RESEARCH & DEVELOPMENT

Fiber Reinforcement for Latex Modified Concrete Overlays

Thomas Stirewalt
Mohammad Pour-Ghaz
Gregory Lucier

Dept. of Civil, Construction and Environmental Engineering
North Carolina State University

NCDOT Project 2020-21

FHWA/NC/2020-21

October 10, 2022

Fiber Reinforcement for Latex Modified Concrete Overlays

FINAL REPORT

Prepared by:

Thomas Stirewalt

Mohammad Pour-Ghaz

Gregory Lucier

A report on research sponsored by:

THE NORTH CAROLINA DEPARTMENT OF TRANSPORTATION

October 10, 2022

Technical Report Documentation Page

1. Report No. **FHWA/NC/2020-21**	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Fiber Reinforcement for Latex Modified Concrete Overlays		5. Report Date October 10, 2022 6. Performing Organization Code
7. Author(s) Stirewalt, Thomas; Pour-Ghaz, Mohammad; and Lucier, Gregory		8. Performing Organization Report No.
9. Performing Organization Name and Address North Carolina State University Constructed Facilities Laboratory 2414 Campus Shore Drive Raleigh, NC 27606		10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address NCDOT Research and Analysis Group 1 South Wilmington Street Raleigh, North Carolina 27601		13. Type of Report and Period Covered Final Report for Contract Period Aug. 1, 2019 through April 30, 2022 14. Sponsoring Agency Code **RP2020-21**
Supplementary Notes:		

16. Abstract

This research studies the use of microfiber to control cracking in Latex Modified Concrete – Very Early Strength (LMC-VES) for bridge deck overlays. The research investigated fibers and fiber dispensing methods that are commercially available and compatible with the volumetric mixing equipment commonly used for LMC-VES overlays. Two fibers were recommend for further study in small-scale laboratory experiments, larger scale laboratory experiments, and a full-scale field trial. Small-scale laboratory experiments studied the effects of fiber on the slump, compressive strength, flexural strength, and bond strength to ordinary concrete of LMC-VES. Larger-scale laboratory experiments studied the tendency of LMC-VES overlays to crack when subjected to vibration or sudden temperature changes during curing. Citric acid, commonly used as a retarder in LMC-VES, was found to effect set time, but also to influence LMC-VES workability. A large scale field trial applied LMC-VES overlays to three lanes of a bridge in central North Carolina. The first lane used LMC-VES with no fiber and the second and third lanes included fiber in the mixture. Concrete strength and concrete slump were measured at regular intervals across the project for mixtures with and without fiber. The field trial illustrated weaknesses in the current field inspection process for LMC-VES. In addition, the field trial highlighted difficulties of including fiber in a volumetric mixing process with LMC-VES. Ultimately, the laboratory and field experiments conducted here point to the conclusion that fiber is not necessary in LMC-VES to control cracking. Rather, enforcing proper construction procedure, including curing techniques and control of citric acid usage are likely more effective ways of controlling cracking.

17. Key Words Concrete overlays, fiber reinforced concrete, latex modified concrete, bridge decks	18. Distribution Statement		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 108	22. Price

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

DISCLAIMER

The contents of this report reflect the views of the author(s) and not necessarily the views of the University. The author(s) are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of either the North Carolina Department of Transportation or the Federal Highway Administration at the time of publication. This report does not constitute a standard, specification, or regulation.

ACKNOWLEDGMENTS

The authors would like to thank the North Carolina Department of Transportation (NCDOT) Office of Research and Development for sponsoring and supporting this research. Many dedicated NCDOT personnel assisted the researchers throughout this project, in particular W. Cabell Garbee and Aaron Earwood. The authors are very grateful to the Constructed Facilities Laboratory (CFL) staff, Johnathan McEntire and Jerry Atkinson, for their technical support and expertise. Assistance provided by undergraduate student Jamison Harris is also acknowledged and appreciated. The research team would like to thank Lanford Brothers Company for accommodating the researchers on their worksite and for providing valuable insight into the construction of LMC-VES overlays. Latex and fiber materials were donated by Trinseo and Forta Corporation, respectively. All of these contributions are appreciated.

EXECUTIVE SUMMARY

This research studies the use of microfiber to control cracking in Latex Modified Concrete – Very Early Strength (LMC-VES) for bridge deck overlays. The research investigated fibers and fiber dispensing methods that are commercially available and compatible with the volumetric mixing equipment commonly used for LMC-VES overlays. Two fibers were recommend for further study in small-scale laboratory experiments, larger scale laboratory experiments, and a full-scale field trial. Small-scale laboratory experiments studied the effects of the selected fiber on the slump, compressive strength, flexural strength, and bond strength to ordinary concrete of LMC-VES. Larger-scale laboratory experiments studied the tendency of LMC-VES overlays to crack when subjected to vibration or sudden temperature changes during curing. Overlay specimens constructed and cured in the laboratory per NCDOT procedures did not crack, even when subjected to extreme environments. As such, fiber was not necessary to control cracking. Citric acid, commonly used as a retarder in LMC-VES, was found to delay set time, but also to increase LMC-VES workability.

A large scale field trial applied LMC-VES overlays to three lanes of a bridge in central North Carolina. The first lane used LMC-VES with no fiber and the second and third lanes included fiber in the mixture. Concrete strength and concrete slump were measured at regular intervals across the field project for one mixture with fiber and the mixture without. The performance of the LMC-VES did not change with fiber, and the LMC-VES cast without fiber, following proper NCDOT procedure, did not crack. The field trial illustrated weaknesses in the current field inspection process for LMC-VES. In addition, the field trial highlighted the difficulties of including fiber in a volumetric mixing process with LMC-VES. Ultimately, the laboratory and field experiments conducted here point to the conclusion that fiber is not necessary in LMC-VES overlays to control cracking. Rather, enforcing proper construction procedure, including curing techniques and control of citric acid usage, are likely more effective ways of controlling overlay cracking.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. Introduction

1.1 Background

When the deck of a concrete bridge degrades, the top layer of concrete must sometimes be removed and replaced. In such cases, a bridge deck overlay can be performed to extend the service life of the bridge without a full structural replacement (Balakumaran et al., 2017). The top layer of the bridge deck is removed, often via hydro demolition, and is replaced with new concrete, called an overlay, to provide a better driving surface and to restore protection to the internal steel reinforcing bars. Due to the aging of bridges, overlays are becoming more frequently used (Balakumaran et al., 2017). The North Carolina Department of Transportation (NCDOT) expects their overlays to increase the service life of a given bridge life by about 25 years (Earwood & Garbee, 2018).

Styrene butadiene Latex-Modified Concrete (LMC) and LMC-Very Early Strength (LMC-VES) are commonly used as overlay materials due to their low chloride ion permeability, high durability, and good-quality driving surface (Alhassan, Mohammad & Suleiman, 2012; Won et al., 2011b). The NCDOT has performed an average of about 25 LMC or LMC-VES overlays per year in recent years, however, yearly utilization is quite variable (Earwood & Garbee, 2018). The incorporation of latex into the concrete is key to better protecting the bridge deck by reducing its permeability to chloride ions. The addition of styrene butadiene latex also improves fresh concrete fluidity (Kim & Park, 2013b), thus making it more workable during construction. Because of the increased workability provided by the styrene butadiene latex, a lower water-to-cement ratio (w/c) can be used, relatively increasing concrete strength and improving durability compared to similar concrete with a higher w/c ratio. Won et al. found that at the same levels of workability, LMC offers better resistance to freeze/thaw, abrasion, and scaling, and provides greater bond strength and lower chloride ion permeability than comparable traditional concrete (Won et al., 2011b). During mixing, the separation or segregation of materials in the concrete is hindered by the latex, due to its viscosity (Lee, Seung-Kee et al., 2017). The latex fills pores and has been reported to improve the bond between aggregate and cement during hydration. This phenomenon forms a film, reduces the permeability, and increases tensile strength (Won et al., 2011b).

LMC-VES is designed for the purpose of opening a road to traffic as soon as possible (Yun & Choi, 2014). NCDOT expects their LMC-VES overlays to be traffic-ready in as few as three hours after casting (Earwood & Garbee, 2018). In recent years, LMC-VES overlays have increased in popularity. In LMC-VES, styrene butadiene latex and very early strength cement are used together to allow for rapid construction (Won, Kim, Park et al., 2009). By reducing lane closure time, LMC-VES can reduce traffic control costs and lessen the inconvenience experienced by the public due to lane closures (Balakumaran et al., 2017). In North Carolina (and many other states) LMC-VES mixture designs typically use calcium sulfoaluminate (CSA) cement. In addition to rapid setting capability, CSA cements also tout environmental advantages. In terms of raw material production, CSA generates 60-65% less CO_2 than alite, the primary component of Portland cement clinker (Gartner, 2004).

The most notable downside of LMC, and specifically LMC-VES overlays, is their high tendency to crack. Balakumaran, Weyers, and Brown noted that LMC-VES overlays are only successful 50% of the time and often exhibit severe cracking. These researchers attribute shortcomings of LMC-VES to temperature, humidity, and high shrinkage (Balakumaran et al., 2017). In the field, a fresh concrete overlay is restrained from shrinkage (notably plastic and drying shrinkage). This restraint causes tensile stress to develop and may result in micro (or even macro) cracking (Soroushian & Ravanbakhsh, 1999). Microcracks increase the permeability of pavement and lead to shorter lifespans of the pavement and of the structure the pavement is supposed to protect (Won et al., 2011) (Won et al., 2011a) (Lee et al., 2017) (Afroughsabet et al., 2019).

The most common type of cracking observed in LMC-VES is map cracking, typically visible three to seven days after placement, but it can show up later. A common theory for the source of map cracking is plastic shrinkage, caused by delayed curing under poor conditions resulting in a lack of bleed water (Yun & Choi, 2014). NCDOT currently prescribes a curing procedure that requires two layers of wet burlap and a single layer of polyethylene sheeting be placed over top of the fresh concrete as soon as the concrete is firm enough to enable application of these materials. The wet burlap and plastic are left in place for at least three hours to mitigate plastic shrinkage (North Carolina Department of Transportation, 2019b). A previous research project completed by North Carolina State University (NCSU) on this topic reported that no plastic shrinkage cracking was found to occur when mixing and curing was performed to NCDOT specification, even at evaporation rates 15% above those allowed by the NCDOT specification (Smyl et al., 2016). Similarly, Won et al. found that LMC-VES did not exhibit plastic shrinkage cracking because the latex reduced the heat of hydration, thus lessening evaporation and mitigating the tensile stress that would subsequently develop on the surface (2009). The previous NCSU project noted that restrained shrinkage cracks (including plastic and drying shrinkage cracks) could only be created when improper construction and curing procedures were used (Smyl et al., 2016). LMC-VES is generally very sensitive to being installed outside of specification limits, and has a very small margin of error during placement and curing, making construction mistakes more likely with the rapidly setting material. (Balakumaran et al., 2017)

Another form of cracking that is possible for LMC-VES overlays to exhibit is transverse cracking, which often forms due to adverse thermal conditions. A theory put forth by Yun and Choi for the cause of this type of cracking is that a temperature differential can develop between the top and the bottom of the overlay (2014). Once the cracks open, they are further propagated by drying shrinkage (Yun & Choi, 2014). This behavior is especially relevant to LMC-VES because this class of material experiences a significantly higher drying shrinkage than similar fly ash and microsilica concretes due to the short moist curing period of LMC-VES (Alhassan & Suleiman, 2012).

A common proposal for mitigating cracking in LMC and LMC-VES overlays is to include non-ferrous fibers in the concrete mixture design. This proposal counts on fibers mixed in with fresh concrete to improve the tensile capacity of the material during the curing stage, thus reducing cracking. While mixing fibers in with the concrete sounds like a simple approach, the field implementation is challenging. Both LMC and LMC-VES must be volumetrically batched and continuously mixed, as discussed in Appendix C. Therefore, fiber addition methods must be compatible with the commercial continuous concrete mixers used in the field. Available options for fiber addition in the realm of continuous mixing are limited, however, commercial solutions for fiber addition do exist. The main potential advantage of adding fiber to LMC-VES is reported to be crack reduction, which leads to decreased permeability and increased durability (Alhassan, Mohammad A. & Issa, 2010; Kim & Park, 2013b; Lee, Joo-Ha et al., 2018; Lee et al., 2017; Oh et al., 2014), and to long-term cost savings (Alhassan & Issa, 2010; Lee et al., 2017). However, many of the studies available in literature that advocate for mixing fiber with LMC-VES have not completed trials at scale with commercially available equipment. The main disadvantages to mixing fiber with LMC-VES are a lack of established construction practices, a lack of standardized and available equipment, and a high initial cost. Concerns about fibers reducing workability and impacting concrete surface quality have also been raised. The current research aims to address many of the questions outlined above by investigating: 1) the ability of non-metallic fibers to mitigate cracking in LMC-VES, and 2) the practicality of deploying fiber addition methods on field-scale volumetric equipment without hindering construction.

1.2 Research Need and Project Objectives

NCDOT has published very specific and comprehensive procedures to address the design and construction of LMC and LMC-VES overlays, as described in Appendix C (North Carolina Department of Transportation, 2019b; North Carolina Department of Transportation, 2019a). Nonetheless, early age cracking is still regularly observed in overlays, as shown in Figure 1-1. Cracking is more commonly found in LMC-VES than LMC. The prior NCSU research completed on this issue concluded that when the specified NCDOT construction procedure was properly followed, restrained shrinkage and plastic shrinkage were not the sources of observed cracking. Instead, the findings attributed cracking to six potential sources (Smyl et al., 2016).

i) Temperature effects due to the high heat of hydration
ii) Bridge deck vibration during placement or curing
iii) Slight differential settlement
iv) The over-finishing of the concrete while in the plastic state
v) The use of non-saturated burlap during curing
vi) Other construction procedure issues

Of these issues, vibration during curing is notable, and, to the best knowledge of the authors, it has yet to be studied in relation to LMC-VES bridge deck overlays. Bonds broken by vibration around the time of initial set in the concrete may not heal (Manning, 1981). Vibration of the overlay concrete cannot practically be controlled on structures where traffic remains active on the bridge in adjacent lanes while a given lane is repaired. Furthermore, the construction equipment itself can easily cause slight vibration during curing. The effect of temperature may also be important, especially with the inclusion of retarder (citric acid) in the concrete. An observation presented by NCDOT personnel and their contractors is that thicker overlays have a higher tendency to crack. Therefore, at the start of this current project, NCDOT expressed an interest in exploring the effect of depth on the cracking of overlays.

The research presented in this report aims to investigate possible causes of cracking in LMC-VES overlays, notably bridge deck vibration, effect of overlay depth, and inclusion of citric acid retarder in the concrete mixture. With regard to these factors, this research aims to address the question: “Will including nonmetallic fiber in LMC-VES overlays mitigate the tendency for cracking?” This research will study this question with experiments in the laboratory, but also at large scale in the field. Very little of the available literature on this subject focuses on the construction aspects of fiber addition in the field, and the current project will aim to change that. Thus, the current research aims to answer the question: “What practices for including fiber in LMC-VES are compatible with established construction practices and are cost effective?” The current study of adding fiber to LMC-VES must consider the practical implications of any proposed fiber addition method on common field practice, not just the potential benefits of adding fiber.

Figure 1-1: Overlay Cracking.

(Photo Courtesy of NCDOT)

1.3 Research Approach

As outlined below, an experimental program was designed and completed to achieve the project objectives.

- *Task 1: Literature Review.* Available literature on the inclusion of fibers in LMC and LMC-VES was reviewed in detail. The literature review included published literature, NCDOT specifications, and other states' specifications regarding the inclusion of fibers in overlays, specifically LMC and LMC-VES overlays. The literature review studied fiber type, fiber length, fiber dosage, and other relevant properties to recommend starting points for these values in planned laboratory experiments. Both the construction aspects of fiber addition and the availability of fiber were studied, including discussions with potential vendors. The literature review addressed the techniques and equipment required to implement fiber in a volumetric mixing process. A summary of the literature review is presented below and detail is provided in the Appendix.

- *Task 2: Fiber Selection and Preliminary Mixture Designs.* Fibers for study were selected based on Task 1 work and five LMC-VES mixture designs were developed, based on a standard design provided by NCDOT.

- *Task 3: Laboratory Scale Testing.* The laboratory testing task was developed with several sub-tasks.
    - *Small-scale experiments.* The five experimental mix designs were developed in a prior task with selected combinations of fiber type, fiber dosage, and retarder content. A variety of test specimens were batched, mixed, cast, cured, and tested from each mix design to evaluate the effects of the selected parameters on slump, compressive strength, chemical bond strength, and flexural performance of the concrete. These initial tests characterized the key material properties of the preliminary mix designs and enabled comparison on the effects of fiber and other parameters. Three of the five mixtures were selected for further study in a subsequent round of larger-scale laboratory experiments.

    - *Mixing method.* As part of the laboratory experiments, a laboratory-scale mixing method for LMC-VES was developed. This method utilizes a small continuous mixer (modified for laboratory use) and mimics the mixing method used at large scale in the field. To the knowledge of the authors', prior laboratory studies of LMC-VES have relied on small-scale mixing methods such as a hand-held drill mixer, which may not accurately mimic the volumetric mixing process used in the field. The developed laboratory-scale volumetric mixing process is outlined in detail in Appendix B.

