

Report No. UT-20.25

POLYESTER POLYMER CONCRETE FOR BRIDGE DECK OVERLAYS

Prepared For:

Utah Department of Transportation
Research & Innovation Division

**Final Report
October 2020**

DISCLAIMER

The authors alone are responsible for the preparation and accuracy of the information, data, analysis, discussions, recommendations, and conclusions presented herein. The contents do not necessarily reflect the views, opinions, endorsements, or policies of the Utah Department of Transportation or the U.S. Department of Transportation. The Utah Department of Transportation makes no representation or warranty of any kind, and assumes no liability therefore. The authors also make no warranty, express or implied, regarding the suitability of findings documented in this report for a particular purpose and shall not be held liable under any circumstances for any direct, consequential, or other damages with respect to claims by users of any findings documented in this report, including claims based on allegations of errors, omissions, or negligence.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Utah Department of Transportation for providing funding for this project and the California Department of Transportation for hosting the scanning tour for this research.

TECHNICAL REPORT ABSTRACT

1. Report No. UT-20.25		2. Government Accession No. N/A		3. Recipient's Catalog No. N/A	
4. Title and Subtitle POLYESTER POLYMER CONCRETE FOR BRIDGE DECK OVERLAYS				5. Report Date October 2020	
				6. Performing Organization Code N/A	
7. Author(s) Robert J. Stevens, Ph.D., W. Spencer Guthrie, Ph.D.				8. Performing Organization Report No. N/A	
9. Performing Organization Name and Address Brigham Young University Department of Civil and Environmental Engineering 430 Engineering Building Provo, UT 84602				10. Work Unit No. 5H08419H	
				11. Contract or Grant No. 15-8775	
12. Sponsoring Agency Name and Address Utah Department of Transportation 4501 South 2700 West P.O. Box 148410 Salt Lake City, UT 84114-8410				13. Type of Report & Period Covered Final, February 2015 to May 2020	
				14. Sponsoring Agency Code PIC No. UT14.403	
15. Supplementary Notes Prepared in cooperation with the Utah Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration					
16. Abstract <p>The objectives of this research were to 1) compile a synthesis of information about polyester polymer concrete (PPC) from the literature; 2) conduct a scanning tour to observe PPC construction, inspect in-service PPC overlays, and discuss topics related to PPC; 3) revise the existing Utah Department of Transportation (UDOT) PPC specification; 4) document a PPC field demonstration project; and 5) perform laboratory characterization of the material properties of field-mixed PPC. The scope of the research included a literature review, a scanning tour, specification revisions, field testing, and laboratory experimentation.</p> <p>Several recommendations relevant to Utah bridge deck preservation practice were developed based on findings from the literature review and scanning tour and were then incorporated into a revised UDOT PPC specification. In the PPC field demonstration project, recommendations regarding hardness testing, skid resistance testing, patching, and surface preparation were developed. In the laboratory, the density, modulus of elasticity, coefficient of thermal expansion, hardness, unconfined compressive strength, splitting tensile strength, rapid chloride permeability, and resin content of field-mixed PPC sampled during the demonstration project were measured.</p>					
17. Key Words Concrete bridge deck, overlay, polyester polymer concrete, quality assurance, scanning tour		18. Distribution Statement Not restricted. Available through: UDOT Research & Innovation Div. 4501 South 2700 West P.O. Box 148410 Salt Lake City, UT 84114-8410 www.udot.utah.gov/go/research		23. Registrant's Seal N/A	
19. Security Classification (of this report) Unclassified	20. Security Classification (of this page) Unclassified	21. No. of Pages 131	22. Price N/A		

TABLE OF CONTENTS

LIST OF TABLES	vii
LIST OF FIGURES	viii
LIST OF ACRONYMS	ix
EXECUTIVE SUMMARY	1
1.0 INTRODUCTION	2
1.1 Problem Statement	2
1.2 Background	3
1.3 Research Objectives and Scope.....	3
1.4 Outline.....	4
2.0 LITERATURE REVIEW	5
2.1 Introduction	5
2.2 Historical Use	5
2.3 Composition	7
2.3.1 Aggregates	7
2.3.2 Binders.....	8
2.3.3 Mixture Formulations	9
2.4 Material Properties	12
2.4.1 UCS	12
2.4.2 Tensile and Flexural Strength.....	12
2.4.3 MOE	13
2.4.4 CTE.....	14
2.4.5 Compatibility and Bond Strength	15
2.4.6 Shrinkage	16
2.4.7 Creep.....	17
2.4.8 Skid Resistance.....	17
2.4.9 Abrasion Resistance	17
2.4.10 Chemical Resistance.....	18
2.4.11 Permeability.....	19
2.5 Design.....	20
2.6 Construction	20

2.6.1 Deck Preparation	21
2.6.2 Placement.....	22
2.7 Performance Factors.....	24
2.7.1 Aggregate Selection.....	24
2.7.2 Resin Content	24
2.7.3 Microfiller.....	25
2.7.4 Mixing Time and Methods	26
2.7.5 Consolidation Time and Methods.....	26
2.7.6 Curing	26
2.7.7 Strain and Loading Rate	28
2.7.8 Temperature.....	28
2.7.9 Moisture.....	29
2.7.10 Temperature and Moisture Cycling.....	29
2.8 Advantages and Disadvantages	30
2.9 Chapter Summary.....	31
3.0 SCANNING TOUR OF POLYESTER POLYMER CONCRETE OVERLAYS ON BRIDGE DECKS IN CALIFORNIA	32
3.1 Introduction	32
3.2 Caltrans History with PPC	32
3.3 Scanning Tour	33
3.3.1 Material Properties	34
3.3.2 Mixture and Overlay Design	35
3.3.3 Laboratory Testing	36
3.3.4 Construction and Field Testing.....	37
3.4 Discussion	42
3.4.1 MOE Testing	43
3.4.2 Bond Beam Testing	43
3.4.3 Resin Demand Testing.....	43
3.4.4 Aggregate Quality Testing.....	43
3.4.5 Set Time Testing.....	44
3.4.6 Compaction Testing.....	44

3.4.7 Hardness and Bond Strength Testing	44
3.4.8 Skid Resistance Testing.....	44
3.5 Chapter Summary.....	45
4.0 FIELD TESTING OF POLYESTER POLYMER CONCRETE OVERLAYS ON	
BRIDGE DECKS IN UTAH	46
4.1 Introduction	46
4.2 Background	46
4.2.1 PPC Material Properties	46
4.2.2 Concrete Bridge Deck Applications	47
4.3 Procedures	48
4.3.1 Site Description	49
4.3.2 Site Testing	51
4.4 Results	55
4.4.1 Hardness Testing	55
4.4.2 Skid Resistance Testing.....	57
4.4.3 Impact-Echo Testing.....	58
4.4.4 VEI Testing.....	61
4.5 Recommendations	64
4.5.1 Hardness Testing	64
4.5.2 Skid Resistance Testing.....	64
4.5.3 Patching	64
4.5.4 Surface Preparation.....	65
4.6 Chapter Summary.....	66
5.0 LABORATORY CHARACTERIZATION OF FIELD-MIXED POLYESTER	
POLYMER CONCRETE FOR BRIDGE DECK OVERLAYS	67
5.1 Introduction	67
5.2 Background	67
5.2.1 Composition.....	68
5.2.2 Performance.....	68
5.3 Procedures	69
5.3.1 Specimen Preparation	69

5.3.2 Specimen Testing	71
5.3.3 Statistical Analysis	75
5.4 Results	76
5.4.1 Density.....	76
5.4.2 MOE	77
5.4.3 CTE.....	78
5.4.4 Hardness	79
5.4.5 UCS	81
5.4.6 STS	82
5.4.7 RCP.....	83
5.4.8 Resin Content	84
5.4.9 Statistical Analysis	85
5.5 Chapter Summary.....	86
6.0 CONCLUSION.....	87
6.1 Summary	87
6.2 Findings and Recommendations	87
6.2.1 Scanning Tour.....	87
6.2.2 Field Testing	89
6.2.3 Laboratory Experimentation.....	90
6.3 Main Contributions	91
REFERENCES	92
APPENDIX A: REVISED UDOT PPC SPECIFICATION	100

LIST OF TABLES

Table 2.1 PPC Mixture Designs.....	10
Table 4.1 Factors Affecting PPC Hardening Rate	56
Table 5.1 Density by Level of Consolidation Effort.....	76
Table 5.2 MOE by Level of Consolidation Effort and Temperature	78
Table 5.3 CTE by Level of Consolidation Effort	79
Table 5.4 Hardness by Level of Consolidation Effort	80
Table 5.5 UCS by Level of Consolidation Effort	81
Table 5.6 STS by Level of Consolidation Effort	82
Table 5.7 Charge Passed by Level of Consolidation	83
Table 5.8 Resin Content.....	84
Table 5.9 p-values by Level of Consolidation Effort	85

LIST OF FIGURES

Figure 3.1 PPC laboratory testing	36
Figure 3.2 PPC construction and testing.....	39
Figure 4.1 Modified paving machine used to place PPC.....	49
Figure 4.2 Bridge deck prior to PPC placement	50
Figure 4.3 Consecutive rebound numbers in the same location on PPC overlays.....	52
Figure 4.4 PPC hardness over time.....	55
Figure 4.5 PPC overlay hardness at 2 years.....	57
Figure 4.6 PPC overlay skid resistance at 2 years.	58
Figure 4.7 Impact-echo map of bridge placement A	59
Figure 4.8 Impact-echo map of bridge placements B (bottom) and C (top).....	60
Figure 4.9 Impact-echo results before and after PPC overlay placement.....	61
Figure 4.10 VEI map of bridge placement A.....	61
Figure 4.11 VEI map of bridge placements B (bottom) and C (top)	62
Figure 4.12 VEI before and after PPC overlay placement.....	63
Figure 4.13 Section view of a concrete bridge deck with PPC overlay.....	65
Figure 5.1 Average density.	77
Figure 5.2 Average MOE at three different temperatures.	78
Figure 5.3 Average CTE.....	79
Figure 5.4 Average hardness.....	80
Figure 5.5 Average UCS.....	81
Figure 5.6 Average STS.....	83
Figure 5.7 Average resin content.	84

LIST OF ACRONYMS

AC	asphalt concrete
ACI	American Concrete Institute
ANOVA	analysis of variance
BAE	bandlimited acoustic energy
BPN	British pendulum number
BPT	British pendulum tester
BYU	Brigham Young University
Caltrans	California Department of Transportation
CTE	coefficient of thermal expansion
DOT	Department of Transportation
FHWA	Federal Highway Administration
LAX	Los Angeles International Airport
MEKP	methyl ethyl ketone peroxide
MOE	modulus of elasticity
PCC	portland cement concrete
PPC	polyester polymer concrete
QA	quality assurance
QC	quality control
RCP	rapid chloride permeability
STS	splitting tensile strength
UCS	unconfined compressive strength
UDOT	Utah Department of Transportation
VEI	vertical electrical impedance

EXECUTIVE SUMMARY

The objectives of this research were to 1) compile a synthesis of information about polyester polymer concrete (PPC) from the literature; 2) conduct a scanning tour to observe PPC construction, inspect in-service PPC overlays, and discuss topics related to PPC; 3) revise the existing Utah Department of Transportation (UDOT) PPC specification; 4) document a PPC field demonstration project; and 5) perform laboratory characterization of the material properties of field-mixed PPC. The scope of the research included a literature review, a scanning tour, specification revisions, field testing, and laboratory experimentation.

The objectives of the scanning tour included observation of a PPC overlay placement, inspection of existing overlays, and discussion of selected topics related to PPC. The scanning tour comprised a 3-day visit to California. Items related to material properties, mixture and overlay design, laboratory testing, and construction and field testing were investigated. Several recommendations relevant to Utah bridge deck preservation practice were developed based on findings from the literature review and the scanning tour and were then incorporated into a revised UDOT PPC specification.

The objective of the field testing was to evaluate specific aspects of construction, quality assurance, and performance of PPC overlays on concrete bridge decks. The scope of the project included testing of a PPC test section overlay and three PPC bridge deck overlays during and after construction. Hardness tests were performed on the test section placements, and hardness, skid resistance, impact-echo, impedance, and resin content determination tests were performed on each of the bridge deck overlays. Recommendations regarding hardness testing, skid resistance testing, patching, and surface preparation were developed based on the findings.

The objectives of the laboratory experimentation were to characterize several material properties of field-mixed PPC sampled from actual bridge deck overlay placements in Utah and compare them to properties of laboratory-mixed PPC reported in the literature. Laboratory testing was conducted on a typical PPC mixture. Properties that were measured include density, modulus of elasticity, coefficient of thermal expansion, hardness, unconfined compressive strength, splitting tensile strength, rapid chloride permeability, and resin content. Measured properties were consistent with typical ranges cited in the literature.

1.0 INTRODUCTION

1.1 Problem Statement

Substantial effort has been invested into finding methods that inhibit the corrosion of rebar caused by the ingress of especially moisture and chloride ions in concrete bridge decks. Application of protective overlays on concrete bridge decks has proven to be one of the most effective methods of preventing corrosive elements from penetrating bridge deck surfaces (Guthrie et al. 2005). Many different materials have been used for protective bridge deck overlays, including but not limited to asphalt concrete, high-density concrete, silica fume concrete, latex-modified concrete, and various types of polymer concrete (Doody and Morgan 1993).

Polyester polymer concrete (PPC) is one type of polymer concrete that has been successfully used for bridge deck overlays. PPC consists of a polyester-based resin binder and natural aggregate. The type of premixed PPC that is commonly used in current practice was first placed on bridge decks by the California Department of Transportation (Caltrans) in the early 1980s (Krauss et al. 2007, NCHRP 2011). The Utah Department of Transportation (UDOT) is currently increasing the use of PPC overlays on bridge decks in Utah. As this material has been recently introduced to several other states, the need for sharing of information about PPC construction, quality assurance (QA), and performance is increasing.

Although Caltrans has developed a thorough PPC mixture design approval process that involves significant laboratory testing and verification of PPC composition and material properties prior to PPC overlay placements, Caltrans does not commonly sample or test any field-mixed PPC for the purpose of QA (Stevens and Guthrie 2020). Instead, QA in the field is limited primarily to visual inspection and oversight by a representative from the PPC supplier. Because the vast majority of PPC used in the United States is furnished by the same supplier, generally under the same or similar specifications as those used in California, the practice of relying almost exclusively on visual inspection for QA has become widespread. For this main reason, the literature is generally absent of field and laboratory test results obtained on field-mixed PPC. Therefore, with increasing use of PPC overlays throughout the United States, additional research on PPC construction, QA, performance, and material properties was needed.

1.2 Background

Although concrete is strong in compression, it is relatively weak in tension. As a result, structural concrete almost always requires the use of reinforcing steel, commonly referred to as rebar, to increase its tensile strength (McCormac and Brown 2014, Mindess et al. 2003). Concrete bridge decks are reinforced with substantial amounts of rebar, with the upper layer, or mat, typically being positioned between 2 and 3 in. below the deck surface (Hema et al. 2004). Although rebar adds significant structural capacity to bridge decks, it is also susceptible to corrosion. Corrosion of steel is caused by contact with water and oxygen and accelerated by chloride ions, which can diffuse through concrete due to its porous nature. Cracks in bridge decks also expose rebar to these corrosive elements (Jones et al. 2015).

While water and oxygen are ubiquitous in most climates, chloride ions are most prevalent in coastal regions exposed to sea water and in cold regions where deicing salt is routinely applied to bridge decks as part of winter maintenance (Guthrie and Linford 2006). When salts are dissolved in water on the bridge deck, chloride ions become concentrated in the deck surface and, over time, diffuse downward into the concrete or pass directly through cracks in the concrete (Mindess et al. 2003). When the steel is exposed to these elements and begins to corrode, it expands by five to seven times its original volume. This expansion generates forces that far exceed the tensile capacity of the concrete, and the concrete eventually cracks, which further exacerbates the deterioration process (Patnaik and Baah 2015). Corrosion of reinforcing steel is responsible for a significant portion of the damage that occurs on bridge decks in cold regions, such as Utah, where large amounts of deicing salts are commonly used (Mindess et al. 2003).

1.3 Research Objectives and Scope

Five objectives were developed for this research:

1. Compile a synthesis of information about PPC from the literature.
2. Conduct a scanning tour to observe PPC construction, inspect in-service PPC overlays, and discuss topics related to PPC.
3. Revise the existing UDOT PPC specification.

4. Document a PPC field demonstration project.
5. Perform laboratory characterization of the material properties of field-mixed PPC.

The scope of this research included a literature review, a scanning tour, specification revisions, field testing, and laboratory experimentation. The literature review encompassed a wide range of publications available on the subject of PPC. The scanning tour involved observation of a PPC overlay placement, inspection of existing overlays, and discussion of selected topics related to PPC. In the field, two PPC test section overlay placements and three PPC bridge deck overlays were tested during and after construction. In the laboratory, testing was conducted on a typical PPC mixture from actual bridge deck overlay placements in Utah, and the effect of consolidation effort on several properties of PPC specimens was investigated.

1.4 Outline

This report contains six chapters. Chapter 1 gives the problem statement, provides background information, states the research objectives, and describes the scope of the research. Chapter 2 presents a synthesis of information about PPC from the existing literature. Chapter 3 explains the findings obtained from the scanning tour. Chapters 4 and 5 describe the procedures and results of the field and laboratory testing, respectively. Chapter 6 offers conclusions and recommendations based on the research findings.

2.0 LITERATURE REVIEW

2.1 Introduction

The purpose of this chapter is to present a synthesis of existing information about PPC based on a comprehensive literature review of related topics. The following sections discuss the historical use, composition, material properties, design, construction, performance factors, and advantages and disadvantages of PPC overlays.

2.2 Historical Use

Polymer concrete was first used for bridge deck overlays in the 1950s. Early polymer overlays consisted of a layer of coal-tar epoxy that was spread onto the bridge deck and a layer of fine aggregate that was broadcast on top. This technique for placing overlays became known as the broom-and-seed method because resin is first broomed onto the deck and then seeded with aggregate. These first applications were not very effective because they were not totally impermeable and lacked durability (NCHRP 2011).

In the 1960s, modifications to improve the original mixture were made by using an oil-extended epoxy. By the 1970s, due in large part to research conducted by the Brookhaven National Laboratory and the Bureau of Reclamation, overlays made with epoxy, polyester-styrene and methyl methacrylate had been developed and were being placed on bridge decks. Although these new materials were an improvement over those used in the first polymer overlays, they were not well understood at the time. As a result, many of these placements exhibited poor performance and failed earlier than expected. One of the most common failure mechanisms during this time was overlay delamination. Delaminations were often caused at least partially by thermal incompatibilities between overlays and bridge deck concrete. Poor construction practices were also a major contributing factor to delaminations and other premature failures of early polymer overlays. In subsequent years, substantial improvements were made to polymer concrete mixtures and overlay construction practices that greatly improved performance (Maass 2003, NCHRP 2011).

In the late 1970s, premixed PPC overlays were developed. Premixed overlays differ from overlays placed using the broom-and-seed method in that the resin and aggregate are blended together and placed in a single layer on the deck. This method allows for easier control over the thickness and ride quality of the overlay and also allows finishing operations to be conducted using PCC equipment and practices. The premixed PPC system was originally developed by the Oregon Department of Transportation (DOT) and later modified by Caltrans. For PPC, the premixed method soon became the standard for overlay placement. The first application of premixed PPC in California was on a section of concrete pavement on Interstate 80 in 1979. The original Oregon mixture was used, and roller compaction was used to consolidate the overlay. Difficulty placing the mixture prompted the modifications later implemented by Caltrans. In order to improve workability, the aggregate gradation used in the original mixture was changed, and a styrene monomer was added to lower the viscosity of the resin (Krauss et al. 2007).

In the early 1980s, Caltrans began placing premixed PPC overlays on bridge decks as a replacement for asphalt concrete membrane systems (personal communication, E. Kaslan, February 17, 2015). Two of these first PPC overlays in California were placed in 1983 on bridges in low-traffic, alpine regions in the northern part of the state. While the history of these bridge decks does not give an indication of the ability of PPC to withstand heavy trafficking, it has shown that PPC can withstand the harsh environmental conditions of alpine environments over time (Krauss et al. 2007). Although problems with other overlays have occurred when errors were made during construction, these original PPC placements in California have lasted for over 30 years (personal communication, E. Kaslan, February 17, 2015).

By the early 1980s, other states had begun experimenting with premixed PPC overlays. Apart from California, the state of New York was one of the biggest proponents of PPC during the early 1980s. In New York City, a 15,500-ft² PPC overlay was placed on Yaphank Avenue in 1982, and a 12,100-ft² overlay was placed on East Main Street in 1983. Seven other PPC overlays were also constructed in the vicinity of New York City around that time (Doody and Morgan 1993).

One of the first very large premixed PPC overlay placements was not on a bridge deck, but on a highway pavement. The placement occurred in 1985 in the Donner Pass region of

California. Caltrans placed PPC on approximately 10 lane-miles of pavement that had experienced severe tire chain damage due to heavy truck traffic. The overlay held up remarkably well, and the success of the Donner Pass project spurred the use of PPC for bridge deck overlays throughout the state. By 1988, more than 25 bridge decks had received PPC overlays in California. With one exception on an experimental project, no signs of distress on any of the overlays had been documented at that time. In 1988, the Federal Highway Administration (FHWA) began accepting PPC overlays in California as non-experimental projects. Since the late 1980s, PPC has been used successfully on numerous overlay applications in California, including projects on high-profile structures such as the Marina Viaduct, Interstate 15, and several bridges in the San Francisco Bay area (Krauss et al. 2007, Maass 2003).

The effectiveness of PPC has been proven in the last 10 to 15 years as PPC has come into widespread use on projects throughout California and elsewhere. PPC specifications and/or reports have been developed for projects in a number of states, including Alaska, California, Colorado, Delaware, Kansas, Montana, Nevada, New York, North Carolina, Utah, and Washington (ADOT&PF 2007, Anderson et al. 2013, Caltrans 2018, CDOT 2014, DelDOT 2012, Meggers 2015, MDT 2014, NDOT 2019, NYSDOT 2019, NCDOT 2016, UDOT 2017).

2.3 Composition

Polymer concrete is a synthetic material that is often used for bridge deck overlays. Like portland cement concrete (PCC), polymer concrete is also comprised largely of aggregate; however, instead of portland cement as the binder, polymer concrete has a polymer resin as the binder. Specifically, binders used in polymer concrete typically consist of methacrylate, epoxy, or polyester resins (Doody and Morgan 1993, Sprinkel 1993, Sprinkel 1997, Sprinkel 2003). The following sections discuss PPC aggregates, binders, and various mixture formulations.

2.3.1 Aggregates

Aggregates used in polymer overlays commonly consist of silica and basalt. Uniformly graded aggregates are used in slurries and premixed overlays, while gap-graded aggregates are used with multiple-layer overlays and for broadcasting on top of overlays. Multiple-layer

overlays are well suited for decks with good existing ride quality, while slurries and premixed overlays can be used to correct surface defects (Sprinkel 1993, Sprinkel 1997, Sprinkel 2003).

Aggregate cleanliness and morphology are important parameters that should be closely controlled. Natural, clean sand and coarse aggregate should be used due to the rounded particle shapes of these materials. Manufactured sand, being more angular, should not be used with PPC to avoid workability problems (personal communication, E. Kaslan, February 17, 2015).

Aggregates used in PPC should be dry and should not contain dirt, clay, asphalt, or other organic materials (Sprinkel 1997). They should also be resistant to fracture and polish (Smith 1991).

2.3.2 Binders

Binders used in polymer overlays typically include a base resin and a curing agent, or initiator. Low-viscosity binders are used in well-graded mixtures, and binders with higher viscosities are used in gap-graded mixtures (Sprinkel 1993, Sprinkel 1997, Sprinkel 2003).

The polyester resin used in PPC is composed of a liquid monomer that reacts with a catalyst (initiator) to become a solid. This reaction is called polymerization, which is an exothermic process (Doody and Morgan 1993, Haddad and Kobaisi 2013, Vipulanandan and Paul 1990). Polyester resin is formed when dicarboxylic acids and dihydroxy alcohols combine in a polycondensation reaction. Isophthalic acids form isophthalic polyesters, while phthalic acids form orthophthalic polyesters. Isophthalic polyester resins are stronger and are considered to be superior to orthophthalic polyester resins (Gorninski et al. 2004, Gorninski et al. 2007).

Although different PPC mixtures have various chemical compositions, the mixture that is now primarily used throughout the United States has an unsaturated isophthalic polyester-styrene resin containing a small percentage of methacryloxypropyltrimethoxysilane (commonly abbreviated as silane). In this mixture, methyl ethyl ketone peroxide (MEKP) is used to “catalyze” the resin (Krauss et al. 2007; Kwikbond 2011a; personal communication, R. Wiegman, May 8, 2015). Although MEKP is commonly referred to as a catalyst, it is an initiator of polymerization because it is consumed during the polymerization reaction.

Unsaturated polyester resins contain double-bonded carbon atoms and are characterized as thermosetting polymers. Unlike thermoplastics, thermosetting polymers form irreversibly cross-linked bonds during the polymerization reaction (Callister 2001).

The addition of silane to PPC resins has been shown to increase mixture strengths (Krauss 1988a, Krauss 1988b, Mani et al. 1987). Silane induces chemical bonding between the resin and the aggregate, which further strengthens the mixture beyond the physical bonding that occurs through Van der Waals forces (Vipulanandan and Paul 1993).

The styrene contained in many polyester resins decreases viscosity, which improves the wetting properties of the resin and the workability of the mixture. The improved workability imparted by the styrene allows for the use of a lower resin content than would otherwise be required. A styrene content of 45 to 50 percent by weight of resin is considered optimum for overlay applications (Krauss 1988a, Krauss 1988b).

2.3.3 Mixture Formulations

Laboratory studies of PPC have used formulations with a wide range of mixture compositions and proportions. Indeed, there have been almost as many different mixtures as separate studies on PPC. However, very few studies have been conducted on the type of PPC most commonly used in modern practice.

The mixture primarily used in California and throughout the United States contains coarse and fine aggregate, as well as a resin binder that comprises approximately 12 percent of the mixture by dry weight of aggregate. The binder is an unsaturated isophthalic polyester-styrene resin containing a small percentage of silane and is catalyzed (initiated) by MEKP (Krauss et al. 2007; Kwikbond 2011a; personal communication, R. Wiegman, May 8, 2015).

