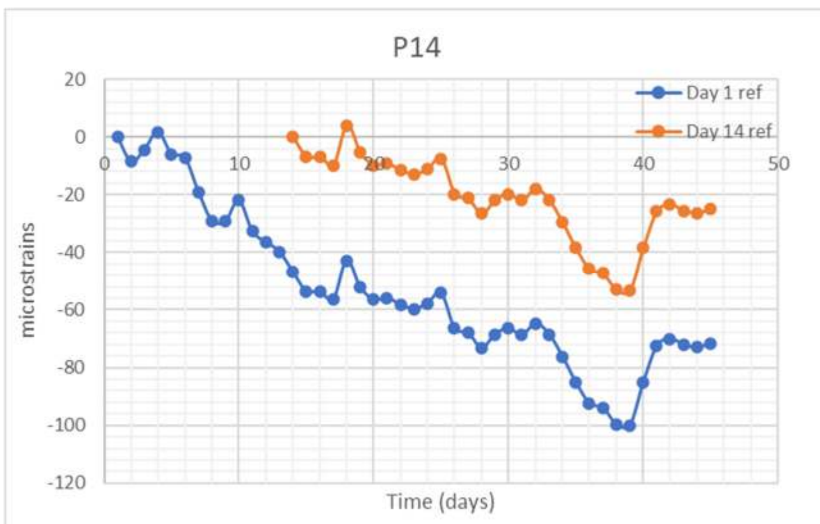

Figure 23 Strain results 14-day plastic curing

2. Curing with wet burlap plus plastic covering

The strain profiles of dog bone specimens cured with burlap and plastic covering for 3, 7, and 14 days were investigated. The results show that wet-cured samples showed 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 24, the 3-day wet cured specimen exhibited a strain drop of about 80µstrains, while the 7-day cured specimen (Figure 25) showed a strain drop of about 60µstrain. Figure 26 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) before the shrinkage.

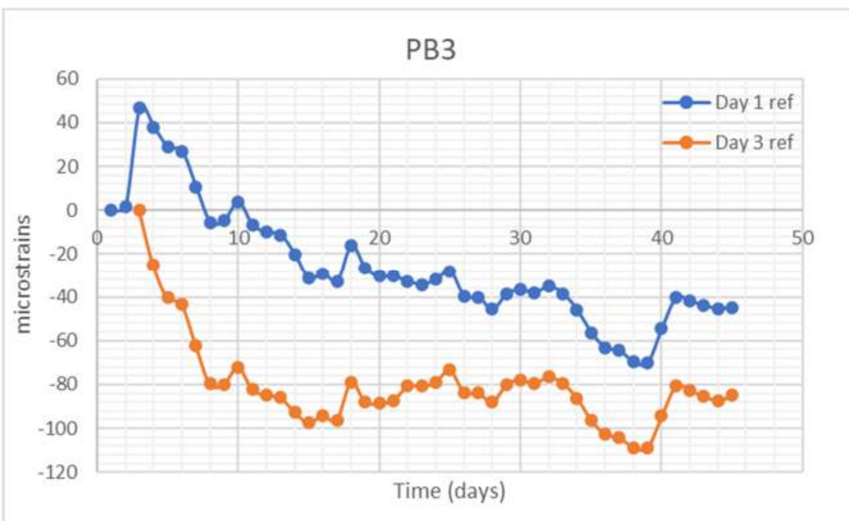

Figure 24 Strain results 3-day wet burlap and plastic curing

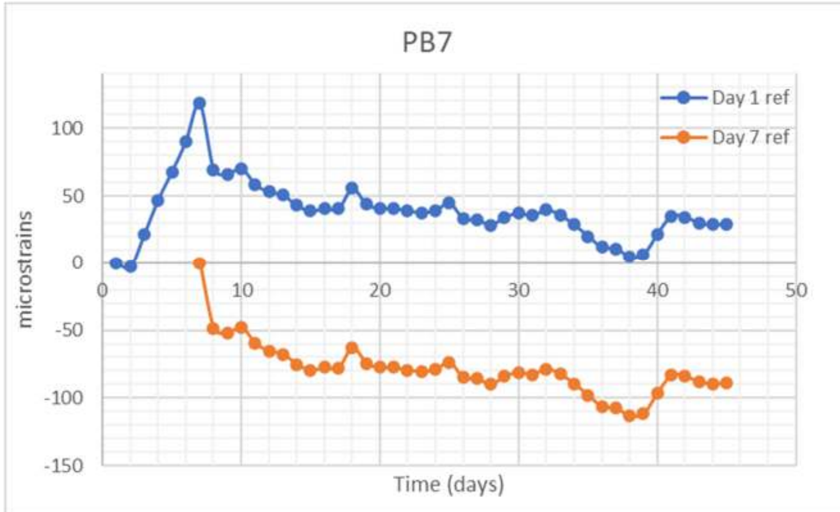

Figure 25 Strain results 7-day wet burlap and plastic curing

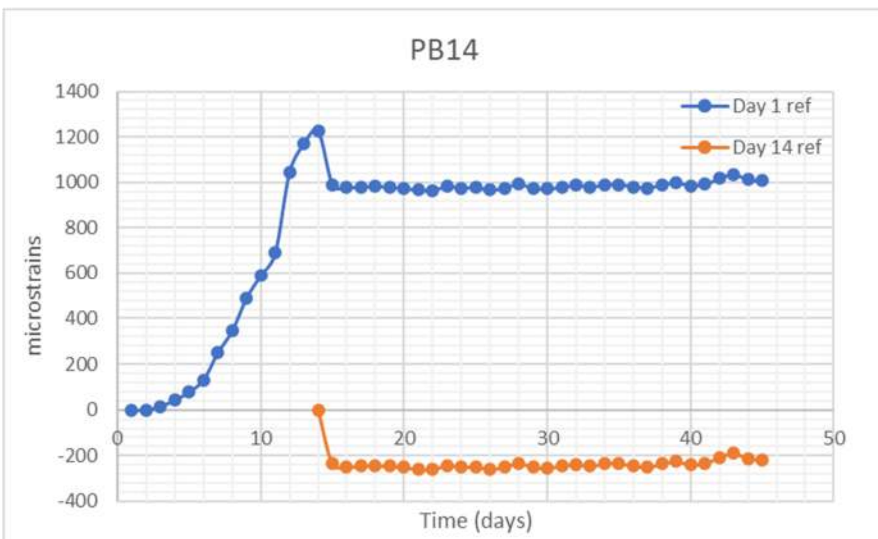

Figure 26 Strain results 14-day wet burlap and plastic curing

Figure 27 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 60µstrain for PB7 in Figure 25. NPB7 performed similarly to the 14-day specimens but with lower strains.

Figure 28 showed the 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 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 open to traffic as soon as possible. Overall, the 7-day wet curing with a 15% cement reduction (NPB7) is recommended, as it performs similarly to the 14-day wet-cured specimen and generates lower tensile strains, while requiring a shorter curing period.

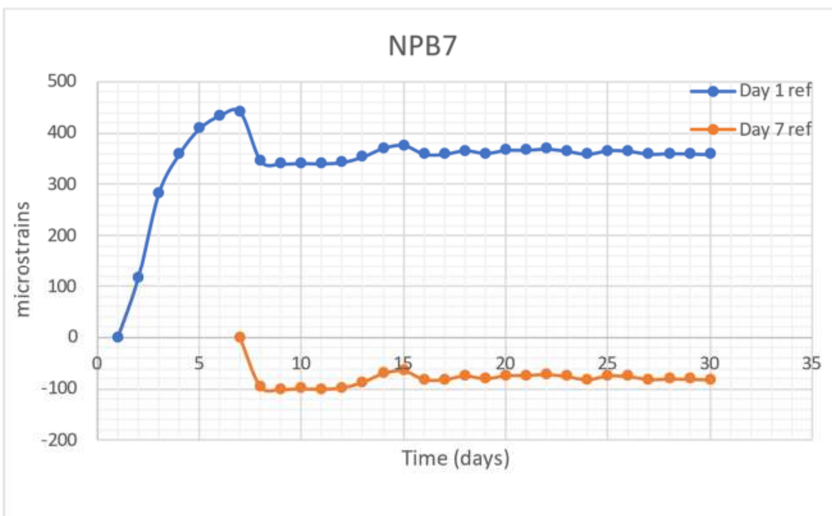

Figure 27 Strain results 7-day wet burlap and plastic curing (15% cement reduction)

Figure 28 Crack formation on the 3-day wet-cured specimen

5.4.2 Unrestrained dog bone specimens (Free shrinkage)

1. Curing with plastic sheathing

The free shrinkage strains experienced in the unrestrained samples were measured as gauge readings and converted to strains. These samples were cured with plastic covering for 3-, 7- and 14-day periods. Strains are recorded such that shrinkage is recorded as negative and expansion as positive strain. The strain results in Figures 29, 30 and 31 show that the 7-day cured specimens experience relatively lower strains compared to 3-day with high expansion and 14-day with higher shrinkage. The 14-day curing with plastic sheathing may result in leakage of air and initiation of shrinkage.