- *Laboratory-scale overlays.* The three mixtures selected from small-scale material tests were used in this subtask to cast overlays of 1" and 3" depth on top of roughened ordinary Portland cement concrete slabs with dimension of up to 4' x 2'. The overlays were cured in accordance with NCDOT specifications. An overlay at each depth was subjected to vibration during curing, similar to what might occur on bridge deck. All specimens were then monitored for cracking to evaluate the ability of fibers to resist crack development. Similar experiments were completed to study the effect of temperature on cracking – OPC slabs were overlaid with LMC-VES at ambient temperature and then immediately placed inside a pre-warmed oven to cure.

- *Citric Acid.* The effect of citric acid on the flowability of CSA cement mortar was investigated. Specimens with varying amounts of citric acid retarder at selected water to cement ratios (w/c) were tested for flowability at 3, 6, and 9 minutes. The effect of each variable on the flowability was analyzed, and the behavior was categorized. Uncontrolled dosing of citric acid into the concrete mixture was commonly observed in the field (and is not prevented by current specification). These laboratory studies help to shed some light on the possible effects of this practice.

- *Task 4: Field Trials.* A full-scale field trial comparing fibrous and non-fibrous LMC-VES was performed on a four-lane highway bridge, including detailed study of compressive strength gain over time of mixtures with and without fibers. The effects of fiber on the cracking of bridge decks was investigated, and the practicality of adding fiber to large-scale volumetric mixing equipment was investigated. Additional causes of cracking were explored through observation and discussion with contractors, testing agencies, and NCDOT personnel.

- *Task 5: Conclusions, Recommendations, and Report.* Conclusions and recommendations were developed for the mitigation of the issues of cracking in LMC and LMC-VES. Recommendations for areas of future study were also proposed. All efforts, results, and recommendations are documented in this report.

2. Literature Review Results

The detailed literature review provided in Appendix A was submitted to NCDOT as part of *Task 2: Fiber Selection and Preliminary Mix Designs.* The research team with NCDOT input elected to test only alkali-resistant (AR) glass and polyvinyl alcohol (PVA) fibers for this project based on the potential to practically apply both fibers in a volumetric mixing process. Due to the capabilities of commercially available fiber distribution systems, a fiber length of 0.5 inches was chosen. The filament diameter and length were selected based on commercial availability of fibers that were compatible with available commercial fiber dispensers. A major limiting factor for fiber selection and fiber dosage was compatibility of desired fibers and available fiber feeder equipment. Spooled glass fibers have been reported to have a practical dosage limit of around 2 lb/yd^3 (Issa et al., 2007). However, a search of the current available fiber dispensers reveals that the maximum dosage rate can be greater depending on the output speed of the volumetric truck. The dosage rate selected for this program varied from 1 to 2 lbs. of AR glass fiber per cubic yard of concrete. Because of the difference in densities between glass and PVA, the selected dosage rate of PVA fibers was chosen to match the volume percentage provided by 2 lbs. per cubic yard of AR glass fibers (0.0427% by volume), equivalent to 0.935 lb/yd^3 of PVA fiber. Additionally, for preliminary testing, PVA fibers at lengths of 0.75 inches and dosage rates of 2 lbs. per cubic yard (0.0913% by volume) were included.

A detailed review of literature related to fiber type, available specifications on fiber from NC and other states, fiber addition methods, fiber size and geometry, and fiber dosage rates is provided in Appendix A.

3. Material Testing

3.1 Introduction

This chapter describes a series of material tests performed to investigate the effects of fiber type, fiber content, and citric acid on selected properties of LMC-VES. Initial tests focused on the impact of fiber content on slump and compressive strength. Subsequent experiments tested the effect of fiber and citric acid on the compressive strength, chemical bond, and flexural performance of LMC-VES. An overview of the experimental program as well as an analysis and discussion of test results is provided in this chapter.

While micro-fibers are intended for crack reduction and not increased strength, any effects of fiber on compressive strength still an important topic of study. Compressive strength of LMC-VES is one of the main ways in which NCDOT characterizes the effectiveness and quality of overlay concrete. Any effects of added materials, such as fiber, on the compressive strength will need to be characterized for this process to remain accurate. Most notably, inclusion of fiber in the mix design should not have a negative effect on compressive strength.

The chemical bond strength is important to this research because of the need for the overlay material to fully bond to the ordinary Portland cement concrete substrate. Any solution to the issue of cracking, such as the addition of fiber, should not come at the expense of bond. Therefore, a question asked by this research is whether the addition of fibers (and citric acid) will adversely affect the chemical bond strength of the overlay material.

Flexural strength is used as a barometer for the ability of fibers to resist crack development and to provide post-cracking strength. Additionally, flexural testing allows for an observation of the method of fiber failure (generally rupture or pullout). The mode of fiber failure indicates the relative strength of the bond between the fiber and the concrete, which is important for the ability of an overlay to resist cracking.

The material tests in this chapter utilized the mixing method outlined in Appendix B.

3.2 Material Properties

The control mixture design is based on the NCDOT requirements for LMC-VES and is shown in Table 3-1. The water to cement ratio (w/c) is calculated using the water listed and the liquid portion of the latex, determined by backing out the percent solids listed in Table 3-3.

Table 3-1: Control Mixture Design.

Material	Quantity/yd^3
Fine Aggregate	1503 lb (SSD)
Coarse Aggregate	1286 lb (SSD)
CSA Cement	654 lb
Latex	210 lb (24.6 gal)
Water	135 lb (16.2 gal)
Air	3.50%
w/c	0.375

The cement used in this research was a commercially available CSA cement classified as a "Very Rapid Hardening Cement" by ASTM C1600 (ASTM International, 2019a). The manufacturer listed initial and final set times of 15 and 20 minutes, respectively. The specific gravity (SG) of the cement was 2.98. The fine aggregate used was a natural sand categorized as an NCDOT #2 sand. The coarse aggregate used was a No. 78M stone. The important aggregate properties for the mixing method discussed in Appendix B are listed in Table 3-2.

Table 3-2: Aggregate Properties.

Property	Fine	Coarse
Dry SG	2.582	2.613
SSD SG	2.604	2.631
Apparent SG	2.640	2.661
Absorption (%)	0.85	0.69

The latex used was a styrene butadiene latex provided by Trinseo. The latex meets all requirements of the NCDOT Standard Specification for Roads and Structures Table 1000-3: Properties of Latex Modifier for Concrete (North Carolina Department of Transportation, 2018). The important latex properties are summarized in Table 3-3.

Table 3-3: Latex Properties.

Property	Value
Polymer Type	Styrene Butadiene: 64% Styrene 36% Butadiene
Average Polymer Particle Size	1880 Angstroms
Emulsion Stabilizers	Anionic and non-ionic surfactants
Solids	47.3%
Weight per gallon	8.43
pH	10.0

The fiber selections of Polyvinyl Alcohol (PVA) and Alkali-Resistant Glass (ARG) were made in Task 2. The ARG fiber was sized (coated during processing) with Vinyl Acetate. Additionally, the use of citric acid (CA) was a variable between mixtures. When used, this research generally considered citric acid to be granular citric acid (99% purity) added at a weight of 0.1% of the cement weight. This amount of citric acid is at the lower limit of the amounts typically used in the field, which reach 0.8% of cement content or more. The combinations of fiber and citric acid used during testing are summarized in Table 3-4. All fibers and citric acid amounts listed were added to the mixture design in Table 3-1.

Table 3-4: Variable Mixture Design Notation.

Mixture	Fiber	Filament Diameter (mm)	Aspect Ratio	Fiber Volume	lb/yd^3	CA/Cement
CA	None	N/A	N/A	0.0000%	0	0.1%
C	None	N/A	N/A	0.0000%	0	0.0%
P.50.1	PVA	0.1	127	0.0427%	0.935	0.1%
G.50.1	ARG	0.01	1270	0.0214%	1.000	0.1%
G.50.2	ARG	0.01	1270	0.0427%	2.000	0.1%

Initial tests to validate the chosen mix designs and to study slump and compressive strength considered mixtures C, P.50.1, G.50.1, and G.50.2 from Table 3-4. Additionally, mixtures P.50.2, P.75.1, and P.75.2, as shown in Table 3-5, were only included in initial pilot testing. The citric acid amounts were varied during preliminary testing as fiber dosage and citric acid content were dialed in to reasonable levels.

Table 3-5: Preliminary Mixtures

Mixture	Fiber	Length (in)	Filament Diameter (mm)	Aspect Ratio	Fiber Volume	lb/yd^3
P.50.2	PVA	0.50	0.1	127	0.0427%	0.935
P.75.1	PVA	0.75	0.2	95	0.0913%	2.000
P.75.2	PVA	0.75	0.2	95	0.0913%	2.000

3.3 Testing Setup

3.3.1 Compressive Strength

Compressive strength was tested following the methods outlined in ASTM C39: Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens (ASTM International, 2021a). All cylinders were sealed with a lid immediately following casting. Concrete strength was studied in the laboratory from a preliminary set of cylinders cast with the slump test specimens. In addition, a second set of cylinders specifically for compression testing was cast simultaneously with the flexure tests. A third set of cylinders for compression testing was cast simultaneously with the laboratory overlay slabs.

A series of pilot compression tests were performed on a set of 4” x 8” cylinders at three hours after casting. The second set of compression tests were performed on 3”x 6” concrete cylinders tested at 3 hours, 24 hours, and 7 days, except for group G.50.1 which could not be tested at 3 hours (too weak). Results at 3-hours and 24-hours for the control mixture with and without citric acid (C and CA) were not available from this second set of cylinder tests, so results for these combinations of parameters were projected from the strengths of similar control (C) and citric acid (CA) tests in the third set of cylinders. Projections were made by scaling the available results by the ratio of seven-day strengths from the two sets. Results from the second set of compressive cylinders were used to determine the compressive strength at the time of bond strength and flexural testing.

The third set of cylinder tests were only performed on three concrete mixtures: the control mixture (C), the control mixture with citric acid (CA), and the mixture with glass fiber at two pounds per cubic yard (G.50.2, which included citric acid). Cylinders of size 4”x 8” were used for all mixtures in this third set. For the control mixtures with and without citric acid, three cylinders each were tested at 3 hours, 24 hours, and 7 days. For the G.50.2 mixture, only two cylinders each were tested at 3 hours and 24 hours; and three cylinders each were tested at 7 days. The results from the third set of cylinder tests were used in conjunction with relevant bond strength tests and laboratory-scale overlay slabs.

3.3.2 Concrete Slump

Concrete slump tests following ASTM C143: Standard Test Method for Slump of Hydraulic-Cement Concrete (ASTM International, 2020a). Slump testing was completed on the preliminary pilot mixtures and then on seven selected concrete mixtures with and without fiber and with and without citric acid.

3.3.3 Chemical Bonding Strength

The chemical bond strength tests followed the slant shear test method of *ASTM C882-20: Standard Test Method for Bond Strength of Epoxy-Resin Systems Used With Concrete By Slant Shear* (ASTM International, 2020c); however, no bonding agent was used at the bond line between pre-cured ordinary Portland cement concrete and LMC-VES. Three inch by six inch cylinders were cast from ordinary Portland cement concrete. These cylinders were then cut at an angle of 30-degrees from vertical using a circular diamond saw. Any hard edges were removed using an angle grinder, leaving a relatively smooth surface with exposed aggregate. The slanted cylinder halves were then put in the bottom of a 3” x 6” cylinder molds and the LMC-VES was cast on top. The cylinders were tested in compression 24 hours after casting. The cylinder testing procedure followed ASTM C39 in accordance with ASTM C882. The bond strength is calculated by dividing the shear stress along the interface by the interface area.

A total of six slant shear groups were tested on bases of Portland cement concrete cast at two different times. Thus, three groups of tests were performed on each base. The controls (with and without citric acid) and G.50.2 were performed on the first base (Base A); G.50.1, G.50.2, and P.50.1 were performed on the second base (Base B). Those cast on Base B were cast simultaneously with the flexure tests; those cast on Base A were cast simultaneously with the overlay slabs.

3.3.4 Flexural Performance

Flexural performance was tested following *ASTM C78: Standard Test Method for Flexural Strength of Concrete* (ASTM International, 2021b). The tests used 6 in. x 6 in. x 21 in. beams over an 18 in. span. Each specimen was loaded at the third points of the span. During casting, the specimens were consolidated by vibration. Specimens were covered in two layers of wet burlap and a single layer of polyethylene plastic sheeting for three hours as per NCDOT Requirements for LMC-VES overlays (North Carolina Department of Transportation, 2019b). The flexure tests were conducted seven days after casting.

3.4 Results, Analysis, and Discussion

3.4.1 Preliminary Results of Compressive Strength and Slump

Results from initial pilot tests of various mix designs are shown in Figure 3-1 and Figure 3-2. Each bar on the chart represents an average of 3 tests with error bands showing the 99% confidence intervals based on a normal distribution.

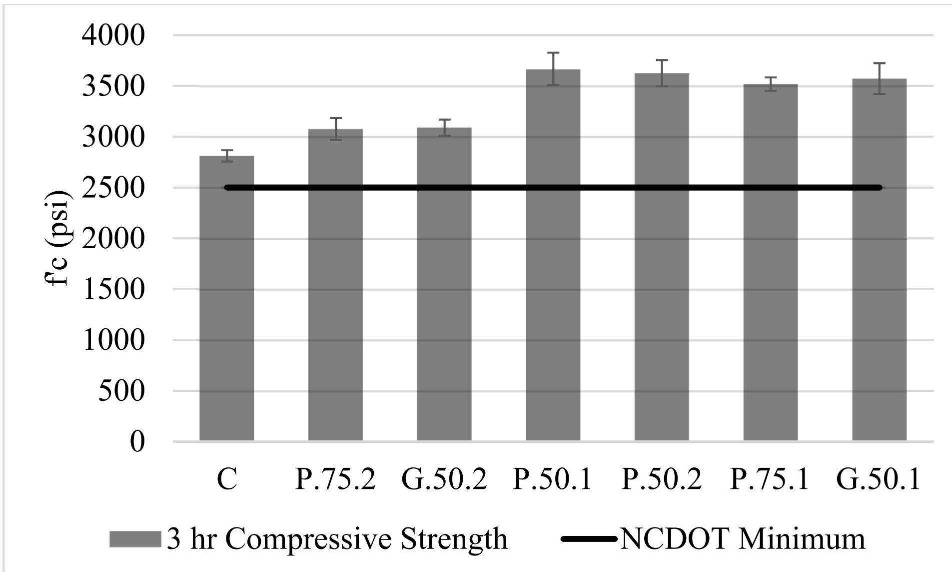


Figure 3-1: Preliminary Compressive Strength with Uncontrolled Citric Acid

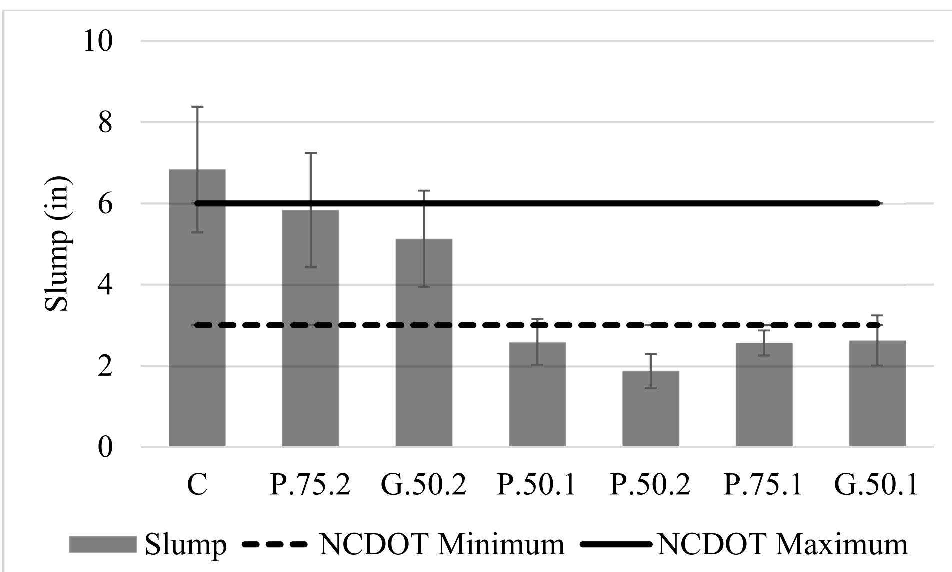


Figure 3-2: Preliminary Slump Results with Uncontrolled Citric Acid

In both figures, tests results are listed in chronological order from left to right along the horizontal axis. During these pilot tests, small amounts of citric acid were included “as needed” per the NCDOT mix design and specification, but citric acid quantity was not strictly controlled (as it is not strictly controlled in the field). For these initial pilot tests, citric acid was thought of as a short-term retarder only, useful only for delaying initial set. However, these experiments quickly demonstrated the importance of citric acid content on 3 hour strength (an NCDOT acceptance interval) and on workability.

Chronologically, tests with higher amounts of citric acid (C, P.75.2, and G.50.2) were performed before those with lower citric acid contents (P.50.1, P.50.2, P.75.1, and G.50.1). Higher citric acid led to a lower 3-hour compressive strength and a higher slump value; lower citric acid led to a higher 3-hour compressive strength and a lower slump value. From these tests, it was determined that citric acid has a major effect on the slump and compressive strength of LMC-VES, probably more so than the effects of fiber. No specific conclusions on the effects of fiber should be drawn from these pilot tests.