Table 2.1 provides a summary of the various mixture designs identified in the literature. The aggregate type(s), aggregate content, resin content, microfiller type(s), microfiller content, and chemical additives for each study are included. Because aggregate, resin, and microfiller proportions were computed differently among the various studies, the basis for the calculation of each percentage is also included. A hyphen indicates that the information was not provided in the

Table 2.1 PPC Mixture Designs

Study	Type	Aggregate Content (%)	Basis	Resin		Type	Microfiller Content (%)	Basis	Chemical Additives
				Content (%)	Basis				
Abdel-Fattah and El-Hawary 1999	Natural sand, quartzite	87-92	Total wt	9-15	Dry mat'l. wt	N/A	0	N/A	-
El-Hawary and Abdel-Fattah 2000	Natural sand, quartzite	85-91	Total wt	9-15	Total wt	N/A	0	N/A	-
Ferreira et al. 2000	Clean sand, foundry sand	-	-	17-20	-	Calcium carbonate	0-25	-	MEKP
Gorninski et al. 2004	River sand	70-81	Total wt	12-13	Total wt	Fly ash	7-18	Total wt	MEKP, cobalt naphthenate
Gorninski et al. 2007	River sand	70-81	Total wt	12-13	Total wt	Fly ash	7-18	Total wt	MEKP, cobalt naphthenate
Haddad and Kobaisi 2013	Sand, basalt	75	Total vol.	17	Total vol.	Fly ash	8	Total vol.	MEKP, methacrylate, cobalt octoate, dimethyl aniline, styrene
Hristova 1982	-	80	Total wt	10	Total wt	-	10	Total wt	Cyclohexanone hydroxide, cobalt naphthenate
Knab 1969	Trap rock	69	Total vol.	31	Total vol.	N/A	0	N/A	MEKP
Maksimov et al. 1999	Sand, crushed granite	80	Total wt	10	Total wt	Limestone flour	10	Total wt	-
Mani et al. 1987	Silica sand, crushed quartzite	83-88	Total wt	12	Total wt	Calcium carbonate	0-5	Total wt	MEKP, cobalt naphthenate, silane, dimethyl phthalate
Mantrala and Vipulanandan 1995	Sand	86	Total wt	14	Total wt	N/A	0	N/A	MEKP, cobalt naphthenate
Mebarkia and Vipulanandan 1995	Blasting sand	86	Total wt	14	Total wt	N/A	0	N/A	MEKP, cobalt naphthenate

Table 2.1 Continued

Study	Type	Aggregate Content (%)	Basis	Resin		Microfiller			Chemical Additives
				Content (%)	Basis	Type	Content (%)	Basis	
O'Connor and Saiidi 1993b	Silica sand, angular basalt	87-88	Total wt	12-13	Total wt	N/A	0	N/A	MEKP, cobalt naphthenate, styrene
Ohama and Demura 1982	River sand, crushed andesite	78	Total wt	11	Total wt	Calcium carbonate	11	Total wt	MEKP, cobalt octoate, styrene
Ohama et al. 1986	River sand, crushed andesite	78	Total wt	11	Total wt	Calcium carbonate	11	Total wt	MEKP, cobalt octoate, styrene
Rao and Krishnamoorthy 1998	Pit sand, angular quartzite	-	-	-	-	Calcium carbonate	-	-	MEKP, cobalt naphthenate
Ribeiro et al. 2003	Foundry sand	80	Total wt	20	Total wt	N/A	0	N/A	MEKP
Ribeiro et al. 2004	Foundry sand	80	Total wt	20	Total wt	N/A	0	N/A	MEKP, styrene
Robles et al. 2009	Sand, gravel	77	Total wt	14	Total wt	Calcium carbonate	12	Agg. wt	MEKP, cobalt octoate, styrene
San-José et al. 2005 (Mixture 1)	Quartz sand	64	Total wt	12	Total wt	Calcium carbonate	21	Total wt	MEKP, cobalt octoate, titanium dioxide
San-José et al. 2005 (Mixture 2)	Quartz sand, quartz gravel	74	Total wt	12	Total wt	Quartz powder, chalk	14	Total wt	-
Sprinkel 1983	Silica sand	-	-	-	-	N/A	0	N/A	MEKP, dimethyl phthalate, benzoyl peroxide, dimethyl aniline
Vipulanandan and Dharmarajan 1987	Ottawa sand	80-90	Total wt	10-20	Total wt	N/A	0	N/A	Benzoyl peroxide, cobalt naphthenate, silane
Vipulanandan and Paul 1990	Ottawa sand	85	Total wt	15	Total wt	N/A	0	N/A	MEKP, cobalt naphthenate, styrene
Vipulanandan and Paul 1993	Ottawa sand	80-90	Total wt	10-20	Total wt	N/A	0	N/A	MEKP, cobalt naphthenate, silane

given research report, and the designation “N/A” signifies that the information is not applicable to the given study.

2.4 Material Properties

The material properties of PPC are highly dependent on mixture design, preparation, curing method, age, and testing conditions and procedures (Vipulanandan and Paul 1990). Although many different studies involving the properties of PPC have been conducted, the results of each study are often highly dependent on the materials and methods used in that particular study. However, general ranges for values of material properties have been identified in the literature. The following sections discuss the unconfined compressive strength (UCS), tensile and flexural strength, modulus of elasticity (MOE), coefficient of thermal expansion (CTE), compatibility and bond strength, shrinkage, creep, skid resistance, abrasion resistance, chemical resistance, and permeability of PPC. In many cases, the properties of PPC are compared with the properties of PCC, which is the typical substrate on which PPC is placed.

2.4.1 UCS

Even though PPC used for bridge deck overlays is relatively flexible and is therefore considered non-structural, it generally has a UCS comparable to that of PCC. While laboratory studies of various types of PPC have produced mixtures with ultimate UCS values ranging from 7,000 to 20,000 psi, mixtures used for overlays typically have UCS values near the bottom of that range (Maksimov et al. 1999, Mantrala and Vipulanandan 1995, O’Connor and Saiidi 1993a). For these typical PPC mixtures, UCS values of 1,000 to 2,000 psi within 3 hours of placement and 4,000 to 6,000 psi within 24 hours are typical. As the material continues to cure, UCS values can increase up to approximately 7,000 psi (Krauss et al. 2007, Kwikbond 2012, O’Connor and Saiidi 1993a, Tarricone 1992).

2.4.2 Tensile and Flexural Strength

PPC mixtures with high tensile and flexural strengths are desirable for overlays because they tend to limit cracking caused by bridge deck movements (Sprinkel 1983). STS values of

around 950 psi and flexural strengths of around 2,000 psi have been reported for some PPC overlay mixtures (Krauss et al. 2007, O'Connor and Saiidi 1993a).

For PCC, the relationship between UCS and splitting tensile strength (STS) used by ACI is given in Equation 2.1 (O'Connor and Saiidi 1993a):

$$f_{ct} = 6.7\sqrt{f'_c} \quad (2.1)$$

where f_{ct} = STS, psi

f'_c = UCS of PCC, psi

A similar relationship for PPC is shown in Equation 2.2 (O'Connor and Saiidi 1993a):

$$f_{ct} = 14\sqrt{f'_c} \quad (2.2)$$

where f_{ct} = STS, psi

f'_c = UCS of PPC, psi

The equation used by ACI to predict modulus of rupture from UCS in PCC is shown in Equation 2.3 (Mindess et al. 2003):

$$f'_r = 7.5\sqrt{f'_c} \quad (2.3)$$

where f'_r = modulus of rupture, psi

f'_c = UCS of PCC, psi

A similar relationship was developed for PPC, as shown in Equation 2.4 (O'Connor and Saiidi 1993a):

$$f'_r = 25\sqrt{f'_c} \quad (2.4)$$

where f'_r = modulus of rupture, psi

f'_c = UCS of PPC, psi

2.4.3 MOE

Flexible overlays experience lower stresses induced by shrinkage, thermal cycling, and traffic movements than brittle overlays and therefore provide better deck protection because they

are less susceptible to cracking (Krauss et al. 2007, Sprinkel et al. 1993). As a measure of flexibility, the MOE of PPC used for overlays is often reported to be around 1.5 million psi (Krauss et al. 2007, Maggenti 2001), although in one study values ranging from 2.7 to 3.1 million psi were measured (Mantrala and Vipulanandan 1995).

The MOE of concrete specimens can be determined using nondestructive techniques (Garbacz and Garboczi 2003, Kolluru et al. 2000). In one study, impact resonance was used to determine the dynamic MOE of PPC specimens, which agreed well with static MOE measurements. For cylinders with a length-to-diameter ratio of 3 to 1, the static and dynamic MOE differed by less than 2 percent (Mantrala and Vipulanandan 1995).

As with PCC, correlations between UCS and other properties have been developed for PPC. For PCC, the relationship between UCS and MOE used by the American Concrete Institute (ACI) is shown in Equation 2.5 (Mindess et al. 2003):

$$E = 33 w^{1.5} \sqrt{f'_c} \quad (2.5)$$

where E = secant MOE, psi

w = unit weight of PCC, pcf

f'_c = UCS of PCC, psi

A similar relationship for PPC is shown in Equation 2.6 (O'Connor and Saiidi 1993b):

$$E = 13.5 w^{1.5} \sqrt{f'_c} \quad (2.6)$$

where E = chord MOE, psi

w = unit weight of PPC, pcf

f'_c = UCS of PPC, psi

2.4.4 CTE

The CTE of PPC is higher than that of PCC. The CTE of PCC ranges from $4.4 \times 10^{-6}/^{\circ}\text{F}$ to $6.7 \times 10^{-6}/^{\circ}\text{F}$ (FHWA 2016), while the CTE of PPC ranges from $7.7 \times 10^{-6}/^{\circ}\text{F}$ to $15.9 \times 10^{-6}/^{\circ}\text{F}$ (Krauss 1988a, Maggenti 2001, O'Connor and Saiidi 1993a).

2.4.5 Compatibility and Bond Strength

With proper surface preparation and application techniques, PPC bonds very well to PCC substrates. However, differences in MOE and CTE between the two materials cause shear stresses at the bond line when they are subjected to thermal movements (Fowler 1999, Krauss 1988b, O'Connor and Saiidi 1993a). If the stresses at the bond line exceed the strength of the bond, delaminations and premature overlay failure can occur (Doody and Morgan 1993, Sprinkel 1983). The lowest thermally-induced stresses would be caused by an overlay material that has a low CTE (close to that of PCC) and a low MOE. However, the CTE and MOE of PPC are affected in opposite ways by the relative proportions of resin and aggregate in the mixture. As resin content increases, for example, MOE decreases while CTE increases. Curing shrinkage also contributes to stresses at the bond line that can lead to overlay failure (Glauz and Maggenti 1993, Sprinkel 1983).

Although the resin gives PPC its flexibility, minimizing the resin content of PPC mixtures reduces shrinkage and thermal movements and thereby also reduces shear stresses at the bond line. In addition, mixtures with low resin contents are more economical because the resin is the most expensive component of the mixture (Krauss 1988a, Krauss 1988b, Rao and Krishnamoorthy 1998). Using the most elastic resin possible also helps to minimize stresses at the bond line; elongation of polyester resins should be adequate at both low and high temperatures (Krauss 1988a, NCHRP 2011). Another way to minimize thermally-induced stresses is to place overlays at a deck surface temperature of 60 to 70°F (O'Connor and Saiidi 1993a, Sprinkel 1983).

The shear stress that develops at the bond line between a polymer overlay and a PCC substrate can be calculated using Equation 2.7, which accounts for temperature changes and the CTE and MOE values of the two materials (Sprinkel 1983):

$$S = \frac{(C_p - C_c) \cdot E_p \cdot E_c \cdot \Delta T}{E_p + E_c} \quad (2.7)$$

where S = shear stress, psi

C_p = CTE of PPC, °F⁻¹

C_c = CTE of PCC, °F⁻¹

E_p = MOE of PPC, psi

E_c = MOE of PCC, psi

ΔT = temperature change, °F

However, shear bond strength is different from tensile bond strength, which is the parameter that is commonly specified for overlay systems. Tensile bond strength is readily measured in the field using pull-off testing, while shear bond strength is more difficult to determine. Minimum tensile bond strengths of 250 psi are often specified by state agencies (Smith 1991, Sprinkel 1993). At tensile bond strengths below 100 psi, the likelihood of delamination significantly increases (Tarricone 1992).

Overlays typically fail in one of three ways: vertical cracking in the overlay, delamination at the bond line, or failure in the substrate (Maggenti 2001, Sprinkel 1983). However, failure of the bond itself is rare, and delaminations are usually attributed to substrate failure rather than actual de-bonding (Maggenti 2001, O'Connor and Saiidi 1993a). While bond strengths can and should exceed substrate tensile strengths, overlays should not be placed on substrates with tensile strengths of less than 150 psi (Krauss et al. 2007, Sprinkel 1997).

Shear and tensile bond strengths of PPC overlays tend to decrease and overlay delaminations tend to increase with age and thermal cycling (Sprinkel 1983, Sprinkel et al. 1993). High-molecular-weight methacrylate primers increase bond strength and reduce the likelihood of delamination (Krauss 1988a). The addition of zinc diacrylate to primer and resin mixtures has also been shown to increase the bond strength of polymer overlays, even when the substrate is wet (NCHRP 2011).

2.4.6 Shrinkage

PPC shrinks as it cures due to a reduction of monomer volume during polymerization. In one study, shrinkage values of 0.1 to 0.3 percent were measured, which is five to six times that of PCC. Shrinkage was also shown to increase linearly with increases in resin content (Rao and Krishnamoorthy 1998). Shrinkage occurs most rapidly during the first few hours after mixing and consolidation. In another study, the highest rates of shrinkage were measured between 5 and 15 hours after mixing and consolidation (Mani et al. 1987). By 24 hours, shrinkage rates

decrease considerably, and additional increases in shrinkage are very small (Mani et al. 1987, Rao and Krishnamoorthy 1998).

2.4.7 Creep

Creep of PPC increases with greater loading time and higher temperature. Especially long-term stresses can cause significant creep in PPC. One laboratory study conducted on high-strength PPC demonstrated that stresses of up to half of the ultimate stress applied over 3,000 hours caused between 2.0 and 2.2 times the strain induced by instantaneous stresses. For those specimens, the creep stress-strain relationship was shown to be essentially linear (Maksimov et al. 1999). When subjected to high temperatures over time, creep is dependent upon the composition and quantity of resin and filler, the level and method of hardening, and the nature of the applied stress (Hristova 1982).

2.4.8 Skid Resistance

PPC overlays that are properly constructed have been shown to provide good skid resistance (Sprinkel 2003). The high skid resistance of PPC is achieved by tining and broadcasting sand onto the surface of the fresh placement. However, if resin contents are too high, excessive bleeding at the surface can lower skid resistance (Krauss et al. 2007). In the field, PPC overlays have exhibited smooth tire skid numbers of 30 to 40 following new construction and numbers in the high 40s after 15 to 20 years of service life (Sprinkel 1997, Sprinkel et al. 1993).

2.4.9 Abrasion Resistance

PPC overlays generally have good abrasion resistance. In one instance, a PPC overlay was placed on a section of interstate in California where concrete pavements experienced severe rutting due to heavy truck traffic. In that location, the recorded average annual surface wear of the overlay in the wheel path was less than 0.015 in./year (Krauss et al. 2007, Maggenti 2001). One supplier reports that PPC has 8 to 10 times the abrasion resistance of PCC (Kwikbond 2012).

However, the durability of PPC may be significantly compromised by grinding. Grinding exposes the PPC aggregate, which is then more vulnerable to wear especially under heavy trafficking. In truck lanes where tire chains have been used extensively, the service life of a PPC wearing surface has been observed to decrease by 60 to 70 percent. In service, PPC does not normally exhibit potholes or delamination; rather, it has been observed to wear thin over time (personal communication, E. Kaslan, February 17, 2015).

2.4.10 Chemical Resistance

PPC is reported to be highly resistant to most common chemicals, including water, salts, acids, and petroleum-based chemicals (Sprinkel 2003). In a study to determine the effect of various chemicals on PPC, the chemical resistance of a PPC mixture was compared to that of PCC. Specimens were exposed to solutions of hydrochloric acid, sulfuric acid, acetic acid, sodium chloride, sodium hydroxide, and magnesium sulfate for 180 days and evaluated based on changes in weight and appearance. With the exception of the sodium hydroxide treatment, no changes in appearance and little to no changes in weight were observed in the PPC specimens after chemical exposure. By contrast, the PCC specimens experienced a range of weight and appearance changes. PPC performed better than PCC in every instance except for sodium hydroxide exposure, in which they performed equally well (Mani et al. 1987). The relatively lower resistance of PPC to changes caused by sodium hydroxide is likely due to saponification, which is alkali attack of the polyester resin (Glauz and Maggenti 1993, Mani et al. 1987).

In a second study of chemical resistance, PPC specimens were subjected to five one-week cycles of exposure to acetic acid, citric acid, formic acid, lactic acid, sulfuric acid, an acidic soft drink, and distilled water. No weight loss was measured in any of the specimens after the chemical exposure period. Reductions in flexural strength after chemical exposure were observed in the PPC specimens, but they performed significantly better than PCC specimens under similar conditions. Based on previous findings and the results of this study, the researchers concluded that chemical attack likely has more of an effect on the bond between resin and aggregate than on the resin itself. The weakening of that bond by aggressive chemicals increases as the porosity of the matrix increases (Gorninski et al. 2007).

Another study was conducted to determine the effect of long-term chemical exposure on the strength of a PPC mixture. Specimens were immersed in solutions of sulfuric acid, sodium chloride, sodium hydroxide, and water for 1 year, after which their UCS and STS values were measured. Both the UCS and STS values decreased as the pH level increased. Although immersion in water reduced the UCS of the PPC specimens by 32 percent, that strength was almost completely recovered when the specimens were dried out. Comparisons in strength reductions between PPC specimens and resin-only specimens reinforce the theory that water diffusion affects the resin-aggregate interface rather than the resin itself (Mebarkia and Vipulanandan 1995).

2.4.11 Permeability

Mercury intrusion porosimetry has shown that the PPC matrix contains closed internal pores, and the closed pore structure and impervious nature of the polyester resin make PPC impermeable to water and other corrosive elements (San-José et al. 2005). Some mixtures include a silane coupling agent, which also contributes to its very low permeability. In one study, the addition of silane to a PPC mixture reduced its diffusion coefficient by more than an order of magnitude (Mebarkia and Vipulanandan 1995).

When PPC overlays remain uncracked, they exhibit low to negligible permeability (Sprinkel 2003). Because of their low permeability, PPC overlays are often specified by agencies seeking to seal bridge decks from corrosive elements that accelerate the deterioration of reinforced concrete. However, the permeability of PPC has been shown to increase over time with exposure to traffic and thermal cycling. These increases in permeability indicate the formation of stress-induced micro cracks. Overlay impermeability can be preserved by using mixtures with flexible binders, which are less susceptible to cracking than more brittle formulations (Sprinkel et al. 1993).

PPC overlay systems also seal bridge decks through the use of high-molecular-weight methacrylate primers. High-molecular-weight methacrylate primers that are used in conjunction with PPC overlays fill small cracks in concrete decks, thereby reducing the permeability of the substrate (Krauss 1988b).

2.5 Design

Careful PPC mixture design is essential for ensuring a quality overlay job. One key parameter for PPC mixtures is resin content. Premixed overlays generally contain between 11 and 14 percent binder by weight of aggregate (Smith 1991), and resin contents of 12 percent are typical (Sprinkel 1997). For one commonly used mixture, the recommended resin content is 12 ± 1 percent by dry weight of aggregate, and the recommended sand-to-coarse aggregate ratio is 2 to 1 (Kwikbond 2011a). These recommendations are based on naturally occurring aggregates found in California and may need to be adjusted for different aggregates. Regardless of the exact amount of binder in the mixture, the ratio of resin to aggregate should be carefully controlled, as variations could lead to problems in the hardened PPC.

Regarding overlay design, PPC can be placed in variable thicknesses, ranging between 0.75 and 12 in. per lift (Kwikbond 2012). Overlay thicknesses of 0.75 in. are common (Krauss et al. 2007, Smith 1991), although thicknesses of 6 to 12 in. have been used for profile corrections and airport runways (Krauss et al. 2007). Given that a minimum PPC overlay thickness of 0.75 in. is recommended, a 1-in. minimum thickness may be specified to allow for the possibility of modifying or correcting the profile after placement (personal communication, S. Cherry, February 10, 2015).

2.6 Construction

In addition to the use of suitable materials, implementation of proper construction practices is one of the most important factors that contributes to the success of PPC bridge deck overlays (Glauz and Maggenti 1993). The performance of PPC overlays is affected by several factors, including substrate soundness, surface preparation, compatibility between the overlay and the substrate, the resin and aggregate used in the mixture, overlay thickness, bridge girder flexibility, environmental and traffic conditions, and quality of workmanship (NCHRP 2011). The following sections describe recommended practices for aspects of PPC overlay construction, including deck preparation and placement.

2.6.1 Deck Preparation

A sound substrate and proper surface preparation are critical for successful overlay installations (Doody and Morgan 1993, Krauss 1988b, Sprinkel 1997). Bridge deck surfaces should be sound, clean, and dry and have STS values of at least 150 psi (Krauss et al. 2007, Sprinkel 1997). Weak or delaminated concrete should be removed and replaced, and rebar in the affected areas should be repaired or replaced, as applicable (Smith 1991). In addition, concrete with chloride concentrations greater than 1.3 to 2.0 lb./yd³ at the level of the reinforcing steel should be removed prior to overlay operations (Mindess et al. 2003, Sprinkel 1997). While jackhammers are often used to remove contaminated and/or unsound concrete from localized areas on bridge decks, hydrodemolition, which involves the use of high-pressure water jets, is sometimes used to remove concrete from large bridge deck areas in preparation for PPC overlay applications or other bridge preservation operations (ICRI 2014). For concrete repairs, magnesium phosphate patches, which are prone to off-gassing, should not be used (Krauss et al. 2007).

In addition to the removal of unsound material, substrate concrete should be scarified to provide a rough surface texture and remove contamination. Asphalt, oil, dirt, rubber, curing compound, paint, carbonation, laitance, weak mortar, or any other contaminant or defect that could interfere with the bond of the overlay should be removed (Sprinkel 1997). Although sandblasting is often used for surface preparation, it is generally considered to be inadequate for scarification. Shot blasting leads to higher bond strengths than sandblasting and should be specified by agencies placing PPC overlays (Krauss 1988b, Maass 2003, Smith 1991, Sprinkel 1997, Tarricone 1992). However, sandblasting may be used in places where shot blasting cannot reach, such as areas close to curbs (Sprinkel 1997).

Joint protection is another important part of deck preparation. Forms should be placed at existing joints to dam the PPC, creating a clean separation between bridge deck spans at the joint. Strip and modular joints require a taper down to the joint or a replacement of the joint entirely. One advantage of PPC is that it bonds with steel, so paving over joint armor and plates is possible (personal communication, E. Kaslan, February 17, 2015). Saw-cutting joints in PPC is not considered acceptable practice (Krauss et al. 2007).

2.6.2 Placement

Polymer overlays have historically been applied in multiple-layer, slurry, and/or premixed form (Doody and Morgan 1993, Sprinkel 1997, Sprinkel 2003, Sprinkel et al. 1993). Multiple-layer overlays, which are placed using the broom-and-seed method (NCHRP 2011, Smith 1991), are composed of two or more layers of binder and gap-graded aggregate, the latter being broadcast on top of each layer before the binder hardens. Slurry overlays consist of a mixture of resin binder and aggregate that is struck off with gage rakes and then covered with broadcast aggregate. Premixed overlays are placed using a modified paving machine and covered with broadcast aggregate (Doody and Morgan 1993, Sprinkel 1993, Sprinkel 2003, Sprinkel et al. 1993).

Contractors selected to place PPC should be experienced in PCC flatwork construction. Although no licensing requirements for placing PPC currently exist, a recommended practice is to require contractors to demonstrate their ability to construct quality PPC overlays on a trial placement under the expected project conditions (Glauz and Maggenti 1993; personal communication, E. Kaslan, February 17, 2015). For quality control (QC) during the overlay process, having a supplier representative on site to oversee the process and answer questions that arise during construction is recommended (personal communication, E. Kaslan, February 17, 2015).

PPC can be placed in a range of temperatures. Successful placements have occurred in temperatures as low as 45°F and as high as 100°F (Glauz and Maggenti 1993). One supplier states that their mixture can be placed in temperatures as low as 40°F (Kwikbond 2011a). If cool temperatures are expected, a set accelerator may be added to the mixture to increase the final set time to an acceptable time period (Kwikbond 2011a).

A high-molecular-weight methacrylate should be used to bond PPC to the substrate material. The methacrylate is used both as a sealer for cracks in existing concrete and as a primer for PPC overlays. Its low viscosity allows it to penetrate the underlying surface quickly. Once the primer penetrates the surface, it polymerizes and forms a barrier against moisture and chloride ingress. The primer also provides a strong bond between the overlay and the substrate

(Kwikbond 2011b). The results of pull-off testing performed on several PPC overlays suggest that the primer may even strengthen the deck itself (Glauz and Maggenti 1993).

PPC must be placed in the same work shift as the primer (Kwikbond 2011b). The primer should be allowed to penetrate the surface of the concrete substrate for 15 minutes prior to placement of the overlay, and the overlay must be placed within 2 hours of primer application. Once the primer has been allowed to penetrate the concrete substrate, PPC may be placed in a similar manner to PCC (personal communication, S. Cherry, February 10, 2015). If primer is applied and cannot be covered by PPC within the same work shift, it must be removed because uncovered primer has very low skid resistance (Kwikbond 2011b).

For PPC placements, automatic proportioning and mixing are preferred over hand mixing (Tarricone 1992). Although PPC may be placed by hand, use of a paving machine is recommended to ensure a smooth and consistent final surface. The ideal arrangement is to mix the PPC continuously, with a paving machine following directly behind a mobile mixing operation (personal communication, E. Kaslan, February 17, 2015). Optimally, a small amount of bleed resin should be visible on the surface, indicating that all of the air has been vibrated out of the mixture (Kwikbond 2011a). When automatic mixers and paving machines are used, PPC overlays can be placed relatively quickly. Application rates of over 100 ft² per minute are possible (Tarricone 1992), and up to a lane-mile of PPC can be placed in one night (Krauss et al. 2007).

Before it hardens, the surface of a PPC overlay must be tined and textured to provide adequate skid resistance (Kwikbond 2011a). Adding texture to the driving surface by broadcasting fine aggregate on top of the PPC during finishing is essential. The sand adheres to the surface of the wet PPC and increases surface friction (MDT 2014, Smith 1991). After it is placed and finished, PPC should not be disturbed until it has reached final set. Disturbances disrupt the cross-linking of the polymers and permanently damage the material, which will not heal itself (Krauss 1988b).

2.7 Performance Factors

The following sections discuss the effects of aggregate selection, resin content, microfiller, mixing time and methods, consolidation time and methods, curing, strain and loading rate, temperature, moisture, and temperature and moisture cycling on the properties of PPC.

2.7.1 Aggregate Selection

The type and gradation of aggregates selected for PPC can affect the strength of PPC mixtures. One study determined that the strength of PPC mixtures can be improved by increasing aggregate contact surface area through optimized aggregate gradations (Mani et al. 1987).

Aggregate selection also has an effect on the workability of fresh PPC mixtures and the durability of hardened PPC overlays. Workability of PPC mixtures is increased by limiting the amount of fines and using round aggregates with low absorption, while durability is improved by using hard aggregates that are as large as practical to reduce the wearing rate of PPC overlays (Krauss 1988b). One author recommends that wearing aggregates be composed of silica or basalt and have a Mohs hardness of 7 (Sprinkel 1997).

2.7.2 Resin Content

One report defines optimum resin content for PPC as the lowest resin content at which strength is maximized. According to this report, optimum resin content varies depending on a number of factors, including particle size, particle porosity, particle texture, and mixture workability (Vipulanandan and Paul 1993).

However, the optimum resin content may differ depending on which properties are considered most important. For example, one study showed a steady increase in STS for resin contents between 10 and 20 percent, while UCS and MOE peaked at a resin content of 15 percent and then declined (Vipulanandan and Paul 1993). The opposite pattern was observed in another study, which showed a steady increase in UCS for resin contents between 8 and 13.5 percent, while STS peaked at a resin content of 12 percent and then declined (Rao and Krishnamoorthy 1998). In another study, PPC specimens made with 12 percent resin had higher

compressive and flexural strengths than specimens produced using 9 and 15 percent resin (Abdel-Fattah and El-Hawary 1999).

In addition to showing that different properties may be optimized at different resin contents for a given mixture, these studies also demonstrate that the optimum resin content for a given property also varies by mixture. Although higher resin contents may sometimes provide further improvements in some areas, the lowest possible resin content is considered to be the optimum resin content with respect to cost, shrinkage, and CTE (Krauss 1988b, Rao and Krishnamoorthy 1998); these factors are of primary importance for PPC overlays.

2.7.3 Microfiller

Several studies have investigated the effects of various microfillers on the properties of PPC. Fly ash has been shown to increase the UCS, flexural strength, and MOE of PPC mixtures (Gorninski et al. 2004, Gorninski et al. 2007). Fly ash has also been shown to reduce porosity and increase resistance to chemical attack (Gorninski et al. 2007).

Calcium carbonate has also been shown to increase the strength of PPC mixtures (Ferreira et al. 2000, Mani et al. 1987, Rao and Krishnamoorthy 1998). However, strength gains are dependent on both microfiller and resin content. In a study on the effects of microfillers on the properties of PPC, calcium carbonate increased strength at higher resin contents and decreased strength at lower resin contents (Ferreira et al. 2000). A similar finding was documented in a comparable study, in which UCS and STS of PPC specimens increased with calcium carbonate content up to a maximum value and then decreased with additional calcium carbonate (Rao and Krishnamoorthy 1998). The authors of the study concluded that up to a certain threshold, microfillers fill in voids and increase the strength of PPC mixtures. This threshold is sometimes described as the optimum microfiller content. At microfiller contents above optimum, particle interference and increased stiffness cause compaction difficulty and subsequently decrease strength. The optimum microfiller content for a given mixture increases as resin content increases and as resin viscosity decreases. In the same study, calcium carbonate actually increased the shrinkage of PPC specimens. The authors suggested that this result could be due to a decrease in frictional restraint caused by microfiller coating of aggregate surfaces

(Rao and Krishnamoorthy 1998). Calcium carbonate has also been shown to lower the chemical resistance of PPC (Mani et al. 1987).

2.7.4 Mixing Time and Methods

The majority of laboratory studies identified in the literature have utilized mechanical mixers for mixture preparation and have not considered the effects of mixing time or method on the properties of PPC mixtures (Abdel-Fattah and El-Hawary 1999, El-Hawary and Abdel-Fattah 2000, Robles et al. 2009). However, in one study, flexural strengths of PPC specimens prepared using an automatic mixer were 27 percent higher than those prepared using a manual mixing procedure (Ferreira et al. 2000). Another study reported that higher strengths were produced when resin was added to well-mixed aggregate blends compared with adding coarse and fine aggregates to the mixture separately (Vipulanandan and Paul 1990).