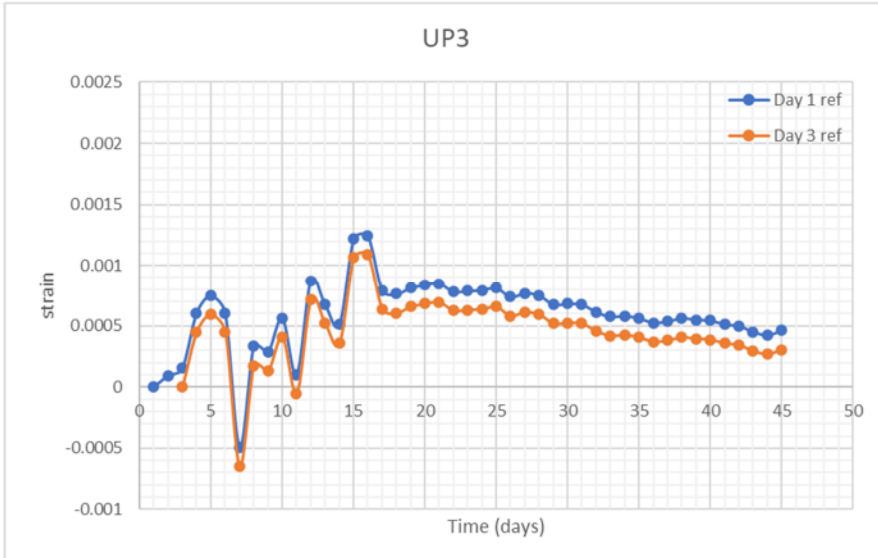

Figure 29 Strain results 3-day plastic curing for unrestrained specimen

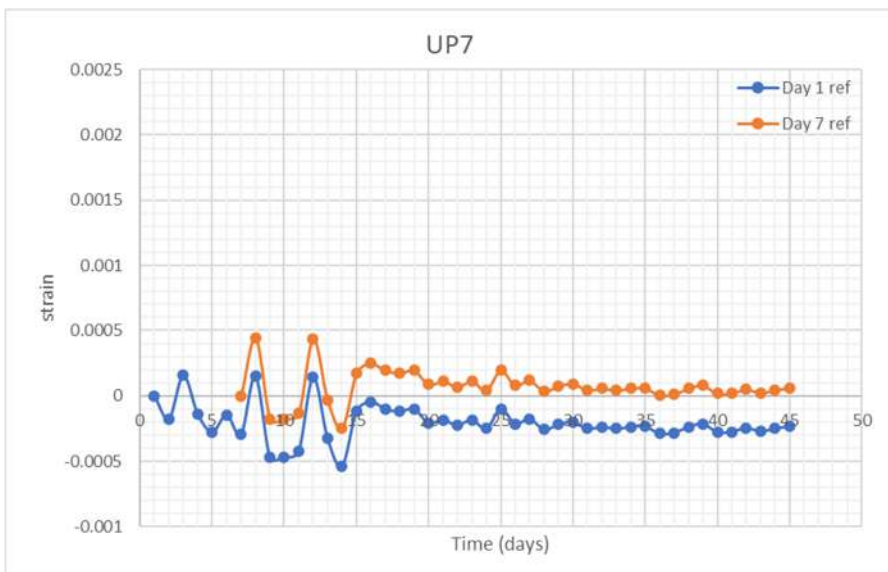

Figure 30 Strain results 7-day plastic curing for unrestrained specimen

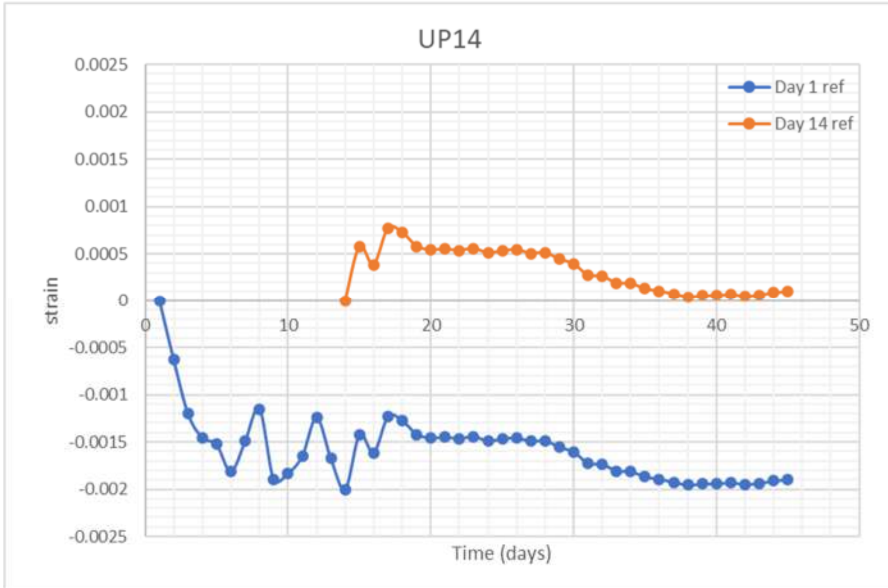

Figure 31 Strain results 14-day plastic curing for unrestrained specimen

2. Curing with wet burlap plus plastic covering

During the wet curing period of 3, 7, and 14 days, the unrestrained concrete specimens experienced free shrinkage. However, temperature effects significantly impacted the strain response during the early stages of curing, except for the samples with no cement reduction. Typically, concrete exhibits slight expansion during the initial curing stage, followed by shrinkage after the end of the curing period. To better understand the strain response of the specimens, we consider the strain values referenced to the end of the curing period (orange plots).

After the 3-day curing period in Figure 32, the strain reduced by about 0.0015, and some strains were regained, likely due to slight changes in humidity. The strain plateaued at around 0.0007. Figure 35 (14-day cured specimen) shows an initial expansion due to the continuous availability of moisture, and after 14 days, there was still a positive change in strains, which later plateaued at around 0.0005. Figure 33 (7-day cured specimen) recorded the least strain change among the three samples with no cement reduction, with a strain change of 0.0003 and a plateau strain of about -0.0001, almost close to 0. Figure 34 (7-day cured specimen with 15% cement reduction) only showed negative strains with little temperature effects in the profile, but the total strain change after the curing was similar to that observed in UPB7 in Figure 33.