As such, citric acid content was carefully controlled for all sets of tests conducted after these pilot tests. In addition, the control mixture was separated into two control mixtures, one with citric acid (CA) and one without citric acid (C) for all data sets after these pilot tests. After these pilot tests, the study of citric acid became an important component of the research.

3.4.2 Compressive Strength Results

The second set of compressive strength results is shown in Figure 3-3, using the notation for mix designs from Table 3-4, including carefully controlled citric acid content. As before, each bar represents the average of multiple specimens with error bands showing a 99% confidence interval assuming a normal distribution. NCDOT currently specifies that LMC-VES must meet a minimum three-hour compressive strength of 2,500 psi (North Carolina Department of Transportation, 2019b). Almost all tested mixtures reached this objective. However, the addition of citric acid to the mixture, without adding fibers, caused the concrete to fail to meet this criterion. As will be discussed later in detail in the field trial section, field samples are usually taken by the inspection crew before citric acid is added “as needed” by the truck operator. These results indicate that post-inspection addition of citric acid, even in a dose as small as 0.1% of cement weight, could cause the concrete to artificially pass the strength requirements put forth by NCDOT. Stated otherwise, concrete placed on the bridge deck at 3 hours might be 2310 psi while cylinders taken as the representative sample of that concrete might test at 2960 psi.

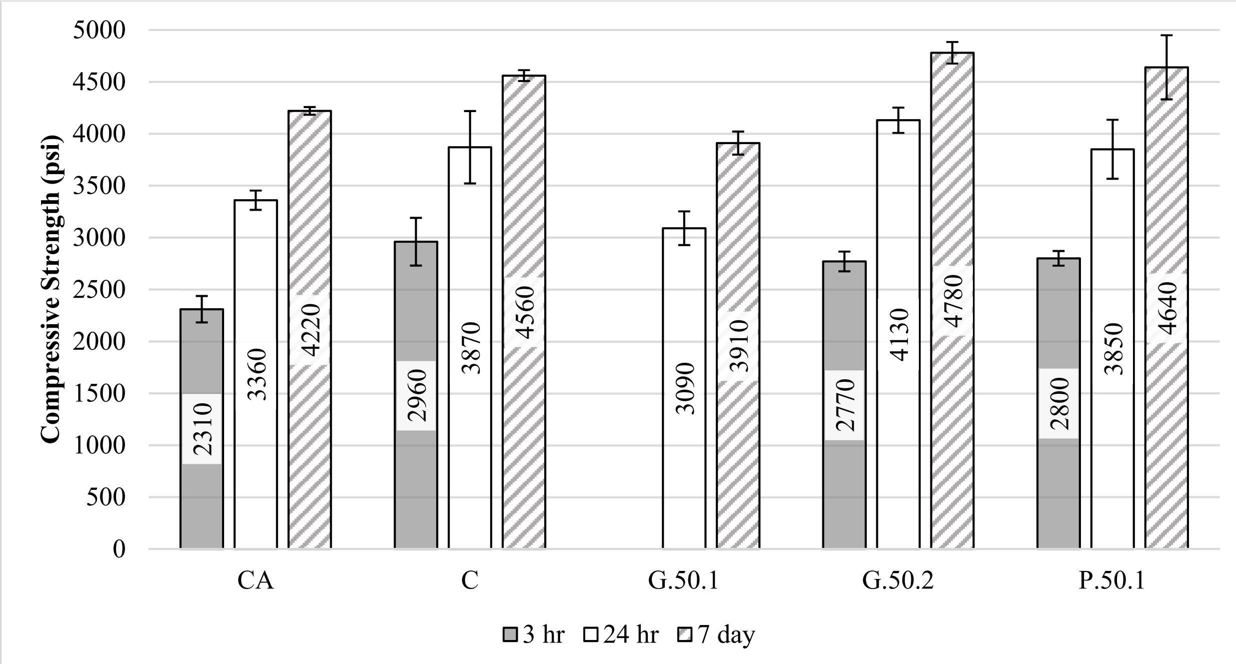


Figure 3-3: Second Set of Compressive Strength Results.

To expand on Figure 3-3, the control mixture (C), the only mixture on the chart that does not include any citric acid retarder, had the highest 3-hour strength (G.50.1 3-hour strength not available). However, by 24 hours, the mixture with two pounds per cubic yard of glass fiber (G.50.2) and the mixture with PVA fiber (P.50.1) displayed similar or greater strengths. G.50.2 and P.50.1, which have the same fiber volume percentage, generally behaved similarly with regards to compressive strength. Both measured strengths for G.50.1 were relatively low. With G.50.1 existing as a halfway point between the CA and G.50.2 mixtures, expectations would have pointed to the compressive strength of G.50.1 falling between the strengths of the other two mixtures. In their experiments, Oh, Kim, and Park found that the compressive strength of LMC with a half dose of fiber generally was between that of plain LMC and full dose LMC (Oh et al., 2014). Therefore, the G.50.1 results should be viewed as possibly unreliable.

Comparing the compressive strengths of the overlapping mixtures within the second set of cylinders (Figure 3-3) and the third set of cylinders (Figure 3-4), it is possible to study the variability of concrete mixed in the continuous mixer. The seven-day strength for the control specimens in Figure 3-3 is 4560 psi, with a corresponding strength of 3930 psi for equivalent specimens in Figure 3-4. Based on a normal distribution, there is no overlap of the 99% confidence interval, pointing to the variability inherent to volumetric mixing. Several factors are important to note. First, CSA cement is more highly reactive than ordinary Portland cement (Gartner, 2004). Second, the continuous mixing process, by its very nature, is subject to variation throughout a mix in different ways than drum mixed concrete is. Any small error in mixing the concrete or adding materials is not spread throughout the concrete, but rather exists only within the portion of concrete that was mixed while the error happened. Therefore, this level of variability is probably representative of that seen in the field and illustrates why a lab-based continuous mixing method is needed to study certain problems.

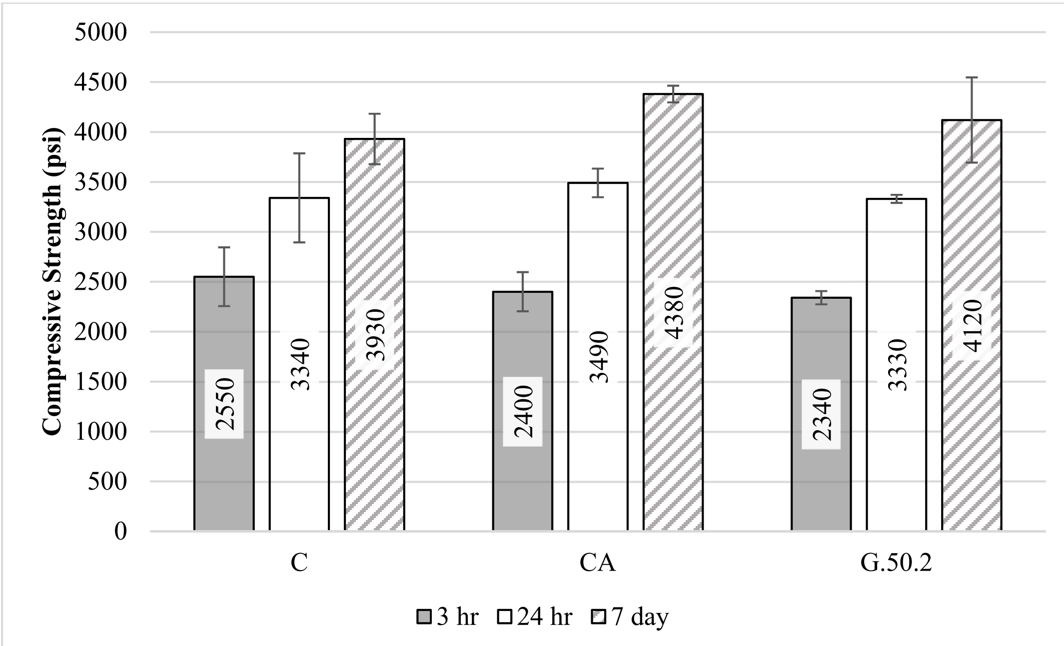


Figure 3-4: Third Set of Compressive Strength Results.

A main conclusion to the compressive strength results from the second and third sets of tests is that the addition of fiber did not likely negatively impact compressive strength. The variability caused by the addition of fiber appears to be less than the variability caused by the mixing method for all three configurations of fiber studied.

3.4.3 Bonding Strength Results

Results from the slant shear tests and the chemical bond strengths calculated from those tests are shown in Figure 3-5. The results shown in grey are from tests on Base A, and results shown in white are from tests on Base B. Imperfections in the sawing of the concrete cylinders were typical, as shown in Figure 3-6, and were distributed such that each mix had an approximately equal distribution of minor cylinder base defects.

Citric acid was shown to have a measurable, although statically insignificant effect on the chemical bond strength between of LMC-VES and Portland cement concrete. The addition of fibers appears to have enhanced bond strength to a small degree. Importantly, the inclusion of fibers does not appear to degrade the bond between LMC-VES and Portland cement concrete.

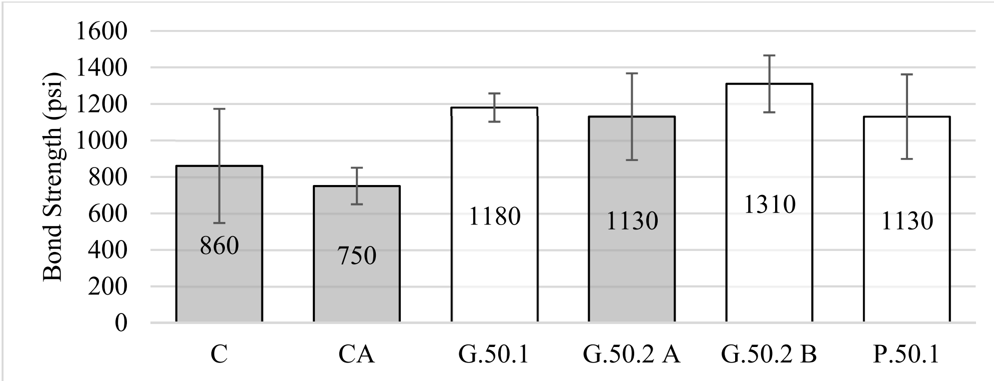


Figure 3-5: Slant Shear Bond Strength.

Figure 3-6: Typcial sawed surface with minor defects such as a tapered edge.

Two failure modes were observed in the slant shear tests: shear bond failure and a combination of shear bond and cracking of the overlay concrete, as shown in Figure 3-7. In both pairs of cylinder halves shown in the figure, the base material is to the left of the overlay material. The combined failure mode appeared to develop when the overlay material was able to flow over the top lip of the Portland cement concrete base piece, mechanically interlocking to the base piece. The ability for such mechanical interlock to develop depended on the degree of random defects along that edge of the base piece. However, in a bridge deck that is intentionally roughened by hydro demolition or similar, significant levels of mechanical interlock would be expected (and intended).

Figure 3-7: Shear Bond Failure (left pair) and Combination Failure (right pair).

As mentioned above, data from the slant shear tests seem to suggest that the addition of fibers increases bond strength. A closer review of the data in Table 3-6 indicates that, strictly speaking, bond strength is likely not impacted, but tension strength is likely increased, giving an increase in slant shear strength in cases where the combined failure mode develops (ie: situations where mechanical interlock between Portland concrete and LMC-VES is achieved). In some cases, fibers appear to have prevented the combined failure modes from developing, allowing the bond mode to develop at higher levels. The non-fibrous mixtures (C & CA) exclusively failed in the combined mode. On the other hand, fibrous mixtures were more likely to fail in pure bond, as occurred 67% of the time. On a mechanically roughened bridge deck, the performance observed in the slant shear tests likely translates into better bond between underlying concrete and LMC-VES overlay for LMC-VES overlays with fibers. The measured compressive strength of the overlay material at time of slant shear testing, shown in Table 3-6, appears to have had little effect on the bond strength.

Table 3-6: Slant Shear Bond Strength Test Results.

	Mixture Design:	C	CA	G.50.1	G.50.2 A	G.50.2 B	P.50.1
	Base:	A	A	B	A	B	B
Test 1	Bond (psi):	1025	781	1131	951	1308	1311
	Failure Mode:	Combo	Combo	Bond	Combo	Bond	Bond
Test 2	Bond (psi):	920	677	1235	1205	1413	1017
	Failure Mode:	Combo	Combo	Bond	Combo	Bond	Combo
Test 3	Bond (psi):	620	804	1174	1245	1204	1076
	Failure Mode:	Combo	Combo	Bond	Bond	Bond	Combo
	Mean (psi):	860	750	1180	1130	1310	1130
	Maximum Difference:	24.6%	8.5%	4.4%	13.4%	8.0%	12.7%
	Overlay Compressive Strength (psi):	3340	3490	3090	3330	4130	3850
	Bond Failures:	0	0	3	1	3	1
	Combination Failures:	3	3	0	2	0	2

In summary, while the phenomenon of combined failure mode and fiber enhanced resistance is helpful for understanding crack prevention in overlays. Considering the roughness of the underlying casting surface, any shrinkage experienced in the field would create a similar tension in the concrete as was created by the edges of the shear bond test bases. The ability of fibers to resist this tension, as shown in this experiment, could be beneficial for resisting shrinkage and preventing cracks, to the extent that any shrinkage did develop.

3.4.4 Flexural Performance

The modulus of rupture results are shown in Figure 3-8. Error bars in the figure represent a 99% confidence interval based on a normal distribution. The coefficient of variation and maximum difference for all individual mixtures fell within the requirements of 6.9% and 19.3% respectively, as specified by ASTM C78 Section 11 (ASTM International, 2021b). The addition of fibers increased the modulus of rupture, although not by a margin greater than the reduction caused by citric acid. Adding a small amount of citric acid to the mixture reduced modulus of rupture by about 12%, all else being equal. The small increase in rupture strength was similar to that found by other researchers (Alhassan & Suleiman, 2012; Kim & Park, 2013b).

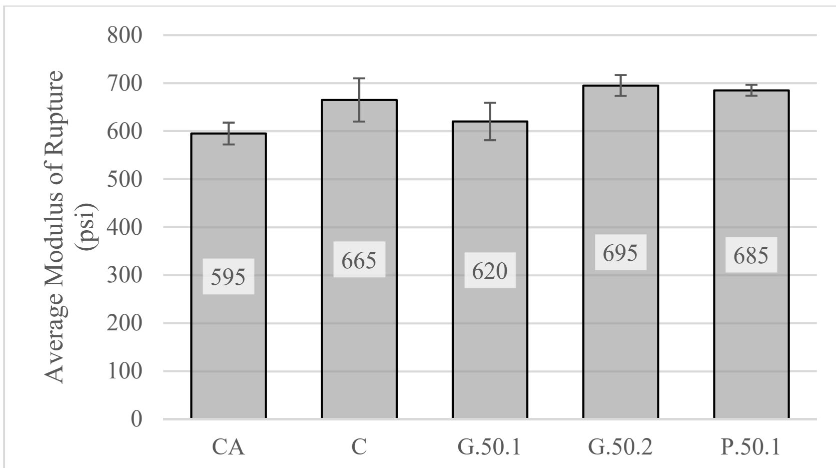


Figure 3-8: Modulus of Rupture.

Table 3-7: Flexural Performance.

Mixture:	**CA**	**C**	**G.50.1**	**G.50.2**	**P.50.1**
Average Modulus of Rupture (psi):	595	665	620	695	685
Compressive Strength (psi):	4219	4563	3911	4783	4636

The glass fiber-reinforced beams showed increased rupture strength but still failed in a brittle manner typical of the control specimens. The fibers did not bridge any macrocracks, nor did they provide any post cracking energy dissipation, despite marginally increasing the overall strength. As seen in Figure 3-9, the glass fibers appear to have failed by rupture (no fibers sticking out of the surface). This failure mode is likely due to their large aspect ratio. A higher aspect ratio (longer length relative to diameter) correlates to a larger surface area for the fiber to bond to the concrete relative to the cross-sectional area. By having more relative surface area to bond to the concrete, the fiber is much more likely to be ‘fully bonded,’ developing its ultimate tensile strength on either side of the crack. The fully bonded fiber ruptures before debonding, leading to a brittle failure. It is also worth noting that increasing the fiber content increases the effectiveness of the fiber reinforcement.

Figure 3-9: G.50.1 Flexural Failure Surface.

For the PVA specimens, the fibers bridged the crack and then pulled out, as shown in Figure 3-10. Subsequently, in addition to increasing the overall MOR strength, the PVA fibers did provide some minor post-cracking strength gains. The commercially available PVA fibers compatible with continuous mixer fiber dispensing attachments have a much larger diameter than do their glass counterparts, and therefore, they were not likely to fail in a brittle manner. At the same volume percentage, the glass and PVA specimens performed very similarly in terms of overall increase in the modulus of rupture, however, the PVA specimens reduced the brittleness of the failure. The practical impact of this distinction on LMC-VES overlays is likely minimal, unless very high fiber dosages were employed.