In the field, poor overlay performance is often the result of improper mixing or proportioning. Although batch mixing is possible, inaccuracies and batch-to-batch inconsistencies are a concern with this method. Automatic mixing machines are preferred and should be carefully calibrated and checked before and during use (Smith 1991).

2.7.5 Consolidation Time and Methods

Few of the laboratory studies identified in the literature have specified the method used to consolidate PPC specimens. However, in one study, specimens were placed in molds and vibrated (Maksimov et al. 1999), while in another study specimens were first consolidated by rodding and then consolidated on a vibrating table for 2 to 3 min (Abdel-Fattah and El-Hawary 1999). In a third study, specimens were either vibrated for 2 minutes at 60 Hz or compressed to a maximum pressure of 100 psi immediately after mixing. Compressed specimens had higher flexural strengths and flexural MOE values than those of vibrated specimens (Vipulanandan and Dharmarajan 1987).

2.7.6 Curing

Polyester resin begins to polymerize as soon as its component chemicals are combined. Polymerization, which is an exothermic process, is the mechanism responsible for the setting and

strength gain of PPC (Haddad and Kobaisi 2013). The rate of polymerization and attendant strength gain is highest during the first several hours after mixing. Although the rate of polymerization levels off quickly, PPC continues to harden and gain strength over time as it cures (Ferreira et al. 2000, Hristova 1982, Ohama and Demura 1982).

PPC strength and stiffness increase as curing temperature increases (Ohama and Demura 1982, Vipulanandan and Paul 1993). An important distinction exists between temperature effects during the testing of hardened PPC and temperature effects during the curing period. If PPC is tested at elevated temperatures, decreases in strength and stiffness are observed. However, if PPC specimens are cured at elevated temperatures and returned to room temperature, higher strengths are obtained than when heat treatment is not applied (El-Hawary and Abdel-Fattah 2000, Ohama and Demura 1982, Vipulanandan and Paul 1993).

Laboratory studies of PPC normally include a period of curing at room temperature that is often followed by a period of tempering or heat treatment at a higher temperature. In studies identified in the literature, room-temperature curing periods ranged from 24 hours to 28 days. Specimens were generally cured at room temperature for either 24 hours or 7 days when heat treatment was subsequently applied. Specimens were heated for periods of 3 to 24 hours at temperatures ranging from 140 to 176°F (El-Hawary and Abdel-Fattah 2000, Haddad and Kobaisi 2013, Hristova 1982, Maksimov et al. 1999, Mantrala and Vipulanandan 1995, Mebarkia and Vipulanandan 1995, Ribeiro et al. 2004, Vipulanandan and Dharmarajan 1987).

Although PPC is typically cured in air, researchers in one study compared the results of specimens cured in water to those cured in air at room temperature. The specimens cured in water did not appear to be affected by hydrolysis and exhibited UCS values similar to those cured in air (Ohama and Demura 1982).

While laboratory curing takes place under carefully controlled conditions, the curing rates of PPC overlays in the field are influenced by a number of factors. These include ambient temperature; deck temperature; relative humidity; exposure to ultraviolet radiation; and binder, catalyst (initiator), and accelerator concentrations (Doody and Morgan 1993, Sprinkel 1997).

Overlay specifications often require both minimum and maximum set times to ensure sufficient time to place the material while simultaneously ensuring that it can receive traffic within an acceptable time period (Sprinkel 1997). At high temperatures, PPC overlays can cure quickly enough to receive traffic within 2 hours or less (Krauss et al. 2007, Smith 1991, Sprinkel 1997), but very high temperatures may warrant night placements. At low temperatures, curing times typically need to be increased to account for slower PPC strength gain. A common temperature range for overlay construction is 45 to 90°F, although placements outside this range have occurred. Schmidt rebound hammer numbers of 22 to 24 usually indicate that the overlay has gained sufficient hardness and strength to receive traffic (Krauss et al. 2007).

2.7.7 Strain and Loading Rate

Strain rate has been shown to have a small influence on the behavior of PPC specimens when axial forces are applied. In one study, specimens were tested at compressive strain rates varying from 0.01 to 6 percent strain per minute. Increases in strain rate caused slight increases in the measured UCS and MOE values and slight decreases in compressive failure strain (Vipulanandan and Paul 1990). In a study of high-strength PPC, various loading rates were applied to specimens in compression and in tension. In general, increased loading rates yielded higher strength and MOE values and higher ultimate strains in both tension and compression. However, these properties were affected much less at low loading rates than at high rates (Knab 1969).

In a study of the flexural behavior of PPC, flexural strain rates were varied from 0.001 to 10 percent strain per minute. The effect of strain rate on flexural strength and flexural modulus was not shown to be significant for specimens in this study (Vipulanandan and Dharmarajan 1987).

2.7.8 Temperature

The mechanical properties of PPC are highly temperature-dependent. Both the strength and stiffness of hardened PPC decrease with increases in temperature (Hristova 1982, O'Connor and Saiidi 1993a, Ribeiro et al. 2004, Vipulanandan and Paul 1993).

One study demonstrated a 25 percent reduction in UCS of PPC specimens when the testing temperature was increased from room temperature to 120°F (O'Connor and Saiidi 1993a). As would be expected, higher temperatures increase the failure strain of PPC specimens (Vipulanandan and Paul 1993).

2.7.9 Moisture

Although hardened PPC is unaffected by water, moisture is detrimental to PPC if moisture exposure occurs before the material has set. Moisture interferes with the cross-linking of the bonds in the resin and inhibits the resin-aggregate bond. In a study on the effect of water in PPC mixtures, specimen analysis using scanning electron microscopy revealed that moisture leaves behind microscopic spherical voids in the resin that weaken its structure. Water also decreases the UCS and flexural strength and increases the CTE of the PPC material (Haddad and Kobaisi 2013).

Because water is so harmful to the structure and performance of PPC mixtures, moisture in PPC aggregates should be as close to 0 percent as possible (Haddad and Kobaisi 2013). Some authors recommend a maximum moisture content of 1 percent by dry weight of aggregate (Ohama et al. 1986, Robles et al. 2009).

2.7.10 Temperature and Moisture Cycling

PPC has also demonstrated good resistance to temperature and moisture cycling. In a durability study of PPC, PPC specimens were exposed to 17 cycles of immersion in water at 185°F, 70 cycles without moisture at temperatures up to 266°F, seven thermal fatigue cycles in water with temperatures varying between 28 and 194°F, and 29 cycles of immersion in water at 28°F. High and low temperatures alone were not shown to have a significant effect on the measured UCS of the specimens, while exposure to hot water and thermal fatigue cycles reduced the UCS of the specimens by 18 and 12 percent, respectively (Robles et al. 2009).

In a second durability study, PPC specimens were subjected to 100 thermal fatigue cycles where the temperature was varied between 68 and 212°F. Specimens were also subjected to 100 freeze-thaw cycles during which the temperature was varied between 14 and 50°F in both wet and dry conditions. Neither the thermal fatigue cycles nor the freeze-thaw cycles were shown to

have a significant effect on the weight loss, flexural strength, or flexural modulus of the PPC specimens (Ribeiro et al. 2004).

In a third durability study of PPC, beam specimens prepared with varying aggregate moisture contents were subjected to 600 freeze-thaw cycles in water where the temperature was varied between 0 and 39°F. Specimens prepared with aggregate moisture contents of 1 percent or less did not sustain significant damage, while specimens prepared with aggregate moisture contents of 3 and 5 percent failed after 300 cycles and experienced dramatic reductions in weight and MOE (Ohama et al. 1986).

2.8 Advantages and Disadvantages

Using PPC as an overlay material has a number of advantages. It offers high protection against moisture and chloride ion ingress (Krauss 1988b, Maass 2003, Sprinkel 1993) and is resistant to water, deicing chemicals, acids, and petroleum products (Sprinkel 1997). PPC also achieves high early strengths and cures rapidly, typically being able to withstand traffic loads within 2 hours of placement (Krauss et al. 2007, Smith 1991, Sprinkel 1997); rapid curing minimizes traffic disturbances and reduces traffic control costs. Its high strength is also coupled with high flexibility, making it resistant to cracking and delamination (Doody and Morgan 1993, Fontana and Bartholomew 1980). In addition, PPC overlays provide high skid and abrasion resistance (Krauss et al. 2007, Maass 2003) and can be placed in temperatures as low as 40°F (Kwikbond 2011a).

Another advantage of PPC is that it can be placed in variable thicknesses. Consequently, PPC overlays can be used to make profile corrections and improve ride quality. The generally thin profiles of PPC overlays may not require modifications to median barriers, guardrails, sign posts, or drainage structures, and clearance problems are easily avoided. Furthermore, thin PPC overlays are relatively lightweight, which minimizes increases in dead load on bridge structures (Doody and Morgan 1993, Maass 2003). One of the main advantages of PPC is its long service life; PPC overlays are generally expected to offer adequate protection to bridge decks for up to 20 years (Smith 1991, Sprinkel 1993).

While PPC offers many advantages as an overlay material, it has several disadvantages that should be carefully considered. Material costs are high (Nizamoff and Hanson 2015), and successful placement requires experienced contractors, careful mixture design, and close monitoring of the construction process. The fresh mixture also emits noxious odors, and the resin and primer are highly flammable (Fowler 1999). Despite these drawbacks, PPC overlays remain a viable option for long-term bridge deck protection.

2.9 Chapter Summary

The purpose of this chapter was to present a synthesis of existing information about PPC based on a comprehensive literature review of related topics. The historical use, composition, material properties, design, construction, performance factors, and advantages and disadvantages of PPC overlays were discussed.

3.0 SCANNING TOUR OF POLYESTER POLYMER CONCRETE OVERLAYS ON BRIDGE DECKS IN CALIFORNIA

3.1 Introduction

Premixed PPC has been used on bridge decks in California since the early 1980s, and Caltrans has had extensive experience with PPC overlays over the last 30 years (Krauss et al. 2007). As this material has been recently introduced to several other states, including Utah, the need for sharing of information about PPC construction, QA, and performance is increasing (Anderson et al. 2013, Meggers 2015, MDT 2014, Nizamoff and Hanson 2015). Although scanning tours have historically been a common means of obtaining new information, reports of scanning tours related to PPC were not identified in the existing literature.

To facilitate research on PPC, Caltrans agreed to host UDOT personnel and Brigham Young University (BYU) researchers on a scanning tour of PPC bridge deck overlays during the fall of 2015. The objectives of the tour included observation of a PPC overlay placement, inspection of existing overlays, and discussion of selected topics related to PPC. Extensive written notes, photographs, video recordings, and training materials related to PPC were obtained. The purpose of this chapter is to provide a summary of the main findings from the scanning tour related to construction, QA, and performance of PPC. Many of the findings are based on the views, observations, and experiences of long-term Caltrans personnel and are expected to be highly valuable to other state departments of transportation (DOTs) implementing the use of PPC overlays on bridge decks. The following sections present relevant background information, explain findings from the scanning tour, and provide discussion.

3.2 Caltrans History with PPC

In 1971, Caltrans observed deterioration of bridge decks and began using asphalt concrete (AC) overlays with membranes as a stop-gap measure to prolong bridge deck service life. One major drawback of these overlays is that they significantly increase dead loads on bridges. They also lack desired longevity and can cause problems with drainage, rail heights, and deck joints. To address these problems, Caltrans engineers began searching for alternatives to

AC overlays that would be lightweight, durable, and relatively thin and also offer sufficient protection to bridge decks within the Caltrans inventory. PPC was subsequently developed to meet these requirements (personal communication, E. Kaslan, February 17, 2015).

The PPC mixture used by Caltrans was originally developed by a now retired Caltrans engineer named Leo Ferroni. Ferroni did not invent PPC, but he did make several key modifications to the mixture that greatly improved its quality. He was a pioneer in the area of PPC development and championed its successful adoption in California. Caltrans began using PPC overlays experimentally in the late 1970s and early 1980s. Specifically, the first application of PPC in California was on a section of concrete pavement on Interstate 80 in 1979. By the early 1980s, Caltrans was replacing AC overlays with premixed PPC overlays on bridge decks in alpine regions of the state. Caltrans later began treating bridge decks throughout California with PPC, including high-profile structures such as the San Francisco-Oakland Bay Bridge. Initially, because the polyester resin made PPC overlays very expensive, Caltrans paid close attention to materials and mixture design and employed highly skilled contractors for the work. Impressively, some of those first careful placements are still in use today (Krauss et al. 2007; personal communication, E. Kaslan, February 17, 2015).

As PPC became more widely used throughout California, however, less emphasis was placed on QC during construction. As a result, the service life of PPC overlays decreased closer to 20 years; for example, Caltrans is now replacing PPC overlays on decks originally treated in the 1990s. In addition, the economic recession of 2007 to 2009 led to changes in personnel for many of the contractors hired by Caltrans, which in turn resulted in a further reduction in the quality of construction for the more recent PPC overlays. Despite these challenges, Caltrans has demonstrated the durability and effectiveness of PPC over the last 30 years. During the last several years, about 5,000,000 lb of PPC has been placed annually by Caltrans (personal communication, Sonny Ferreira, September 29, 2015).

3.3 Scanning Tour

The scanning tour comprised a 3-day visit to California. The first morning was spent in the Caltrans materials laboratory in Sacramento discussing materials, equipment, and procedures

related to testing and acceptance of PPC. That afternoon was spent inspecting PPC overlays in the alpine areas along Interstate 80 between Sacramento and Truckee. The following morning was spent meeting with Caltrans engineers at their office in Sacramento to discuss deck preparation procedures, materials approval, use of automated placement equipment, methods of QC and QA (before, during, and after PPC placement, as applicable), and programmatic policies regarding use of PPC overlays. The tour concluded at the Los Angeles International Airport (LAX) with the observation of a PPC placement. The placement occurred at night on an elevated bridge structure adjacent to the airport terminals. Deck preparation, mixing, placing, finishing, and QC testing operations were observed.

The following sections present the findings of the scanning tour by topic. Topics include material properties, mixture and overlay design, laboratory testing, and construction and field testing.

3.3.1 Material Properties

Findings related to the material properties of chemical resistance, MOE, and moisture susceptibility are presented in this section. Regarding chemical resistance, when PPC is mixed and placed correctly, it is a long-lasting, durable material that is resistant to attack from common chemicals (Mani et al. 1987). When problems with PPC overlays occur, they have usually been attributed to workmanship issues rather than problems with the materials used.

With a low MOE, PPC is more flexible than PCC. While the MOE of PCC typically ranges from 3,500 to 5,000 ksi (Mindess et al. 2003), Caltrans prefers PPC to have an MOE of 1,000 to 2,000 ksi to limit cracking of the overlay. Modulus values greater than 3,000 ksi are believed to increase the probability of PPC cracking.

Hardened PPC is very moisture resistant, but even small amounts of water can be detrimental to fresh PPC. Moisture in the aggregate can cause problems with the PPC mixture because water disrupts the cross-linking of the polymers in the resin. To minimize problems with PPC bonding and curing, Caltrans requires the weighted-average aggregate absorption to be less than 1 percent and the in-situ moisture content to be less than 0.5 percent by weight of dry

aggregate. Dried aggregate prepared for PPC installation is typically transported and stored in sealed bags to prevent moisture ingress.

3.3.2 Mixture and Overlay Design

Findings related to resin demand, aggregate specifications, chemical additives, and lift thickness are presented in this section. Concerning resin demand, although a value of 12 percent resin content by weight of dry aggregate is often specified for PPC mixtures, it is not a rigid requirement, as the resin demand can vary by aggregate. For example, aggregates furnished by some suppliers require 14 to 16 percent resin. While use of excessive resin with a given aggregate causes undesirable filling of tining grooves in PPC overlays, too little resin results in tearing of the overlay surface during tining.

Not only must the aggregates have low absorption values, but they must also be rounded rather than crushed. Because rounded aggregate provides greater PPC workability than crushed aggregate, resin demand decreases as angularity decreases. Natural, non-igneous rounded rock with a maximum size of 0.38 in. and beach sand with a maximum size of 0.19 in. are commonly supplied for use in PPC mixtures in California. Conversely, a crushed fine aggregate (typically with a maximum size of 0.05 in.) is specified for the broadcast sand that is placed on the surface of the fresh PPC to provide skid resistance.

Setting of both the primer and the resin used in PPC can be accelerated using chemical additives to decrease final setting times from typical values of 2 to 4 hours to as short as 1 hour. These accelerators are not normally necessary but can compensate for low ambient temperatures and/or allow early trafficking of new PPC overlays.

A thin lift minimizes drainage, guard rail height, and dead load issues on bridge decks. A minimum lift thickness of 0.75 in. is often specified for PPC overlays to maintain adequate moisture resistance even after years of traffic wear. However, Caltrans recommends using a 1.0-in. PPC thickness in areas that experience accelerated wear from tire chains and/or snow plows. Caltrans does not specify placement of lifts thicker than 1.5 in.

3.3.3 Laboratory Testing

Findings related to PPC materials testing and approval are presented in this section. Extensive laboratory testing is performed by Caltrans to approve PPC materials and mixture designs that are submitted in advance of overlay projects and to verify mixture properties after overlay placements. Caltrans laboratory personnel test every batch of PPC placed in California, where a batch usually weighs 40,000 to 80,000 lb. Beyond viscosity, specific gravity, styrene content, tensile strength, and elongation testing of the neat polyester resin, resin demand of the aggregate and resin content and bond beam testing of the PPC mixture are also performed. Figure 3.1 shows some of the laboratory testing equipment.

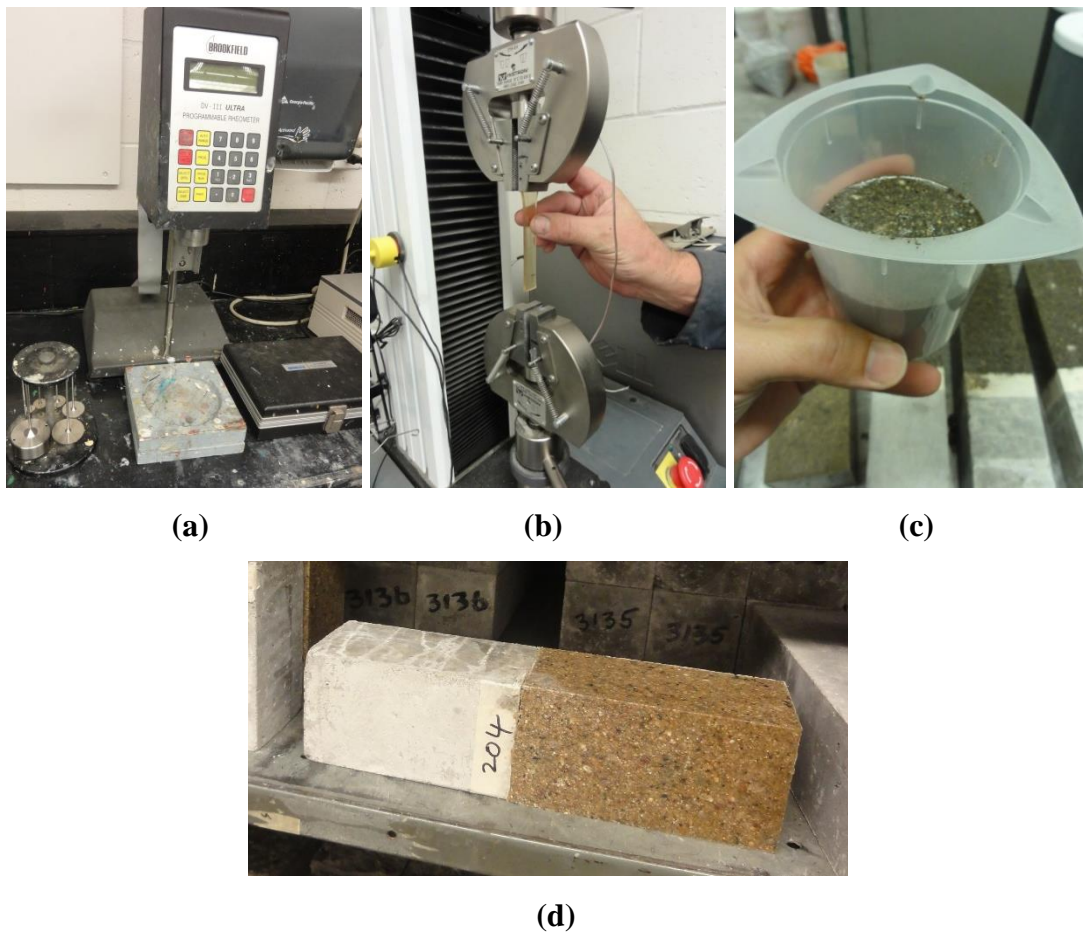


Figure 3.1 PPC laboratory testing: (a) Brookfield rheometer used for viscosity testing, (b) resin tensile strength and elongation testing, (c) resin demand test, and (d) PPC bond beam.

A resin-demand test is recommended for the aggregate. This test involves vibrating a small amount of PPC in a cup and measuring the amount of resin that bleeds to the top. The test should produce a 0.125-in. resin buildup on the surface of the sample. The result of a successful resin-demand test is shown in Figure 3.1. The resin content of hardened samples can be determined using a burn-off test performed at 842°F.

Caltrans personnel measure the bond strength of PPC mixtures by casting and testing bond beams, which consist of PCC on one side and PPC on the other. Figure 3.1 shows an example of a typical bond beam. The force required to break the bond joining the two parts of the beam in flexure is measured and used to determine the bond strength between the two materials.

One purpose for this test is to determine if adequate silane is contained in the resin. The bond strength generally reaches or exceeds 500 psi in 24 hours with silane but is typically only 150 to 200 psi without silane. However, perhaps because the bond surfaces within the beams are not treated with primer, laboratory personnel reported the regular occurrence of failed bond beam tests even with adequate silane in the resin.

3.3.4 Construction and Field Testing

Findings related to PCC construction and repair, trial slabs, PCC preparation, PPC placement, PPC testing, and PPC repair are presented in this section.

3.3.4.1 PCC Construction and Repair

Caltrans applies PPC for protection of newly constructed PCC decks and rehabilitation of existing PCC decks. For newly constructed decks, Caltrans recommends that a time period of 6 months to 1 year elapse before a PPC overlay is placed so that initial PCC drying, shrinkage, creep, and cracking can occur without damaging the overlay. However, when construction contracts cannot be held open for such long periods of time, PPC may instead be placed 28 days after new construction, and cracks that do form can be subsequently treated with methacrylate.

For rehabilitation, because PPC will bond to itself, PCC, and other patching materials, PPC can be used to patch damaged, delaminated areas of existing bridge decks prior to PPC

overlay applications. In general, PPC patch depths are limited to 3 in., and the area of the patch may not be greater than 5 ft by 5 ft. For deeper or wider repairs, cementitious patch materials are specified. Figure 3.2 shows PPC patches that were installed prior to PPC overlay placement at LAX.

3.3.4.2 Trial Slabs

Before a PPC overlay is placed, project specifications often require the construction of at least one PPC trial slab on a representative PCC concrete surface on or near the project to verify that the contractor is capable of providing a high-quality product and to address problems that may occur during construction. Caltrans requires that a new trial slab be constructed if there are changes in the contractor's crew, significant delays in construction, or differences in deck slope (from bridge to bridge) on a given job.

3.3.4.3 PCC Preparation

Adequate PCC surface preparation is crucial to the success of PPC overlays. Bridge deck concrete should be sound, dry, and free of contamination prior to overlay placement. After any earlier overlays are removed and damaged areas are patched and cured, as required, propane driers can be used to remove surface moisture prior to the application of PPC overlays. Surface contamination is generally removed using shot blasting, as shown in Figure 3.2, immediately before PPC placement. A "near white" deck surface condition should result; Figure 3.2 shows the contrast between original and shot-blasted concrete prior to PPC overlay placement at LAX. Bridge deck joints should be blocked out prior to PPC placement, and provisions should be made to protect the PPC from moisture until it has cured.

3.3.4.4 PPC Placement

For placement of PPC overlays, Caltrans specifies a two-step process that involves application of a methacrylate primer and then a single lift of premixed PPC to the surface of the concrete deck in the same work shift. The application of the methacrylate primer is an important step because it strengthens the bond between the overlay and the deck concrete. The primer also



Figure 3.2 PPC construction and testing: (a) PPC patches flush with existing concrete surface, (b) shot blasting, (c) contrast between shot-blasted (middle) and original (left) concrete, (d) application of primer to a deck surface, (e) mobile mixer connected to paving machine, (f) custom-built paver for PPC, (g) tining attachment on the back of a paving machine, (h) hardness testing using a Schmidt hammer, (i) raveling in a PPC bridge deck overlay.

acts as a “healer/sealer” since it can seal existing cracks if it is allowed to soak into the deck for a sufficient period of time prior to placement of the overlay. Figure 3.2 shows the application of methacrylate primer just prior to PPC placement at LAX.

Custom-built mobile mixer trucks, which are typically calibrated on site to ensure accurate proportioning of the PPC during overlay construction, are used to combine and mix the coarse aggregate, fine aggregate, resin, and catalyst (initiator) that comprise PPC. The mixer truck then deposits the PPC directly into the hopper of the paving machine using a conveyor belt as shown in Figure 3.2. Caltrans specifies a minimum contact time of 9 to 11 seconds between the aggregate and resin during mixing to ensure that individual aggregate particles are fully coated with resin.

Also shown in Figure 3.2, the paving machine spreads, consolidates, and strikes off the PPC to the specified thickness. Adequate compaction is typically characterized by a thin film of resin flushing to the surface. Contractor personnel then manually finish the surface using standard concrete finishing tools. Tining may be performed using an attachment on the back of the paving machine or by hand. A typical tining attachment is shown in Figure 3.2. Finally, sand is broadcast onto the freshly-placed PPC surface to enhance the initial skid resistance of the overlay. Tapers are installed at locations of construction joints.

One issue that requires careful attention is moisture management. Specifically, moisture on or in the deck, moisture in the aggregates, and condensation inside mixer trucks must be minimized. To address the issue of moisture condensation inside the mixer trucks, the first few feet of material placed during every shift is deliberately wasted just in case the truck was contaminated overnight.

A successful PPC overlay placement requires careful planning, skilled workers, and attention to detail. PPC overlays can delaminate within weeks if they have not been installed correctly.

3.3.4.5 PPC Testing

PPC testing in the field is performed for QC and QA purposes. Testing may involve measurement of several PPC properties, including hardness, bond strength, smoothness, and skid resistance.

The hardness of PPC is assessed using a Schmidt hammer, which can provide an instantaneous and repeatable measurement of the relative hardness of the overlay as it cures. Caltrans typically requires that PPC overlays achieve a Schmidt hammer reading of 26 or higher within 2 hours of placement. At LAX, a reading of 24 or higher was required before trafficking was allowed on the overlay. Because this was a time-sensitive project, an accelerator was used to decrease setting times. Although the manufacturer indicated that the minimum set time is typically 1.5 to 2.0 hours, the accelerator allowed the PPC to reach the required hardness within 1 hour after placement in most cases. Figure 3.2 shows a worker measuring the hardness of new PPC with a Schmidt hammer at LAX; a test was performed every 10 ft in the longitudinal direction.

The bond strength of PPC is measured using a pull-off test, which involves applying a tensile load to a metal disc epoxied to the circular face of a cylindrical cut that extends from the upper surface of the overlay downward into the substrate. Caltrans requires a minimum bond strength of 250 psi. If failure occurs at the epoxy-disc interface at a load below 250 psi, the test is considered invalid. Chain dragging of new PPC overlays is also recommended to verify that good bonding has been achieved with the underlying concrete surface.

Smoothness is another parameter that is often measured on PPC overlays. Transverse smoothness is measured with a 12-ft straightedge, while longitudinal smoothness is measured using a profilograph. Caltrans requires surface deviations to be less than 0.25 in. in the longitudinal and transverse directions.

The skid resistance of PPC overlays is tested using a device called a drop wheel, which gives a spot reading of the surface friction coefficient. Engineers determine testing locations using random sampling or visual inspection to check areas of concern; Caltrans requires a minimum coefficient of friction of 0.35. The limited availability of drop wheels and the

requirement for precise drop wheel calibration have prompted Caltrans to consider transitioning to the dynamic friction tester in the future.