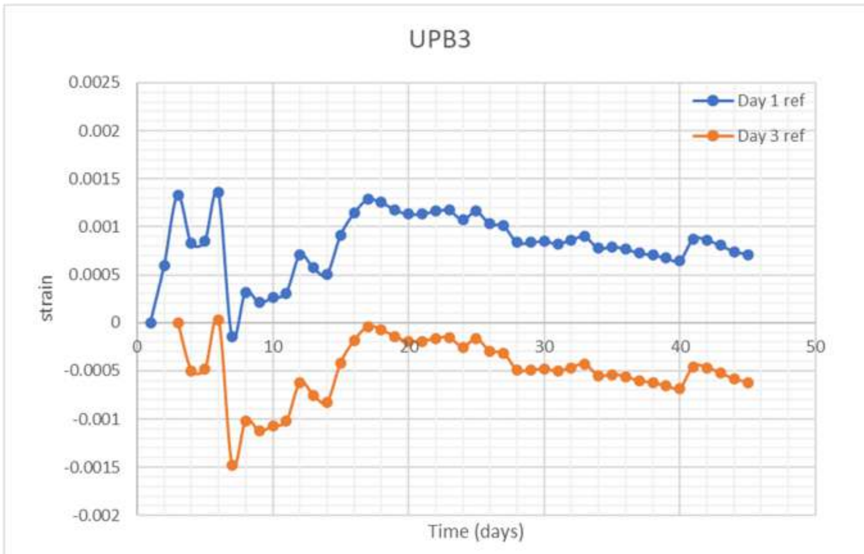

Figure 32 Strain results 3-day wet curing for unrestrained specimen

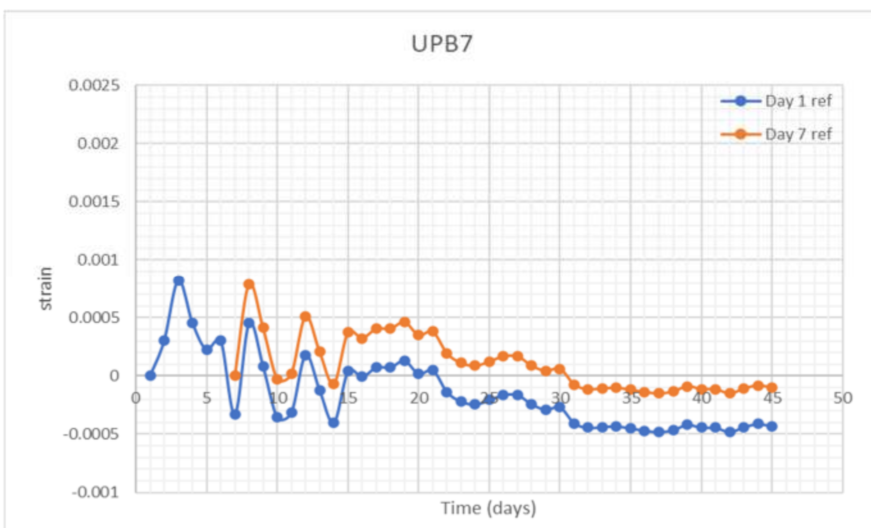

Figure 33 Strain results 7-day wet curing for unrestrained specimen

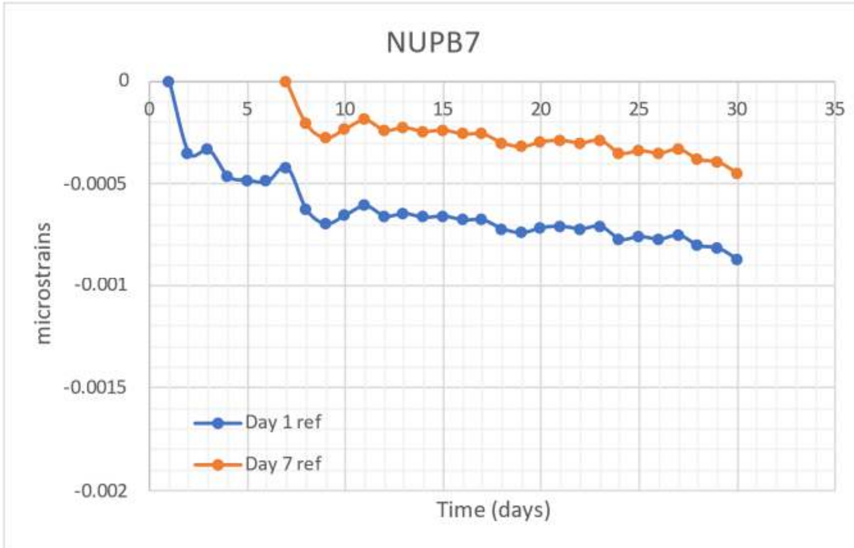

Figure 34 Strain results 7-day wet curing for the unrestrained specimen (15% less cement)

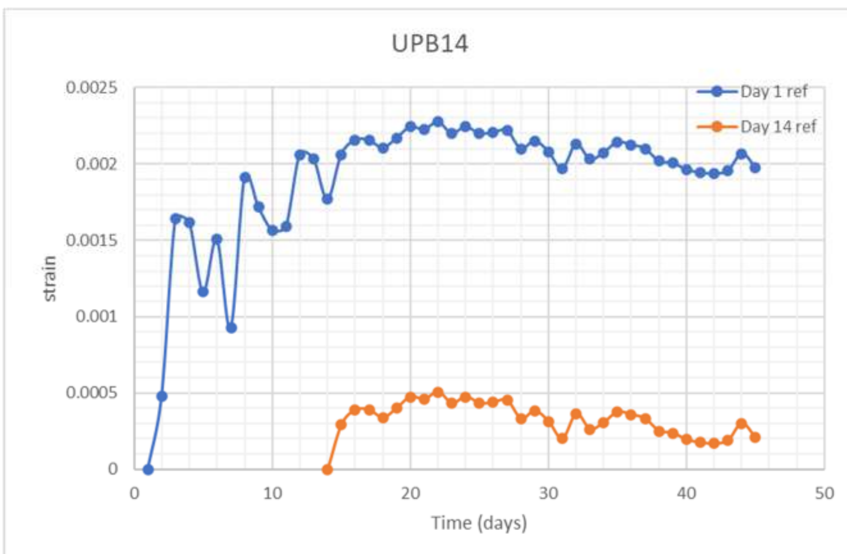

Figure 35 Strain results 14-day wet curing for unrestrained specimen

Based on the test results, the 14-day wet curing (with wet burlap) method is ideal for the concrete overlay slab. However, this may be impractical for many bridge overlay construction projects as it affects opening the road to traffic. Overall, the 7-day wet curing is recommended for concrete overlays, as all restrained and unrestrained samples show that it provides the optimal strain response in the concrete samples.

5.5 Rapid Chloride test (Salt ponding)

The 28-day rapid chloride test provided preliminary results to be augmented with the 90-day rapid chloride test results later. 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. Table 14 summarizes the results of the 5-min and 24-hr rapid chloride tests. The net change in chloride ion content at depth 0-0.25in. and 0.25-0.5in. are shown in Figure 36 and 37, respectively. Further details of the test results are shown in the Appendix.

Table 14 Summary of 28-day Rapid Chloride test

Slab ID	Mix ID	Average Chloride content Original concrete (%) *		Average net change in Cl- (%) * (0-0.25in)		Average net change in Cl- (%) * (0.25-0.5in)	
		5min test	24 hr. test	5 min test	24 hr. test	5 min test	24 hr. test
Slab 1	NC-IL	0.045	0.052	0.177	0.237	0.043	0.049
Slab 2	FRC	0.039	0.050	0.251	0.289	0.067	0.070
Slab 3	CR-15	0.063	0.084	0.163	0.201	0.044	0.026
Slab 4	FRC-15	0.065	0.077	0.168	0.209	0.031	0.031
Slab 5	FAMC	0.061	0.070	0.202	0.243	0.037	0.038
Slab 6	LMC	0.054	0.073	0.121	0.143	0.013	0.001
Slab 7	NC-I	0.080	0.091	0.121	0.219	0.012	0.021

*all values are percent chloride by concrete weight

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.