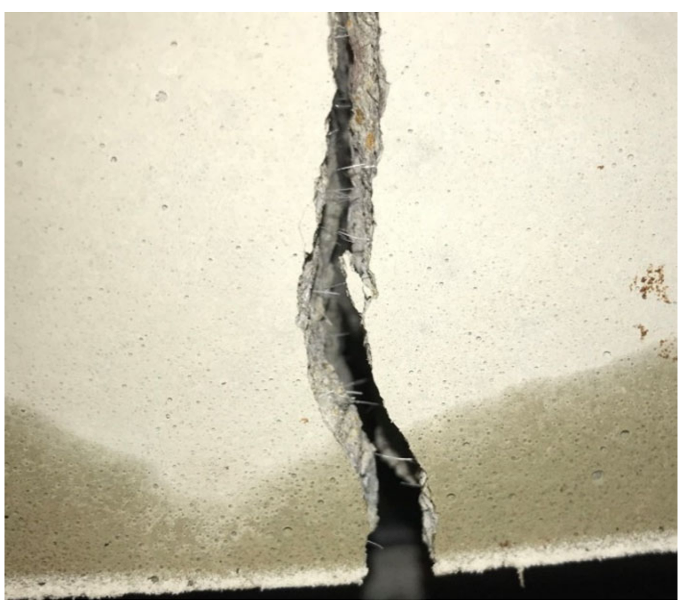


Figure 3-10: P.50.1 Crack Bridging and PVA Fiber Pullout.

3.5 Summary

The purpose of the material tests was to investigate the effect of fiber and citric acid on the material properties of LMC-VES. To achieve this goal, compressive strength, bond strength, and flexural strength were investigated. Test results indicate that removing citric acid from the mixture increased the compressive and flexural strengths. The addition of PVA and AR glass fibers did not appear to have a significant impact on the compressive strength, especially relative to the inherent variability of LMC-VES. The addition of citric acid to the mixture was shown to have the potential to cause the compressive strength to fail the NCDOT 3-hour requirement. If citric acid is not added until after a material sample is taken, concrete on a bridge deck could fall below requirements despite the sample passing inspection.

Based on the slant shear test results, inclusion of fibers increases the effective bond strength with the substrate by increasing the tensile strength of the overlay concrete and therefore enhancing the strength provided by mechanical interlock with the substrate. The inclusion of fiber, both PVA and AR glass, increased the modulus of rupture; and, as expected, increasing the fiber volume percentage had further positive effects on strength. At the same fiber volume percentage, PVA and AR glass fibers generally caused similar effects on the key material properties. However, even on a volume basis, AR glass fibers are much less expensive than PVA fibers. In addition, available fiber addition methods for full-scale continuous mixers tend to be more compatible with AR glass fibers. Therefore, after the completion of the material-scale stage of testing, only G.50.2 was carried forward to the laboratory-scale overlay testing and field trial as a fiber reinforced LMC-VES mixture.

4. Effects of Citric Acid on Flowability

4.1 Background

Early in the this research program, it was observed that citric acid content had a substantial effect on the flowability of LMC-VES made with calcium sulfoaluminate (CSA) cement. A review of the literature addressing the topic of citric acid in CSA cement mortar and concrete yielded few specific in terms of the effect of citric acid on flowability, although citric acid was recognized to improve workability. The issue of the effect of citric acid on the flowability of CSA cement concrete is important for field work and for the upcoming field trial in this research in particular. Despite the common use of CSA cement, relatively little is known about the mixture design and the effects of additives like citric acid on properties such as flowability of CSA cement concrete.

Citric acid is the most commonly used retarder with CSA cements. Some research has been completed on the retarding properties of citric acid and its effects on heat of hydration, setting time, and strength development of CSA cement concretes (Belhadi et al., 2019; Burris & Kurtis, 2018; Gwon et al., 2018; Hu et al., 2017; Khalil, 2008; Velazco et al., 2014; Winnefeld & Klemm, October 2013). However, very little research has explored the effect that citric acid has on flowability. While citric acid is commonly classified as a retarder, it has been postulated that citric acid also functions as a water reducer (Gwon et al., 2018). Because flowability is often one of the primary concerns of the construction crew, and citric acid was shown to have a notable effect on flowability in other tests, a series of experiments was conducted to investigate this phenomenon. The effect of citric acid on workability as a function of time was explored experimentally. Cement paste samples with w/c of 0.35 and 0.40 were tested for flowability at selected curing times between three and nine minutes. Citric acid dosages between 0.0% and 0.3% of the cement weight were studied.

4.2 Experimental Methods

4.2.1 Materials and Mixture Proportions

The cement and citric acid used in this experimentation was the same as described in Section 3.2. Flowability was tested for selected w/c (0.35 and 0.40), citric acid contents (0%, 0.025%, 0.0375%, 0.05%, 0.10%, and 0.30% of cement mass), and time of testing (3 minutes, 6 minutes, and 9 minutes after start of mixing). The two w/c ratios are representative of lower and higher commonly used values. The contents were selected to represent the lower end of the doses that reasonably could be prescribed in the field. In the field trial for this project, retarder dosages used by the contractor reached at least 0.85% of cement weight, so even the 0.30% dosage used in this laboratory study can be considered a low to moderate dose. At least three tests were performed at each citric acid level and w/c combination for a testing time of 6 minutes. For 3 minutes and 9 minutes, only one test was performed per combination. Deviations were assumed to be similar for the three- and nine-minute tests as for the six-minute tests. 0.0375% citric acid was only tested at nine minutes.

4.2.2 Testing Method

To measure flowability, the method prescribed by *ASTM C1437: Standard Test Method for Flow of Hydraulic Cement Mortar* (ASTM International, 2020c) was followed with one noted exception. In this test, a prescribed volume of mixed material is placed at the center of a drop table. The table is dropped and the material expands outward, with the final diameter of the puddle representing flowability. For this study, 15 drops, as opposed to 25, was chosen by the authors to prevent the puddle diameter from exceeding 9 inches (the table diameter). Similar to how the standard slump test described in ASTM C143 is not applicable for slumps less than ½ or greater than 9 inches (ASTM International, 2020b), the flowability test method should also have practical upper and lower limits. In general, for the flow test, the more flowable the material, the more its diameter expands with each table drop. However, the rate of outward expansion decreases as the diameter increases. Because the flowability measurements for this research are for comparative uses within a common set of specimens changing a single parameter at a time, specimen diameter is taken a rough approximation of "workability" or "flowability" of a given mixture. Results are expressed as a percentage increase relative to original base diameter, with larger numbers indicating greater flow.

The CSA cement, citric acid, and water were all weighed separately, and the citric acid was mixed into the water. The water and citric acid were then added to cement. The materials were mixed with a rotating paddle mixer (hand held drill mixer). The time of testing was taken from the point where water and citric acid first contacted the dry cement. The time of mixing was 1 minute, 2 minutes and 30 seconds, and 6 minutes for the testing times of 3 minutes, 6 minutes, and 9 minutes, respectively. In all cases, the material was sufficiently mixed prior to flow testing.

4.3 Results and Discussion

For the design of CSA cement concrete with citric acid, it is important to understand the effect of citric acid on flowability, how w/c ratio impacts this effect, and the influence of time. Accordingly, this study examines flowability at individual citric acid contents, water to cement ratios, and times. The interaction between the three independent variables is also examined. The average measured flowability of the mortar mixtures are summarized in Table 4-1.

Table 4-1: Average Flowability of Mortar.

Citric Acid Content:		0.00%	0.025%	0.0375%	0.05%	0.10%	0.30%
3 minutes mixing	w/c = 0.35	29%	62%	-	67%	63%	62%
	w/c = 0.40	57%	96%	-	97%	110%	97%
6 minutes mixing	w/c = 0.35	13%	45%	-	71%	64%	69%
	w/c = 0.40	23%	74%	-	95%	104%	103%
9 minutes mixing	w/c = 0.35	0%	2%	6%	64%	80%	81%
	w/c = 0.40	0%	35%	44%	95%	111%	115%

Figure 4-1 and Figure 4-2 display the flowability at individual w/c ratios. In these figures, there is a noticeable maximum achievable flow at each w/c ratio. The results indicate that, at each testing time, there is a limiting threshold of the effect of citric acid content on workability. Above this threshold, the measured flow is shown to be relatively constant. The maximums showed only slight variance between testing times at the same w/c. This threshold citric acid content should not automatically be extrapolated beyond the mixing times or citric acid contents used here. Extremely high citric acid contents could prevent the cement from ever setting, or extremely long times could cause the cement to set no matter the citric acid content. More research will need to study these trends with longer times and higher citric acid contents.

In practical terms, the results available from this work to date indicate that the effect of citric acid on workability is mostly "on" or "off". Increasing levels of citric acid quickly improve workability, with roughly proportional effects on workability below a minimum threshold value of about 0.05%. Continuing to add citric acid above the threshold value of 0.05%, or perhaps 0.1%, rapidly becomes irrelevant in terms of workability.

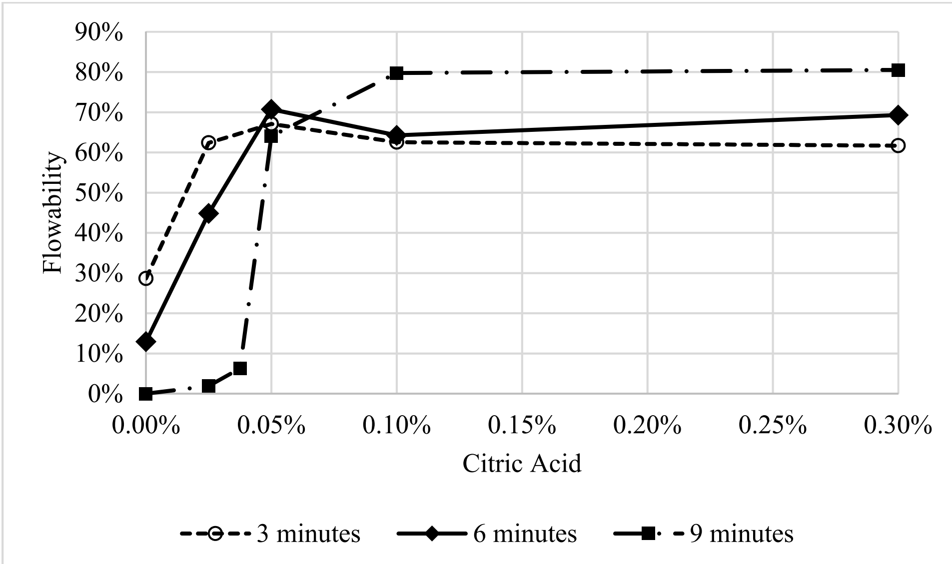


Figure 4-1: Flowability vs Citric Acid Content at w/c=0.35.

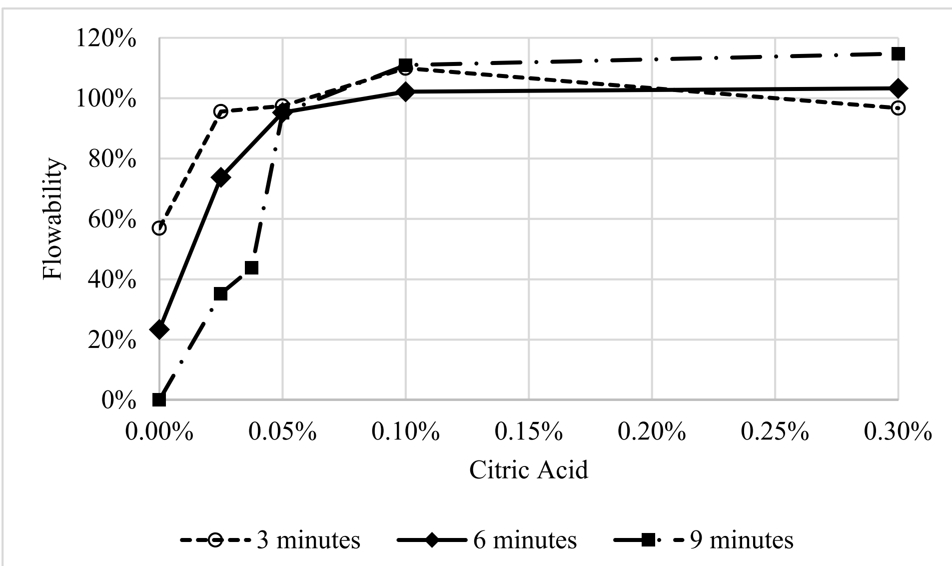


Figure 4-2: Flowability vs Citric Acid Content at w/c=0.40.

The standard deviations and maximum differences of the six-minute tests are shown in Table 4-2. The standard deviations ranged between 2.3% and 6.7%, with maximum differences between 4.7% and 13.4%. It is expected that the standard deviations and differences for the three- and nine-minute tests would be similar to those shown in the six-minute tests. Many of the standard deviations and maximum differences were greater than the allowable precisions of 4%

and 11%, respectively, as listed in ASTM C1437 Section 11.1 (ASTM International, 2020b), despite proper procedure being used. Virtually no enough data has been put forth regarding the flowability of CSA cement mortar, so these data can only be compared to the allowable precisions of conventional mortar. The somewhat higher deviations measured in these experiments are likely partially due to the short setting time of CSA cement. Because of how quickly this material sets, small differences in timing have a much greater effect than with ordinary Portland cement concrete. Regardless, the standard deviation and maximum difference, while not quite meeting the requirements of ASTM C1437, are not far from those requirements. As such, the results obtained here are still likely to be reasonably predictable, and the trends described above appear to have validity.

Table 4-2: Six Minute Flowability Deviations.

Citric Acid Content		0.000%	0.025%	0.050%	0.100%	0.300%
w/c = 0.35	St. Dev	2.3%	3.4%	4.7%	2.4%	4.1%
	Diff	4.7%	6.8%	8.9%	4.7%	8.1%
w/c = 0.40	St. Dev	5.1%	6.7%	4.2%	4.0%	4.2%
	Diff	10.0%	13.4%	8.0%	7.0%	7.3%

4.3.1 Effect of Time on Flowability

As set time increased, the shape of the curves and the initial flowability of the mixtures changed significantly. Three-minute tests exhibited substantial flowability with no citric acid. For the 9-minute tests, samples without citric acid had begun to set and therefore gave a flowability of zero. Additions of citric acid sharply increased flowability at both w/c ratios, indicating that a very small difference in citric acid content can substantially change the flowability of LMC-VES concrete. Trends in these data confirm the finding above that further gains to flow are not generally possible beyond a relatively low citric acid threshold of 0.05% to 0.1% by cement weight.

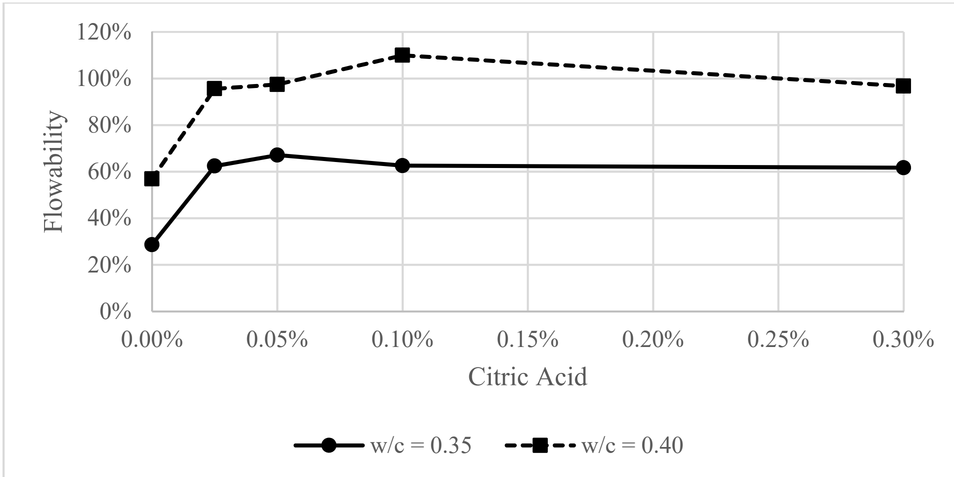


Figure 4-3: Flowability vs Citric Acid at 3 Minutes.

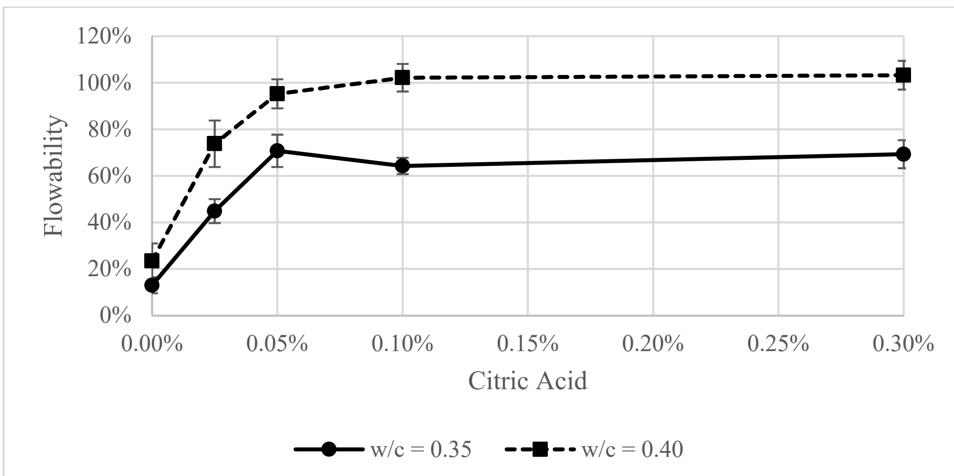


Figure 4-4: Average Flowability vs Citric Acid at 6 Minutes.