3.3.4.6 PPC Repair

Environmental conditions or construction errors occasionally necessitate correction or replacement of PPC overlays. Repair of early-age cracking, which can be caused by settlement and/or thermal movements of the bridge, is accomplished by filling the cracks with methacrylate. Areas of a PPC overlay that exhibit low resin content and/or raveling, as shown in Figure 3.2, can be corrected by applying a coat of resin over the affected areas and immediately broadcasting fine aggregate into it. Areas of a PPC overlay that exhibit low skid resistance, possibly resulting from excessive resin content, can be improved by removing 0.125 to 0.25 in. of the surface of the affected area via micro-milling. While grinding of high spots to improve smoothness is not recommended for standard practice, it can generally be performed without compromising PPC performance.

A PPC overlay can be repeatedly repaired or replaced during the service life of a bridge deck. If a worn PPC overlay is being replaced with a new PPC overlay, full removal (with diamond grinding, for example) is not necessary if the material closest to the deck is in good condition. PPC bonds to itself, so leaving some PPC material on the deck is acceptable during replacement projects. Primer is still applied prior to placement of the new overlay.

3.4 Discussion

While the scanning tour yielded valuable information about the construction, QA, and performance of PPC, discussions with Caltrans personnel also led to the identification of potential improvements to PPC laboratory and field testing procedures of particular interest to UDOT. Recommendations regarding MOE, bond beam, resin demand, aggregate quality, set time, compaction, hardness, bond strength, and skid resistance testing are presented in the following sections.

3.4.1 MOE Testing

MOE is an important property of PPC overlays because stiffness affects both cracking potential and stresses that develop at the bond line between the overlay and the substrate (Sprinkel 1983). Although Caltrans specifies low modulus values for PPC overlays, Caltrans does not typically measure the MOE, and actual values of the mixtures most commonly in use are not well defined. MOE testing of commonly used PPC mixtures is an area that warrants further study and possible implementation into QA specifications.

3.4.2 Bond Beam Testing

Although bond strength is an important property, one practice that may be less effective is the testing of PPC bond beams. PPC bond beams are expensive and time-consuming to produce and test. They are also not representative of actual constructed overlays because the bond line is not treated with primer. In addition, the beams sometimes fail to produce adequate bond strengths even when silane is present in the resin. Alternative methods for measuring bond strength and assessing silane content could be developed that would be less expensive and less time-consuming and would also yield more relevant results. Transportation agencies should consider removing bond beam production and testing procedures from PPC specifications.

3.4.3 Resin Demand Testing

In contrast with bond beam testing, the resin demand test for aggregates is inexpensive, quick, and easy to perform. A resin demand test should be specified so that the resin demand for different aggregate materials can be determined. Application of this test would enable determination of an appropriate resin content for a given aggregate and avoid indiscriminate application of a single resin content to all aggregate sources.

3.4.4 Aggregate Quality Testing

Regarding aggregate quality, Caltrans's primary PPC supplier has historically provided high-quality aggregates, so Caltrans does not perform durability testing such as abrasion or polish testing on PPC aggregates. However, these tests could be useful for aggregates from different sources. Cleanliness and sand equivalence tests could also be specified.

3.4.5 Set Time Testing

Set time is an important property of PPC mixtures because it governs the timing of overlay placement operations in the field. Caltrans laboratory personnel have observed that mixtures submitted by some manufacturers have occasionally exhibited setting problems. These mixtures remain sticky to the touch long after specified set times. Laboratory personnel recommend that specifications should allow rejection of mixtures that fail to set within specified time limits.

3.4.6 Compaction Testing

Proper compaction directly affects the quality of PPC overlays. Caltrans job specifications sometimes require the use of a nuclear density gauge for measuring PPC compaction on trial slabs. Adequate compaction is characterized by a thin film of resin flushing to the surface of a PPC overlay as determined by visual inspection. Resin flushing is therefore the basis for establishing a target density for compaction testing. Performing compaction testing with a nuclear density gauge may not be necessary since compaction can be assessed based on visual inspection alone.

3.4.7 Hardness and Bond Strength Testing

Although these tests are not always performed by Caltrans, Schmidt hammer and pull-off testing could also be specified to measure hardness and bond strength, respectively, on trial slabs and overlays for QA purposes. These tests are quick and easy to perform, and they provide objective results that relate directly to overlay quality.

3.4.8 Skid Resistance Testing

Skid resistance is a critical property of PPC overlays that affects driver safety. The limited availability of drop wheels for measuring skid resistance has prompted Caltrans to consider the use of dynamic friction testers; however, these testers are expensive. One alternative is the British pendulum, which is a manually operated device that also gives a spot reading of skid resistance. The British pendulum test provides instant and repeatable results that can be easily correlated with skid numbers. It is also relatively inexpensive, quick, and easy to perform.

Agencies should consider the use of the British pendulum as an alternative for measuring skid resistance.

3.5 Chapter Summary

The purpose of this chapter was to provide a summary of the main findings from the scanning tour related to construction, QA, and performance of PPC. The objectives of the scanning tour included observation of a PPC overlay placement, inspection of existing overlays, and discussion of selected topics related to PPC. The scanning tour comprised a 3-day visit to California. Items related to material properties, mixture and overlay design, laboratory testing, and construction and field testing were investigated. Several recommendations relevant to Utah bridge deck preservation practice were developed based on the findings.

4.0 FIELD TESTING OF POLYESTER POLYMER CONCRETE OVERLAYS ON BRIDGE DECKS IN UTAH

4.1 Introduction

After a scanning tour of PPC overlays on bridge decks in California was completed and a new draft PPC specification was developed (Stevens and Guthrie 2020), a pilot project was initiated to evaluate specific aspects of construction, QA, and performance of PPC overlays placed on concrete bridge decks under the new specification, which is provided in the appendix. The scope of the project included testing of a PPC test section overlay and three PPC bridge deck overlays during and after construction. Hardness tests were performed on the test section placements, and hardness, skid resistance, acoustic impact-echo, vertical electrical impedance (VEI), and resin content determination tests were performed on each of the bridge deck overlays. The purposes of this chapter are to report the findings of the pilot project and provide recommendations for additional changes to the PPC specification in Utah. The following sections provide relevant background information, describe the procedures, discuss the results, and present recommendations.

4.2 Background

The following sections describe typical PPC material properties and concrete bridge deck applications.

4.2.1 PPC Material Properties

The properties of PPC aggregates are tightly controlled. The weighted average aggregate absorption and the in-situ moisture content are often specified to be less than 1.0 percent and less than 0.5 percent by weight of dry aggregate, respectively. Not only should the aggregates have low absorption values, but they should also be rounded rather than crushed. Natural, non-igneous rounded rock with a maximum size of 0.38 in. and beach sand with a maximum size of 0.19 in. are commonly supplied for use in PPC mixtures (Stevens and Guthrie 2020).

The material properties of PPC depend extensively on the properties of the polyester resin utilized in the mixture. The polyester resin is composed of a liquid monomer that reacts with a catalyst (initiator) to become a solid in a process called polymerization (Doody and Morgan 1993, Haddad and Kobaisi 2013, Vipulanandan and Paul 1990). Polymerization of the resin begins as soon as its component chemicals are combined and is the mechanism responsible for the setting and strength gain of PPC (Haddad and Kobaisi 2013). Although the rate of polymerization and attendant strength gain is highest during the first several hours after mixing, PPC continues to harden and gain strength at a lower rate over a period of several weeks after mixing (Ferreira et al. 2000, Hristova 1982, Ohama and Demura 1982).

The rate of hardening of PPC overlays is affected by a number of factors, including ambient temperature, deck temperature, relative humidity, level of exposure to ultraviolet radiation, and the amounts of resin, catalyst (initiator), and accelerator present in the mixture (Doody and Morgan 1993, Sprinkel 1997). PPC overlay specifications often indicate both minimum and maximum set times to ensure sufficient time to place the material while simultaneously ensuring that it can receive traffic within an acceptable time period (Sprinkel 1997).

Regarding the amount of resin, PPC overlays generally contain between 11 and 14 percent binder by weight of dry aggregate (Smith 1991), and resin contents of 12 percent are typical (Sprinkel 1997). For one commonly used mixture, the recommended resin content is 12 ± 1 percent by weight of aggregate (Kwikbond 2011a).

PPC overlays have been shown to provide good skid resistance over time (Sprinkel 2003). The high skid resistance of PPC is achieved by tining and broadcasting sand, typically with a maximum size of 0.05 in., onto the surface of the fresh placement. Although some resin at the surface is important for bonding the sand to the PPC surface, excessive resin can lower the skid resistance (Krauss et al. 2007).

4.2.2 Concrete Bridge Deck Applications

PPC overlays placed on concrete bridge decks are usually specified to be 0.75 in. to 1.0 in. in thickness, and they are bonded to the concrete with a low-viscosity methacrylate that is

applied immediately before PPC placement (Stevens and Guthrie 2020). Several benefits of using PPC for bridge deck overlays include excellent protection against moisture and chloride ingress (Krauss 1988a), rapid curing and high early strengths, high skid and abrasion resistance (Krauss et al. 2007), and placement in variable thickness (Doody and Morgan 1993).

A sound substrate and proper surface preparation are critical for successful PPC overlay installations on concrete bridge decks (Doody and Morgan 1993, Krauss 1988b). Weak or delaminated concrete should be removed and replaced, and rebar in the affected areas should be repaired or replaced, as applicable (Smith 1991). In addition to the removal of unsound material, substrate concrete should be scarified to remove surface contamination and provide a rough surface texture (Sprinkel 1997). Although sandblasting is often used for surface preparation, it is generally considered to be inadequate for scarification. Instead, shot blasting is recommended because it leads to higher bond strengths with PPC overlays (Krauss 1988b, Maass 2003, Smith 1991, Sprinkel 1997, Tarricone 1992). Sandblasting may be used in places where shot blasting cannot reach, such as areas close to curbs (Sprinkel 1997).

Hydrodemolition is sometimes used to remove contaminated and/or unsound concrete from bridge decks in preparation for PPC overlay applications or other bridge preservation operations (ICRI 2014). Hydrodemolition involves the use of high-pressure water jets to either remove concrete that is below a given strength or remove concrete within a given depth from the surface (ICRI 2014, Momber 2005). Because bridge deck concrete is not homogenous, however, the resistance to removal with hydrodemolition varies from point to point on a deck, causing variable depths of removal using this process; the result can be a highly variable deck profile with “peaks” and “valleys” that are well above and below the average removal depth, respectively. Thus, while hydrodemolition provides a substrate with rough microtexture and macrotexture that is ideal for bonding to PPC overlay materials (ICRI 2014), precisely controlling the depth of concrete removal is not generally possible.

4.3 Procedures

The following sections describe the overlay sites and the procedures used to test the overlay placements.

4.3.1 Site Description

The pilot project performed for this research ultimately included two PPC test section placements and three PPC bridge deck overlay placements on two separate bridges. These placements are referred to as test sections 1 and 2 and bridge placements A, B, and C in the following sections. All five placements were constructed during the fall of 2016 using the same material supplier, general contractor, and subcontractor.

4.3.1.1 Test Sections

The UDOT PPC specification requires contractors to demonstrate their ability to construct a bridge deck overlay by first placing a test section to the satisfaction of the state engineer (UDOT 2017). The test section for the pilot project was placed in the median of Interstate 215 on the west side of Salt Lake City. The contractor used a volumetric mixer truck and a modified paving machine, depicted in Figure 4.1, to mix and place the material.

The initial test section placement appeared to have a resin content that was too low, so the contractor placed a second section immediately adjacent to the first one. Both sections were approximately 10 ft wide by 15 ft long and were placed within approximately 30 minutes of each other.



Figure 4.1 Modified paving machine used to place PPC.

4.3.1.2 Bridge Placements

Two days after the test section placements, bridge placement A was constructed at night on a bridge deck on the south side of Salt Lake City. The deck surface was shot blasted before the PPC overlay was placed.

Bridge placement B was constructed approximately one week after placement A and covered half the deck of a bridge on the east side of the city. Bridge placement C was constructed one week later and covered the other half of the same deck. Prior to overlay operations at bridge placements B and C, hydrodemolition was used to prepare the deck surface, as depicted in Figure 4.2. Although major blow-throughs did not occur (Roper 2018), hydrodemolition removed significant amounts of concrete in many areas. Just before bridge placements B and C were constructed, many of the deeper voids were filled with a rapid-setting, portland-cement-based concrete patching material as shown in Figure 4.2. Many of the patches were still relatively soft when the PPC overlays were placed.

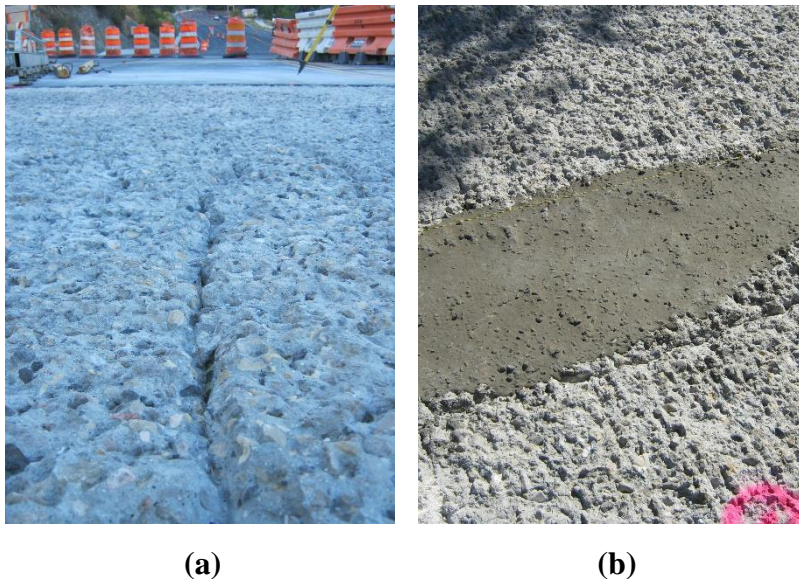


Figure 4.2 Bridge deck prior to PPC placement: (a) hydrodemolished surface, (b) freshly patched void.

4.3.2 Site Testing

Extensive testing was performed before, during, and after the PPC test section and bridge placements. The procedures associated with hardness, skid resistance, impact-echo, and VEI testing are described in the following sections.

4.3.2.1 Hardness Testing

Hardness testing using a Schmidt rebound hammer was performed on all of the test section overlays and the bridge overlays at the time of placement and on the bridge overlays approximately 2 years after placement. Rebound testing is often used to monitor the hardness of PPC overlays for QC and QA purposes and so that determinations regarding final set and opening to traffic can be made. The Schmidt rebound hammer is constructed of a cylindrical steel housing, which encases a mass that is connected to a spring. When a plunger that protrudes from the hammer is depressed, it pushes the mass upwards into the hammer via a shaft, extending the spring. The spring is extended until the mass trips a release mechanism and is propelled into the depressed plunger. The mass then rebounds a distance that is governed by the hardness of the test surface. The rebound number is a measure of this distance and is observed through an indicator window on the side of the hammer. To perform the test, the hammer was held vertically, with the plunger in contact with surface of the overlay. The hammer was slowly depressed until the mass inside the hammer impacted the plunger. The rebound number was then recorded, and the process was repeated two more times in the exact same location.

At the test section placements, nine locations were selected for hardness monitoring. Three transverse rows were established within each placement, being spaced 4 ft apart in the longitudinal direction and including three locations spaced 2 ft apart in the transverse direction. Testing was performed at all nine locations, with three repetitions each.

At the bridge placements, nine locations within the first pass along one side were selected for hardness monitoring. Three transverse rows were again established, one being 50 ft from one end of the bridge, one being 50 ft from the other end of the bridge, and one being in the middle. Each row, which was centered transversely in the pass, included three locations spaced 3 ft apart

in the transverse direction. Testing was performed at all nine locations, with three repetitions each.

At each placement, three to four sets of rebound tests were performed over time at each location while the overlay hardened. Each successive set of tests was performed approximately 1 in. from the previous set to ensure independent test results. The highest of the three repetitions at a given location was considered to be the rebound number for that location because, when several consecutive rebound tests are performed at a given location, the first one or two tests generally yield lower numbers than subsequent tests; the first impacts of the hammer cause crushing of the fine aggregates on the surface of the overlay, which absorbs energy that would otherwise contribute to the rebound of the mass inside the hammer. The rebound numbers determined for each location were then averaged across each placement for each measurement time.

At 2 years after both bridge placements, follow-up testing was performed at two locations, one being 6 in. into the shoulder and one being in the center of the outer wheel path of the adjacent lane, that were established 50 ft from each end on both sides of each bridge, for a total of eight locations per bridge. Because bridge placements B and C were on the same bridge, only four locations at each of those placements were subjected to follow-up testing. Informed by the results shown in Figure 4.3 for 10 consecutive tests previously performed at each of two

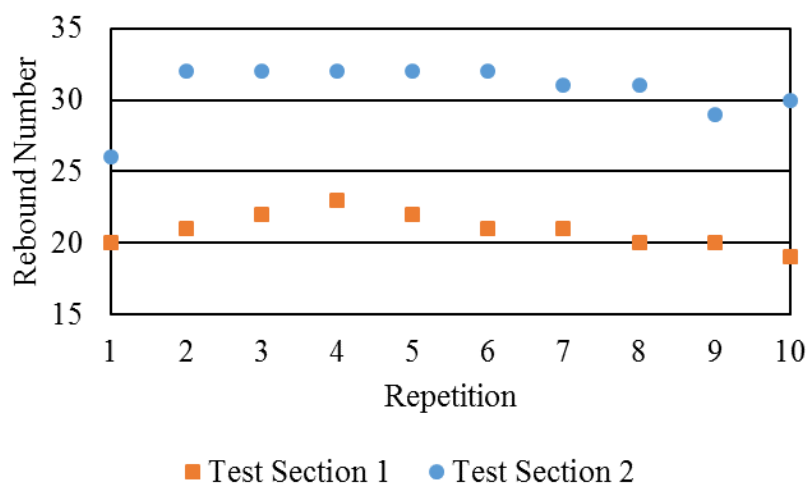


Figure 4.3 Consecutive rebound numbers in the same location on PPC overlays.

locations, one within each test section placement, the follow-up testing involved four consecutive repetitions at each location. The highest of the four repetitions at a given location was considered to be the rebound number for that location.

4.3.2.2 Skid Resistance Testing

Skid resistance testing using a British pendulum tester (BPT) was performed on the bridge overlays approximately 2 years after placement in the same locations as the follow-up hardness testing. Skid resistance testing is often used to verify that the skid resistance of a bridge deck is at or above a minimum threshold for public safety. The BPT is an apparatus with a pendulum arm that is connected to a base assembly. During the test, the pendulum arm is released from an elevated horizontal position and allowed to swing downward. A rubber pad on the end of the pendulum arm slides across the test surface in a pre-determined strike path before the arm continues its upward swing. The arm pushes an indicator needle to the high point of its swing, and the needle points to the British pendulum number (BPN) on a scale observed by the operator, where a high BPN corresponds to high skid resistance.

To perform the test, the BPT was oriented parallel to the direction of traffic flow, which was also parallel to the longitudinal tining in the overlay. The device was leveled and calibrated, and a 5-in. strike path was set. The strike path was cleared of debris with a brush, and a sprayer was used to saturate the surface with water prior to every swing. After a first swing that was disregarded by protocol, the BPNs from four consecutive swings were recorded and averaged to obtain the BPN at each location.

4.3.2.3 Impact-Echo Testing

Impact-echo testing was performed using a recently-developed, multi-channel, air-coupled, impact-echo device (Larsen et al. 2020). Initial testing was performed 2 days before bridge placements A and B and approximately one week before bridge placement C. Follow-up testing was performed approximately one month after each of the bridge placements. Acoustic methods like impact-echo testing are often used to detect delaminations in concrete bridge decks because, unlike more invasive procedures such as coring, they are nondestructive and can be

used to efficiently test large deck areas (Guthrie et al. 2019). The impact-echo apparatus utilized in this research was a trailer-mounted unit equipped with a series of mallets fitted with brass heads. When fully deployed, the device is approximately the same width as a traffic lane.

To perform the testing, the trailer was towed across the bridge decks with enough passes to substantially cover the areas of each deck for which traffic control was provided; because scanning of the lanes in both directions was not always permitted, data were collected in only one direction in some cases. As the trailer moved along the bridge, the mallets repeatedly struck the surface of the deck to generate an acoustic response, which was then recorded by microphones mounted on the device near the points of impact. High-frequency responses denoted intact concrete, while low-frequency responses indicated the presence of a delamination. Processing of the recorded data yielded bandlimited acoustic energy (BAE) values for each mallet strike, and these BAE values were then plotted on maps of the decks. A BAE value exceeding 225,000 indicated delamination (Larsen et al. 2020). During the initial testing, a rainstorm prevented data from being collected at bridge placement C.

4.3.2.4 VEI Testing

VEI testing was performed using a recently-developed VEI apparatus (Mazzeo and Guthrie 2019). Initial testing was performed two weeks before bridge placement A and 2 days before bridge placements B and C. Follow-up testing was performed approximately 2 years after each of the bridge placements. VEI is a measure of the difficulty with which an electrical current passes through a material when an alternating electrical potential is applied. VEI can be used to quantify the level of protection against water and chloride ion ingress in concrete bridge decks because the same factors that increase the VEI of concrete also increase the resistance of the concrete to the ingress of those corrosive elements. Increased VEI, which would be expected from the application of a bridge deck surface treatment, for example, is therefore desirable, as it indicates increased protection from corrosion (Argyle 2014). The VEI device is a trailer-mounted unit equipped with a series of probes and electrodes that remain in contact with the surface of the deck during testing. When fully deployed, the device is approximately the same width as a traffic lane.

To perform the testing, the trailer was towed across the bridge decks with enough passes to substantially cover the areas of each deck for which traffic control was provided; during the follow-up testing, limited areas were available for scanning due to traffic control constraints. As the trailer moved along the deck, the deck surface was sprayed with water immediately ahead of the probes to facilitate an electrical connection between the probes and the concrete surface. VEI data were recorded by the apparatus, and maps were generated for each deck. For interpreting the maps, VEI values less than 10^4 ohms were considered low, values between 10^4 and 10^5 ohms were considered medium, and values greater than 10^5 ohms were considered high (Mazzeo and Guthrie 2019).

4.4 Results

The following sections describe the results of the hardness, skid resistance, impact-echo, and VEI testing performed on the overlay placements. In all of the bar charts presented in this section, the error bars span one standard deviation above and below the given average.

4.4.1 Hardness Testing

Average hardness data for each placement at each measurement time are plotted in Figure 4.4. As expected, rebound numbers typically increased relatively rapidly within the first few

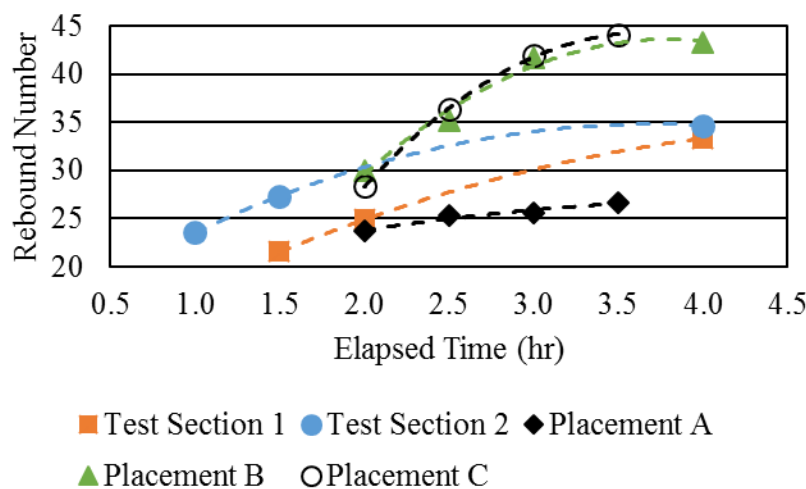


Figure 4.4 PPC hardness over time.

hours after the material was placed, and then the rate of change slowed over time. Although the general trends were similar, substantial variability in the rate of increase in rebound numbers occurred among the different placements. Variability in hardness can be attributed to variability in several factors that can affect the rate of hardening of PPC overlays. Four of these parameters, including starting deck temperature, catalyst (initiator) concentration, accelerator concentration, and resin content, were recorded for the first pass of the paving machine at the three bridge placements and are shown in Table 4.1. Although the average resin content was specified as part of the PPC mixture design to be 12 percent by weight of dry aggregate, the other parameters varied depending on ambient conditions and construction requirements. As one example shown in Figure 4.4, the overlay at bridge placement A hardened at a much slower rate than the other four placements; given that bridge placement A was constructed at night at lower temperatures than the other placements and with no exposure to ultraviolet radiation, the slower hardening rate is not unexpected despite the use of accelerator.

Not only can the parameters that affect rates of hardening vary from site to site, but they can often change relatively quickly at a given site. For example, although the starting deck temperature at bridge placement C was less than 76°F, recorded deck temperatures rose to 93°F during the placement. While not all of the factors that could affect rates of hardening were measured, these differences demonstrate the variability inherent in PPC overlay placements.

Schmidt rebound numbers of 22 to 24 usually indicate that the overlay has gained sufficient hardness and strength to receive traffic (Krauss et al. 2007). The current UDOT PPC specification defines final set as the point when the overlay achieves a Schmidt rebound number of 25 and requires that overlays reach final set within 4 hours of placement and before receiving

Table 4.1 Factors Affecting PPC Hardening Rate

Placement	Starting Deck Temperature (°C)	Catalyst Concentration (%)	Accelerator Concentration (%)	Average Resin Content (%)
A	18.4	1.75-2.00	0.05-0.10	11.6
B	36.7	1.50-2.00	0.00	12.1
C	< 24.5	2.00	0.00	12.7

traffic (UDOT 2017). With the exception of bridge placement A, all of the placements achieved a rebound number of 25 by 2 hours.

Results from the follow-up hardness testing are presented in Figure 4.5. Rebound testing performed in the shoulder is considered to be representative of ultimate overlay hardness, though little difference in hardness between the shoulder and the wheel path was generally observed; on average, rebound numbers were 2 units lower in the wheel path than in the shoulder across the three bridge placements.

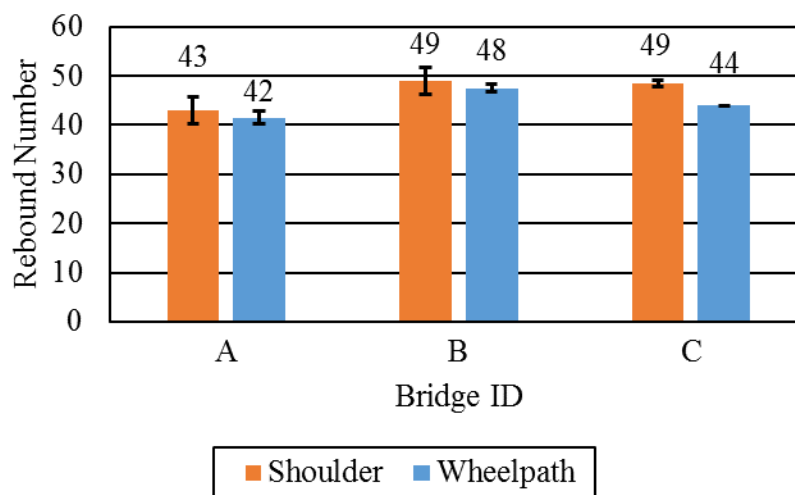


Figure 4.5 PPC overlay hardness at 2 years.

4.4.2 Skid Resistance Testing

Results from the skid resistance testing are presented in Figure 4.6. While trafficking had little effect on overlay hardness, it does appear to have had a significant impact on skid resistance as evidenced by the reduction in the average BPNs in the wheel paths compared to those in the shoulder; on average, BPNs were 9 units lower in the wheel path than in the shoulder across the three bridge placements. However, these values are still at or above the minimum BPN of 45 required by UDOT (UDOT 2017).

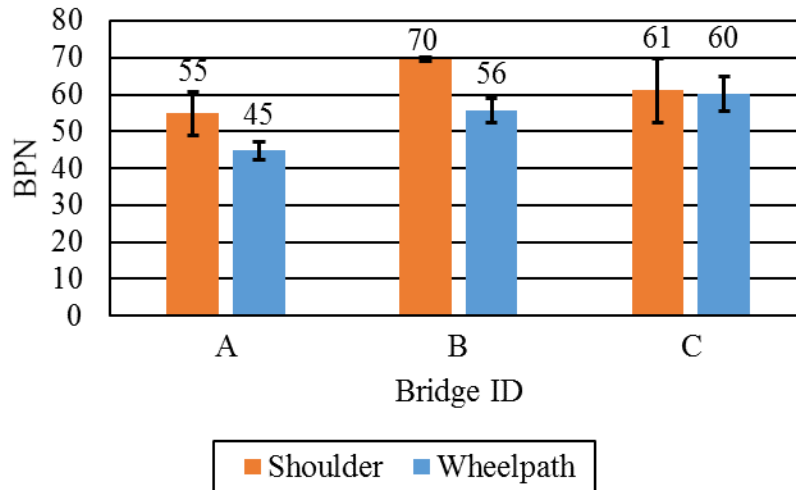


Figure 4.6 PPC overlay skid resistance at 2 years.