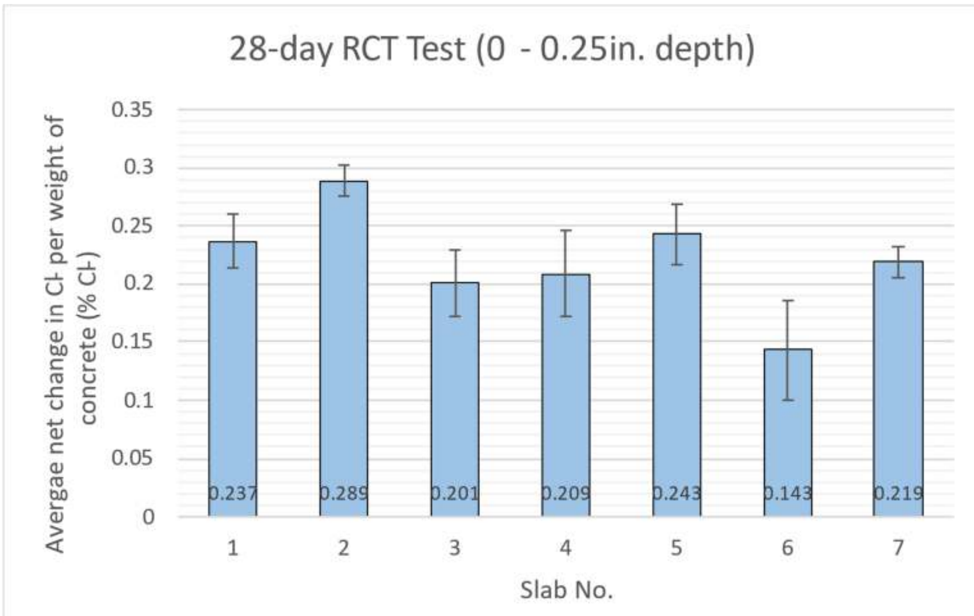

Figure 36 Net change of chloride ions at 0-0.25in. depth after 28 days

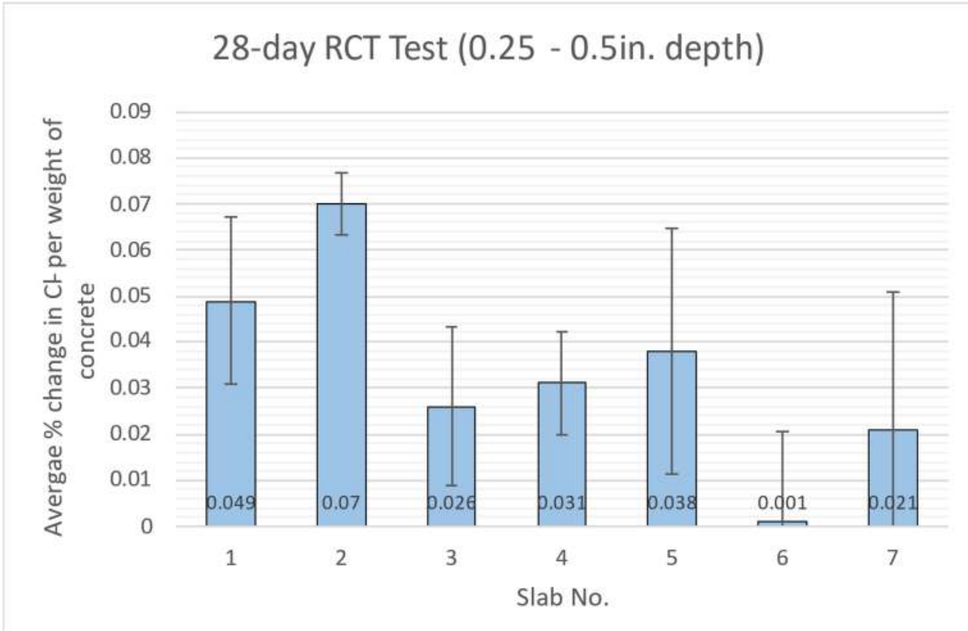

Figure 37 Net change of chloride ions at 0.25-0.5in. depth after 28 days

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary of Test Results

6.1.1 Overlay Slabs

The performance and adequacy of various mix designs for low-slump deck slab overlays were assessed through field and laboratory testing. The compressive strength results showed that all seven mix designs exhibited very high strengths with values ranging from 7700 to 11000 psi. Adding PVA fiber to the mixes (FRC & FRC-15) with or without the reduction of cement content (while maintaining the water-to-cement ratio) resulted in higher compressive strengths. The latex modified concrete had the lowest compressive strength, but still exhibited a substantially high strength. Although the first impression may be that high strength is good, that is not the case when cracking due to inelastic strains such as shrinkage is an issue. Higher strengths mean higher stiffness, which results in higher restraint stresses that can contribute to cracking. The structural purposes of the overlay can be met with substantially reduced compressive strengths.

The following observations and conclusions regarding the performance of the overlay slabs were made:

1. The current WisDOT Grade E overlay mix developed early cracking in the field tests. This indicates that the current mix design should be improved to reduce the potential for cracking.
2. The slabs fabricated from Grade E mix with Type IL cement and those modified by reducing the cement content or including PVA fiber, fly ash, or latex, did not show visible cracks as of the time of writing this thesis.

In conclusion, the current Wisconsin Grade E mixture is susceptible to cracking and should be modified. Adding PVA fiber and fly ash to the mix or reducing cement content may help improve the slab performance. The curing method should be carefully examined as it has an important influence on the performance of overlay.

6.1.2 Dog bone specimens

The dog bone laboratory tests were used to assess the effect of curing conditions on the original WisDOT Grade E mix. Based on the test result, The 14-day curing results with plastic covering alone was not effective in keeping the specimens moist during curing and this resulted in higher shrinkage during curing. The 14-day wet curing provided the best strain response in the specimens. In overlay slabs construction, 14-day wet may be too long in situations where rapid traffic reopening is important. For this reason, the 7-day wet curing period is recommended in addition to reducing the cement content of the mix to minimize restraint stress and cracking potential of overlays.

6.1.3 Salt ponding

It is important to note that the 28-day rapid chloride test is not a substitute for the 90-day rapid chloride test. However, the results obtained can be used to make preliminary assessments of the chloride content and potential durability of the concrete samples. Based on the results obtained from the 24-hr. rapid chloride test, The fiber reinforced mix (FRC), fly ash modified mix (FAMC), and original mix (NC-IL) for concrete overlay slabs show higher chloride penetration after 28 days of exposure. The latex-modified mix and Type I cement mix (NC-I) had lower chloride ions penetration. The 90-day rapid chloride test will provide a more reliable conclusion regarding this.

6.2 Recommendations for Future Research

Based on the test results of this research, the following recommendations should be considered for future research:

1. Investigate the effect of the recommended 7-day wet curing method using the dog bone specimens for the seven mix designs proposed in the study while considering other overlay types.
2. Computational models could be used to understand further the effects of different curing methods and temperatures on the stresses and strain in different overlay types.
3. The effects of environmental factors such as temperature and humidity on concrete should be studied to understand better how it affects concrete performance.

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APPENDIX

28-day Rapid Chloride Test (after 5 min)

Measurement of the acid soluble chloride content of HARDENED CONCRETE by the RCT method

1.5 gram of concrete dust dissolved in a RCT-1023 vial with 10 ml of extraction liquid

Report #:	**1.1**	Structure:	**Original**	Project:	**5 min test**
Date:	**4/19/2023**	Electrode #:		Person:	**Gregory Vieira**
Testing Lab:	**UWM**	Phone:		Fax:	
Address:					

Enter the calibration values for the electrode in this table:

Liquid:	Clear	Purple	Green	Pink
% Cl⁻ :	0.005	0.020	0.050	0.500
mV :	102	73	52	-3

* The chart below will update automatically when values are captured in the enclosed tables. *
** This chart and tables are prepared for 240 samples on 6 pages. **