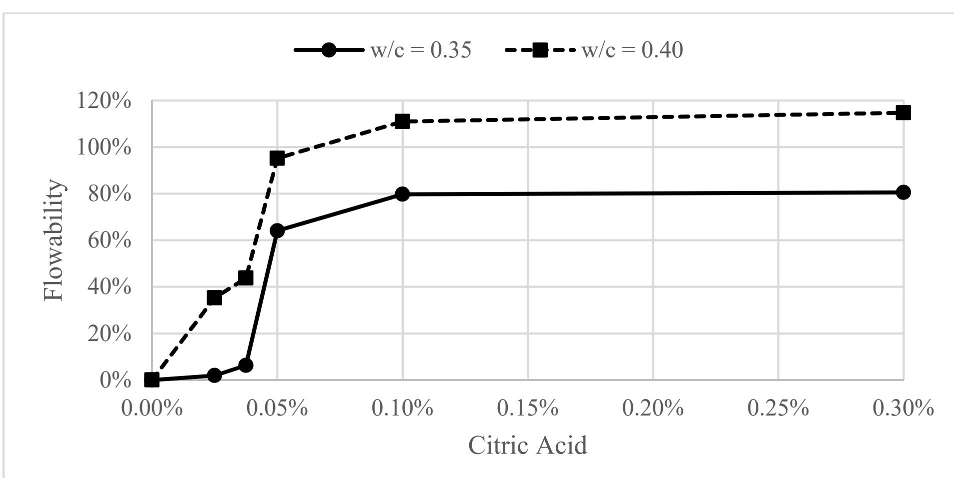


Figure 4-5: Flowability vs Citric Acid at 9 Minutes.

4.4 Summary and Conclusions on Citric Acid

To better understand the effects of citric acid on CSA cement, the influence of citric acid dosage on CSA cement mortar flowability was investigated. The impact of time and water content were also examined. The water-to-cement ratio is the main factor determining the magnitude of maximum flowability. The time of testing has a significant effect on flowability, determining both the threshold citric acid content required to reach maximum flowability and the shape of the flowability curve before reaching that threshold. The effect of adding a certain amount of citric acid is dependent on the amount of citric acid already in the system. Above the threshold content, a maximum flowability is quickly reached and not exceeded with additional citric acid dosage.

The difference in flowability between CSA concrete mixtures with 0.05% and 0.3% citric acid is minimal, and likely indistinguishable visually or with slump/flow tests. It is also likely, although not yet proven, that very high doses of citric acid (say 1% or more) do not impact workability beyond the effects of a 0.1% dose. In practical terms, this result indicates that once citric acid is added above the threshold that generates maximum workability (say 0.1%), the contractor and inspectors have no visual indication, even if slump tests are performed. While high doses of citric acid do not impact workability, they do degrade the final concrete properties. Thus, a contractor can dial up the citric acid "as required" on a LMC-VES overlay pour with no negative consequences at the time of casting.

In field applications, varying citric acid content throughout a single concrete pour can cause inconsistent flowability, in addition to variations in strength. The effects of citric acid on flowability should be considered when designing a CSA concrete mix, and should certainly be factored into the inspection process. It is advised that maximum citric acid dosage be specified by the mixture designer and regulated by specification, with inspection of 3 hour strength taking place at the maximum allowable citric acid content. The value of slump testing LMC-VES made with citric acid is questionable. A slump specification should be met with no citric acid in the mix (to limit water content) and a 3 hour strength specification should be met with maximum allowable citric acid in the mix (to verify the lowest strength material being produced).

Future research on this topic will need to focus on the effect citric acid has on the flowability of CSA concrete with aggregates (only mortar was studied here). The inclusion of aggregates and latex is vital to fully understanding the effects of citric acid on overall flowability in field applications.

5. Laboratory Scale Overlays

5.1 Introduction

This chapter describes a laboratory evaluation of cracking in larger-than-material scale LMC-VES overlay slabs. The effectiveness of fibers at reducing this cracking is also studied. Potential causes of cracking were outlined in Section 1.2. Notably, the current research aims to study the tendency of overlays to crack when subjected to vibration, akin to what may occur on a bridge deck with live traffic. Another important factor studied with these laboratory overlay slabs was the tendency of high temperature (specifically, large temperature increases) to cause cracking. Finally, the effect of LMC-VES overlay depth on cracking was investigated, as thermal effects through the overlay depth are postulated to contribute to cracking. Shrinkage of the overlay material was implicitly included in these experiments, but not isolated as a variable. Methods, findings, and analysis related to these experiments are provided in this chapter.

5.2 Vibration Testing Methods

The laboratory overlay and vibration portion of the experimental program consisted of casting overlay material onto a base slab having a surface roughness designed to simulate that typical of hydro demolition. A cross sectional schematic of the typical specimen is shown in Figure 5-1 with the LMC-VES overlay and Ordinary Portland cement Concrete (OPC) base slab indicated. The three LMC-VES mixtures selected for further experimentation in Section 3.5 (mixtures C, CA, and G.50.2) were tested. All mixed proportions remained the same as those outlined for these mixes in Section 3.2. The material tests in this chapter utilized the mixing method outlined in Appendix B.

Four overlay slabs were cast for each mix: two slabs at an overlay depth of one inch and two slabs at an overlay depth of three inches. One slab of each overlay depth was subjected to vibrations similar to those that might be experienced on a bridge deck during construction. The non-vibrated slabs were used to identify any cracking from sources other than vibration (shrinkage). While curing in the laboratory under specified curing conditions (wet burlap and plastic), slabs were visually checked for cracking every half hour up to three hours, again at four hours, and finally at five hours. After this, the plastic and burlap were removed and the slabs were then placed outside the laboratory in ambient outdoor conditions. They were regularly inspected for cracking over the next four weeks. A core was then taken from one specimen of each mixture at four weeks after casting to inspect the bonded interface between concrete base and LMC-VES overlay. Detailed results were outlined below, but in general, cracking was not observed.

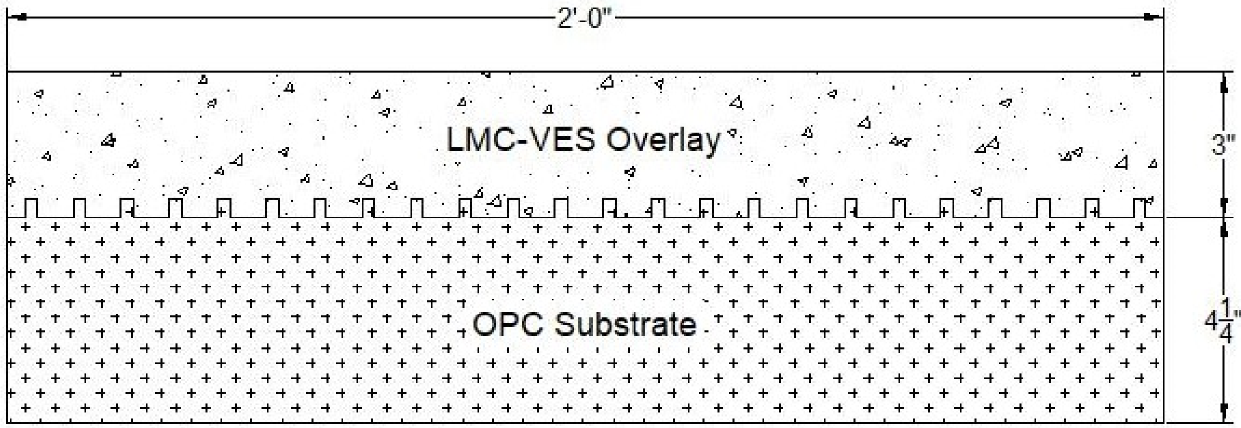


Figure 5-1: 3" Overlay Slab Cross Section.

5.2.1 Description and Creation of the OPC Base Slabs

Ordinary Portland cement Concrete (OPC) base slabs were designed to replicate the prepared bridge deck surface onto which overlays are typically cast. As described in the the construction procedure overview (Appendix A), the deck surface is cleaned and roughed by hydro demolition and scarification. The hydro demo process cuts through both cement paste and aggregate, leaving a very rough surface with both aggregates and cement exposed, as shown in Figure 5-2.


Figure 5-2: Typical Bridge Deck Surface after Hydro Demo.

Formwork for the base slabs was created from 7/16” thick oriented strand board and 2x8 lumber. The specimens intended for 3” thick overlays were 3’9” long and 2’0” wide with an OPC thickness of 4.25”. The one-inch-thick specimens were 1’9” long and 1’0” wide with an OPC thickness of 6..25”. The OPCC base material was cast to a level below the top of the formwork equal to the specified overlay depth (1” or 3”). A 0.5” thick rubber mat with holes

0.75” in diameter (Shown in Figure 5-3) was then used to replicate the typical hydro demo surface. The rubber mats were cut to size and coated in a surface retarder. Surface retarder is most commonly used to expose aggregates in concrete, allowing for the surface cement paste to be washed away after the remaining cement paste has already set. As the concrete began to reach its plastic state, the rubber was pressed into the top surface, as shown in Figure 5-4. After 24 hours, the rubber was removed, leaving the roughened surface (still coated in cement paste) shown in Figure 5-5. The base slab surfaces were then pressure washed, washing away the cement affected by the surface retarder, and exposing a roughed aggregate surface.

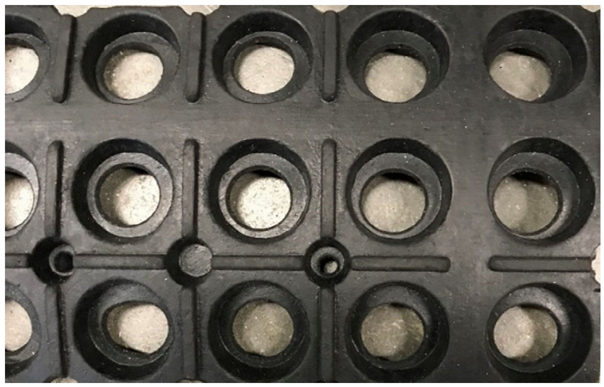


Figure 5-3: Rubber for Roughening Slab Surfaces.

Figure 5-4: Rubber Pressed into Base Slab Surfaces.

Figure 5-5: Intermediate Base Slab Surface (after removing mat, prior to pressure washing).

The final base slab surface is shown in Figure 5-6. A consistent, clean, and rough surface was achieved with both aggregates and cement paste exposed. A comparison of the laboratory base slab surface and the typical hydro demo surface is shown in Figure 5-7.

Figure 5-6: Final Base Slab Roughened Surface in the Laboratory.

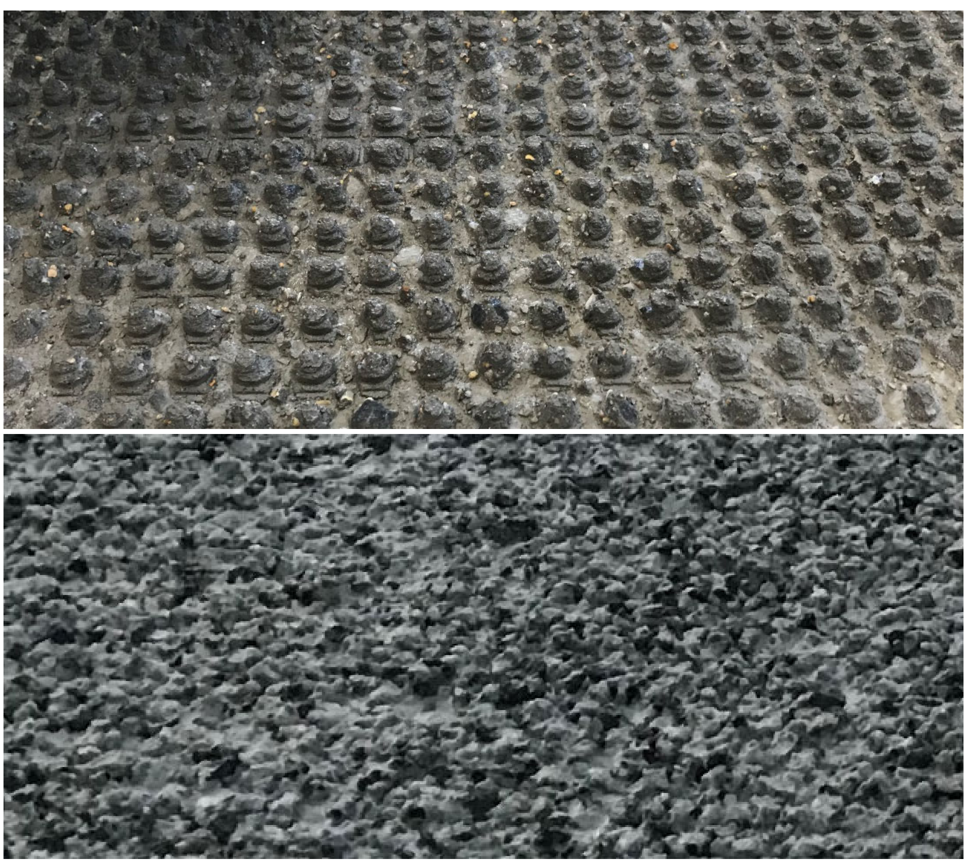


Figure 5-7: Comparison of Simulated Base Slab Surface (above) and Typical Scarified Bridge Deck Surface (below).

The concrete used for the base slabs was an NCDOT Class AA mixture provided by S.T. Wooten. The mixture design is provided in Table 5-1. The compressive strength of the base concrete at the time of LMC-VES overlay casting was 3.75 ksi.

Table 5-1: Slab Base Mixture Design.

Material	Quantity/yd^3
#67 Stone	1800 lb
Sand	1060 lb
Cement	565 lb
Flyash	160 lb
Air	2 oz
Midrange	42 oz
Recover	29 oz
Water	11 gal

Casting the LMC-VES Overlays

The casting process for the laboratory overlays mimicked that required by NCDOT. The base slab surface and formwork were cleaned and saturated with water. Excess water was then removed with compressed air, but the surface was left damp. Overlay concrete was mixed using the method described in Appendix B. The concrete was spread and leveled by hand and finished using a small vibrating screed, shown in Figure 5-8. After finishing, the surface was covered in two layers of wet burlap and a single layer of polyethylene plastic sheeting for three hours, per NCDOT PSP 004 (North Carolina Department of Transportation, 2019b). In the case of the vibrated specimens, the overlays were cast while the table was vibrating.

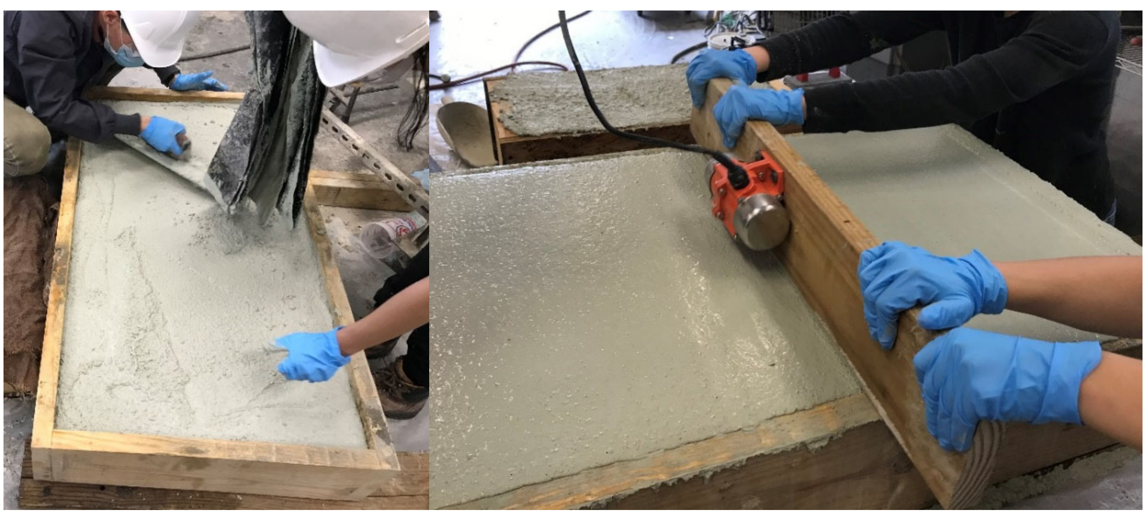


Figure 5-8: Casting and Finishing Laboratory Overlay Slabs.

5.2.2 Vibration

Bridge deck vibration was simulated using a vibration table manufactured by Cleveland Vibrator Company. The table was set to vibrate at a frequency of 6.5 Hz. The base slabs were placed on the table, and the overlays were cast while the table was vibrating. The specimens were then vibrated continuously for another five hours after casting. That specific length of time was chosen to encompass all setting of the concrete and to include significant time after the minimum three-hour traffic-ready requirement. By the five-hour point, the LMC-VES is well past its weakest stage and should not incur any new vibration-created cracking that would not have occurred earlier.

The acceleration of the vibration table was measured using three 50 m/s^2 ARF-A low-capacity acceleration transducers attached to the top of the base slabs (left on the table for their mass). The exact placement of these accelerometers is shown in Figure 5-9.