Historically, PPC overlays have exhibited skid numbers of 30 to 40 under a smooth tire following new construction and 45 to 50 after 15 to 20 years of service life (Sprinkel 1997, Sprinkel et al. 1993). Correlations between skid numbers, which are obtained using a skid trailer over a distance of approximately 100 ft, and BPNs, which are obtained using a BPT at a single location, are still needed for PPC overlays.

4.4.3 Impact-Echo Testing

Results from the acoustic impact-echo testing are shown in Figures 4.7 and 4.8. In Figure 4.8, the bottom and top portions of each map represent placements B and C, respectively. For both bridge decks evaluated, less than 1 percent of the interrogated areas were delaminated before and after overlay placement. (Although impact-echo testing of the deck was not performed before bridge placement C occurred, Figure 4.8 shows that very few detectable delaminations were present afterwards.) These results suggest that both the substrate and the bond between the overlay and the substrate at bridge placements B and C remained intact, despite the rapid placement and overlay of patches following the hydrodemolition process.

The results of the impact-echo testing are summarized in Figure 4.9. For both placements, the average BAE values were well below the threshold for delamination. Although a slightly higher average BAE value was calculated after bridge placement A compared to before placement A, the difference is not large enough to be practically important.

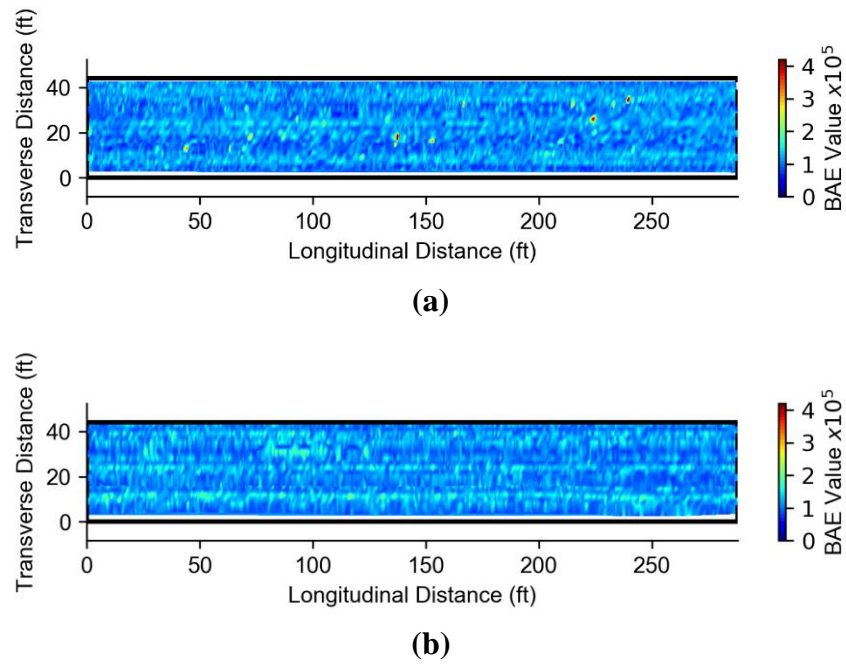
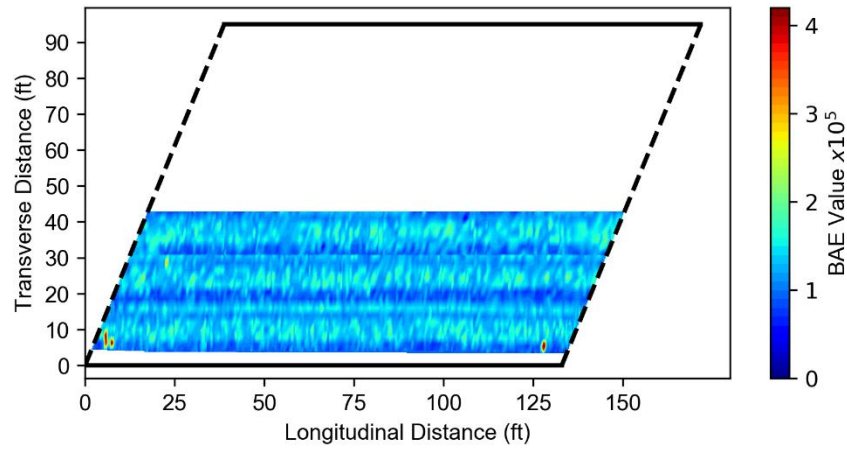
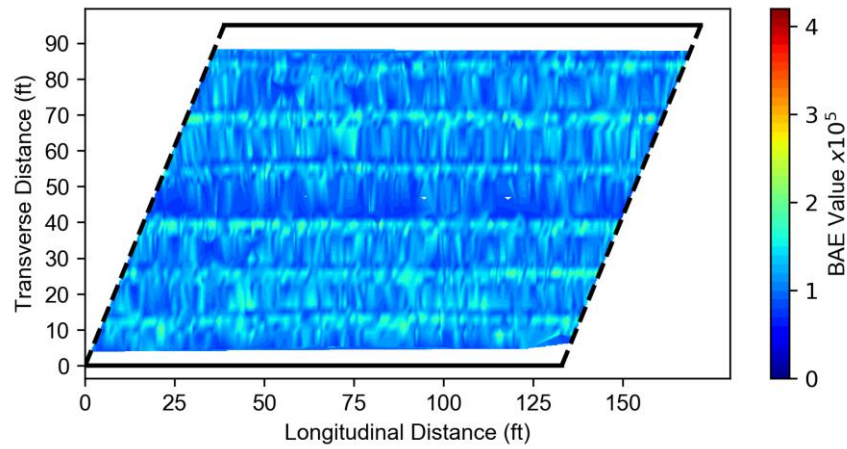


Figure 4.7 Impact-echo map of bridge placement A: (a) before PPC overlay and (b) after PPC overlay.



(a)



(b)

Figure 4.8 Impact-echo map of bridge placements B (bottom) and C (top): (a) before PPC overlay and (b) after PPC overlay.

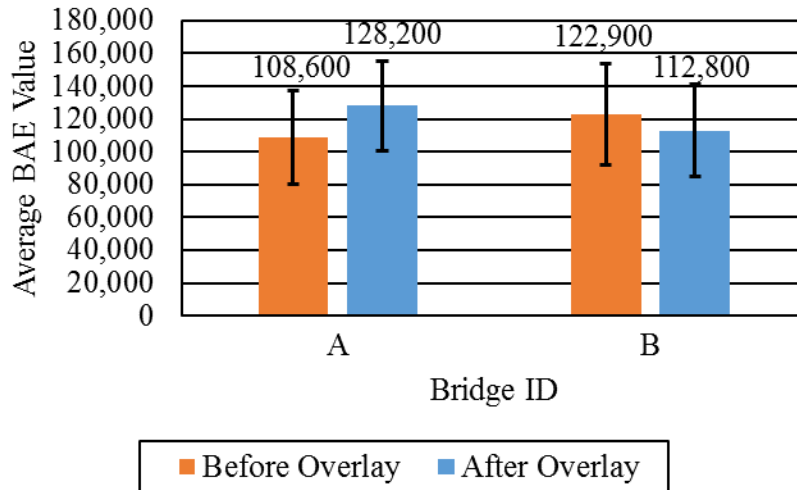


Figure 4.9 Impact-echo results before and after PPC overlay placement.

4.4.4 VEI Testing

Results from the VEI testing are shown in Figures 4.10 and 4.11. Before the overlay at bridge placement A, 13, 69, and 18 percent of the interrogated deck area were in the low,

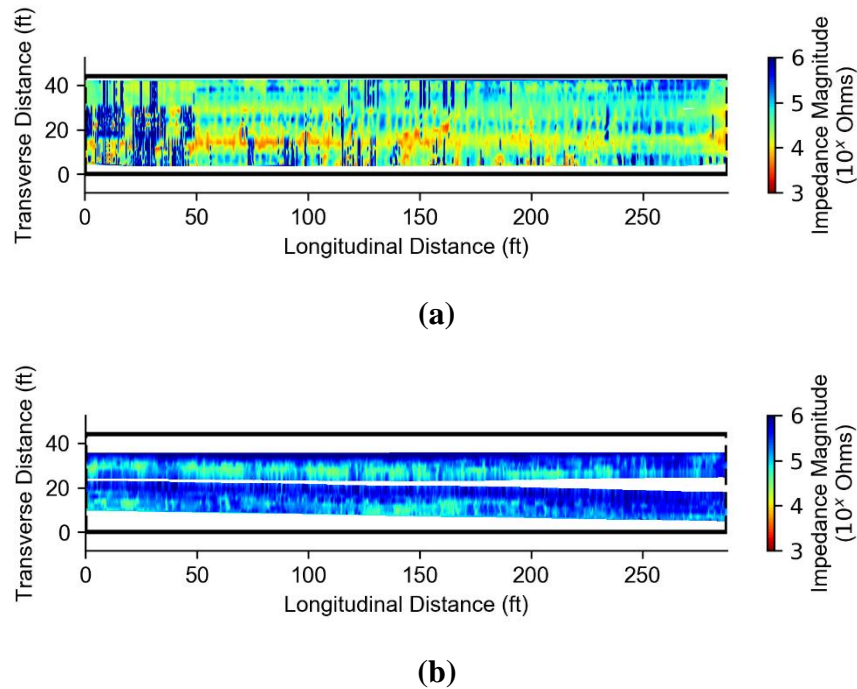
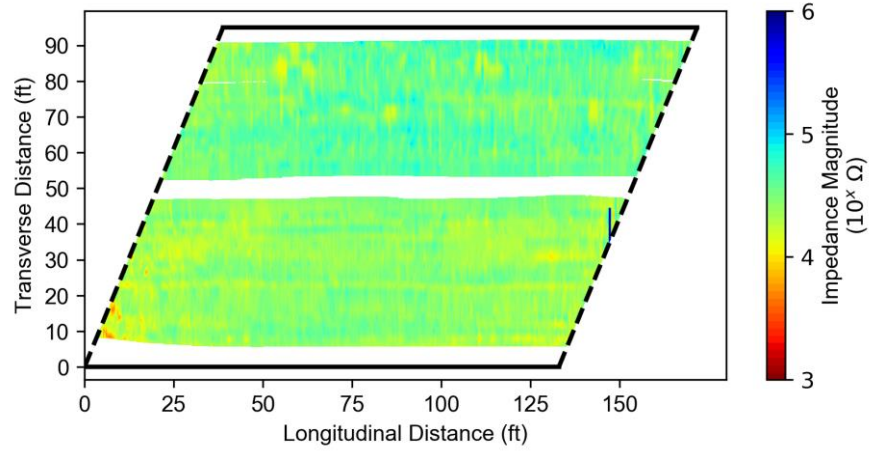
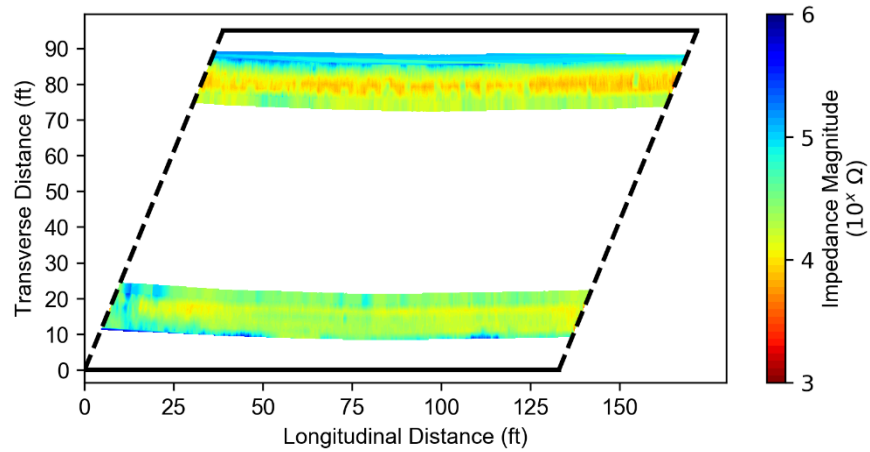


Figure 4.10 VEI map of bridge placement A: (a) before PPC overlay and (b) after PPC overlay.



(a)



(b)

Figure 4.11 VEI map of bridge placements B (bottom) and C (top): (a) before PPC overlay and (b) after PPC overlay.

medium, and high categories, respectively. After the overlay, those values changed to 0, 24, and 76 percent. Before the overlay at bridge placement B, 2, 98, and 0 percent of the interrogated deck area were in the low, medium, and high categories, respectively. After the overlay, those values changed to 1, 96, and 3 percent. Before the overlay at bridge placement C, 0, 100, and 0 percent of the interrogated deck area were in the low, medium, and high categories, respectively. After the overlay, those values changed to 25, 70, and 5 percent.

Results from the VEI testing are summarized in Figure 4.12. As expected, the average VEI at bridge placement A is significantly higher after the overlay placement than before overlay placement. Conversely, the VEI at bridge placements B and C is approximately the same and lower, respectively, after overlay placement than before overlay placement. These unexpected results of the VEI testing may be explained by the hydrodemolition process. The process of hydrodemolition removes surface contamination from the deck and increases the porosity of the exposed concrete substrate. Cleaner concrete with increased porosity allows water and chloride ions to more easily penetrate the concrete, lowering its VEI. This effect would normally be negated by the presence of an intact overlay. However, another result of the hydrodemolition process is that it can leave peaks in the concrete substrate that are nearly equal in elevation to the original deck surface, which was to be matched in this case by the PPC overlay. At the locations of the peaks, the thickness of the PPC overlay was therefore significantly reduced, causing it to be much more vulnerable to cracking at those locations. While the target overlay thickness at all three bridge placements was 0.75 in., the actual overlay thickness at bridge placements B and C was less than 0.1 in. in some locations immediately above the peaks. The occurrence of cracking would also lead to lower VEI values as observed at bridge placements B and C.

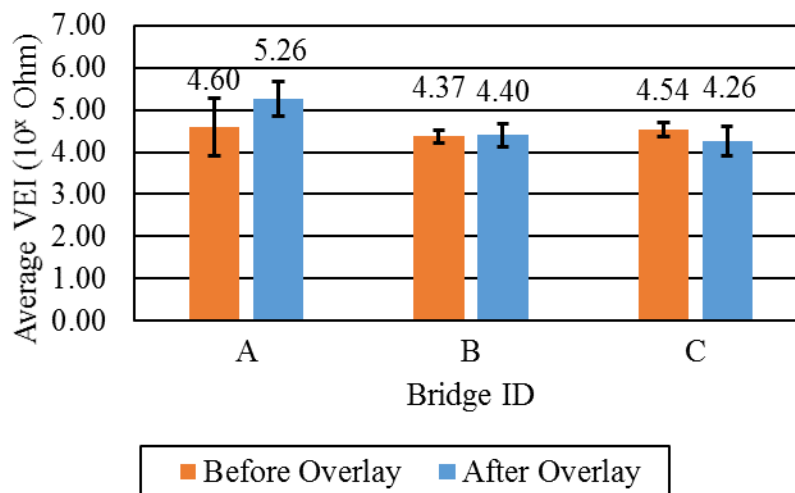


Figure 4.12 VEI before and after PPC overlay placement.

4.5 Recommendations

The pilot project yielded valuable information about the construction, QA, and performance of PPC overlays. In particular, several potential improvements to construction and QA procedures were identified. Recommendations regarding hardness testing, skid resistance testing, patching, and surface preparation are presented in this section.

4.5.1 Hardness Testing

Although the hardness of PPC is inherently variable to some degree, the consistency of hardness measurements performed with a Schmidt rebound hammer is improved when maximum values at each location are obtained. Using maximum values helps to account for operator error and reduces the variability associated with crushing fine aggregates on the surface of the overlay. A standard practice is to record the highest of three consecutive rebound numbers obtained at a given location. However, test results from the pilot project suggest that four tests are more likely to achieve the actual maximum value than three tests. When measuring overlay hardness, agencies should consider recording the highest of four consecutive rebound numbers obtained at a given location.

4.5.2 Skid Resistance Testing

Skid resistance is a critical property of PPC overlays that affects driver safety. Skid resistance is often measured using a skid trailer. However, skid trailer testing cannot be performed until overlay operations are completely finished, and it requires distances greater than the span lengths of many bridge decks. In contrast, the BPT provides localized measurements of skid resistance that are rapid and repeatable, can be obtained as soon as the PPC material achieves final set, and are expected to correlate with the results of skid trailer testing. Agencies should consider the use of the BPT for measuring skid resistance on PPC overlays.

4.5.3 Patching

Rehabilitation activities that involve the removal and replacement of contaminated or deteriorated concrete are frequently performed on bridge decks prior to overlay operations. Although PPC can be used as a patching material in some instances, replacing structural deck

concrete with a structural patching product is usually desirable. In particular, a rapid-setting cementitious material was used to patch the bridge decks that were subjected to hydrodemolition during the pilot project. Although the patches had not fully cured at the time the PPC overlays were placed, subsequent impact-echo testing indicated that intact bonding was nonetheless achieved. Therefore, agencies may specify use of a rapid-setting patch material prior to PPC overlay placement on projects similar to the pilot project studied in this research.

4.5.4 Surface Preparation

Proper surface preparation is critical to the success of a PPC overlay and may be accomplished using different methods depending on the scope of the project. Shot blasting is typically used to prepare decks for PPC overlays, but hydrodemolition was used on one bridge during the pilot project. Example section views of PPC overlays on typical and hydrodemolished deck surfaces are shown in Figure 4.13, in which the dashed line in the second drawing indicates the intended interface between the PPC overlay and the concrete substrate. While the overlay on a typical deck has a uniform thickness, the overlay on a hydrodemolished deck has a highly variable thickness because of the peaks and valleys in the profile of the substrate. Because the peaks, in particular, can perforate the overlay and subsequently lead to cracking when original elevations are maintained, agencies should consider first milling the surface of the deck to a depth equal to the specified overlay thickness, which would ensure a more uniform PPC overlay thickness while still allowing for removal of unsound concrete below that depth using hydrodemolition.

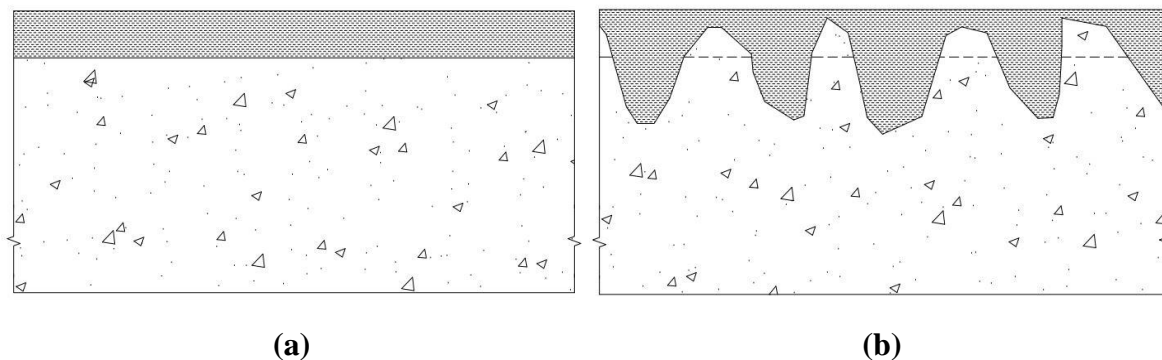


Figure 4.13 Section view of a concrete bridge deck with PPC overlay: (a) typical deck surface and (b) hydrodemolished deck surface.

4.6 Chapter Summary

The purposes of this chapter were to report the findings of the pilot project and provide recommendations for additional changes to the PPC specification in Utah. The scope of the project included testing of a PPC test section overlay and three PPC bridge deck overlays during and after construction. Hardness tests were performed on the test section placements, and hardness, skid resistance, acoustic impact-echo, VEI, and resin content determination tests were performed on each of the bridge deck overlays.

The pilot project yielded valuable information about the construction, QA, and performance of PPC overlays. Recommendations regarding hardness testing, skid resistance testing, patching, and surface preparation were developed based on the findings.

5.0 LABORATORY CHARACTERIZATION OF FIELD-MIXED POLYESTER POLYMER CONCRETE FOR BRIDGE DECK OVERLAYS

5.1 Introduction

Although Caltrans has developed a thorough PPC mixture design approval process that involves significant laboratory testing and verification of PPC composition and material properties prior to PPC overlay placements, Caltrans does not commonly sample or test any field-mixed PPC for the purpose of QA (Stevens and Guthrie 2020). Instead, QA in the field is limited primarily to visual inspection and oversight by a representative from the PPC supplier. Because the vast majority of PPC used in the United States is furnished by the same supplier, generally under the same or similar specifications as those used in California, the practice of relying almost exclusively on visual inspection for QA has become widespread. For this main reason, the literature is generally absent of test results obtained on field-mixed PPC specimens.

Motivated by the need to verify material properties of field-mixed PPC placed under the new PPC specification developed for UDOT (UDOT 2017), the primary objectives of this research were to characterize several material properties of field-mixed PPC sampled from actual bridge deck overlay placements in Utah and compare them to properties of laboratory-mixed PPC reported in the literature. A secondary objective was to quantify the effect of level of consolidation effort on the properties of PPC. Specific properties that were measured include density, MOE, CTE, hardness, UCS, STS, rapid chloride permeability (RCP), and resin content. Because the specific PPC mixture evaluated in this research is commonly used nationwide, the results of this study are expected to be valuable to numerous agencies across the United States. The following sections provide relevant background information, explain the procedures, and present the results.

5.2 Background

The following sections discuss the composition and performance of PPC used for bridge deck overlays.

5.2.1 Composition

The material properties of PPC depend extensively on its composition. PPC mainly consists of a polyester-based resin binder and natural aggregate, although it may also include chemical additives and microfillers. Laboratory studies of PPC have used formulations with a wide range of mixture compositions and proportions; indeed, there have been almost as many different mixtures as separate studies on PPC. However, very few studies have been conducted on the type of PPC most commonly used in modern practice. The mixture primarily used in California and throughout the country contains coarse and fine aggregate, as well as a resin binder that makes up approximately 12 percent of the mixture by dry weight of aggregate. The binder is an unsaturated isophthalic polyester-styrene resin that contains a small percentage of silane and is catalyzed (initiated) by MEKP (Krauss et al. 2007; Kwikbond 2011a; personal communication, R. Wiegman, May 8, 2015).

5.2.2 Performance

The material properties of PPC largely govern its resistance to damage under trafficking and environmental factors. PPC typically achieves high early strengths and cures rapidly, being able to withstand traffic loads within as few as 2 hours after placement (Krauss et al. 2007, Smith 1991, Sprinkel 1997); Schmidt rebound hammer numbers of 22 to 24 usually indicate that the overlay has gained sufficient hardness and strength to receive traffic (Krauss et al. 2007). PPC overlays also generally provide high skid and abrasion resistance (Krauss et al. 2007, Maass 2003).

In addition to traffic loads, PPC overlays must withstand sometimes harsh environmental conditions, including exposure to thermal cycles. Differences in MOE and CTE between the overlay and the substrate cause shear stresses at the bond line when the deck is subjected to thermal movements (Fowler 1999, Krauss 1988b, O'Connor and Saiidi 1993a). Flexible PPC overlay materials, characterized by adequate resin contents, experience lower stresses caused by thermal movements than brittle overlay materials and therefore provide better deck protection because they are less susceptible to cracking (Krauss et al. 2007, Sprinkel et al. 1993). The MOE of PPC used for bridge deck overlays is often reported to be around 1.5 million psi (Krauss et al. 2007), although one study reported values ranging from 2.7 to 3.1 million psi (Mantrala and

Vipulanandan 1995). While the CTE of PCC ranges from 4.4 to $6.7 \times 10^{-6}/^{\circ}\text{F}$ (FHWA 2016), the CTE of PPC ranges from 7.7 to $15.9 \times 10^{-6}/^{\circ}\text{F}$ (O'Connor and Saiidi 1993a). The cracking susceptibility of PPC is also reduced by its comparatively high STS, with values of around 950 psi having been reported for some overlay mixtures (Krauss et al 2007, O'Connor and Saiidi 1993). High STS can especially limit cracking caused by bridge deck movements (Sprinkel 1983).

Application of protective overlays on concrete bridge decks has proven to be one of the most effective methods of preventing corrosive elements from penetrating bridge deck surfaces (Guthrie et al. 2005); specifically, preventing the ingress of water and chloride ions is important for reducing the corrosion of reinforcing steel in concrete, which in turn leads to concrete delamination and steel section loss. PPC is one material that is desirable as an overlay because it is long-lasting and exhibits low to negligible permeability when placed and densified correctly (Doody and Morgan 1993, Sprinkel 2003).

5.3 Procedures

The following sections describe the procedures used to prepare and test the PPC specimens that were used in this research.

5.3.1 Specimen Preparation

Specimen preparation included fabrication, milling, and heat treatment as explained in the following sections.

5.3.1.1 Fabrication

In order to evaluate a PPC material that is representative of overlays constructed in the field, the specimens tested in this research were fabricated with PPC from three actual bridge deck overlay placements in Utah. The three placements are referred to as placements A, B, and C. At each overlay placement, the material was sampled during the first pass of the paving machine at two locations. For each location, four cylindrical plastic molds having a 4-in. diameter and an 8-in. height were filled with PPC in two equal-volume lifts immediately after the

material was sampled. Based on a recommendation from a supplier's representative that specimens should receive approximately 10 rods per lift, each lift of the material was consolidated using 5, 10, 15, or 20 strokes of a 3/8-in.-diameter bull-nosed tamping rod. The number of strokes of the rod was varied among the specimens so that the effects of consolidation on the properties of PPC could be investigated. Twelve strikes of a rubber mallet were applied to the sides of the molds after placement of each lift. A small trowel held in the vertical position was then used to finish the top surfaces of the specimens using a sawing motion so as to avoid additional consolidation. After the specimens were finished, they were capped with a plastic lid and placed in an insulated container to cure. Two sets of four cylindrical specimens were cast at each bridge placement for a total of 24 test specimens. The specimens were then transported to the laboratory where they were removed from their molds and stored for a minimum of 4 weeks at a temperature of 70 to 73°F and a relative humidity of 25 to 50 percent.

5.3.1.2 Milling

Height measurements needed to determine specimen densities were difficult to perform because the bottom and top surfaces of the specimens were not completely smooth or flat. To facilitate the speed and accuracy of future measurements, specimen ends were milled to produce smooth, flat surfaces that were exactly perpendicular to the longitudinal axes of the specimens. A milling machine with a concrete grinding wheel attachment was used to remove 0.04 to 0.08 in. from each end of each specimen.

5.3.1.3 Heat Treatment

Because heat treatment can accelerate the PPC curing process (Ohama and Demura 1982), the specimens were placed in an oven at 140°F for 24 hours prior to the performance of tests involving thermal changes to ensure that they would be substantially cured before the testing. The elimination of additional curing during the testing process provided consistency for specimens that were cast at different times and prevented the test measurements from being influenced by curing effects.

5.3.2 Specimen Testing

Testing was performed to measure density, MOE, CTE, hardness, UCS, STS, RCP, and resin content, as described in the following sections. Specimens fabricated from PPC material collected at the two sampling locations at each placement and consolidated using the same effort were considered replicates of each other. The nondestructive tests, including density, MOE, CTE, and hardness, were performed on replicate specimens from both locations, and results were averaged together. However, the destructive tests were conducted on just one replicate from each placement; one replicate was subjected to UCS testing, while the other replicate was cut into smaller lengths for STS and RCP testing.

5.3.2.1 Density

For determination of specimen densities, the heights, weights, and diameters of the specimens were carefully measured. To account for potential surface variability, specimen heights were measured at four evenly-spaced locations on the top surfaces of the cylinders using a micrometer mounted on a stand. The average of the four measurements for a given specimen was considered to be the specimen height. Specimen weights were measured using a digital laboratory scale. Specimen diameters were measured at three evenly-spaced locations along the lengths of the cylinders using digital calipers, and the average of the three measurements for a given specimen was considered to be the specimen diameter. The height, weight, and diameter measurements were then used to compute the density of each specimen. The densities of the replicate specimens were averaged together, and standard deviations were computed.