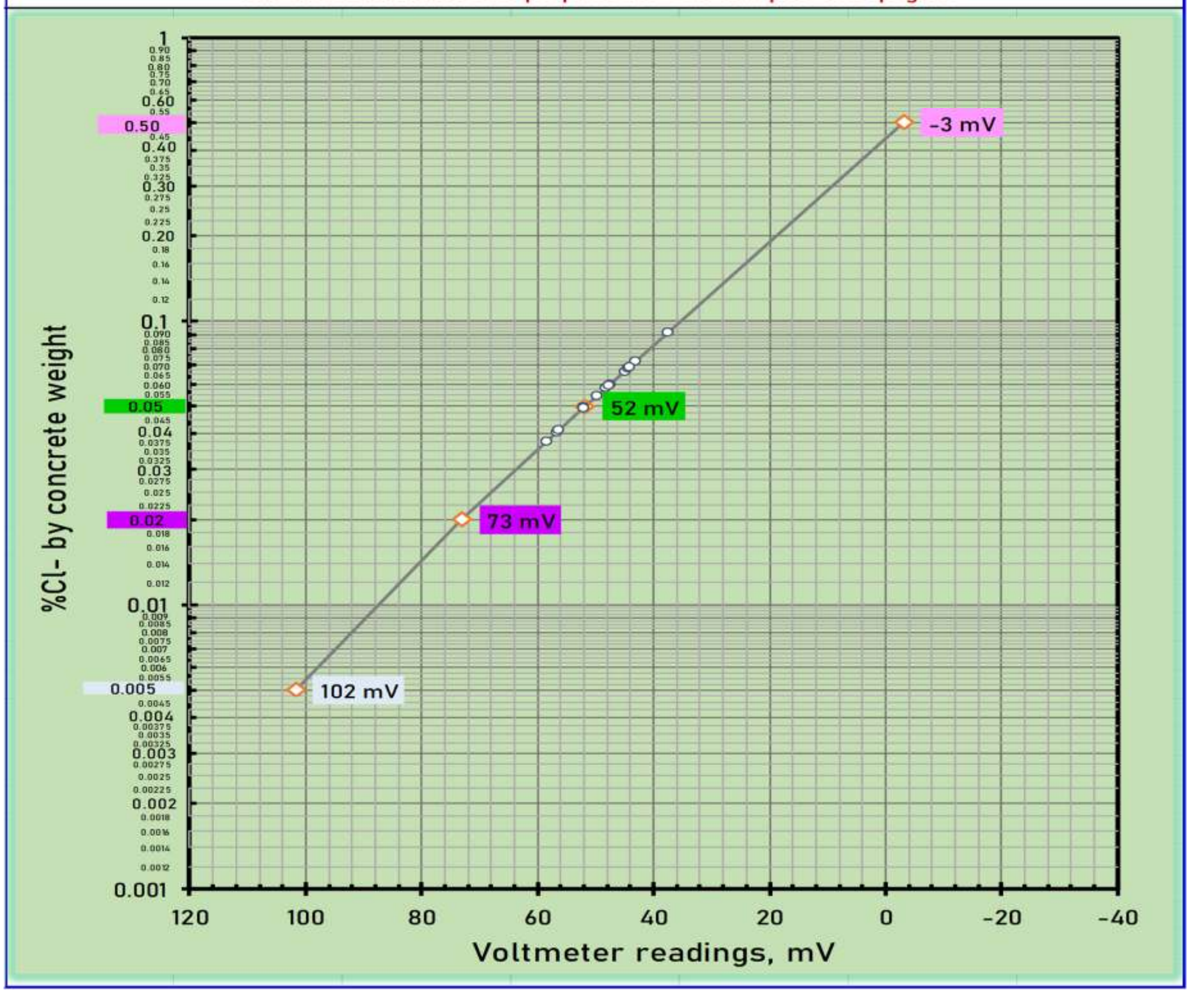

Figure 38 RCT Test 5min (original samples)

Table 15 Results for RCT 5-minute test on Original concrete samples

Sample no.	mV readings	% Cl- by concrete weight	Standard deviation	Average % Cl-
S1-1	56.7	0.040	0.007	0.045
S1-2	51.9	0.050		
S2-1	56.3	0.041	0.002	0.039
S2-2	58.4	0.038		
S3-1	47.4	0.060	0.005	0.063
S3-2	45.0	0.067		
S4-1	43.1	0.072	0.0099	0.065
S4-2	48.2	0.058		
S5-1	49.8	0.054	0.0099	0.061
S5-2	44.3	0.068		
S6-1	47.8	0.059	0.007	0.054
S6-2	52.1	0.049		
S7-1	44.1	0.069	0.015	0.080
S7-2	37.5	0.091		

Measurement of the acid soluble chloride content of HARDENED CONCRETE by the RCT method

1.5 gram of concrete dust dissolved in a RCT-1023 vial with 10 ml of extraction liquid

Report #:	1.1	Structure:	0 - 0.25 in	Project:	5 min test
Date:	4/19/2023	Electrode #:		Person:	Gregory Vieira
Testing Lab:	UWM	Phone:		Fax:	
Address:					

Enter the calibration values for the electrode in this table:

Liquid:	Clear	Purple	Green	Pink
% Cl⁻ :	0.005	0.020	0.050	0.500
mV :	102	73	52	-3

* The chart below will update automatically when values are captured in the enclosed tables. *

** This chart and tables are prepared for 240 samples on 6 pages. **

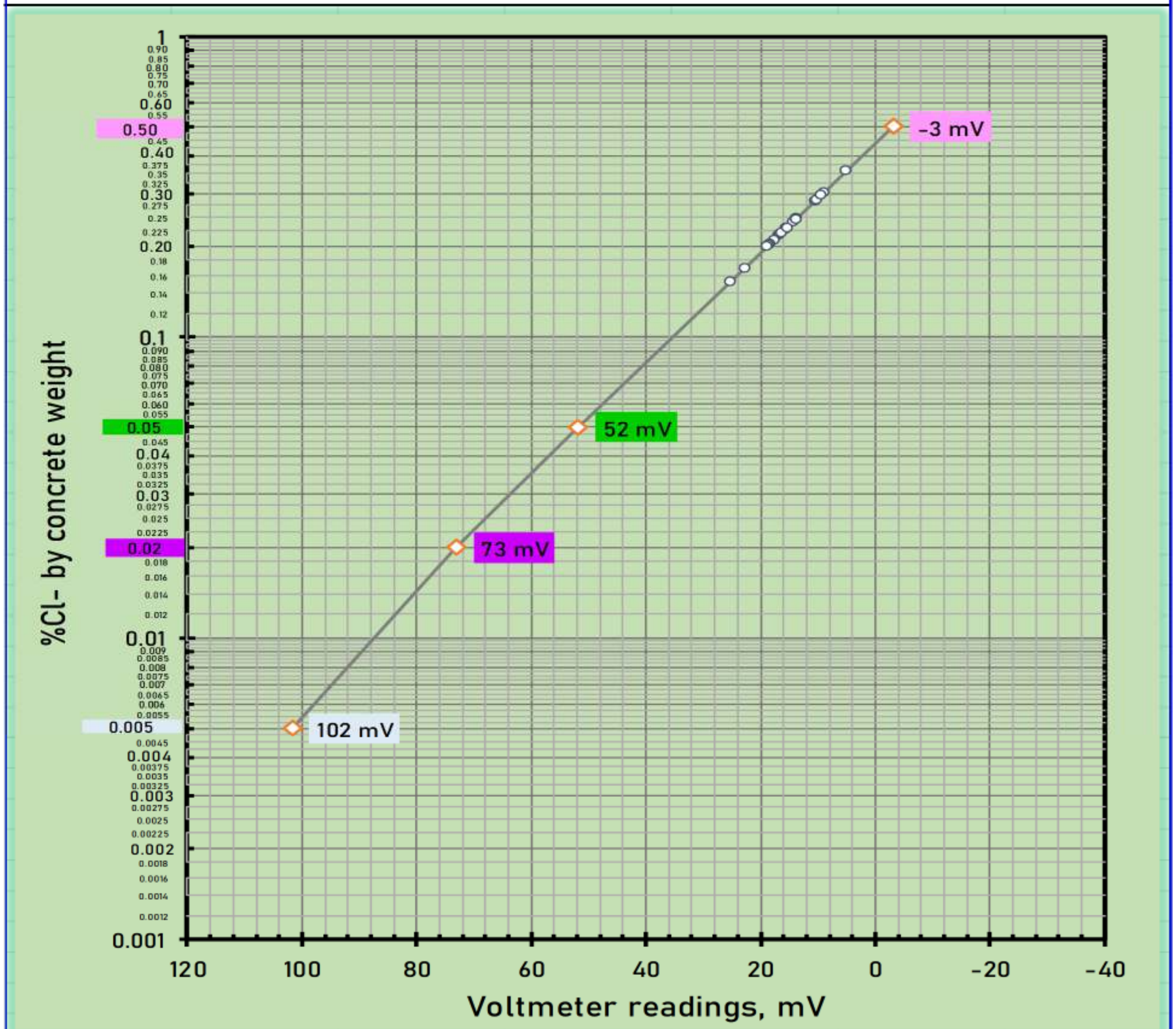

Figure 39 RCT Test 5min (0 - 0.25in)