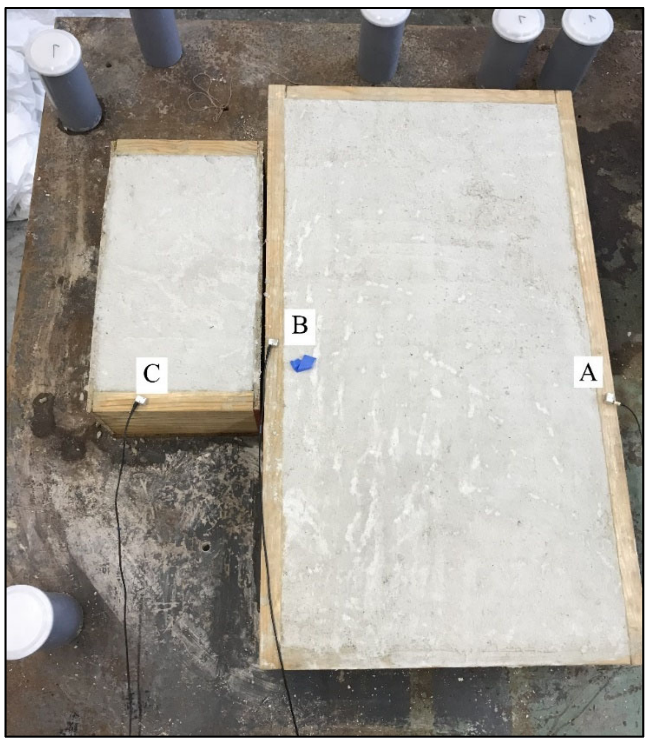


Figure 5-9: Accelerometer Placement.

A sinusoidal regression was performed on the data from each of the three accelerometers using the least sum of squared residuals method. The resulting peak to trough displacement amplitude, known as the double amplitude, was calculated. Results for each accelerometer are shown in Table 5-2. For reference, Harsh and Darwin used a double amplitude of 0.04 inches at a frequency of 4 Hz (Harsh & Darwin, 1986) to simulate bridge deck vibration. Levels used here were 6.5Hz (as slow as the available table would run) and a double amplitude of about 0.04 inches. For analysis purposes, the peak particle velocity and peak particle acceleration are considered as the best indication of the risk of damage (Manning, 1981). Results for each accelerometer are shown in Table 5-2. The amplitude and frequency of the vibration experiments well represented a level of vibration that could be reasonably expected on a typical bridge deck due to traffic and trucks.

Table 5-2: Sinusoidal Regression Results.

Accelerometer	A	B	C
Double Amplitude (in)	0.0491	0.0406	0.0368
Peak Particle Velocity (in/s)	1.0001	0.8274	0.7493
Peak Acceleration (in/s^2)	40.75	33.71	30.52

5.3 Temperature-Effects Testing Methods

The laboratory-scale overlay slabs tested for the effects of temperature changes during curing consisted of overlays cast on top of base slabs, similar to those used for vibration testing. The base slabs for the temperature testing were created in the same manner as those for the vibration tests described above. For each of the three tested LMC-VES mixtures, two overlays were cast, one with a depth of 1 inch and one with a depth of 3 inches. All specimens used for temperature testing were 12 inches by 16 inches to fit inside the available thermal chamber.

Because these overlay slab specimens were smaller, a drill mixer was used for casting the overlays, as shown in Figure 5-10. All slabs, formwork, and materials were equilibrated to laboratory ambient temperature (73F) prior to casting. Five minutes after casting, specimens were covered in wetted burlap and polyethylene sheeting, per NCDOT requirements. After the plastic sheeting was installed, specimens were placed in a pre-heated environmental chamber set to 97°F +/- 5°F (right side of Figure 5-10). As allowed by specification, the burlap and sheeting were removed after 3 hours of curing. The slabs were checked for cracking and then remained in the chamber for 22-24 additional hours. After this time, they were checked again, moved outside the laboratory, and routinely checked for cracking over the following 4 weeks.

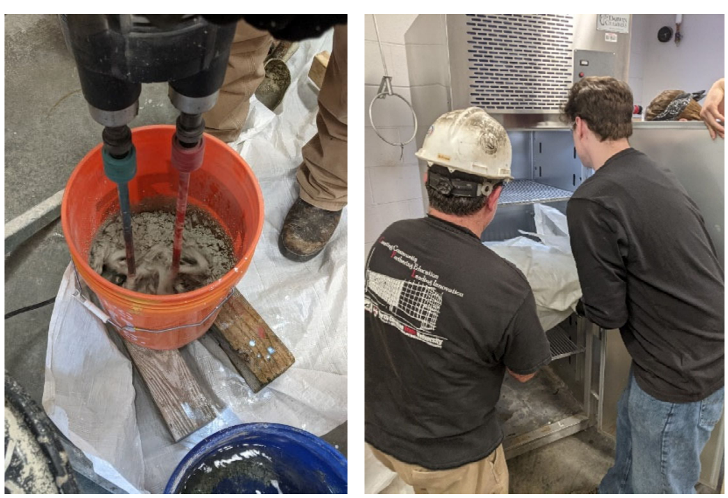


Figure 5-10: Mixing (left) and Curing (right) Specimens for Temperature-Effect Testing.

5.4Vibration Results, Analysis, and Discussion

5.4.1 Control (C) Specimens

There was no visible cracking at any stage after casting in either the vibrated or non-vibrated control specimens (no fibers, no citric acid). The surface of the vibrated specimens is shown in Figure 5-11 at 3 hours. A core taken from the 3-inch-thick non-vibrated sample is shown in Figure 5-12. As seen from the core, a good bond was achieved between the overlay and the base slab, and no cracking was detected at the interface. The surface of the 1-inch-thick specimens had cooled to roughly room temperature within 30 minutes of casting. The temperature of the 3-inch-thick specimens cooled to ambient after roughly two and a half hours. As expected, the thicker specimens exhibited a much greater total hydration heat and subsequently, a longer lasting thermal gradient.

Figure 5-11: C Vibrated Specimen Surface at 3 Hours (no cracks).

Figure 5-12: C 3-inch Slab Core (Overlay on top, OPC base slab on bottom).

5.4.2 Citric Acid (CA) Specimens

Some very small visible surface cracking, on the order of 1/8" in length, appeared on the CA control slabs (citric acid, no fiber) about one hour after casting, as shown in Figure 5-13. This cracking was much more prevalent on the vibrated slabs. However, these cracks were superficial, short and shallow, not structural. Aside from these trivial surface cracks, there was no substantial cracking for any of the CA specimens at any point in the experiment. It is again worth noting that the amount of citric acid used here was at the low end of the dosing often used in the field. A higher citric acid content might cause the observed microcracks to develop at a more significant levels.

The surface of the vibrated specimens at three hours after casting is shown in Figure 5-14. A core taken from the 3-inch-thick non-vibrated sample is shown in Figure 5-15. Similar to the control test without citric acid, a complete bond was developed between the overlay and the base slab, and no cracking was detected at the interface. The surface of the 1-inch-thick specimens cooled to around room temperature within 45 minutes after casting. The surface of the 3-inch-thick specimens cooled to room temperature between three and four hours after casting. Again, the deeper the specimens, the more total hydration heat was generated. The addition of citric acid seemed to cause the specimens to emit heat for longer after casting, similar to the findings of Burris and Kurtis (Burris & Kurtis, 2018).

Figure 5-13: Very Minor Surface Cracking in CA Specimens.

Figure 5-14: CA Vibrated Specimens at 3 Hours.

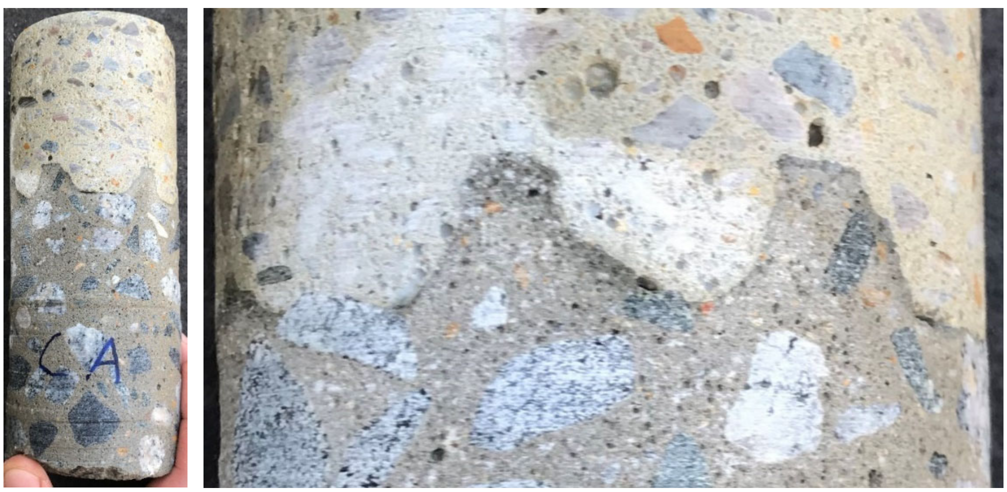


Figure 5-15: CA 3-inch Slab Core.

5.4.3 Glass Fiber (G.50.2) Specimen

The G.50.2 three-inch-thick overlay specimens showed the same small, superficial cracking as did the CA specimen (both had citric acid). Similar to the CA mixture, no substantial cracking was observed for any G.50.2 specimens at any point through the 4 weeks observed. The surface of the vibrated specimens at three hours after casting is shown in Figure 5-16. The surface finish was not affected by the inclusion of fibers. A core taken from the 3-inch-thick vibrated sample is shown in Figure 5-17. Once again, a good bond was developed between the overlay and the base slab, and no cracking was detected at the interface. The inclusion of fibers did not appear to impact the interface between OPC and LMC-VES at all. As expected, the surface temperature behavior of G.50.2 was similar to the CA specimens.

Figure 5-16: G.50.2 Vibrated Specimens at 3 Hours.

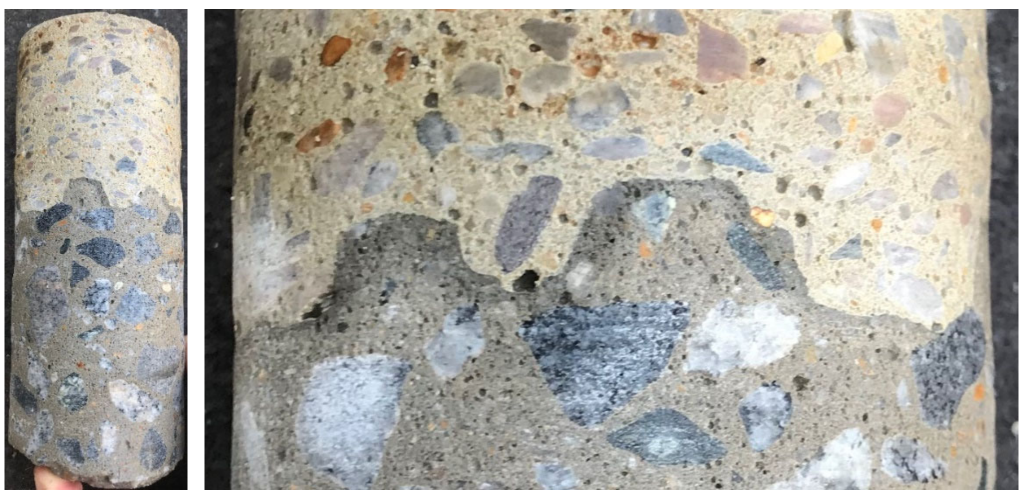


Figure 5-17: G.50.2 3-inch Slab Core (overlay material on top and OPC slab on bottom).

5.5 Temperature Effect Results, Analysis, and Discussion

5.5.1 Control (C) Specimens

The first pair of specimens tested for temperature were the control mixture (no fibers, no citric acid). These control specimens used the mixture design shown in Table 3-1. There was no visible cracking at any point on either specimen through the 4 weeks observed. The resulting surface is shown in Figure 5-18. As no cracking occurred, fibers were deemed unnecessary to control temperature effects when citric acid is not used.

Figure 5-18: Control Specimens at 3" (left) and 1" (right) in Depth.

5.5.2 Citric Acid Specimen

The CA specimens added 0.1% citric acid to the standard control mix design (by cement weight). Once again, there was no visible cracking on either specimen through the 4 weeks observed. The specimen surface is shown in Figure 5-19. Due to the lack of cracking, fibers were deemed not necessary to control thermal effects for mixtures having low amounts of citric acid.

Figure 5-19: CA Citric Acid Specimens at 3" (left) and 1" (right).

5.5.3 Higher Citric Acid Content Specimen

As none of the previous specimens displayed any cracking, including tests with fibers was not relevant. Thus, it was instead decided to do a final test at a much higher citric acid content. For these specimens, citric acid was added to the control mixture at 0.95% of cement weight. This dosage was chosen because it is slightly higher than the approximate maximum dosage used by the construction crew on the field trial (discussed below).

With this dosage of citric acid, at three hours when the burlap and plastic were removed, the concrete was not completely set. While the surface was hard, it was still somewhat malleable and easily scratched by hand. Strictly speaking, it was not cracked, but would easily crack if deformed or flexed. The top layer of cement paste could be removed by rubbing the surface with a glove. The increased malleability of this mixture is also evidenced by the impression of the burlap pattern onto the surface. The resulting surfaces are shown in Figure 5-20.

Figure 5-20: High Citric Acid Specimens at 3" (left) and 1" (right) in Depth.

5.6 Summary of Laboratory Scale Slabs

The purpose of the laboratory overlay slab tests was to investigate depth, temperature, and vibration as possible causes of cracking in LMC-VES overlays. To achieve this goal, overlays of different thickness, fiber contents, and citric acid contents were cast on top of ordinary concrete base slabs with simulated hydro demo surfaces. No significant cracking was found for any combination of depth, mix design, and vibration. Cores taken from cured samples (along with the specimen sides exposed by formwork removal) showed an excellent bond between the two surfaces in all cases. For the temperature effects testing, no significant cracks developed at any combination of depth and citric acid content. Due to the small size of the environmental chamber, the evaporation rate on the specimens was likely not as great as it would have been in the field at the similar temperatures. However, the thermal shock of the laboratory experiments was probably greater than anything typical of the field. While cracking did not technically develop in a specimen with 0.95% citric acid, curing of this specimen was incomplete at 3 hours when burlap and plastic were removed. In a field setting, such interrupted curing (even to a lesser degree) could be problematic. Based on the results, when proper construction procedure is followed and citric acid is used at a reasonably low dose, cracking in LMC-VES overlays should not occur due to vibration, temperature, or shrinkage at depths up to three inches. Thus, fibers should not be necessary to mitigate the effects of vibration, temperature, or shrinkage. Fibers could be used to possibly mitigate the effects of heavy citric acid use, but this seems like the wrong prescription for the problem. Controlling citric acid use is the wiser approach.

6. Full-Scale Field Trial

6.1 Introduction

A full-scale field trial of a fiber-reinforced LMC-VES overlay was performed to investigate whether the addition of fiber would be practical at scale. In particular, the trial was intended to evaluate LMC-VES construction methods and their compatibility with fiber. The trial also aimed to explore the degree of variability in the overlay concrete properties and to evaluate current methods of inspection. The trial project consisted of a four lane, four span bridge along US 64 over Interstate 40 in Mocksville, North Carolina. While all four lanes were overlaid with LMC-VES, only three were used for this research. Lane numbers in this report are assigned sequentially in the order they were poured. The nominal overlay depth was 1 inch for three spans and 1.25 inches for one span. The trial bridge is heavily trafficked and subjected to frequent truck loads. The overlays were completed one lane at a time. The first lane poured did not include any fibers. The second lane poured included fibers and used a fiber dispensing system mounted to the volumetric mixing equipment. The third lane poured included fibers dispensed into the mixing auger by hand. The selected fiber was Forta Mobile Mesh ½” precut AR glass at 2 lbs. per cubic yard. The pre-construction state of the bridge is shown in Figure 6-1.

Figure 6-1: Bridge Prior to Overlay.

Table 6-1: Outline of the Field Trial

<table>
<tr><th>Lane Poured</th><th>Overlay Material</th><th>Fibers</th><th>Fiber Dosing</th><th>Field Data</th></tr>
<tr><td>#1</td><td rowspan="4">LMC-VES</td><td colspan="2">None</td><td rowspan="2">- Observations
- Slump
- Compression Cylinders</td></tr>
<tr><td>#2</td><td rowspan="2">AR Glass, ½” long, precut

2 lbs. per cubic yard dosage target</td><td>Into mixing auger with mechanical feeder</td></tr>
<tr><td>#3</td><td>Into mixing auger by hand from pre-measured cups</td><td>Observations Only</td></tr>
<tr><td>#4</td><td colspan="2">None</td><td>Not Studied</td></tr>
</table>

6.2 Field Observations

As a part of the project, the overlay casting process was observed in detail to identify any potential areas of concern or opportunities for improvement. Photos of the general process are shown in Figure 6-2 through Figure 6-4. Two or three trucks per lane were used, one immediately after the other.

Figure 6-2: Truck Operation.

Figure 6-3: Concrete Placement (left) and Bidwell Screed (right).

Figure 6-4: Finishing and Burlap.

Generally, the process of spreading, vibrating, screeding, finishing, and curing the concrete was performed in a satisfactory manner. The crew was professional and experienced, maintained a constant pace, and communicated well with the truck operator. Wet burlap and plastic were installed rapidly behind the finishing screed. Yet, there were several potential areas of concern identified: inspection, use of uncontrolled retarder, and fiber dispersion.