5.3.2.2 MOE and CTE

MOE and CTE tests were performed simultaneously. To investigate the effects of temperature on the MOE of PPC and to determine its CTE, the heights, resonant frequencies, and weights of the specimens were measured at three different temperatures. Temperatures of 129, 72, and -22°F were selected to represent the range of temperatures likely to be experienced by a bridge deck in Utah, where the high and low temperatures were achieved using a laboratory oven and a chest freezer, respectively. For this testing, a high-accuracy linear variable differential

transformer attached to a stand was used to perform height measurements. To facilitate rapid and repeatable measurements, the base of each specimen was aligned with a mark on the base of the stand so that the height readings would be consistently made at the same location on the top surfaces of the cylinders. A free-free resonant column apparatus was used to measure resonant frequencies. The specimens were laid on their sides and acoustically isolated from the laboratory bench using polystyrene foam. An accelerometer was attached to one end of each specimen using a thin layer of modeling clay, and the other end was struck with an instrumented hammer to induce the propagation of elastic waves within the specimen. The response measured by the accelerometer was then used to determine the resonant frequency of each specimen. A digital laboratory scale was used to measure weights. All three height, resonant frequency, and weight measurements were performed in rapid succession to minimize temperature changes in the specimens that would affect the test results. For a given specimen, height readings were taken within 10 seconds of its removal from the oven or freezer. Resonant frequencies were measured immediately after specimen heights were recorded, given that resonant frequency is less sensitive to rapid temperature changes than height. Specimen weights, which are not temperature-dependent, were measured last. The MOE of each specimen was calculated using Equation 5.1:

$$E = \frac{\frac{\gamma}{32.2} \cdot (2 \cdot l \cdot f)^2}{144} \quad (5.1)$$

where E = Young's modulus, psi

γ = density of the specimen, pcf

l = length of the specimen, ft

f = resonant frequency of the specimen, Hz

The MOE values of the replicate specimens were averaged together, and standard deviations were computed. The CTE of each specimen was calculated using Equation 5.2:

$$\alpha = \frac{\left(\frac{\Delta l}{l} \right)}{\Delta T} \quad (5.2)$$

where α = CTE of the specimen, °F⁻¹

l = length of the specimen, in.

T = temperature of the specimen, °F

The CTEs of the replicate specimens were then averaged together, and standard deviations were also computed.

5.3.2.3 *Hardness*

Specimen hardness was measured using a Schmidt rebound hammer at three evenly-spaced locations on the top surfaces of the cylinders. When rebound tests are performed on PPC, the same location is commonly struck multiple times with the hammer before a reading is recorded. The first impacts of the hammer typically cause crushing of the fine aggregates on the surface of the material, which absorbs energy that would otherwise contribute to the rebound of the mass inside the hammer. However, because the top surfaces of the specimens were milled smooth, multiple hammer strikes at each location were not needed. During the testing, the specimens were held firmly in place on a clean, flat concrete floor to minimize energy loss from specimen translation or rotation. One rebound test was performed at each location, for a total of three rebound numbers per specimen. The average of the three measurements for a given specimen was considered to be the specimen rebound number. The rebound numbers of the replicate specimens were averaged together, and standard deviations were computed.

5.3.2.4 *UCS*

UCS testing was performed with a computer-controlled hydraulic press. Because they had previously been milled, the ends of the specimens were not capped prior to testing. The cylinders were loaded into the press in the vertical position and centered between the upper platen of the press and a floating base. The hydraulic press was used to apply a compressive load to the specimens at a rate of 0.05 in./min. until failure. The maximum recorded load was divided by the cross-sectional area of the given specimen to determine the UCS.

5.3.2.5 STS

STS testing was also performed with a computer-controlled hydraulic press. To facilitate specimen alignment with the longitudinal axis of the machine, parallel diametric lines bisecting both ends of the specimens were marked. The centerline of the platen on the hydraulic press was also marked. Wooden bearing strips approximately 0.125 in. thick, 1.0 in. wide, and 4 in. long were cut, and lines bisecting their widths were marked. Specimen lengths and diameters were measured using digital calipers. Specimen lengths were measured at two locations along the lines bisecting the ends of the specimens. The average of the two measurements was considered to be the specimen length. Specimen diameters lying in the plane of the bisecting lines were measured at three evenly-spaced locations along the lengths of the cylinders. The average of the three measurements was considered to be the specimen diameter. The specimens were positioned on their sides in the hydraulic press, with a wooden bearing strip being placed along the full length of the top and bottom of each specimen. The specimens were positioned such that the lines bisecting the middle of the bearing strips, the lines bisecting the specimen ends, and the centerline of the platen of the hydraulic press were all in the same plane. The centers of the specimens were also aligned with the center of the platen on the press. The hydraulic press was then used to apply a compressive load to the specimens at a rate of 0.05 in./min. until failure, and the maximum load was recorded. The STS of each specimen was then calculated using Equation 5.3:

$$STS = \frac{2 \cdot P}{\pi \cdot l \cdot d} \quad (5.3)$$

where STS = splitting tensile strength, psi

P = maximum applied load, lb

l = length of the specimen, in.

d = diameter of the specimen, in.

5.3.2.6 RCP

Prior to RCP testing, the specimens were conditioned using vacuum saturation. The specimens were placed in a pressure vessel to which a vacuum was applied for 3 hours, after

which the chamber was flooded with de-aired water until the specimens were submerged. After the specimens were submerged, the vacuum was applied to the system for another 1 hour. The vacuum was then removed, and the samples were soaked for an additional 18 hours. After the 18-hour soaking period, the specimens were placed in RCP test cells. One side of each cell was filled with an aqueous solution of 3 percent sodium chloride, and the other side was filled with an aqueous solution of 0.3 N sodium hydroxide. A 60-volt potential difference was applied across the specimens for a period of 6 hours, and the total charge passed through each specimen was measured by the RCP test apparatus.

5.3.2.7 Resin Content

Because the resin content of the specimens was not affected by the testing performed in this research, specimens used for UCS and RCP testing were later used for resin content determination. Two specimens from both sampling locations at each overlay placement were selected for resin content testing, for a total of four specimens per placement. To determine the resin contents, burn-off testing of the specimens was conducted by UDOT laboratory personnel, and the results were adjusted for aggregate weight loss, which was determined separately through burn-off testing of neat coarse and fine aggregate samples obtained during PPC placement in the field. An adjusted resin content by dry weight of aggregate was then reported for each specimen. The resin contents of the replicate specimens were averaged together, and standard deviations were computed.

5.3.3 Statistical Analysis

Using commercially available statistical software, a one-way analysis of variance (ANOVA) was performed on the results of the testing that involved two replicates to determine if the differences caused by varying levels of consolidation effort were statistically significant. A p -value of 0.05 was selected as the threshold for statistical significance (Ramsey and Schafer 2013); p -values less than or equal to 0.05 indicated that at least one level of consolidation effort was significantly different than another, while p -values greater than 0.05 indicated that insufficient evidence was available to detect significant differences among any of the levels. For test results having p -values less than or equal to 0.05, Tukey's mean separation procedure was

used to determine which levels of consolidation effort were different from each other; a threshold of 0.05 was again used for determining statistical significance (Ramsey and Schafer 2013).

5.4 Results

The following sections describe the results of the density, MOE, CTE, hardness, UCS, STS, and RCP testing at the four levels of consolidation effort used to prepare the specimens. The results of resin content testing and the statistical analysis are also included. In all of the bar charts presented in this section, the error bars span one standard deviation above and below the given average.

5.4.1 Density

The results of density testing are presented in Table 5.1, which shows density at the four levels of consolidation effort for the specimens from each bridge placement. Figure 5.1 shows a bar chart of the average density of the specimens from each placement. Differences in specimen density among the three placements are indicative of the variability inherent in the constructed material. Although all of the specimens were prepared following the same procedures, the

Table 5.1 Density by Level of Consolidation Effort

Bridge ID	Rods/Lift	Density (pcf)	
		Avg.	St. Dev.
A	5	137.6	0.1
	10	136.9	0.4
	15	137.0	0.7
	20	137.1	0.4
B	5	134.8	0.2
	10	134.7	1.7
	15	135.2	1.5
	20	134.9	1.2
C	5	133.4	0.6
	10	134.0	0.1
	15	134.4	0.1
	20	133.7	0.6

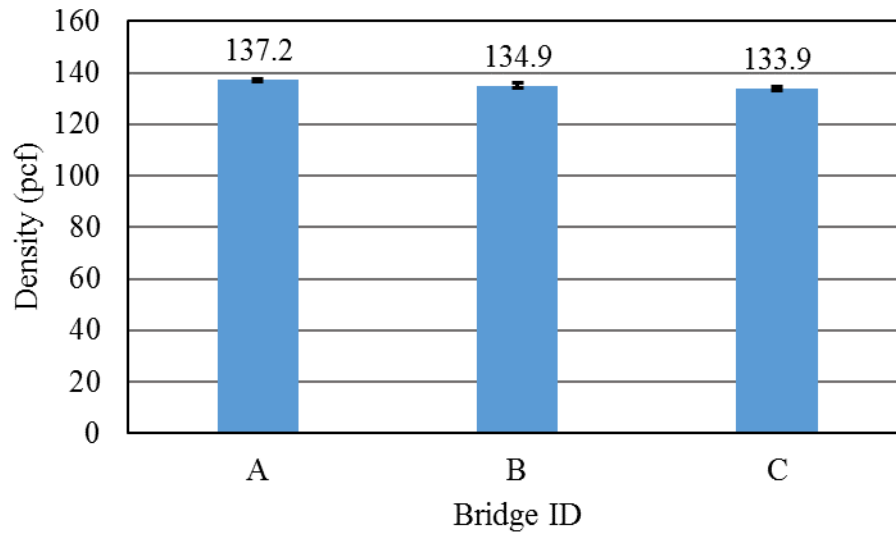


Figure 5.1 Average density.

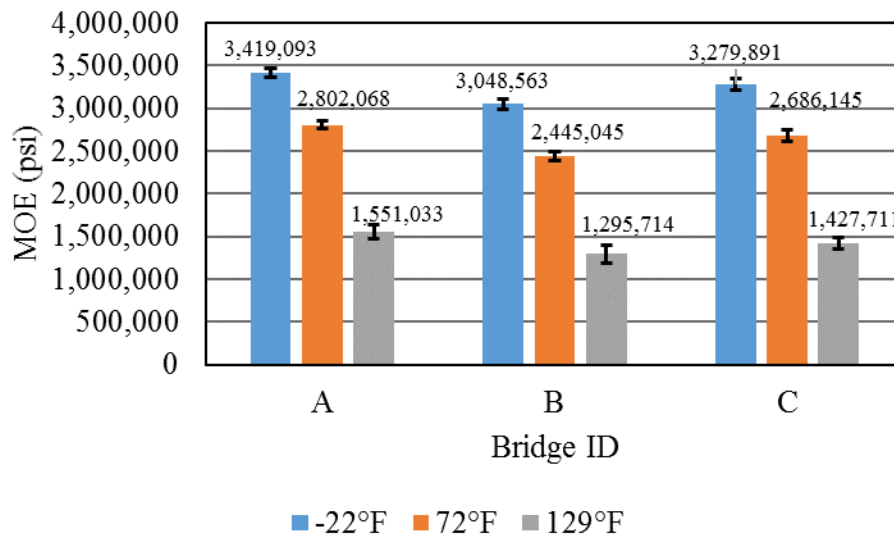
material sampled from the three different placements had average densities varying from 133.9 to 137.2 pcf. For laboratory-mixed PPC specimens, densities ranging from 117.4 to 139.8 pcf have been reported (Rao and Krishnamoorthy 1998), and one supplier gives an expected range of 134.0 to 136.0 pcf (Kwikbond 2011).

5.4.2 MOE

The results of MOE testing are presented in Table 5.2, which shows MOE at the four levels of consolidation effort at the three different testing temperatures for the specimens from each bridge placement. Figure 5.2 shows a bar chart of the average MOE of the specimens from each placement at the three different temperatures. As expected, testing temperature had a significant effect on the MOE of the specimens in this study; with average values ranging from 1.3 to 3.4 million psi, lower temperatures increased the MOE and higher temperatures decreased the MOE of the specimens relative to the values measured at room temperature. The moderate variability among the three placements is once again evident in these results. For laboratory-mixed PPC specimens tested at room temperature, MOE values ranging from 18,300 to 21,200 MPa (2.7 to 3.1 million psi) have been reported (Mantrala and Vipulanandan 1995).

Table 5.2 MOE by Level of Consolidation Effort and Temperature

Bridge ID	Rods/Lift	Average MOE (psi)					
		-22°F		72°F		129°F	
		Avg.	St. Dev.	Avg.	St. Dev.	Avg.	St. Dev.
A	5	3,413,582	13,202	2,766,883	9,918	1,492,408	73,642
	10	3,355,722	22,364	2,761,937	15,564	1,493,706	25,056
	15	3,439,579	52,928	2,815,036	17,823	1,580,875	109,599
	20	3,467,490	3,240	2,864,417	8,368	1,637,142	7,373
B	5	3,003,629	88,186	2,392,654	56,502	1,230,591	132,783
	10	3,015,911	53,580	2,418,679	39,765	1,283,154	130,247
	15	3,099,930	13,733	2,494,598	8,280	1,355,205	129,665
	20	3,074,784	5,338	2,474,247	1,430	1,313,907	89,058
C	5	3,203,863	97,235	2,632,076	89,972	1,339,156	20,662
	10	3,261,475	12,216	2,666,400	35,036	1,410,358	52,757
	15	3,351,793	51,130	2,745,456	75,256	1,481,253	36,654
	20	3,302,432	36,800	2,700,650	62,292	1,480,075	1,326

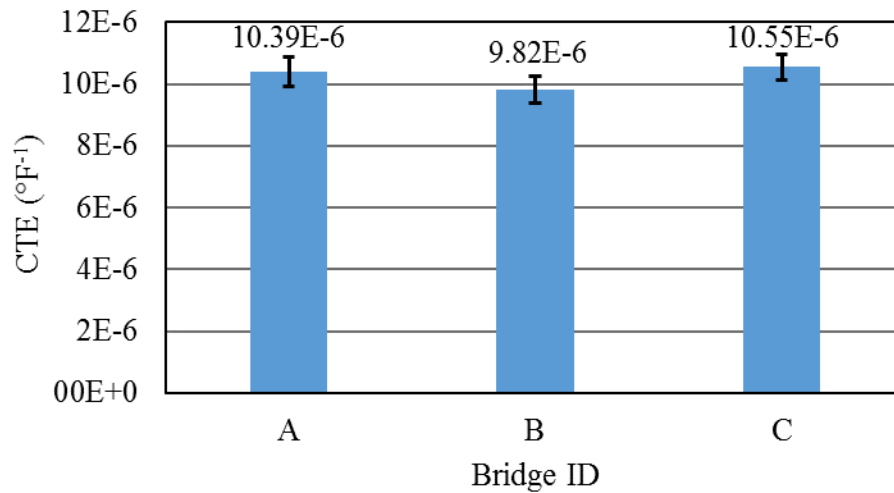
**Figure 5.2 Average MOE at three different temperatures.**

5.4.3 CTE

The results of CTE testing are presented in Table 5.3, which shows CTE at the four levels of consolidation effort for the specimens from each bridge placement. Figure 5.3 shows a bar chart of the average CTE of the specimens from each placement. Very little variability is observed in these specimens, which have average values ranging from 9.82 to $10.55 \times 10^{-6}/^{\circ}\text{F}$.

Table 5.3 CTE by Level of Consolidation Effort

Bridge ID	Rods/Lift	CTE ($^{\circ}\text{F}^{-1}$)	
		Avg.	St. Dev.
A	5	10.92E-6	863.2E-9
	10	10.31E-6	108.0E-9
	15	10.09E-6	32.4E-9
	20	10.25E-6	142.4E-9
B	5	10.26E-6	37.8E-9
	10	9.89E-6	132.6E-9
	15	9.53E-6	122.2E-9
	20	9.63E-6	862.0E-9
C	5	11.03E-6	299.0E-9
	10	10.13E-6	313.0E-9
	15	10.47E-6	244.3E-9
	20	10.57E-6	142.7E-9

**Figure 5.3 Average CTE.**

For laboratory-mixed PPC specimens, CTE values ranging from 7.7 to 15.9 x 10⁻⁶/°F have been reported (Maggenti 2001, O'Connor and Saiidi 1993).

5.4.4 Hardness

The results of hardness testing are presented in Table 5.4, which shows rebound number at the four levels of consolidation effort for the specimens from each bridge placement. Figure 5.4 shows a bar chart of the average rebound number of the specimens from each placement.

Hardness measurements performed in the shoulders of bridge placements A, B, and C at approximately the same time yielded average rebound numbers of 43, 49, and 49, respectively. By contrast, the average rebound numbers of the specimens from placements A, B, and C that were tested in the laboratory were 42, 41, and 39, respectively. These differences in measured hardness demonstrate the effect that overlay thickness has on rebound number. While both situations involved testing of the hardness of PPC placed on top of a concrete surface, specimens tested in the laboratory were approximately 10 times thicker than the overlays tested in the field.

Table 5.4 Hardness by Level of Consolidation Effort

Bridge ID	Rods/Lift	Rebound Number	
		Avg.	St. Dev.
A	5	44	2
	10	42	0
	15	41	1
	20	40	2
B	5	39	0
	10	41	1
	15	41	1
	20	42	1
C	5	40	2
	10	38	0
	15	40	1
	20	39	0

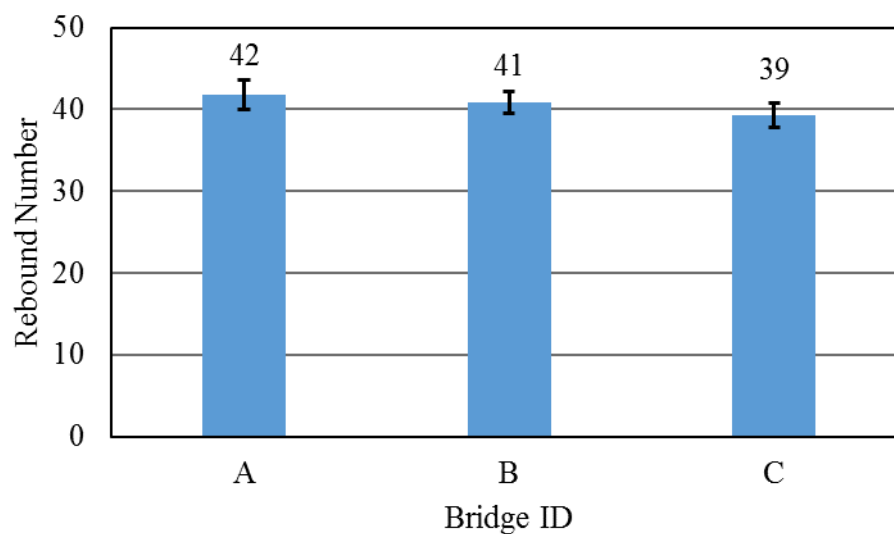


Figure 5.4 Average hardness.

5.4.5 UCS

The results of UCS testing are presented in Table 5.5, which shows UCS at the four levels of consolidation effort for the specimens from each bridge placement. Figure 5.5 shows a bar chart of the average UCS of the specimens from each placement. The UCS values of the specimens in this study are typical of PCC strengths, with average values ranging from 5,128 to 5,652 psi. For laboratory-mixed PPC specimens, UCS values ranging from 4,000 to 6,000 psi

Table 5.5 UCS by Level of Consolidation Effort

Bridge ID	Rods/Lift	UCS (psi)
A	5	5,665
	10	5,591
	15	5,659
	20	5,694
B	5	5,096
	10	5,090
	15	5,197
	20	5,128
C	5	5,349
	10	5,595
	15	5,672
	20	5,652

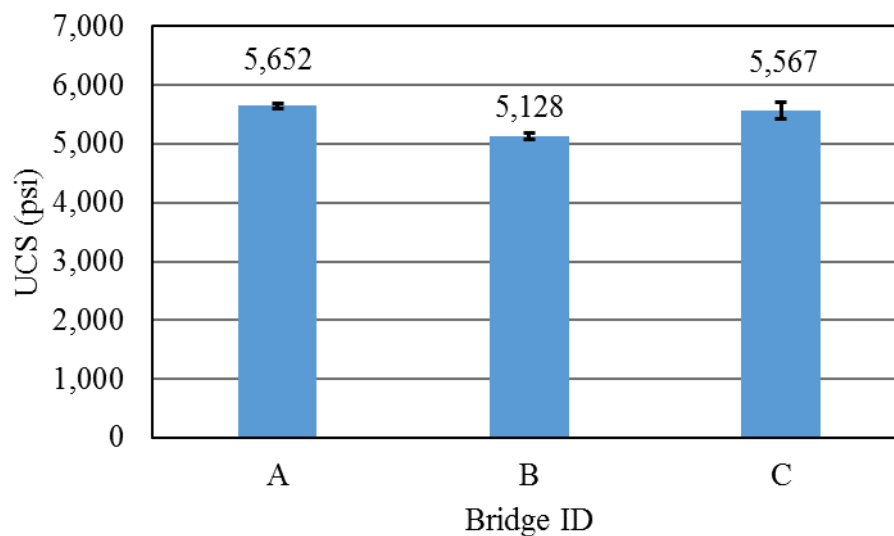


Figure 5.5 Average UCS.

within 24 hours after mixing and ultimate strengths of approximately 7,000 psi have been reported (Krauss et al. 2007, Kwikbond 2012).

5.4.6 STS

The results of STS testing are presented in Table 5.6, which shows STS at the four levels of consolidation effort for the specimens from each bridge placement. Figure 5.6 shows a bar chart of the average STS of the specimens from each placement. Although expected variability in average STS is evident among the three placements, ranging from 967 to 1,059 psi, the strengths of the specimens from within a given placement were very similar to one another. For laboratory-mixed PPC specimens, STS values ranging from 400 to 2300 psi have been reported (Krauss et al. 2007, O'Connor and Saiidi 1993). While the UCS values of the PPC specimens are typical of PCC, the STS values are approximately twice as high as would be expected for PCC with the same UCS.

Table 5.6 STS by Level of Consolidation Effort

Bridge ID	Rods/Lift	STS (psi)
A	5	1056
	10	1066
	15	1057
	20	1058
B	5	974
	10	973
	15	960
	20	962
C	5	1012
	10	1019
	15	1008
	20	976

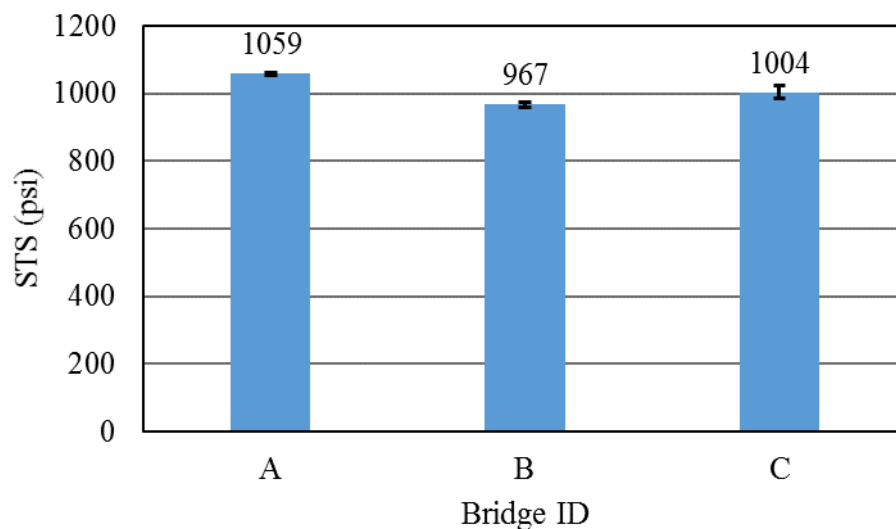


Figure 5.6 Average STS.

5.4.7 RCP

The results of RCP testing are presented in Table 5.7, which shows RCP at the four levels of consolidation effort for the specimens from each bridge placement. As expected, no charge was passed through any of the specimens throughout the duration of the test. These results confirm that intact PPC is impermeable to water and dissolved chloride ions.

Table 5.7 Charge Passed by Level of Consolidation

Bridge ID	Rods/Lift	Charge (coulombs)
A	5	0
	10	0
	15	0
	20	0
B	5	0
	10	0
	15	0
	20	0
C	5	0
	10	0
	15	0
	20	0

5.4.8 Resin Content

The results of resin content testing are presented in Table 5.8, which shows resin content for specimens from the two sampling locations at each bridge placement. Figure 5.7 shows a bar chart of the average resin content of the specimens from each placement, which ranged from 11.4 to 12.5 percent. The average resin content at each placement was therefore consistent with

Table 5.8 Resin Content

Bridge ID	Sample Location	Resin Content (%)	
		Avg.	St. Dev.
A	1	11.6	0.3
	2	11.2	0.0
B	1	12.2	0.1
	2	11.8	0.2
C	1	12.8	0.4
	2	12.2	0.2

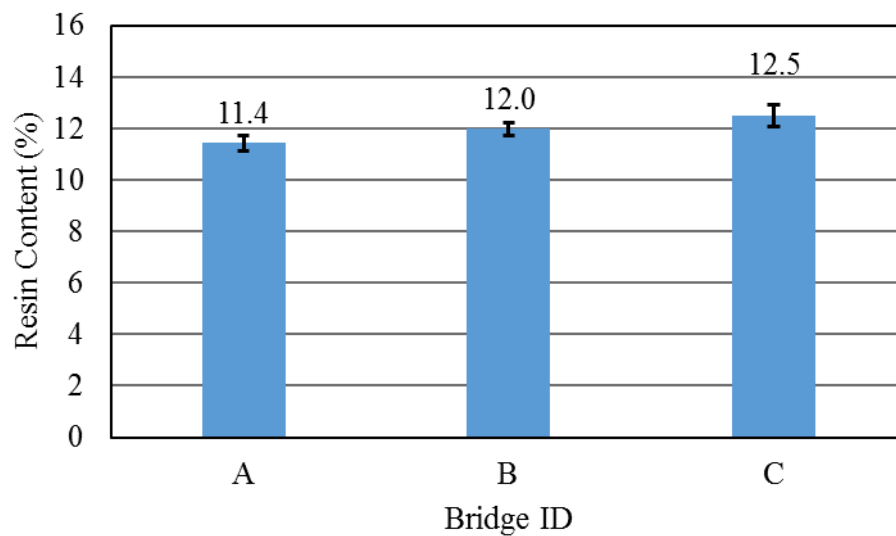


Figure 5.7 Average resin content.

the PPC mixture design specification, which indicated a target resin content of 12 ± 1 percent. For laboratory-mixed PPC specimens, resin contents ranging from 8 to 20 percent have been reported (Rao and Krishnamoorthy 1998, Vipulanandan and Paul 1993).

5.4.9 Statistical Analysis

Table 5.9 presents p -values for the results of the testing used to evaluate the effect of consolidation effort, including density, MOE, CTE, and rebound number. With only one exception, the p -values for all of the test results were well above the threshold for statistical significance. Only the p -value obtained for MOE at bridge placement A was below the threshold, and Tukey's mean separation procedure revealed that the specimens that received 5 and 10 rods per lift were both significantly different than the specimens that received 20 rods per lift; however, these differences are not considered to be practically important. While the effects of consolidating PPC specimens with 25 rods per lift were not explicitly considered in this research, the test specimens were not shown to be sensitive to the level of consolidation effort. Therefore,

Table 5.9 p -values by Level of Consolidation Effort

Placement A	p - value
Avg. Density (kg/m^3)	0.524
Avg. MOE (MPa)	0.005
Avg. CTE ($^{\circ}\text{C}^{-1}$)	0.378
Avg. Rebound Number	0.249
Placement B	p - value
Avg. Density (kg/m^3)	0.980
Avg. MOE (MPa)	0.119
Avg. CTE ($^{\circ}\text{C}^{-1}$)	0.449
Avg. Rebound Number	0.100
Placement C	p - value
Avg. Density (kg/m^3)	0.245
Avg. MOE (MPa)	0.481
Avg. CTE ($^{\circ}\text{C}^{-1}$)	0.100
Avg. Rebound Number	0.322

a standard specifying 25 rods per lift, consistent with consolidation procedures for PCC, may also be reasonable for the preparation of PPC test specimens.

5.5 Chapter Summary

The primary objectives of this research were to characterize several material properties of field-mixed PPC sampled from actual bridge deck overlay placements in Utah and compare them to properties of laboratory-mixed PPC reported in the literature. Laboratory testing was conducted on a typical PPC mixture. Properties that were measured include density, MOE, CTE, hardness, UCS, STS, RCP, and resin content. Although similar measurements of hardness and RCP are not available in the literature for comparison, the other measurements, including density, MOE, CTE, UCS, STS, and resin content values, are consistent with typical ranges cited in the literature for laboratory-mixed specimens.