Table 16 Results for RCT 5-minute test on Ponded samples taken at depth 0 to 0.25in

Sample no.	mV readings	% Cl- by concrete weight	Standard deviation	Average % Cl-	Average %Cl in Original slab	Change in % Cl-
S1-1	16.7	0.218	0.005	0.222	0.045	0.177
S1-2	15.6	0.228				
S1-3	16.5	0.220				
S2-1	10.4	0.284	0.009	0.290	0.039	0.251
S2-2	9.0	0.301				
S2-3	10.3	0.285				
S3-1	15.5	0.229	0.015	0.227	0.063	0.163
S3-2	17.6	0.210				
S3-3	14.3	0.241				
S4-1	13.7	0.247	0.012	0.233	0.065	0.168
S4-2	16.2	0.223				
S4-3	15.4	0.230				
S5-1	13.7	0.247	0.028	0.263	0.061	0.202
S5-2	13.8	0.246				
S5-3	9.4	0.296				
S6-1	18.3	0.204	0.026	0.175	0.054	0.121
S6-2	22.7	0.169				
S6-3	25.3	0.152				
S7-1	18.5	0.202	0.001	0.201	0.080	0.121
S7-2	18.5	0.202				
S7-3	18.8	0.200				

Measurement of the acid soluble chloride content of HARDENED CONCRETE by the RCT method

1.5 gram of concrete dust dissolved in a RCT-1023 vial with 10 ml of extraction liquid

Report #:	**1.1**	Structure:	**0.25 - 0.5 in**	Project:	**5 min test**
Date:	**4/19/2023**	Electrode #:		Person:	**Gregory Vieira**
Testing Lab:	**UWM**	Phone:		Fax:	
Address:					

Enter the calibration values for the electrode in this table:

Liquid:	Clear	Purple	Green	Pink
% Cl⁻ :	0.005	0.020	0.050	0.500
mV :	102	73	52	-3

* The chart below will update automatically when values are captured in the enclosed tables. *
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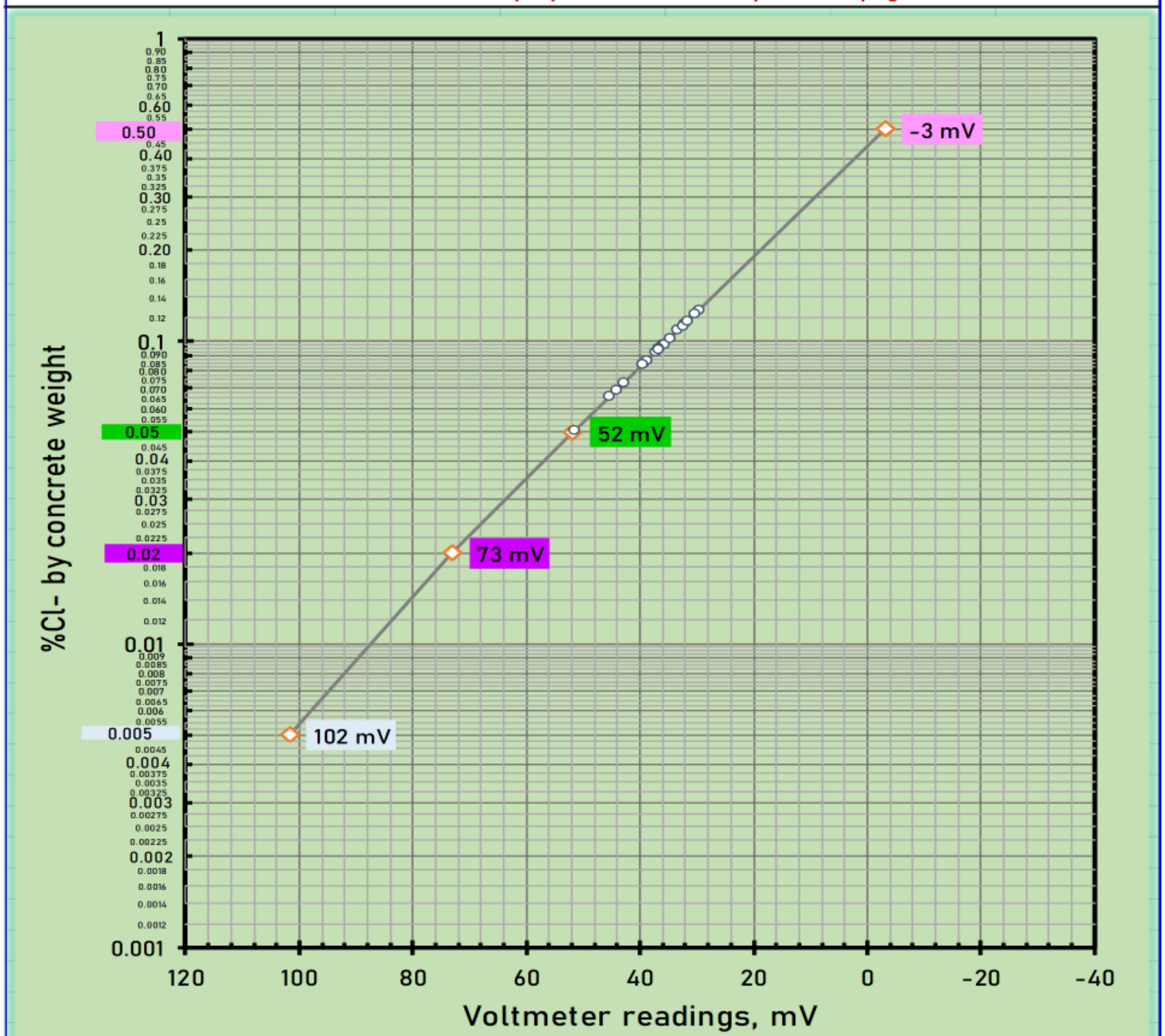

Figure 40 RCT Test 5min (0.25 - 0.5in)

Table 17 Results for RCT 5-minute test on Ponded samples taken at depth 0.25 to 0.5in

Sample no.	mV readings	% Cl- by concrete weight	Standard Deviation	Average % Cl-	Average %Cl in Original slab	change in % Cl-
S1-1	35.9	0.097	0.013	0.088	0.045	0.043
S1-2	36.7	0.094				
S1-3	42.8	0.073				
S2-1	35.8	0.098	0.008	0.107	0.039	0.067
S2-2	33.3	0.109				
S2-3	32.2	0.114				
S3-1	36.6	0.095	0.011	0.108	0.063	0.044
S3-2	32.5	0.112				
S3-3	31.7	0.116				
S4-1	37.3	0.092	0.005	0.096	0.065	0.031
S4-2	34.7	0.102				
S4-3	36.8	0.094				
S5-1	39.5	0.084	0.025	0.098	0.061	0.037
S5-2	39.3	0.084				
S5-3	29.6	0.127				
S6-1	38.7	0.087	0.018	0.068	0.054	0.013
S6-2	45.3	0.066				
S6-3	51.5	0.051				
S7-1	39.4	0.084	0.027	0.092	0.080	0.012
S7-2	30.3	0.123				
S7-3	44.1	0.069				

28-day Rapid Chloride Test (after 24 hours)

Measurement of the acid soluble chloride content of HARDENED CONCRETE by the RCT method

1.5 gram of concrete dust dissolved in a RCT-1023 vial with 10 ml of extraction liquid

Report #:	1.2	Structure:	Original	Project:	24hr test
Date:	4/20/2023	Electrode #:		Person:	Gregory Vieira
Testing Lab:	UWM	Phone:		Fax:	
Address:					

Enter the calibration values for the electrode in this table:

Liquid:	Clear	Purple	Green	Pink
% Cl⁻ :	0.005	0.020	0.050	0.500
mV :	96	71	51	-3

* The chart below will update automatically when values are captured in the enclosed tables. *
** This chart and tables are prepared for 240 samples on 6 pages. **