6.2.1 Observations on the Inspection Process

When measuring slump and air content and casting cylinders, common practice (and approved quality control plans) seem to dictate that an inspector should obtain a representative sample of concrete after the continuous mixer has reached a homogeneous mixture, but before any concrete is placed on the bridge. It is noted that this requirement is not specifically stated in the NCDOT Standard Specifications for Roads and Structures or PSP 004. NCDOT PSP 008 on Volumetric Mixers does note that the first 3 cubic feet of material initially discharged from the mixer should be discarded, but specific details on when, where, and under what time constrains to sample LMC-VES are not spelled out in detail in the relevant specification documents. For the project observed, trucks would pull into an inspection area at the edge of the project, initiate mixing, discard a small portion of mixed material, provide the inspector with a sample, and then proceed onto the bridge.

Figure 6-5: Preparing to Discharge Initial LMC-VES in the Inspection Area.

For the trucks observed in this study, the onsite inspector would take a sample early in the initial discharge process, arguably before a truly representative mixture was achieved. Understandably, mixer operators were not inclined to discard more concrete than absolutely necessary in the inspection area, and the inspectors were not inclined to take samples from any location other than the designated sampling area. In multiple observed cases, the sampled concrete was soupy (too wet) and did not (or obviously would not) initially pass slump requirements. Usually, the inspector would dump out an excessively wet sample prior to testing, the machine operator would make an adjustment, and a new sample would be obtained. In one such case, an inspector was observed to tell another to simply let the wet sample sit for five minutes prior to running the slump test, which would enable the concrete to pass. The comment was seemingly made in good faith, with the inspector thinking he was making a helpful suggestion to facilitate the process. In this case, the inspectors waited, the concrete was allowed to stiffen, and it artificially passed the slump requirement. This one example is anecdotal, but it illustrates the potential for inadequately trained inspection and mixer crews to dramatically influence the quality of overlay concrete. This anecdote also illustrates the need for more specific guidance to be included in Specifications or PSPs on sampling and inspecting LMC-VES. Crews inspecting LMC-VES in particular should be specially trained on the specifics of the material. A crew familiar with inspecting ordinary concrete, or even regular LMC, may not automatically have the background to properly inspect LMC-VES without additional training.

It was observed that the mixer operator would usually continue to make adjustments (citric acid) throughout the first cubic yard or so of concrete poured on the deck until a truly homogenous mixture with the desired level of workability and set time was achieved. Therefore, samples taken by inspectors at the beginning of the mixing process are not likely representative of the final LMC-VES mixture as installed on the bridge. It is also likely that overlay concrete quality varies significantly over the length of a pour, particularly in areas where trucks initiate their initial discharge. It should be noted that variable concrete does not necessarily indicate bad concrete, as it is possible that all variations meet specification. However, the inspection process as implemented is not capable of determining whether the concrete actually placed on the deck meets specification. The current inspections can only demonstrate that the materials in a given truck are capable of meeting specification with the settings used in the inspection area.

For reference, ASTM C172: *Standard Practice for Sampling Freshly Mixed Concrete* Section 5.2.4 suggests at least 5 cubic feet of material be discharged <u>after</u> all proportioning adjustments have been made before sampling (ASTM International, 2017a). Additionally, it was observed on the field project that the inspection team would usually determine their final slump and air content results only after concrete was already being placed on the deck. In one case, during the time inspectors were running tests on sampled concrete, the volumetric truck left the sampling area and started pouring material on the bridge deck. When inspectors indicated the material did not pass, the truck had to be called back to the sampling area and retested after adjustments were made. As a result, the first portion of the overlay was cast using substandard concrete (Figure 6-6), which was later removed and replaced.

Some practical limitations regarding inspection should be outlined. Requiring a truck to discharge enough material in the inspection area to truly achieve a consistent and homogenous mixture would be wasteful and difficult (likely a cubic yard or more of material would need to be discharged). Forcing a truck to sit in the inspection area while tests are completed, at least for LMC-VES, would mean the mixed and partially-mixed material sitting in the auger would stiffen or even harden, which is obviously undesirable. Cleaning out the auger after sampling is possible, but not efficient, and would necessitate re-initializing the mixing process on the bridge, which would defeat the purpose of waiting in the sampling area to begin with. Thus, it may not be practical for trucks to wait while inspection samples are completed, at least when LMC-VES is involved.

Figure 6-6: Substandard LMC-VES Concrete (Ripped out Later).

Another factor that must be considered with regards to reviewing the inspection process on this field trial is that the crews were being observed by many individuals not typically present on a jobsite - researchers from NC State and many additional NCDOT personnel. In addition, the particular work site did not have the time pressure associated with many LMC-VES projects (there was no requirement to reopen these lanes with a short time window). As such, the inspection procedures and quality control observed on this project are likely typical or better than those completed elsewhere under more time pressure with less oversight.

This above discussion should not be interpreted criticism of any particular inspectors, but rather should be viewed as highlighting the importance of careful LMC-VES inspection by a well-trained, diligent inspection crew. Training for inspection crews working with LMC-VES can likely be improved, and specification documents can also be improved to provide more specific guidance on inspection procedures. Proposed changes to specification documents are presented later in this chapter.

6.2.2 Observations on Citric Acid

On the approved LMC-VES mixture design, citric acid retarder was listed “as needed”, which is typical of these mixture submittals according to NCDOT personnel. During mixing, citric acid can be turned on and off, and the dosage adjusted at will by the truck operator. On the trial project, the operator did not introduce citric acid to the mixture until pouring concrete on the bridge deck was well underway. This approach is allowable per the project documents, and the contractor on the trial project did nothing wrong in this regard. However, the “as needed” approach means that the sample of LMC-VES taken by the inspector did not include citric acid (nor was it required to).

As discussed in Chapter 4, citric acid has substantial effects on the flowability of the LMC-VES concrete, up to a certain threshold. By adjusting citric acid as needed, a mixer operator can increase (or decrease) LMC-VES slump at any given time to provide the crew a more (or less) workable mix. Ability to adjust workability without adding water is not necessarily a bad thing, as workability of the concrete mixture plays a role in the quality of the finished overlay. However, when citric acid is added post-inspection with no upper or lower limits, effects of the retarder on compressive strength are not accounted for. As demonstrated in the laboratory-scale tests, effects of citric acid on LMC-VES strength, particularly early strength at 3 hours, can be important. Laboratory tests also implied that excessively high doses of citric acid could enable conditions more likely to exhibit cracking. Essentially, the specifications as written allow a contractor to adjust flowability (slump) and work time as desired without being held responsible for any side effects of citric acid on compressive strength and overlay performance. It appears that this situation has the potential to leave NCDOT with a subpar overlay, and could even explain some prior instances of unexplained overlay cracking. Figure 6-7 shows areas of distinctly different piles of fresh concrete on the field trial as the truck operator transitioned citric acid into the mixture. Notice the change in both consistency and color of the most recent line of concrete (left) relative to the previous lines.

While the contractor did not appear to use extreme levels of citric acid on this specific project, it is worth noting they were following the specification as written and are allowed to use citric acid as desired. It should also be noted that the contractor working on this particular field trial was excellent, had tremendous experience with and working knowledge of LMC-VES, and did an excellent job with many extra observers present. The crew was professional and well prepared, in compliance with NCDOT specifications, and was willing to work with the research team. The contractor provided much helpful insight into the intricacies of working with LMC-VES, and the researchers are grateful their support. The discussion in this report should not be viewed as criticism of the contractors or inspectors, but rather, is intended to point out areas in the typical specifications and construction processes that may contribute to lower-than-desired overlay quality and increased cracking risk.

Figure 6-7: Transition to Retarder (citric acid at left, no citric acid at right).

As a final note on citric acid in the field trial, the exact formula for the retarder used by this contractor is a trade secret, and therefore, is not included in this report. Based on available information, it is estimated that citric acid dosages in this field trial tended to average around 0.425% of cement weight with up to about 0.850% used during periods of hot temperature. For reference, Burris and Kurtis tested the effect of citric acid content on setting time for two different CSA cement mortars. For the CSA cement most similar with that used on this field project, they found that 0.5% citric acid by weight of cement increased the initial setting time by 16 minutes (320%) and the final set time by 18 minutes (180%) compared to plain CSA cement mortar; 1.0% citric acid increased initial set by 36 minutes (720%) and final set by 50 minutes (500%) (Burris & Kurtis, 2018).

The laboratory-scale material tests performed on LMC-VES with citric acid indicate that citric acid dosage in the ranges used on the field trial are likely to reduce concrete strength compared to a control mixture with no citric acid. However, there is no known literature on the effects of citric acid on LMC-VES (ie: CSA cement with latex and aggregate). As discussed in Section 3.4.1 and in Figure 3-3, the presence of citric acid does delay strength development of LMC-VES at dosage levels far below those used on the field trial. It is reasonable to assume that long delays in set time and strength development could make an LMC-VES overlay more prone to cracking due to temperature, vibration, plastic shrinkage (Smyl et al., 2016), and other sources. As the amount of citric acid used in the field appears to be far higher than that used in the laboratory research of this project, more study on this issue would be useful to draw a firm conclusion.

6.2.3 Observations on Fiber Dispersion

The fibers chosen for the second and third lanes of the field trial had issues with dispersion. The fiber used for both was an AR glass fiber. AR glass fibers are manufactured as individual filaments and then 'sized,' a process where multiple fiber filaments are bundled together as a strand with a sizing agent. The AR glass fibers used as a part of the field trial are different from those used in the laboratory trials of Chapter 4. A comparison of the properties of these two similar glass fibers is shown in Table 6-2. Field fibers were selected after laboratory fibers, and field fiber selection was guided by fiber feeder equipment available to the contractor at the time of the field trial.

Table 6-2: Laboratory and Field Fiber Comparison.

Use	Filament Diameter (mm)	Filament Aspect Ratio	Sizing Agent	Bundle Diameter (mm)	Bundle Aspect Ratio
Lab	0.01	1270	vinyl acetate	0.109	117
Field	0.018	706	coupling agent, film former and polymeric resin/emulsion	0.109	117

Of significant importance, the particular glass fibers used in the laboratory-scale tests easily dispersed from their sizing during drill and volumetric mixing in the laboratory. Therefore, the fibers acted as individual filaments, with each filament fully encased in the surrounding concrete. On the other hand, the fibers used in the field trial largely remained in their original small bundles during and after mixing. The resulting discrete bundles of fiber are shown circled in red in the LMC-VES in Figure 6-8. The fiber bundles were dispersed throughout the concrete, but the bundles themselves did not break apart well, limiting dispersion of individual filaments throughout the mixture. Likely causes of this poor dispersion are a lack of sufficient solubility of the sizing in water or a lack of sufficient mixing energy (agitation over time) in the auger. Fibers developed for a drum mixing process may not be suitable to the very short mixing times typical of volumetric mixing.

With poor fiber dispersion, only the filaments on the outside surface of each bundle had any contact with concrete. Thus, the vast majority of filaments were likely not bonded with the surrounding concrete, and subsequently, the bundles failed by pullout. With most filaments kept together in the bundles, any benefit from fibers in Lane 2 of the field trial was unlikely.

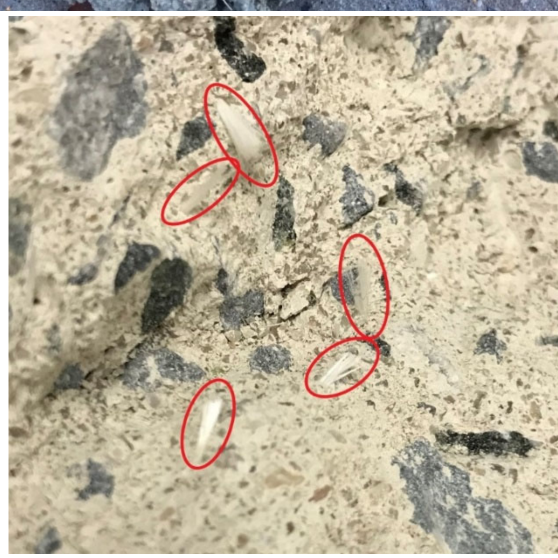


Figure 6-8: Poor Fiber Dispersion in Fresh (top) and Hardened (bottom) Concrete.

Samples of the two similar fibers shown in Table 6-2 were immersed in tap water in the laboratory for 5 minutes. The "lab" fiber broke apart easily in water while the "field" fiber remained clumped in bundles, as shown in Figure 6-9. The clumps of "field" fiber could be easily broken apart by light agitation, whereas the "lab" fiber largely separated on its own. This difference in behavior highlights the need to select a fiber for volumetric mixing that has been qualified and tested with that process. Fibers developed for drum mixing may not automatically be suitable for continuous volumetric mixing.

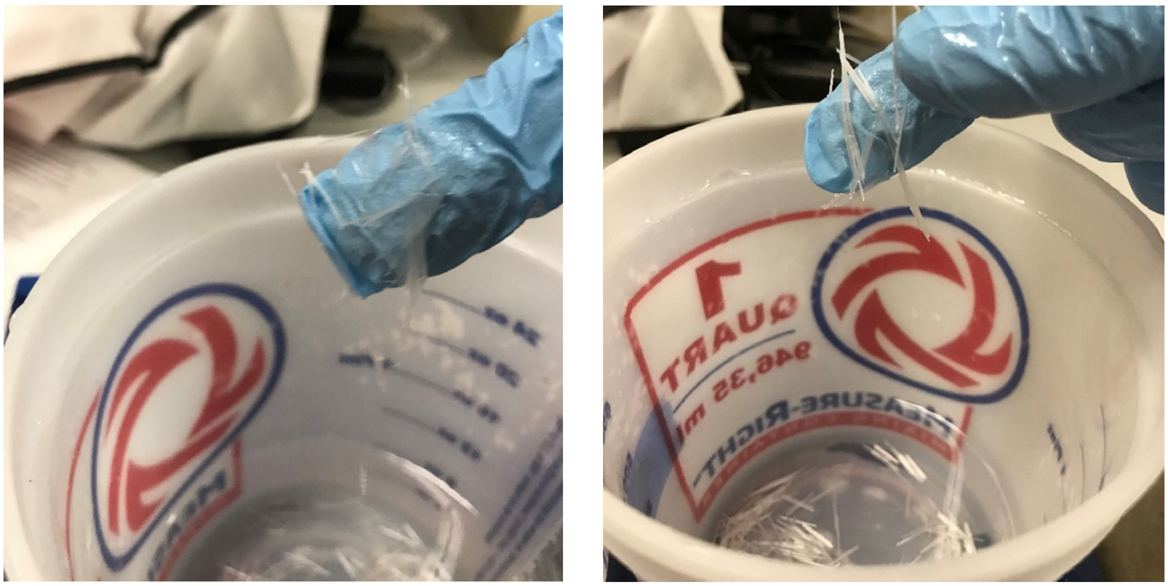


Figure 6-9: Dispersion after 5 Minutes in Water for Lab Fibers (left) and Field Fibers (right)

6.3 Fiber Dispenser System

The fiber dispenser system used for the field trial was a precut fiber dispenser (the Ranger made by Forta Corporation). A schematic of the system and a photograph of the system on the mixing truck is shown in Figure 6-10. More background information on fiber dispensing is provided in the literature review in the Appendix (see A.3).

The Ranger used on this field trial is powered by the hydraulic system of the continuous mixing truck. Pressurized hydraulic fluid flows through a variable flow valve operated by an electronic control box. The variable valve controls the rate of fluid flow to the auger drive motor. This motor runs both the agitator and discharge auger through a series of gears. The agitator fluffs up fibers in the drum before they enter the discharge auger. The discharge auger transports the fibers down and out of the discharge tube into the mixer. The variable valve controls the rate of hydraulic fluid flow to the auger motor, and thus, the rotational speed of the auger and discharge rate of fiber.

After passing through the first motor, the hydraulic fluid flows to a second motor. This motor controls the declumper fan at the end of the discharge tube. This fan breaks up clumps of fiber as they exit through the discharge chute. As the hydraulic motors are plumbed in series, the speed of the second motor is locked in a fixed ratio with the first. That is, as the variable valve is used to slow down the rate of fiber discharge, the declumper fan slows down in proportion.

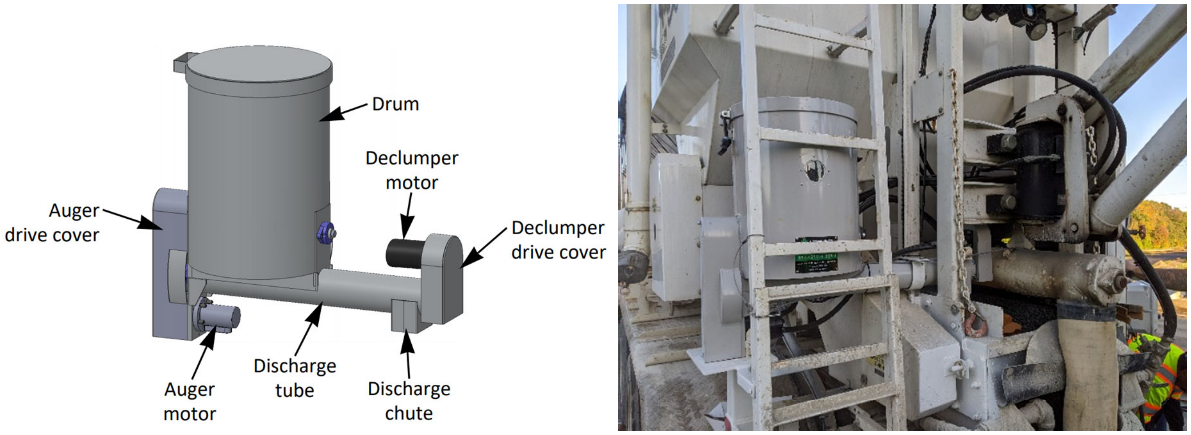


Figure 6-10: Ranger Schematic by Forta (left) and Photo on Field Trial Truck (right).