A secondary objective was to quantify the effect of level of consolidation effort on the properties of PPC. The test specimens were not shown to be sensitive to level of consolidation effort within the ranges studied in this research.

6.0 CONCLUSION

6.1 Summary

Because the vast majority of PPC used in the United States is furnished by the same supplier, generally under the same or similar specifications as those used in California, the practice of relying almost exclusively on visual inspection for QA has become widespread. For this main reason, the literature is generally absent of field and laboratory test results obtained on field-mixed PPC. Therefore, with increasing use of PPC overlays throughout the United States, additional research on PPC construction, QA, performance, and properties was needed. To address these deficiencies, five objectives were developed for this research:

1. Compile a synthesis of information about PPC from the literature.
2. Conduct a scanning tour to observe PPC construction, inspect in-service PPC overlays, and discuss topics related to PPC.
3. Revise the existing UDOT PPC specification.
4. Document a PPC field demonstration project.
5. Perform laboratory characterization of the material properties of field-mixed PPC.

The research therefore included a literature review, a scanning tour, specification revisions, field testing, and laboratory experimentation.

6.2 Findings and Recommendations

Findings and recommendations from the scanning tour, field testing, and laboratory experimentation are summarized in the following sections.

6.2.1 Scanning Tour

While the scanning tour yielded valuable information about the construction, QA, and performance of PPC, discussions with Caltrans personnel also led to the identification of potential improvements to PPC laboratory and field testing procedures of particular interest to UDOT. Recommendations regarding MOE, bond beam, resin demand, aggregate quality, set

time, compaction, hardness, bond strength, and skid resistance testing are presented in this section.

MOE is an important property of PPC overlays because stiffness affects both cracking potential and stresses that develop at the bond line between the overlay and the substrate (Sprinkel 1983). Although Caltrans specifies low modulus values for PPC overlays, Caltrans does not typically measure the MOE, and actual values of the mixtures most commonly in use are not well defined. MOE testing of commonly used PPC mixtures is an area that warrants further study and possible implementation into QA specifications.

Although bond strength is an important property, one practice that may be less effective is the testing of PPC bond beams. PPC bond beams are expensive and time-consuming to produce and test. They are also not representative of actual constructed overlays because the bond line is not treated with primer. In addition, the beams sometimes fail to produce adequate bond strengths even when silane is present in the resin. Alternative methods for measuring bond strength and assessing silane content could be developed that would be less expensive and less time-consuming and would also yield more relevant results. Transportation agencies should consider removing bond beam production and testing procedures from PPC specifications.

In contrast with bond beam testing, the resin demand test for aggregates is inexpensive, quick, and easy to perform. A resin demand test should be specified so that the resin demand for different aggregate materials can be determined. Application of this test would enable determination of an appropriate resin content for a given aggregate and avoid indiscriminate application of a single resin content to all aggregate sources.

Regarding aggregate quality, Caltrans's primary PPC supplier has historically provided high-quality aggregates, so Caltrans does not perform durability testing such as abrasion or polish testing on PPC aggregates. However, these tests could be useful for aggregates from different sources. Cleanliness and sand equivalence tests could also be specified.

Set time is an important property of PPC mixtures because it governs the timing of overlay placement operations in the field. Caltrans laboratory personnel have observed that mixtures submitted by some manufacturers have occasionally exhibited setting problems. These

mixtures remain sticky to the touch long after specified set times. Laboratory personnel recommend that specifications should allow rejection of mixtures that fail to set within specified time limits.

Proper compaction directly affects the quality of PPC overlays. Caltrans job specifications sometimes require the use of a nuclear density gauge for measuring PPC compaction on trial slabs. Adequate compaction is characterized by a thin film of resin flushing to the surface of a PPC overlay as determined by visual inspection. Performing compaction testing with a nuclear density gauge may not be necessary since compaction can be assessed based on visual inspection alone.

Although these tests are not required by Caltrans, Schmidt hammer and pull-off testing could also be applied to measure hardness and bond strength, respectively, on trial slabs and overlays for QA purposes. These tests are quick and easy to perform, and they provide objective results that relate directly to overlay quality.

Skid resistance is a critical property of PPC overlays that affects driver safety. The limited availability of drop wheels for measuring skid resistance has prompted Caltrans to consider the use of dynamic friction testers; however, these testers are expensive. One alternative is the British pendulum, which provides instant and repeatable results that can be easily correlated with skid numbers. It is also relatively inexpensive, quick, and easy to perform. Agencies should consider the use of the British pendulum as an alternative for measuring skid resistance.

6.2.2 Field Testing

The pilot project yielded valuable information about the construction, QA, and performance of PPC overlays. In particular, several potential improvements to construction and QA procedures were identified. Recommendations regarding hardness testing, skid resistance testing, patching, and surface preparation are presented in this section.

A standard practice is to record the highest of three consecutive rebound numbers obtained at a given location. However, test results from the pilot project suggest that four tests are more likely to achieve the actual maximum value than three tests. When measuring overlay

hardness, agencies should consider recording the highest of four consecutive rebound numbers obtained at a given location.

Skid resistance is often measured using a skid trailer. However, skid trailer testing cannot be performed until overlay operations are completely finished, and it requires distances greater than the span lengths of many bridge decks. In contrast, the BPT provides localized measurements of skid resistance that are rapid and repeatable, can be obtained as soon as the PPC material achieves final set, and are expected to correlate with the results of skid trailer testing. Agencies should consider the use of the British pendulum for measuring skid resistance.

Although PPC can be used as a patching material in some instances, replacing structural deck concrete with a structural patching product is usually desirable. A rapid-setting cementitious material was used to patch the bridge decks that were subjected to hydrodemolition during the pilot project. Although the patches had not fully cured at the time the PPC overlays were placed, subsequent impact-echo testing indicated that intact bonding was nonetheless achieved. Therefore, agencies may specify rapid-setting patch material prior to PPC overlay placements on projects similar to the pilot project studied in this research.

While the overlay on a typical deck has a uniform thickness, the overlay on a hydrodemolished deck has a highly variable thickness because of the peaks and valleys in the profile of the substrate. Because the peaks, in particular, can perforate the overlay and subsequently lead to cracking when original elevations are maintained, agencies should consider first milling the surface of the deck to a depth equal to the specified overlay thickness, which would ensure a more uniform PPC overlay thickness while still allowing for removal of unsound concrete below that depth using hydrodemolition.

6.2.3 Laboratory Experimentation

The primary objectives of the laboratory experimentation were to characterize several material properties of field-mixed PPC sampled from actual bridge deck overlay placements in Utah and compare them to properties of laboratory-mixed PPC reported in the literature. Although similar measurements of hardness and RCP are not available in the literature for comparison, the other measurements, including density, MOE, CTE, UCS, STS, and resin

content values, are consistent with typical ranges cited in the literature. A secondary objective was to quantify the level of consolidation effort on the properties of PPC. In the statistical analysis, the test specimens were not shown to be sensitive to level of consolidation effort within the ranges studied in this research. While the effects of consolidating PPC specimens with 25 rods per lift were not explicitly considered in this research, the test specimens were not shown to be sensitive to the level of consolidation effort. Therefore, a standard specifying 25 rods per lift, consistent with consolidation procedures for PCC, may also be reasonable for the preparation of PPC test specimens.

6.3 Main Contributions

This research has substantially advanced the body of knowledge on PPC bridge deck overlays through field and laboratory observation and experimentation. As a result of the literature review, a synthesis of existing information about PPC was compiled. A scanning tour of PPC overlays on bridge decks in California was then conducted as a first step toward addressing deficiencies identified in the literature review. Findings and recommendations from the scanning tour were documented, and substantial changes to the existing UDOT PPC specification were made. A field demonstration project in Utah was then developed to evaluate specific aspects of construction, QA, and performance of PPC overlays placed on concrete bridge decks under the new specification. The findings and recommendations from the field demonstration project, which included testing not previously performed on PPC overlays, were subsequently documented. The pilot project also provided the opportunity to collect field-mixed PPC for laboratory testing. The specimens obtained during the field testing were used to characterize several material properties of field-mixed PPC and compare them to properties of laboratory-mixed PPC reported in the literature. In summary, with increasing use of PPC overlays throughout the United States, this research provided information on PPC construction, QA, performance, and material properties that is expected to be highly valuable to other state DOTs implementing the use of PPC overlays on bridge decks.

REFERENCES

- Abdel-Fattah, H., and El-Hawary, M. (1999). "Flexural behavior of polymer concrete." *Construction and Building Materials*, 13(5), 253-262.
- Alaska Department of Transportation and Public Facilities (ADOT&PF). (2007). *Parks Highway Susitna River Bridge Repairs, BH-0A4-2(6)/5847*. Alaska Department of Transportation and Public Facilities, Anchorage, AK.
- Anderson, K., Russell, M., Littleton, K., McKernan, D., Uhlmeier, J., Weston, J., and Simonson, C. (2013). Polyester Polymer Concrete Overlay. Materials Laboratory, Washington State Department of Transportation, Turnwater, WA.
- Argyle, H. (2014). "Sensitivity of electrochemical impedance spectroscopy measurements to concrete bridge deck properties." M.S. Thesis. Department of Civil and Environmental Engineering, Brigham Young University, Provo, UT.
- California Department of Transportation (Caltrans). (2018). *Polyester Concrete Overlays*. Standard Specifications, Section 60-3.04B (1). California Department of Transportation, Sacramento, CA.
- Callister, W. (2001). *Fundamentals of Materials Science and Engineering*, Fifth Edition. John Wiley & Sons, Inc., New York, NY.
- Colorado Department of Transportation (CDOT). (2014). *Thin Bonded Overlay (Polyester Concrete)*. Section 519. Colorado Department of Transportation, Denver, CO.
- Delaware Department of Transportation (DelDOT). (2012). *Polyester Polymer Concrete Overlay*. Section 602733. Delaware Department of Transportation, Dover, DE.
- Doody, M., and Morgan, R. (1993). Polymer-Concrete Bridge-Deck Overlays. Special Report 110. New York State Department of Transportation, Albany, New York.
- El-Hawary, M., and Abdel-Fattah, H. (2000). "Temperature effect on the mechanical behavior of resin concrete." *Construction and Building Materials*, 14(6), 317-323.

- Federal Highway Administration (FHWA). (2016). "Thermal Coefficient of Portland Cement Concrete." <<https://www.fhwa.dot.gov> > (Oct. 23, 2018).
- Ferreira, A., Tavares, C., and Ribeiro, C. (2000). "Flexural properties of polyester resin concretes." *Journal of Polymer Engineering*, 20(6), 459-468.
- Fontana, J., and Bartholomew, J. (1980). "The use of concrete polymer materials in the transportation industry." *American Concrete Institute Committee 548 Symposium*, Puerto Rico.
- Fowler, D. (1999). "Polymers in concrete: A vision for the 21st century." *Cement and Concrete Composites*, 21(5), 449-452.
- Garbacz, A. and Garboczi, E. (2003). Ultrasonic Evaluation Methods Applicable to Polymer Concrete Composites. NISTIR 6975. National Institute of Standards and Technology, Gaithersburg, MD.
- Glauz, D., and Maggenti, R. (1993). "Bonded polyester concrete overlays used in California." *Structural Engineering in Natural Hazards Mitigation*, ASCE, Irvine, CA, 1002-1007.
- Gorninski, J., Molin, D., and Kazmierczak, C. (2004). "Study of the modulus of elasticity of polymer concrete compounds and comparative assessment of polymer concrete and portland cement concrete." *Cement and Concrete Research*, 34(11), 2091-2095.
- Gorninski, J., Molin, D., and Kazmierczak, C. (2007). "Comparative assessment of isophthalic and orthophthalic polyester polymer concrete: different costs, similar mechanical properties and durability." *Construction and Building Materials*, 21(3), 546-555.
- Guthrie, W., Larsen, J., Baxter, J., and Mazzeo, B. (2019). "Automated air-coupled impact-echo testing of a concrete bridge deck from a continuously moving platform." *Journal of Nondestructive Evaluation*, 38(32).
- Guthrie, W.S., and Linford, E.T. (2006). "Development of an Index for Concrete Bridge Deck Management in Utah." Report UT-06.05, Utah Department of Transportation, Salt Lake City, UT.

- Guthrie, W. S., Nelsen, T., and Ross, L.A. (2005). Performance of Concrete Bridge Deck Surface Treatments. Report UT-05.05. Utah Department of Transportation, Salt Lake City, UT.
- Haddad, H., and Kobaisi, M. (2013). "Influence of moisture content on the thermal and mechanical properties and curing behavior of polymeric matrix and polymer concrete composite." *Materials and Design*, 49, 850-856.
- Hema, J., Guthrie, W.S., and Fonseca, F.S. (2004). "Concrete Bridge Deck Condition Assessment and Improvement Strategies." Report UT-04.16, Utah Department of Transportation, Salt Lake City, UT.
- Hristova, J. (1982). "Behavior of polyester polymer concrete at temperature up to 70°C." *Proceedings of the Third International Congress on Polymers in Concrete*, College of Engineering, Nihon University, Koriyama, Japan, 1151-1160.
- International Concrete Repair Institute (ICRI). (2014). *Guide for the preparation of concrete surfaces for repair using hydrodemolition methods*, Guideline No. 310.3R-2014, Rosemont, IL.
- Jones, S., Martys, N., Lu, Y., and Bentz, D. (2015). "Simulation studies of methods to delay corrosion and increase service life for cracked concrete exposed to chlorides." *Cement and Concrete Composites*, 58(1), 59-69.
- Knab, L. (1969). "Polyester concrete: Load rate variance." *Highway Research Record*, 287, 19-31.
- Kolluru, S., Popovics, J., and Shah, S. (2000). "Determining elastic properties of concrete using vibrational resonance frequencies of standard test cylinders." *Cement Concrete and Aggregates*, 22(2).
- Krauss, P. (1988a). "Polymer concrete helps to keep the traffic moving, with minimal maintenance." *Modern Plastics*, 65(12), 92.

- Krauss, P. (1988b). "Status of polyester-styrene resin concrete bridge deck and highway overlays in California." *43rd Annual Conference*, Composites Institute, The Society of the Plastics Industry, Inc., New York, 1-7.
- Krauss, P., Klail, A., and Maggenti, R. (2007). "Development history, specifications, and case studies of polyester polymer concrete for bridge deck protection." *24th Annual International Bridge Conference*, Engineers Society of Western Pennsylvania, Pittsburgh, PA.
- Kwikbond. (2011a). "Product Data Sheet: PPC- 1121." <www.kwikbondpolymers.com> (February 24, 2015).
- Kwikbond. (2011b). "Product Data Sheet: KBP 204." <www.kwikbondpolymers.com> (February 24, 2015).
- Kwikbond. (2012). "PPC 1121 Polyester Polymer Concrete." <www.kwikbondpolymers.com> (February 24, 2015).
- Larsen, J., McElderry, J., Baxter, J., Guthrie, W., and Mazzeo, B. (2020). "Automated sounding for concrete bridge deck inspection through a multi-channel, continuously moving platform." *NDT & E International*, 109.
- Maass, J. (2003). "How polyester polymer concrete highway and bridge deck overlays became 'State of the Art.'" *ACI Special Publication 214: Polymers in Concrete: The First Thirty Years*, 214, 39-50.
- Maggenti, R. (2001). Polyester Concrete in Bridge Deck Overlays Report. California Department of Transportation, Sacramento, CA.
- Maksimov, R., Jirgens, L., Jansons, J., and Plume, E. (1999). "Mechanical properties of polyester polymer-concrete." *Mechanics of Composite Materials*, 35(2), 99-110.
- Mani, P., Gupta, A., and Krishnamoorthy, S. (1987). "Comparative study of epoxy and polyester resin-based polymer concretes." *International Journal of Adhesion and Adhesives*, 7(3), 157-163.

- Mantrala, S., and Vipulanandan, C. (1995). "Nondestructive evaluation of polyester polymer concrete." *ACI Materials Journal*, 92(6), 660-668.
- Mazzeo, B., and Guthrie, W.S. (2019). Vertical Electrical Impedance Scanner for Concrete Bridge Deck Assessment without Direct Rebar Attachment. Final Report for NCHRP IDEA Project 202. Transportation Research Board, Washington, DC.
- McCormac, J. and Brown, R. (2014). *Design of Reinforced Concrete*, Ninth Edition. John Wiley & Sons, Inc., Hoboken, NJ.
- Mebarkia, S., and Vipulanandan, C. (1995). "Mechanical properties and water diffusion in polyester polymer concrete." *Journal of Engineering Mechanics*, 121(12), 1359-1365.
- Meggers, D. (2015). "The Kansas experience with polymer concrete bridge deck overlays." TRB Annual Meeting, Transportation Research Board of the National Academies, Washington, DC.
- Mindess, S., Young, J., and Darwin, D. (2003). *Concrete*, Second Edition. Prentice Hall, Upper Saddle River, NJ.
- Momber, A. W. (2005). *Hydrodemolition of concrete surfaces and reinforced concrete structures*, Aachen University, Aachen, Germany.
- Montana Department of Transportation (MDT). (2014). Experimental Projects Construction Report, Kwik Bond 1121 Polyester Polymer Concrete (PPC) Overlay. Research Programs, Montana Department of Transportation, Helena, MT.
- National Cooperative Highway Research Program (NCHRP). (2011). *Long-term performance of polymer concrete for bridge decks*. NCHRP Synthesis 423, Transportation Research Board, Washington, D.C.
- Nevada Department of Transportation (NDOT). (2019). *Polymer Concrete*. Section 496. Nevada Department of Transportation, Carson City, NV.

- New York State Department of Transportation (NYSDOT). (2019). *Polymer Overlay Wearing Surface for Structural Slabs (PPC)*. Item 584.40000009. New York State Department of Transportation, Albany, NY.
- Nizamoff, D., and Hanson, M. (2015). “Rehabilitation of Bridge I-585 on Augustine Cutoff.” TRB Annual Meeting, Transportation Research Board of the National Academies, Washington, DC.
- North Carolina Department of Transportation (NCDOT). (2016). *Polyester Polymer Concrete Bridge Deck Overlay (Special)*. Contract and Contract Bonds for Contract No. C203818. North Carolina Department of Transportation, Raleigh, NC.
- O’Connor, D., and Saiidi, M. (1993a). “Compatibility of polyester-styrene polymer concrete overlays with portland cement concrete bridge decks.” *ACI Materials Journal*, 90(1), 59-68.
- O’Connor, D., and Saiidi, M. (1993b). “Polyester concrete for bridge deck overlays.” *Concrete International*, 15(12), 36-39.
- Ohama, Y., and Demura, K. (1982). “Relation between curing conditions and compressive strength of polyester resin concrete.” *The International Journal of Cement Composites and Lightweight Concrete*, 4(4), 241-244.
- Ohama, Y., Sugi, M., and Hamatsu, M. (1986). “Freeze-thaw durability of polyester concrete made with wet aggregates.” *Proceedings of the Twentieth Japan Congress on Materials Research*, The Society of Materials Science, Japan, Kyoto, Japan, 167-170.
- Patnaik, A., and Baah, P. (2015). *Cracking behavior of structural slab bridge decks*, Report No. FHWA/OH-2015/4, Ohio Department of Transportation, Columbus, OH.
- Ramsey, F., and Schafer, D. (2013). *The Statistical Sleuth*, Third Edition. Brooks/Cole, Boston, MA.

- Rao, V., and Krishnamoorthy, S. (1998). "Influence of resin and microfiller proportions on strength, density, and setting shrinkage of polyester polymer concrete." *ACI Structural Journal*, 95(2), 153-162.
- Ribeiro, M., Nóvoa, P., Ferreira, A., and Marques, A. (2004). "Flexural performance of polyester and epoxy polymer mortars under severe thermal conditions." *Cement and Concrete Composites*, 26(7), 803-809.
- Ribeiro, M., Reis, J., Ferreira, A., and Marques, A. (2003). "Thermal expansion of epoxy and polyester polymer mortars—plain mortars and fibre-reinforced mortars." *Polymer Testing*, 22(8), 849-857.
- Robles, M., Galan, S., and Aguilar, R. (2009). "Durability of polyester polymer concrete under varying temperature and moisture." *Excellence in Concrete Construction Through Innovation*, Taylor and Francis Group, London.
- Roper, E. (2018). "Chloride concentration and blow-through analysis for concrete bridge decks rehabilitated using hydro-demolition." M.S. Thesis. Department of Civil and Environmental Engineering, Brigham Young University, Provo, UT.
- San-José, J., Vegas, I., and Ferreira, A. (2005). "Reinforced polymer concrete: Physical properties of the matrix and static/dynamic bond behaviour." *Cement and Concrete Composites*, 27(9), 934-944.
- Smith, A. (1991). "Overlaying concrete bridge decks with polymer concrete." *Concrete Construction*, < <http://www.concreteconstruction.net>> (Mar. 7, 2016).
- Sprinkel, M. (1983). "Thermal compatibility of thin polymer-concrete overlays." *Transportation Research Record*, 899, 64-73.
- Sprinkel, M. (1993). "Polymer concrete bridge overlays." *Transportation Research Record*, 1392, 107-116.
- Sprinkel, M. (1997). "Nineteen year performance of polymer concrete bridge." *ACI Special Publication*, 169, 42-74.

- Sprinkel, M. (2003). "Twenty-five-year experience with polymer concrete bridge deck overlays." *ACI Special Publication 214: Polymers in Concrete: The First Thirty Years*, 214, 51-62.
- Sprinkel, M., Sellars, A., and Weyers, R. (1993). *Concrete bridge protection and rehabilitation: Chemical and physical techniques*. SHRP-S-344, Strategic Highway Research Program, Washington, D.C.
- Stevens, R., and Guthrie, W.S. (2020). "Scanning tour of polyester polymer concrete overlays on bridge decks in California." *2020 Tran-SET Conference*, Transportation Consortium of South-Central States, Baton Rouge, LA.
- Tarricone, P. (1992). "Overlays on deck." *Civil Engineering*, (62), 42-45.
- Utah Department of Transportation (UDOT). (2017). *Polyester Concrete Overlay Specification*. Special Provision, Section 03373S. Utah Department of Transportation, Salt Lake City, UT.
- Vipulanandan, C., and Dharmarajan, N. (1987). "Flexural behavior of polyester polymer concrete." *Cement and Concrete Research*, 17(1), 219-230.
- Vipulanandan, C., and Paul, E. (1990). "Performance of epoxy and polyester polymer concrete." *ACI Materials Journal*, 87(3), 241-251.
- Vipulanandan, C., and Paul, E. (1993). "Characterization of polyester polymer and polymer concrete." *Journal of Materials in Civil Engineering*, 5(1), 62-82.

APPENDIX A: REVISED UDOT PPC SPECIFICATION

October 19, 2017

SPECIAL PROVISION

**PROJECT #
PIN #**

SECTION 03373S

POLYESTER CONCRETE OVERLAY

Add Section 03373.

PART 1 GENERAL

1.1 SECTION INCLUDES

- A. A polyester concrete overlay system applied to concrete bridge decks and approach slabs.

1.2 RELATED SECTIONS

- A. Section 01721: Survey

1.3 REFERENCES

- A. AASHTO T 27: Sieve Analysis of Fine and Coarse Aggregates
- B. AASHTO T 84: Specific Gravity and Absorption of Fine Aggregate
- C. AASHTO T 85: Specific Gravity and Absorption of Coarse Aggregate
- D. AASHTO T 112: Clay Lumps and Friable Particles in Aggregate
- E. AASHTO T 255: Total Evaporable Moisture Content of Aggregate by Drying
- F. AASHTO T 308: Determining the Asphalt Binder Content of Hot Mix Asphalt (HMA) by the Ignition Method

- G. AASHTO T 335: Determining the Percentage of Fracture in Coarse Aggregate
- H. ASTM C 469: Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression
- I. ASTM C 805: Rebound Number of Hardened Concrete
- J. ASTM C 1583: Tensile Strength of Concrete Surfaces and the Bond Strength or Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull-off Method)
- K. ASTM D 323: Vapor Pressure of Petroleum Products (Reid Method)
- L. ASTM D 618: Conditioning Plastics for Testing
- M. ASTM D 638: Tensile Properties of Plastics
- N. ASTM D 1475: Density of Liquid Coatings, Inks, and Related Products
- O. ASTM D 2196: Rheological Properties of Non-Newtonian Materials by Rotational Viscometer
- P. ASTM D 2369: Volatile Content of Coatings
- Q. ASTM D 3278: Flash Point of Liquids by Small Scale Closed-Cup Apparatus
- R. ASTM D 4285: Indicating Oil or Water in Compressed Air
- S. ASTM E 303: Measuring Surface Frictional Properties Using the British Pendulum Tester
- T. California Test (CT) 550: Method of Test for Surface Abrasion Resistance of Concrete Specimens
- U. California Test (CT) 551: Determining Suitability of Materials for Overlayment and Repair of Portland Cement Concrete Pavement and Structures

1.4 DEFINITIONS

- A. Primer – A preparatory coat that bonds the polyester concrete to the receiving concrete substrate.

- B. Polyester Concrete – A type of concrete that uses polyester polymer resin in place of cement as a binder.
- C. Overlay – A polyester concrete overlay system consisting of a high molecular weight methacrylate (HMWM) resin primer, polyester concrete, and finishing sand that are fully compatible with one another and the receiving concrete substrate.
- D. Provider – The manufacturer furnishing the polyester concrete overlay system.
- E. Installer – The Contractor or subcontractor preparing the receiving concrete substrate surfaces and installing and finishing the polyester concrete overlay system.
- F. Initial Set Time – The number of minutes between the time the catalyst is added to the resin, when mixing the polyester concrete, and the time that the in-place polyester concrete cannot be deformed when pressed with a finger, indicating that the polyester resin binder is no longer in a liquid state.
- G. Final Set Time – The number of minutes between the time the catalyst is added to the resin, when mixing the polyester concrete, and the time that the in-place polyester concrete achieves a Schmidt rebound number of at least 25.

1.5 SUBMITTALS

- A. Provider Qualifications for review before ordering materials. Include at least the following:
 - 1. The company name.
 - 2. The name, phone number, and documented experience of the Provider's technical support representative.
 - 3. List of at least 15 projects of similar size, scope, and climatic conditions completed in the last 5 years in which the overlay from the Provider has been used with satisfactory performance. List the following for each project:
 - a. Project name, bridge locations (state, routes, and bridge identifiers), owner, scope of work, and approximate date of project opening to traffic.
 - b. The overlay quantities, components, mix proportions, structural pothole patching quantities and material type, application methods, and equipment used.
 - c. Two owner/agent references and their contact information (phone and email).

- 1) Satisfactory references are those responsible for oversight or inspection of the project.
- B. Installer Qualifications for review before ordering materials.
1. Include at least the following when a continuous mixer and automatic paving and finishing equipment are used:
 - a. List of at least 10 projects of similar size and scope completed in the last 5 years in which the Installer's superintendent and the Installer's continuous mixer operator have, in these roles, placed and finished polyester concrete overlay for Caltrans and to Caltrans standards with satisfactory performance. Thin bonded polymer overlay installations do not qualify. List the following for each project:
 - 1) Project name, bridge locations (state, routes, and bridge identifiers), owner, scope of work, and approximate date of project opening to traffic.
 - 2) The polyester concrete overlay quantities, structural pothole patching material type and quantities, application methods, and equipment used.
 - 3) Two owner/agent references and their contact information (phone and email).
 - a) Satisfactory references are those responsible for oversight or inspection of the project.
 - 4) The names and documented experience of the Installer's superintendent and continuous mixer operator.
 2. Include at least the following when mechanical mixers and alternative concrete paving and finishing equipment are used:
 - a. List of at least 10 projects of similar size and scope completed in the last 5 years in which the Installer has placed and finished cast-in-place bridge deck concrete or polyester concrete overlay to Department standards with satisfactory performance. Thin bonded polymer overlay installations do not qualify. List the following for each project:
 - 1) Project name, bridge locations (state, routes, and bridge identifiers), owner, scope of work, and approximate date of project opening to traffic.
 - 2) The name of installed system (cast-in-place concrete deck or polyester concrete overlay system), deck or overlay quantities, structural pothole patching material type and quantities, application methods, and equipment used.
 - 3) Two owner/agent references and their contact information (phone and email).
 - a) Satisfactory references are those responsible for the oversight or inspection on the project.