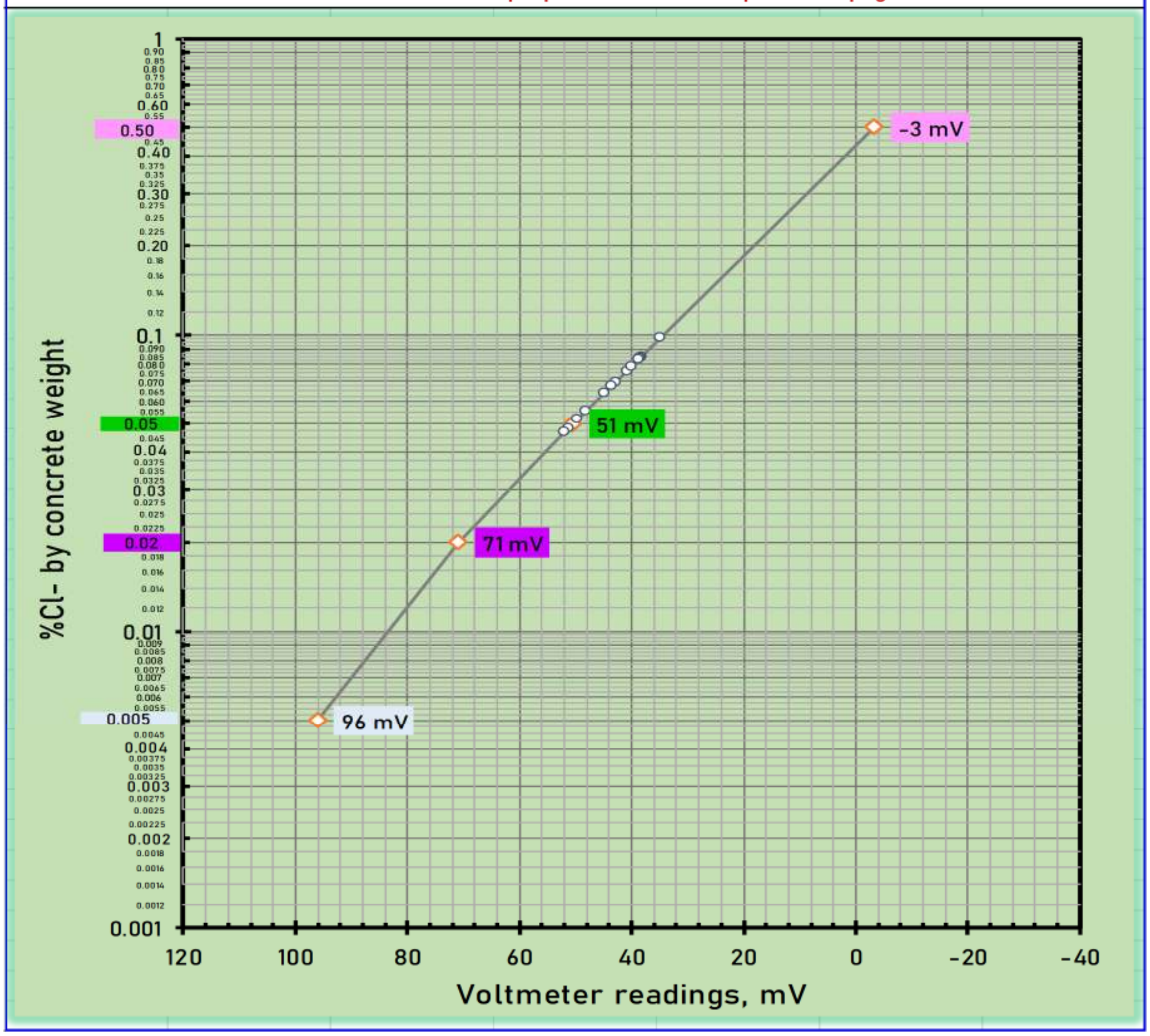

Figure 41 RCT Test 24 hr. (original samples)

Table 18 Results for RCT 24-hour test on Original concrete samples

Sample no.	mV readings	% Cl- by concrete weight	Standard deviation	Average % Cl-
S1-1	51.3	0.048	0.006	0.052
S1-2	48.1	0.056		
S2-1	49.6	0.052	0.003	0.050
S2-2	51.9	0.047		
S3-1	38.2	0.085	0.0007	0.084
S3-2	38.5	0.084		
S4-1	38.4	0.084	0.0099	0.077
S4-2	42.8	0.070		
S5-1	44.9	0.064	0.0084	0.070
S5-2	40.9	0.076		
S6-1	40.0	0.079	0.0084	0.073
S6-2	43.6	0.067		
S7-1	38.7	0.083	0.0107	0.091
S7-2	34.8	0.098		

Measurement of the acid soluble chloride content of HARDENED CONCRETE by the RCT method

1.5 gram of concrete dust dissolved in a RCT-1023 vial with 10 ml of extraction liquid

Report #:	**1.2**	Structure:	**0 - 0.25 in**	Project:	**24hr test**
Date:	**4/20/2023**	Electrode #:		Person:	**Gregory Vieira**
Testing Lab:	**UWM**	Phone:		Fax:	
Address:					

Enter the calibration values for the electrode in this table:				
Liquid:	Clear	Purple	Green	Pink
% Cl⁻ :	0.005	0.020	0.050	0.500
mV :	96	71	51	-3

* The chart below will update automatically when values are captured in the enclosed tables. *
** This chart and tables are prepared for 240 samples on 6 pages. **

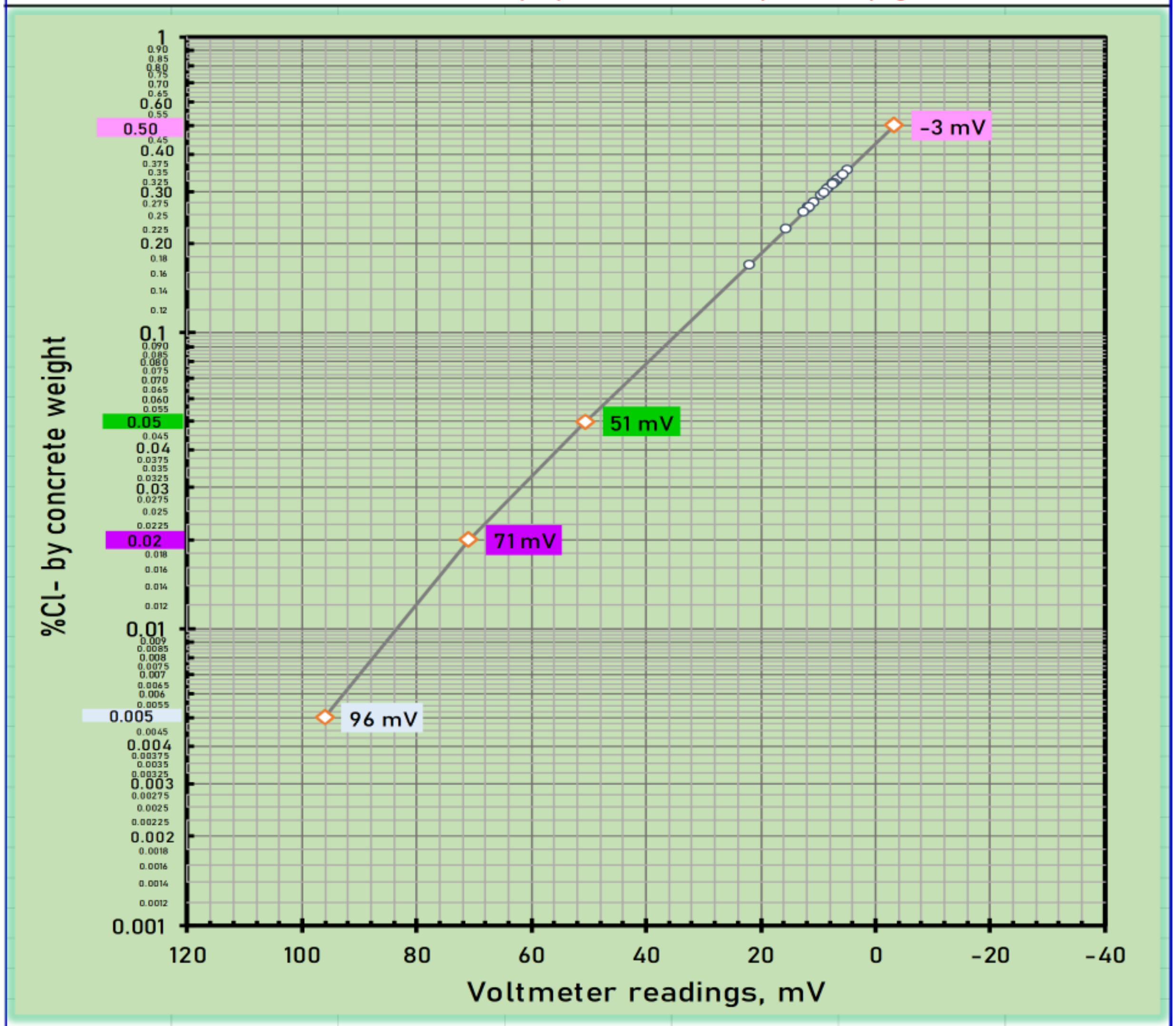

Figure 42 RCT Test 24 hr. (0 - 0.25in)

Table 19 Results for RCT 24-hour test on Ponded samples at depth 0-0.25in

Sample no.	mV readings	% Cl- by concrete weight	Standard deviation	Average % Cl-	Average %Cl in Original slab	change in % Cl-
S1-1	8.1	0.307	0.023	0.289	0.052	0.237
S1-2	9.0	0.296				
S1-3	16.5	0.263				
S2-1	5.8	0.339	0.013	0.339	0.050	0.289
S2-2	4.9	0.352				
S2-3	6.7	0.326				
S3-1	7.3	0.318	0.029	0.285	0.084	0.201
S3-2	10.6	0.276				
S3-3	11.8	0.262				
S4-1	6.5	0.329	0.037	0.286	0.077	0.209
S4-2	11.6	0.265				
S4-3	11.5	0.266				
S5-1	8.3	0.305	0.026	0.313	0.070	0.243
S5-2	9.3	0.292				
S5-3	5.6	0.342				
S6-1	12.5	0.255	0.043	0.216	0.073	0.143
S6-2	15.6	0.223				
S6-3	22	0.170				
S7-1	7.1	0.321	0.013	0.310	0.091	0.219
S7-2	7.5	0.315				
S7-3	9	0.296				

Measurement of the acid soluble chloride content of HARDENED CONCRETE by the RCT method

1.5 gram of concrete dust dissolved in a RCT-1023 vial with 10 ml of extraction liquid

Report #:	1.2	Structure:	0.25 - 0.5 in	Project:	24hr test
Date:	4/20/2023	Electrode #:		Person:	Gregory Vieira
Testing Lab:	UWM	Phone:		Fax:	
Address:					

Enter the calibration values for the electrode in this table:

Liquid:	Clear	Purple	Green	Pink
% Cl⁻ :	0.005	0.020	0.050	0.500
mV :	96	71	51	-3

* The chart below will update automatically when values are captured in the enclosed tables. *
** This chart and tables are prepared for 240 samples on 6 pages. **

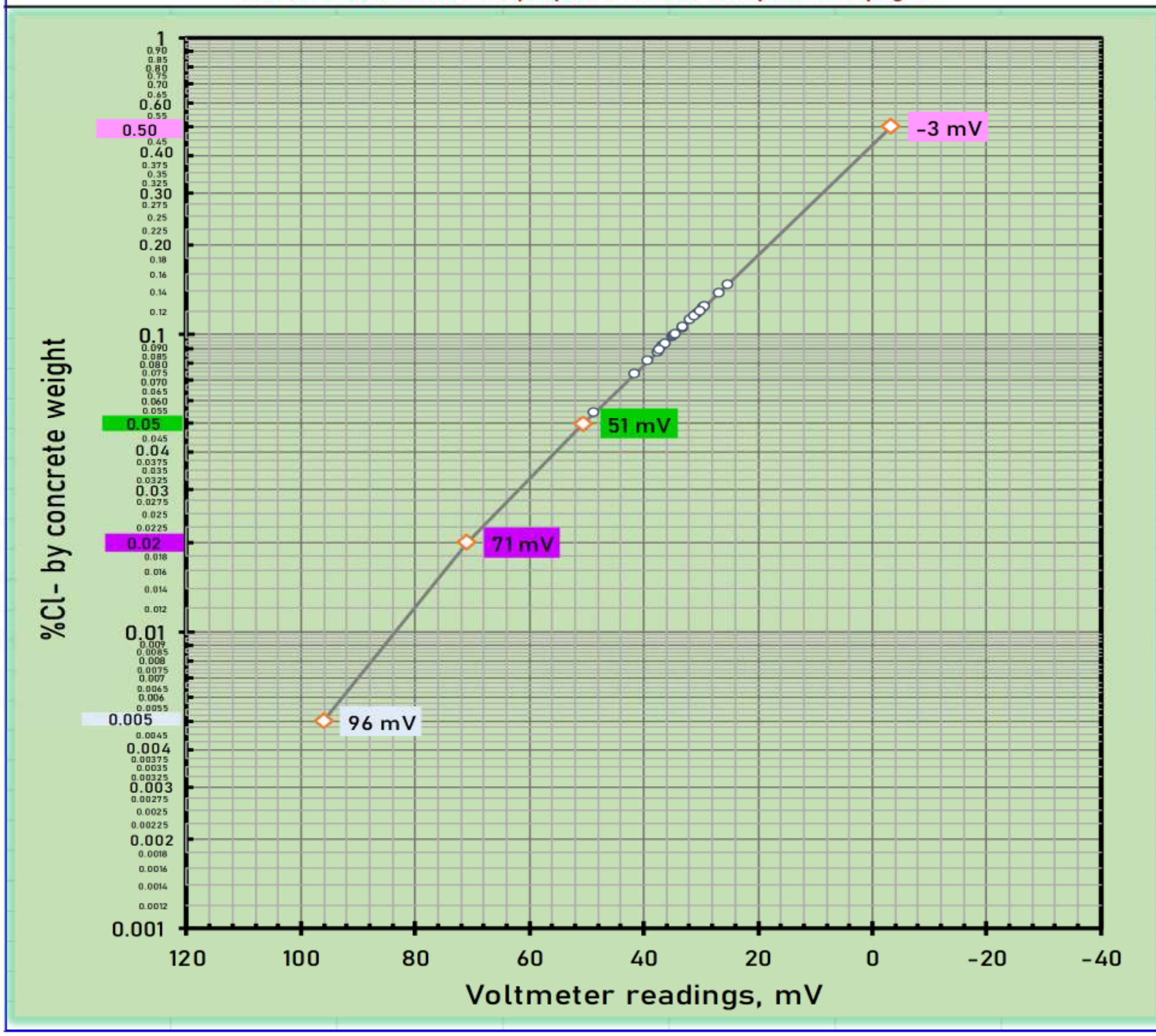

Figure 43 RCT Test 24 hr. (0.25 - 0.5in)

Table 20 Results for RCT 24-hour test on Ponded samples at depth 0.25-0.5in

Sample no.	mV readings	% Cl- by concrete weight	Standard deviation	Average % Cl-	Average %Cl in Original slab	change in % Cl-
S1-1	30.7	0.117	0.0183	0.101	0.052	0.049
S1-2	33.2	0.105				
S1-3	39.2	0.081				
S2-1	31.8	0.112	0.0066	0.120	0.050	0.070
S2-2	29.3	0.124				
S2-3	29.5	0.123				
S3-1	36.6	0.091	0.0173	0.110	0.084	0.026
S3-2	31	0.116				
S3-3	29.3	0.124				
S4-1	34.8	0.098	0.0111	0.108	0.077	0.031
S4-2	30.2	0.120				
S4-3	33.1	0.106				
S5-1	37.6	0.087	0.0267	0.108	0.070	0.038
S5-2	34.6	0.099				
S5-3	26.8	0.138				
S6-1	36.1	0.093	0.0195	0.074	0.073	0.001
S6-2	41.6	0.073				
S6-3	48.6	0.054				
S7-1	34.3	0.100	0.03	0.112	0.09	0.021
S7-2	25.3	0.147				
S7-3	37.1	0.09				