C. Materials

1. Submit the following for review before ordering materials:
 - a. Product Data Sheets and manufacturer's recommended installation instructions for all overlay components.
 - b. Material Safety Data Sheets for all overlay components.
 - c. The Provider's certification stating that the Provider is the sole provider of all components of the polyester concrete overlay system and that all components:
 - 1) Comply with the requirements in this Section.
 - 2) Are fully compatible with one another.
 - 3) Have been used on projects identified in the Provider qualifications.
 - d. The Installer's certification, with the Provider's written concurrence, that the overlay is fully compatible with the proposed structural pothole patching materials.
2. Representative samples of material for components of the overlay system for verification when requested by the Engineer.
 - a. 1 gal each of HMWM resin primer and polyester resin binder.
 - b. Catalysts, promoters, and other additives in quantities that are equivalent to the amount used in 1 gal of HMWM resin primer or polyester resin binder, as applicable.
 - c. 50 lb of each dry component.
3. Certificate of Compliance for properties of polyester concrete overlay system components (HMWM resin primer, polyester resin binder, aggregate, and finishing sand) listed in Tables 1 to 5 of this Section.
 - a. Include test results from an independent nationally recognized laboratory for testing required in this Section.
 - b. Each lot of polyester resin binder must be tested and certified.
 - c. Tests must be performed and certification must be provided within the one-year period before the overlay installation unless otherwise specified.

D. An Overlay Placement Plan for review before beginning the overlay test section placement. Include the following:

1. Schedule of overlay work and testing for each bridge.
2. Description of materials and processes for cleaning and preparing the bridge deck and approach slabs.
3. Description of equipment for applying HMWM resin primer.
4. Description of equipment for measuring, mixing, placing, and finishing the Overlay.
5. Method for grade control for finished surface.
6. Method for isolating expansion joints, reestablishing working joints as shown, and protecting drains in the deck and approach slabs.
7. Expected initial and final set times for polyester concrete.

8. Storage and handling of HMWM resin and polyester concrete (polyester resin binder and aggregates).
 9. Disposal of excess HMWM resin, polyester concrete, and containers.
- E. A Public Safety Plan for review before beginning the overlay test section placement. Include the following:
1. Materials, equipment, and methods to be used.
 2. Potential health, environmental, and safety risks.
 3. Provider's safety requirements.
 4. Precautions that will be taken by personnel performing or inspecting the work.
 5. Safety monitoring plan.
- F. Working Drawings for review. Include at least the following for each bridge:
1. Detailed drawings showing
 - a. Phasing and sequence of overlay placement compatible with traffic phasing
 - b. Survey and design data at each survey point corresponding to cross-sections with intervals of no more than 10 ft along the longitudinal edges of each phase of overlay placement, along lane lines, and at grade breaks, including:
 - 1) Station and offset (from pre-overlay survey)
 - 2) Top of concrete elevation (from pre-overlay survey)
 - 3) Top of overlay elevation
 - 4) Overlay thickness at each survey point.
 - c. Grind areas from contract plans
 - d. Necessary grade corrections and additional grind areas discovered as a result of the pre-overlay survey
 - e. Procedures and details for varying the depth of the temporary forms that are used to form the longitudinal edges of phases when a variable depth overlay is shown and equipment without automatic grade control capabilities is allowed.
 2. Estimated Overlay Quantity
 - a. The estimated overlay quantity is the difference between the existing top of concrete surface (from the pre-overlay survey) and the final top of overlay elevations shown.
 - b. Determine the estimated overlay quantity in cubic feet using the end section area method based on sections taken at 10 ft intervals along the longitudinal edges of each phase and along lane lines.
 3. Pre-overlay survey data.
 4. Estimated overlay quantity calculations.

- G. Continuous Mixer Printouts
 - 1. Furnish recording of aggregate volumes and the corresponding resin volumes at the end of each work shift.
- H. Acceptance Testing Results
 - 1. Include results of acceptance testing required in this Section, Article 1.6.
- I. A Warranty Letter before physical completion stating that the Contractor guarantees the overlay against material and installation defects for a period of 5 years.
 - 1. The guarantee period begins on the date of physical completion.
 - 2. Include in the letter:
 - a. State Project Designation
 - b. State Project Name
 - c. State Structure Numbers
 - d. Contractor, Provider, and Installer names
 - 3. Defects (performance failures) include:
 - a. Spalling: Broken or missing pieces of overlay due to material degradation.
 - b. Scaling: Visible, exposed, rough surface texture resulting from a loss of aggregate or resin.
 - c. Delamination: Visible or audible debonding of the overlay at the interface between the overlay and the concrete substrate.
 - d. Cracking: A visible crack not reflected from a crack in the existing concrete substrate.
 - e. Loss of skid resistance: Skid resistance less than 45 as measured using a 3 inch pad according to ASTM E 303.
 - f. Cold joint separation: Lack of tightness of cold joint between phases of overlay placement.
 - 4. The guarantee covers 100 percent of the polyester concrete overlay system materials and installation costs.
 - 5. The Contractor removes and replaces failed sections of the polyester concrete overlay.
 - 6. The Department will notify the Contractor of defects to be repaired during the guarantee period.
 - a. Submit detailed plans and procedures of corrective work according to Provider's recommendations and obtain the Department's authorization before commencing work.
 - b. Perform corrective work within 60 days of notification.

1.6 ACCEPTANCE

- A. Mixer Calibration
 - 1. Calibrate continuous mixer in the presence of the Engineer.

- a. Measure weight of each of three consecutive batches of 125 lb of aggregate using the mixer and a certified scale. Repeat until three consecutive weights are within 2 percent.
 - b. Measure weight of each of three consecutive batches of 20 lb of resin using the mixer and a certified scale. Repeat until three consecutive weights are within 2 percent.
 2. Calibrate before Overlay Test Section and again before production for the first application.
- B. Average Resin Content
 1. Obtain at least one sample per 2500 ft² of overlay placed. Sampling occurs after the polyester concrete exits the mixer and before it enters the paver.
 - a. The Department witnesses the sampling, takes possession of the sample immediately, and begins testing resin content.
 2. The average resin content must be 12 (± 1) percent by weight of dry aggregate as measured using AASHTO T 308 Method A.
 - a. The Department rejects overlay placed that does not meet a resin content of 12 (± 1) percent by weight of dry aggregate.
 - 1) Remove and replace rejected overlay.
- C. Schmidt Rebound Number
 1. Perform at least one test per 500 ft² of overlay after 60 minutes and before 4 hours of overlay placement.
 - a. The Engineer determines testing locations that are representative of the overlay area being evaluated.
 - b. The Department witnesses the measurements.
 - c. Perform the test according to ASTM C 805, modified as follows:
 - 1) Make four readings at each test location.
 - 2) Make each reading on exactly the same spot.
 - 3) Do not smooth the polyester concrete surface with a grinding stone before testing.
 - 4) The Schmidt rebound number at a given location is the highest value obtained from four individual measurements performed in rapid succession at that location.
 - 5) Gradually push the Schmidt rebound hammer toward the test surface during the test until the hammer impacts.
 2. A Schmidt rebound number of at least 25 is required for a successful test.
 - a. The Department rejects overlay placed that does not meet a Schmidt rebound number of at least 25 within 4 hours of being placed on the concrete substrate.
 - b. Remove and replace rejected Overlay.

3. Do not open to traffic or equipment until a Schmidt rebound number of at least 25 has been reached.

D. Skid Resistance

1. Perform at least one test per 2500 ft² of overlay after the overlay reaches a Schmidt rebound number of at least 25.
 - a. The Engineer determines testing locations that are representative of the overlay area being evaluated.
2. A skid resistance of at least 45, measured using a 3 inch pad according to ASTM E 303, is required for the overlay surface at each test location.
 - a. The skid resistance at a given test location is the average value recorded from four swings of the pendulum applied at the same location in rapid succession after an initial, unrecorded swing is applied.
3. Measure and record skid resistance.
 - a. The Department witnesses the measurements.
4. Deficient Skid Resistance – Correct overlay that does not meet a skid resistance of at least 45.
 - a. The Provider's Technical Support Representative must concur with the recommended repair.

E. Thickness

1. Measure overlay thickness at intervals of 25 ft or less in the longitudinal direction for each pass of the overlay placement.
 - a. The Department witnesses the measurements.
2. The average overlay thickness must be within $\frac{1}{8}$ inch of the required thickness.
 - a. The overlay thickness at a given test location is the vertical distance between the lower edge of a 10 ft straightedge, placed transversely across the top of the overlay and overhanging a longitudinal edge of the overlay, and the top surface of the receiving concrete substrate immediately beneath the overhanging end of the straightedge.
 - 1) A depth probe may be used to verify overlay thickness in lieu of a straightedge when approved by the Engineer.
 - b. Measure and record the overlay thickness to the nearest $\frac{1}{16}$ inch.
3. Deficient Thickness – Correct overlay that is more than $\frac{1}{8}$ inch less than the required overlay thickness.
 - a. The Provider's Technical Support Representative must concur with the recommended repair.

- F. Bond Strength
1. Perform at least one test in the overlay test section 24 hours after the overlay test section is placed.
 - a. The Engineer determines testing locations that are representative of the overlay area being evaluated.
 - b. Repair test locations with the authorized overlay system if part of permanent work.
 2. The Engineer may require that bond strength tests be performed during production work.
 3. A bond strength of at least 250 psi, measured according to ASTM C 1583, between the overlay and the concrete substrate is required at each test location.
 - a. The Department does not reject the overlay if the concrete substrate fails at a strength less than 250 psi.
 4. Measure and record overlay bond strength results.
 - a. The Department witnesses the measurements.
 5. Correct overlay areas that do not meet the bond strength of at least 250 psi.

1.7 PROVIDER SERVICE REQUIREMENTS

- A. The Provider's technical support representative must:
1. Have at least 5 years of experience with the proposed overlay system and with guiding and assisting Installers in overlay installation.
 2. Provide technical support and training to the Installer and the Department regarding handling, storage, production, and placement.
 3. Attend the preconstruction meeting.
 4. Instruct the Installer, Contractor, and Engineer of anything that could adversely affect the performance of the overlay.
 5. Be present during placement of polyester concrete for the overlay application for the project, including the test section.
 - a. The Engineer may waive the requirement for the Provider's technical support representative to be onsite after completion of the first structure.
 - 1) The Provider's technical support representative must be available for consultation throughout the duration of the application.
 - 2) The Department reserves the right to require the Provider's technical support representative to be onsite if at any time the Engineer is concerned with the product installation quality.

1.8 INSTALLER REQUIREMENTS

- A. The Installer's authorized superintendent and the Installer's authorized continuous mixer operator must:
 - 1. Attend the preconstruction meeting.
 - 2. Be present during the placement of polyester concrete for overlay application for the project, including the test section.

1.9 DELIVERY, STORAGE AND HANDLING

- A. Deliver materials in their original containers bearing the Provider's label specifying trade name, manufacture date, lot number, and quantity.

1.10 OVERLAY QUANTITY ADJUSTMENT

- A. The Contractor may request an adjustment to the overlay volume quantity when the final overlay quantity differs from the quantity shown.
 - 1. The adjusted overlay quantity is the volume of overlay placed and is the difference between the top of concrete elevations from the pre-overlay survey and the top of overlay elevations from the post-overlay survey.
 - a. Refer to this Section, 3.2C for the pre-overlay survey.
 - 2. Perform the post-overlay survey.
 - a. Survey the bridge deck and approach slab surfaces after the overlay placement is complete and the overlay has cured for at least 4 hours.
 - 1) Refer to Section 01721 for requirements of bridge element surveys.
 - 2) Survey the same locations as the pre-overlay survey.
 - 3. Determine the adjusted overlay quantity by end section area method based on sections at 10 ft intervals along the longitudinal edges of each phase, along lane lines, and at grade breaks.
 - 4. Include survey data and calculations in the request for change order.
 - 5. The Department will not adjust the overlay quantity without a pre-overlay survey and a post-overlay survey.

PART 2 PRODUCTS

2.1 POLYESTER CONCRETE OVERLAY SYSTEM

- A. Provide a polyester concrete overlay system consisting of HMWM resin primer, polyester concrete, and finishing sand from a single source Provider with experience supplying and servicing projects of similar size and scope.

1. Meet the requirements in Table 1.
2. Test and certify the polyester concrete overlay system, the HMWM resin primer, and the polyester concrete components within the one-year period before the overlay placement.
3. Test and certify the finishing sand within the two-year period before the overlay placement.

Table 1

Polyester Concrete Overlay System Properties		
Property	Requirement	Test Method
Abrasion Resistance	< 2 g weight loss (at 12% resin content by weight of the dry aggregate)	CT 550*
PCC Saturated Surface Dry Bond Strength	500 psi minimum at 24 hrs and 70 degrees F (without HMWM resin primer, at 12% resin content by weight of the dry aggregate, on Saturated Surface Dry Specimen)	CT 551*
Modulus of Elasticity	1,000 ksi to 2,000 ksi (at 12% resin content by weight of the dry aggregate)	ASTM C 469
* CT 550 and CT 551 specifications are available from the Engineer		

- B. HMWM resin primer
1. Meet the requirements in Table 2.
 2. Must be low-odor and wax-free.
 3. Do not use if HMWM resin primer containers have been unsealed for one year or longer.

Table 2

HMWM Resin Primer		
Property	Requirement	Test Method
Volatile Content *	30% maximum	ASTM D 2369
Viscosity *	25 cP maximum (Brookfield RVT with UL adaptor, 50 RPM at 77°F)	ASTM D 2196
Specific Gravity *	0.90 minimum, at 77°F	ASTM D 1475
Flash Point *	180°F minimum	ASTM D 3278
Vapor Pressure*	0.039 in. Hg maximum, at 77°F	ASTM D 323
PCC Saturated Surface-Dry Bond Strength	700 psi minimum at 24 hours and 70 ± 1°F	CT 551, Part 5**
* Test must be performed before adding initiator.		
** CT 551 specification is available from the Engineer		

C. Polyester concrete

1. Use a polyester concrete mix consisting of a polyester resin binder and aggregate.
 - a. Initial set time of at least 30 minutes and at most 120 minutes.
 - b. Final set time not exceeding 4 hours.
2. Polyester resin binder
 - a. Comprised of an unsaturated isophthalic polyester-styrene co-polymer.
 - b. Contains at least 1% by weight gamma-methacryloxypropyltrimethoxysilane, an organosilane ester silane coupler.
 - c. Use a promoter compatible with suitable methyl ethyl ketone peroxide and cumene hydroperoxide initiators.
 - d. Meet the requirements in Table 3.
3. Aggregate
 - a. Comprised of fine aggregate (aggregate passing the No. 8 sieve) consisting of natural sand only.
 - b. Meet the requirements of Tables 4 and 5.

Table 3

Polyester Resin Binder Properties		
Property	Requirement	Test Method
Viscosity *	75 to 200 cP (RVT, No. 1 Spindle, 20 RPM at 77°F)	ASTM D 2196
Specific Gravity *	1.05 to 1.10 at 77°F	ASTM D 1475
Elongation	35% minimum Type I at 0.45 inch/min. Thickness = 0.25 ± 0.04 inch	ASTM D 638
	Sample Conditioning: 18/25/50 + 5/70	ASTM D 618
Tensile Strength	2500 psi minimum Type I at 0.45 inch/min. Thickness = 0.25 ± 0.04 inch	ASTM D 638
	Sample Conditioning: 18/25/50 + 5/70	ASTM D 618
Styrene Content *	40% to 50% by weight	ASTM D 2369
*Test before adding Initiator.		

Table 4

Aggregate Properties		
Property	Requirement	Test Method
Sieve Analysis	Gradation limits indicated in Table 5 of this Section	AASHTO T 27
Clay Lumps and Friable Particles in Aggregate	1% maximum	AASHTO T 112
Fractured Face	45% maximum (for particles retained on the No. 8 sieve)	AASHTO T 335
Weighted Average Aggregate Absorption	< 1%	AASHTO T 84 and T 85
Moisture Content at Time of Mixing with the Resin	≤ the lesser of ½ of Weighted Average Aggregate Absorption or 0.5%	AASHTO T 255

Table 5

Aggregate Gradation	
Sieve Size	Percentage Passing (by weight)
$\frac{3}{8}$ inch	100
No. 4	62-85
No. 8	45-67
No. 16	29-50
No. 30	16-36
No. 50	5-20
No. 100	0-7
No. 200	0-3

- D. Finishing sand
1. Commercial-quality blast sand.
 2. At least 95 percent passing the No. 8 sieve and at most 5 percent passing the No. 20 sieve according to AASHTO T 27.
 3. An average absorption of at most 1 percent according to AASHTO T 84 and AASHTO T 85.

2.2. EQUIPMENT

- A. Use a continuous mixer to mix polyester concrete that:
1. Employs an auger screw/chute device and produces a satisfactory product consistently during the Overlay Test Section and production.
 2. Is equipped with an automatic metering device that measures and records aggregate volumes and corresponding resin volumes.
 3. Has a visible readout gauge that displays volumes of aggregate and resin being recorded.
 4. Is calibrated with certified scales provided by the Contractor.
- B. Use automatic paving and finishing equipment to place and finish polyester concrete that:
1. Is a self-propelled slip-form paver modified or specifically built to effectively place and finish polyester concrete overlays.
 - a. Capable of forward and reverse motion under its own power.
 - b. Advancing finishing equipment with winches or pulling devices is not allowed.

2. Is equipped with hydraulically controlled grade automation and sensing devices that control the thickness, longitudinal grade, and transverse cross slope.
 - a. Capable of providing a roadway surface meeting the required smoothness .
 - b. Use of fixed-height skid-supported strike-off equipment is not allowed.
 3. Strikes off the polyester concrete to the established grade and cross slope.
 4. Is fitted with vibrators or other mechanisms capable of consolidating and finishing the polyester concrete to the required overlay thickness.
 5. Has a paving width of at least 12 ft.
- C. Mechanical mixers, each of at most 9 ft³ capacity, may be used to mix polyester concrete for total applications less than 80 yd³ or when authorized by the Engineer.
- D. Alternative concrete paving and finishing equipment may be used to place and finish polyester concrete for total applications less than 80 yd³ or when authorized by the Engineer. Use concrete paving and finishing equipment that:
1. Has grade control capabilities.
 2. Consolidates and finishes the overlay to the required grade and cross section.
 3. Uses a vibratory-type mechanical screed riding on preset forms/rails.
 4. Strikes off the Overlay to the established grade, cross section and depth shown.
 - a. Keep a slight excess of polyester concrete in front of the cutting edge at all times.

PART 3 EXECUTION

3.1 GENERAL

- A. Follow the authorized overlay placement plan, public safety plan, and working drawings.

3.2 OVERLAY TEST SECTION

- A. Complete a test section before beginning production work. The test section must:
1. Be placed within the project limits at a location approved by the Engineer.

- a. Locations outside the project limits must be approved by the Engineer.
 2. Be placed on a previously cast and cured concrete surface with a surface slope equal to $\pm 1\%$ of the transverse surface slope and $\pm 1\%$ of the longitudinal surface slope of the actual project.
 3. Measure at least 12 ft wide and 10 ft long and be the same thickness as the project overlay.
 4. Have a width equal to the maximum width in the authorized overlay placement plan unless otherwise authorized by Engineer.
 5. Be constructed using the same equipment and personnel as the production work.
 6. Replicate field conditions, preparation of the concrete substrate surface, and installation procedures of the production work.
 7. Demonstrate the effectiveness of the mixing, placing, and finishing equipment.
 8. Determine the polyester concrete initial and final set times.
 9. Be completely removed if not determined to be acceptable to the Engineer.
- B. Perform acceptance testing according to this Section, Article 1.6.
- C. Notify the Engineer 10 calendar days before placing the test section. Place the test section in the presence of the Engineer.
1. The test section is evaluated by the requirements of this Section and the visual appearance of the test section.
- D. Complete a second test section if the first test section is rejected.
1. Resubmit the overlay placement plan with modifications that remedy the issues and failures noted by the Engineer from the first test section before proceeding with the second test section.
- E. The Department will find the Installer unqualified after two rejected test sections.
2. Replace an unqualified Installer. Submit qualifications for review of a new Installer according to this Section, Article 1.5.
- F. Remove and dispose of materials used in the test section, unless directed otherwise by the Engineer.
- G. Allow at least 48 hours for acceptance of each test section by the Engineer.
- H. Do not proceed with overlay production work before receiving the Engineer's approval of the test section.

3.3 PREPARATION

- A. Hold a Pre-Activity Meeting within 48 hours before overlay placement.
 - 1. Contractor, Department, and Provider personnel involved with completing the work must attend the pre-activity meeting.
 - 2. Notify the Engineer of the meeting at least 10 days in advance.
 - 3. Discuss items specific to overlay work including the following:
 - a. Methods and controls for grinding.
 - b. Methods for placing, finishing, and curing.
 - c. Schedule, production rates, construction practices, and quality control procedures.
 - d. Authorized submittals.
 - e. Sampling and testing.
- B. Prepare the entire concrete substrate surface by removing materials that may be detrimental to overlay bonding and curing according to the Provider's recommendations.
 - 1. Do not begin surface preparation work before completing existing overlay removal and structural porthole patching, if required.
 - 2. Remove loose disintegrated concrete, dirt, paint, oil, asphalt, rubber, laitance, carbonation, curing materials, and other foreign material from the concrete substrate.
 - 3. Remove surface mortar and expose aggregates as required by the Provider.
 - 4. Preparation must include shot blasting with steel shot.
 - a. Protect metal deck drains and areas of the curb or railing above the proposed surface from the shot blast.
 - 5. Protect deck and approach slab drains to prevent surface preparation and overlay materials from entering the drains.
 - 6. Use a vacuum truck or air compressor to remove dust and other loose materials.
 - a. Refer to ASTM D 4285.
 - b. Do not use brooms.
 - 7. Comply with the Provider's recommendations for preparation if they exceed the requirements in this Section.
- C. Perform a pre-overlay survey.
 - 1. Survey the existing bridge deck and approach slab top of concrete surfaces according to the authorized working drawings after removing existing overlays and before beginning the overlay placement.
 - a. Survey the bridge deck surface after it is recast and cured when rehabilitation requires the complete removal and recasting of the concrete surface.

- b. Survey elevations at cross-sections with intervals of no more than 10 ft along the longitudinal edges of each phase, along lane lines, and at grade breaks.
 - c. Refer to Section 01721 for requirements of bridge element surveys.
 - 2. The Department may adjust the top of overlay elevations based on the pre-overlay survey.
- D. Isolate expansion joints shown before placing the overlay.
 - 1. Saw cutting at bridge expansion joints is not allowed.
- E. Do not expose cleaned surfaces to vehicular or pedestrian traffic other than that required by the overlay operation.
- F. The Engineer will inspect and accept structural pothole patching and surface preparation before overlay placement begins.

3.4 LINE AND GRADE CONTROL

- A. Mark the deck and approach slab surfaces with the following according to the authorized working drawings before placing the overlay:
 - 1. The locations of the longitudinal edges of each phase and the locations of surveyed points along the lane lines.
 - 2. The finished grade elevations along the longitudinal edges of each phase at locations shown.
 - 3. The location and required depths of areas for grinding, where minimum overlay thickness shown cannot be met.
- B. Temporary forms for longitudinal edges of phased overlay placement when alternative concrete paving and finishing equipment is used
 - 1. Place forms at longitudinal edges marked according to this Section, Article 3.3, paragraph A1.
 - 2. Vary the depth of forms, such that the top surface is a smooth profile (which matches the top of overlay at the edges of each phase) matching the finished grade elevations shown in the working drawings.
 - 3. Keep forms free from warps, bends and kinks.
 - 4. Do not provide a gap between forms and top of receiving surface for polyester concrete to leak through. Tightly join adjacent form sections.
 - 5. Stop overlay installation if the side forms do not meet or hold line and grade.
- C. Grinding
 - 1. Profile grind the receiving surface to the required depths at the locations marked according to this Section, Article 3.3, paragraph

A3 using the procedures and details shown in the authorized working drawings.

- D. Surface smoothness
 - 1. Limit transverse pavement deviations to less than $\frac{1}{8}$ inch from the lower edge of a 10 ft straightedge.
 - 2. Limit profile (longitudinal parallel to traffic) pavement deviations to less than $\frac{1}{8}$ inch from the lower edge of a 10 ft straightedge.

3.5 APPLICATION

- A. Before beginning application
 - 1. The concrete substrate surfaces must be cured as follows:
 - a. New structural concrete: at least 28 days.
 - b. New pothole patches:
 - 1) Using structural concrete: at least 28 days
 - 2) Using rapid setting repair mortar: Attain a minimum compressive strength of 3,500 psi, cure for a minimum of 72 hours, reach 80 percent of the 28-day compressive strength, and follow rapid setting repair mortar supplier's and overlay provider's recommendations.
 - 3) Using polyester concrete: Follow overlay provider's recommendations.
 - 2. The concrete substrate surface must be dry before placing the HMWM resin primer.
 - a. The surface must be free of standing water or surface darkening that would indicate locations of previously standing water.
 - b. The entire concrete substrate surface must appear to be uniformly light in color and show no further lightening when drying methods such as blowing compressed air or heating with a propane torch are applied.
 - c. Cracks in the concrete substrate must also be dry.
 - 3. The temperature of the concrete substrate surface must be between 50 degrees F and 90 degrees F.
 - 4. Clean the concrete substrate surface once again by blowing it with clean and dry compressed air immediately before applying the HMWM resin primer.
 - 5. Extend functional deck and approach slab joints through the overlay.
 - a. Align the joint edges of the polyester concrete and the concrete substrate in a single vertical plane.
 - b. Seal joints as shown.

- B. HMWM Resin Primer
1. Thoroughly mix the components of the HMWM resin primer.
 2. Apply the HMWM resin primer to the concrete substrate surface:
 - a. Within five minutes of mixing.
 - b. At 90 ft²/gal or a rate recommended by the Provider.
 - c. With uniform and complete coverage of the surfaces to be overlaid.
- C. Polyester Concrete
1. Initiate the polyester resin binder and blend completely. Add aggregate, proportion binder content in polyester concrete mix such that the polyester resin binder is 12 (± 1) percent of the weight of the dry aggregate, and mix until uniform in texture and appearance.
 2. Record aggregate volumes and corresponding resin volumes at intervals of at most 5 minutes with the time and date of each recording.
 3. Place the polyester concrete:
 - a. After 15 minutes and up to 120 minutes from when the HMWM resin primer was applied.
 - b. Within 15 minutes of adding initiator or earlier as needed to ensure proper placement and finishing. Discard polyester concrete not placed within this time.
 4. Measure the polyester concrete initial and final set times.
 - a. Remove and replace the material if the set times do not meet the requirements in this Section, Article 2.1, paragraph C1.
 5. Consolidate and finish the overlay to the required thickness, longitudinal profile, and transverse cross slope.
 - a. Keep a slight excess of polyester concrete in front of the cutting edge at all times.
 6. Taper the overlay edges if the overlay is not completed within the allowable lane closure time and is more than 3/4 inch higher in elevation than the adjacent deck surface.
 - a. Taper both longitudinal and transverse edges at a 4:1 (horizontal:vertical) slope or as directed by the Engineer.
 - b. Tapers may remain and be overlaid with a subsequent overlay pass.
 7. Reestablish working joints such as the deck to approach slab joints as shown and according to the authorized overlay placement plan.
- D. Finishing Sand
1. Apply the finishing sand at a rate of at least 1.9 lb/yd² before initial set of the polyester concrete occurs.
 - a. Apply finishing sand until refusal, eliminating glassy or smooth areas.

2. Finish and texture the overlay on the bridge deck and approach slabs before initial set of the polyester concrete occurs.
 - a. Use a texture process that produces regular $\frac{1}{8}$ inch wide transverse grooves spaced randomly from $\frac{1}{2}$ inch to $\frac{3}{4}$ inch on centers and $\frac{1}{8}$ inch deep.
- E. After finishing sand application
 1. Protect the overlay from moisture for at least 4 hours.
 2. Do not allow traffic or equipment on the overlay until a Schmidt rebound number of at least 25 is reached.
 3. Sound the entire overlay surface in a manner acceptable to and in the presence of the Engineer after final set of the polyester concrete to ensure total bond of the overlay to the concrete substrate.
 - a. Remove and replace unbonded areas of polyester concrete.
 4. Thoroughly fill and seal cracks in the overlay with HMWM resin primer, except those that are determined by the Engineer to be of sufficient extent and/or severity that removal and replacement of the affected overlay sections is required.
 - a. Apply two applications of HMWM resin primer to cracks that are greater than or equal to $\frac{1}{16}$ inch in width.
 - b. Coat the wetted surface with finishing sand for an abrasive finish immediately following the application of the HMWM resin primer.
- F. Comply with the Provider's recommendations for application if they exceed the requirements in this Section.
- G. Remove and dispose of the loose/excess finishing sand that has not properly bonded to the overlay before opening the overlay to traffic.

3.6 QUALITY ASSURANCE

- A. The Provider's technical support representative may consult with the Engineer to suspend any item of work that is suspect and does not meet the requirements of this Section.
 1. Work may resume only after the Provider's technical support representative and the Engineer are satisfied that the Installer has taken appropriate remedial action.

END OF SECTION