Fiber dispensers were used on the second lane of the field trial (one dispenser on each of two trucks). Throughout the entire lane, the fiber dispensers on both trucks did not deliver a constant rate of fiber addition. Each dispenser would intermittently operate at a fast rate followed by a stalled period instead of operating at a consistent slow rate. The resulting mixture was inconsistent from the perspective of fiber distribution, with some areas of concrete having far more fiber than was specified and some having no fiber at all. Post-inspection by the research team of the equipment at the contract's yard revealed that issues with the fiber dispensers had a lot to do with an incompatibility between the hydraulic design of the dispenser and the hydraulic system of the mixing truck. The truck operated with large fixed-displacement gear pumps and open-center hydraulics (constant oil flow at highly variable pressure). The dispensers required a small oil flow at constant pressure which the truck could not deliver without generating significant heat by bypassing the excess flow. On the job site, operating another hydraulic function on the truck (mixing auger on/off, up/down, or left/right) would cause a large pressure change to the dispenser hydraulic supply. As such, the fiber feeders were abandoned for the 3rd lane poured, and the contractor instead assigned personnel to meter fiber into the mixing auger by hand using pre-measured cups and a stopwatch. Hand feeding was inefficient, and impractical for anything other than a short trial, but it did appear to create fiber delivery that was less inconsistent than the mechanized feeders. A fiber feeder designed with variable-speed electric motors would likely be a better choice for many contractors.

To meet the required 2 lb./yd^3 of fiber, the fiber dispensing auger of the feeder used on the field trial needed to run at a very low speed – near the bottom end of what the unit was capable of. Slow speed control was hampered by limited electrical settings for the variable valve in low speed (pulse width modulated valve could not operate at low counts). In addition, the slow-running declumper fan was easily stalled by a buildup of fibers. Stalling of the declumper contributed to the intermittent starting and stopping of fibers dispensed into the mix.

After the field trial, NCSU borrowed the fiber dispensing system to inspect it in the laboratory. At this time, the feeder design having two hydraulic motors plumbed in series was discovered. To prevent the declumper motor from stalling, the hydraulic system was plumbed to run the declumper motor in parallel with the system supply, ahead of the variable control valve. Thus, the declumper motor would run at full speed whenever the system had hydraulic pressure, even if the auger motor was running slowly or not at all. An additional hydraulic solenoid valve will be required before putting the system back in field service so that the declumper motor can be turned on and off with the fiber feeder control system.

Laboratory adjustments to the feeder hydraulics resulted the declumper not stalling in laboratory benchtop trials (operating the fiber feeder not on a truck). However, even the high speed declumper motor did not help to break up the fiber bundles from their sizing as was hoped. Consequently, while the introduction of fibers to the mixing auger would have been much more uniform with the adjusted dispenser, the fibers would still not have dispersed from their bundles in the concrete.

In summary, the trialed combination of fiber feeder, truck hydraulics, and selected fiber were found to be inadequate for use in volumetrically mixed LMC-VES. It is possible that modifications to all systems could provide improved performance.

6.4 Compressive Strength and Slump

During the field trial, LMC-VES concrete was sampled at selected intervals and locations, compressive strength cylinders were cast and tested, and slump tests were performed to evaluate concrete properties over the duration of the construction process. Research cylinders were also taken in the inspection area at the time NCDOT cylinders were taken at the beginning of each truckload of material. Additional research cylinders were taken approximately at the ¼, ½, and ¾ points through each truckload. Slump testing was performed at the beginning and midpoint of selected truckloads. Concrete was sampled directly from the volumetric mixer on the bridge deck as LMC-VES was flowing onto the bridge, except for the initial samples taken in the inspection area. NCSU mobilized compression testing equipment to the jobsite to enable testing a large number of cylinders at 1, 3, and 9 hours after testing (Figure 6-11). Additional cylinders were transported back to the laboratory in Raleigh for testing at 24 and 72 hours.

Figure 6-11: Compression Testing Equipment (in a Truck) on the Field Trial.

Figure 6-12: Typical Slump Test at the Field Trial

6.4.1 Compressive Strength Testing

LMC-VES compressive strength was tested in accordance with ASTM C39 (ASTM International, 2021a). Cylinders sized 4” x 8” were used. The beginning and midpoint cylinders were tested at 1, 3, 9, 24, and 72 hours. The quarter and three-quarter point cylinders were tested at three hours only. For the third lane of the field trial, compressive strength was only measured at nine hours after casting, and cylinders were only taken from the midpoint of each truckload. For the second lane poured (concrete with fibers using the mechanical fiber dispenser), the second truck sprung a hydraulic leak just over ¼ of the way through its load and was replaced with a third truck to finish the lane. A summary of all compression tests taken is presented in Table 6-3 and a summary of results is presented in Table 6-4.

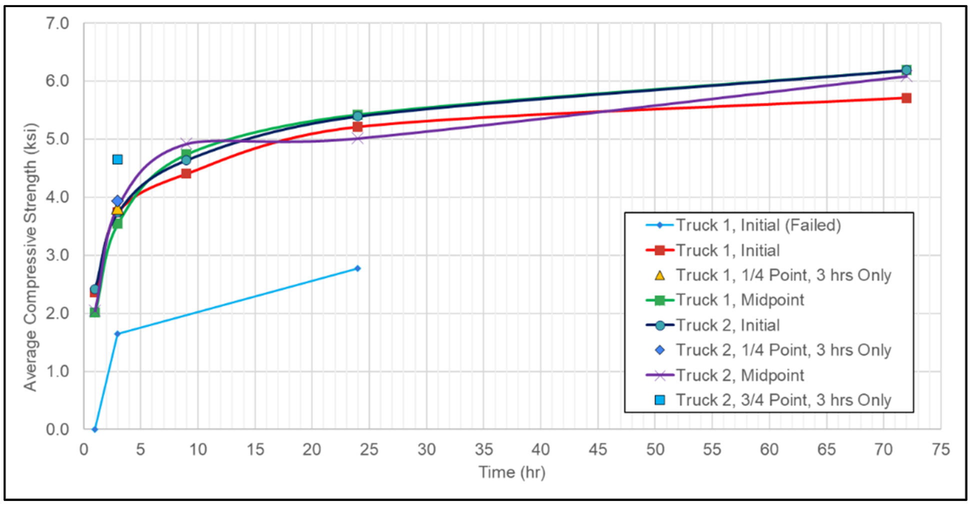
Table 6-3: Points of Compression Testing on Field Trial

Lane	Truck	Time	Test Time (2 or 3 Cylinders Averaged per Test)				
			1 hour	3 hours	9 hours	24 hours	72 hours
1 (no fiber)	1	Initial, Fail	x	x		x	
		Initial, Retest	x	x	x	x	x
		1/4 Point		x			
		Midpoint	x	x	x	x	x
	2	Initial	x	x	x	x	x
		1/4 Point		x			
		Midpoint	x	x	x	x	x
		3/4 Point		x			
2 (fiber by feeder)	1	Initial, Fail	x	x	x	x	
		Initial, Retest	x	x	x	x	x
		1/4 Point		x			
		Midpoint	x	x	x	x	x
		3/4 Point		x			
	2	Initial	x	x	x	x	x
		1/4 Point		x			
	3	Initial	x	x	x	x	x
		Midpoint	x	x	x	x	x
3 (fiber by hand)	1	Midpoint			x		
	2	Midpoint			x		

Table 6-4: Compression Testing Results from Field Trial

Lane	Truck	Time	Test Time (2 or 3 Cylinders Averaged per Test)				
			1 hour	3 hours	9 hours	24 hours	72 hours
1 (no fiber)	1	Initial, Fail	0.00	1.65	-	2.77	-
		Initial, Retest	2.36	3.74	4.40	5.21	5.71
		1/4 Point	-	3.81	-	-	-
		Midpoint	2.01	3.55	4.74	5.42	6.19
	2	Initial	2.42	3.74	4.64	5.39	6.19
		1/4 Point	-	3.94	-	-	-
		Midpoint	2.05	3.85	4.92	5.02	6.09
		3/4 Point	-	4.64	-	-	-
2 (fiber by feeder)	1	Initial, Fail	0.00	3.04	4.17	5.42	-
		Initial, Retest	0.00	3.90	4.82	6.22	6.47
		1/4 Point	-	3.92	-	-	-
		Midpoint	2.64	4.18	4.71	5.66	5.98
		3/4 Point	-	3.74	-	-	-
	2	Initial	2.28	3.42	4.47	4.99	5.37
		1/4 Point	-	3.83	-	-	-
	3	Initial	1.90	2.91	3.69	4.01	4.25
		Midpoint	1.16	3.88	5.58	5.50	5.97
3 (fiber by hand)	1	Midpoint	-	-	4.98	-	-
	2	Midpoint	-	-	5.88	-	-

All cylinder results shown in the tables above and the figures below are the average of two or three individual cylinder tests. The same average data shown in the tables above are plotted versus time in Figure 6-13 (a) for Lane 1 and (b) Lane 2. Data indicate very high scatter in compressive strengths early in the overlay curing process, through about 24 hours. Scatter at 1 hour and at 3 hours is tremendous, with some samples showing no strength at 1 hour and one sample exceeding 2.5 ksi. Scatter reduces significantly with time, and all sampled concrete that was not failed by inspectors achieved suitable strength over time. The LMC-VES produced during the first pour (no fibers) was more consistent than the second pour (fibers by mechanical feeder), with the obvious exception of the rejected concrete first sampled in Lane 1. There is no evidence to suggest that the fibers themselves caused greater inconsistency in Lane 2 results. However, increased mechanical problems with the trucks due to the fiber feeders (see Section 6.3 above), and the operator having to pay attention to fiber addition as an additional variable during construction could have played a role.



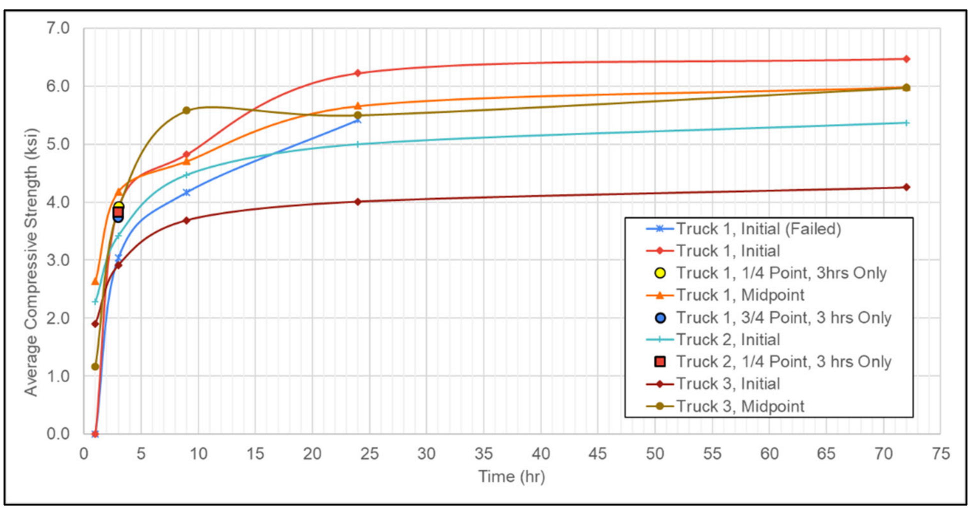


Figure 6-13 (a) and (b): Compressive Strength Results for Lane 1 (above) and Lane 2 (below).

The compressive strength requirement for LMC-VES is 2.5 ksi after 3 hours (North Carolina Department of Transportation, 2019b). All sampled concrete not rejected by inspection met this requirement. Despite this, compressive strength was highly variable across the project, particularly at a young age (1-3 hours) and particularly in the second lane cast. The coefficient of variation of all strength data across the project are shown in Table 6-5 for each time interval tested (excluding samples rejected by inspection). All concrete produced on the project was created from the same mix design using the same materials (except for adding fibers), so comparing consistency across the project is not unreasonable. As shown in the table, early-age strengths vary dramatically. While not a problem from the perspective of compliance with current specifications, such wide variability in early age strength indicates that some early age LMC-VES may be more vulnerable to damage from vibration, temperature changes, shrinkage, and other factors.

Table 6-5: Coefficient of Variation for All Field Trial Strength Data.

Time of Test after Sampling:	1 hour	3 hours	9 hours	24 hours	72 hours
CoV% of Compression Data Set:	56.5%	17.5%	12.4%	18.6%	12.0%

6.4.2 Slump Testing in the Field

The slump testing was performed on field trial concrete in accordance with ASTM C143 (ASTM International, 2020a). Slump was measured at the beginning and midpoint of the two main truckloads of material used for the first two lanes. Slump was not tested on the third lane. Results are shown in Table 6-6.

Table 6-6: Field Trial Slump Measurements.

Lane 1				Lane 2			
Truck 1		Truck 2		Truck 1			Truck 2
Initial Test (Failed)	Initial Retest	Initial Test	Middle of Load (Would Fail)	Initial Test (Failed)	Initial Retest	Middle of Load	Initial Test
12 in	5 in	5.75 in	7 in	8 in	4 in	3 in	4.5 in

NCDOT specifies that the slump must be between 3 and 6 inches (North Carolina Department of Transportation, 2018). In addition PSP 008 requires that samples taken from a mixer at random intervals not vary by more than 1 inch. High slump measurements were caught and failed by inspection at the beginning of two truckloads. These high slumps correspond with very weak early age compression strengths documented above. From this perspective, initial slump testing in the inspection area was effective at catching and eliminating obviously inadequate concrete. Slump tests also showed slump varying by more than the allowable 1 inch over the course of the overlay.

6.5 Cracking Observations

The main purpose of the field trial was to view the effect of fibers on overlay cracking. The first and second lanes were examined carefully for cracking during pouring of the second and third lanes, respectively. Additionally, observations were made after the lanes had been in use for over five months.

6.5.1 Initial Observations

On some previous overlays, NCDOT has noticed cracking early after casting, sometimes within a matter of hours. Initially, there was no visible cracking on the first lane. The lane surface one week after casting is shown in Figure 6-14.

Figure 6-14: Lane 1 Surface (Water Applied to Look for Cracks).

During casting the second lane, construction was paused to address a hydraulic leak in the middle of the job. During this delay, the crew spread and finished the remaining concrete already on the deck. As this concrete set, they used a jackhammer to create as even a cold joint as possible. One week after casting, cracking in the concrete that had been cast just prior to the cold joint was observed, as shown in Figure 6-15. The cracking was largely contained within a relatively small area, and was likely due to vibrations caused by the jackhammer. A few stray hairline cracks were also observed in the second lane, no more than two feet in length. These cracks were most likely caused by shrinkage or over-finishing.

Figure 6-15: Lane 2 Cracking Near Cold Joint.

6.5.2 Final Observations after Curing and Grooving

Final observations were made after the surface of all lanes was grooved and then opened to traffic for about five months. At this time, no cracking was visible in any lane. All minor cracking previously detected was likely removed by the grooving process, or was sufficiently small to not be visible on dry pavement. Thus, all initially observed cracking was likely superficial. There was no discernible difference in lane quality and no fibers were visible at the surface in any lane. The final representative surface is shown in Figure 6-16.

Figure 6-16: Final Grooved Surface, Typical of All Lanes.

6.6 Conclusions for Field Trial

The purpose of the field trial was to investigate the difference between cracking behavior in fibrous and non-fibrous LMC-VES, to study fiber distribution systems, and any potential construction issues. To achieve this goal, three lanes were cast, one lane with each of the following: without fibers, with fibers distributed by a mechanical fiber distribution system, and fiber distributed by hand.

The fiber distribution system used did not meet the standards that would be required of such equipment to operate reliably on a volumetric mixer in the field. The dispenser was not compatible with the trucks' hydraulic system and was not capable of running at low speeds. Multiple adjustments to the hydraulic system had to be made to allow for consistent output. Most importantly, the selected fiber did not break free of its sizing. Even running the dispenser at a higher speed, this issue would persist. A different dispenser system and fiber combination should be tried in the future.

Regarding potential construction issues, the concrete mixture was found to vary significantly over the course of a truckload, a lane, and an entire bridge. The initial portion of concrete was found to have the potential to not be properly proportioned. More concrete should be 'wasted' by the truck operator to make sure that a proper mixture is achieved before sampling and proceeding to the bridge. Inspection procedure should be updated to allow for a more accurate representation of the concrete used on the overlay. ASTM C172 suggests that samples should be taken after at least five cubic feet of homogeneous material has been discharged (ASTM International, 2017a). The five cubic feet should come after the truck operator has made final adjustments, not during adjustments. The unrestricted use of citric acid is potentially problematic. Too much retarder may cause a big delay in the setting behavior. This delay could mean that current NCDOT practices for finishing and curing might not effectively prevent shrinkage cracking. Thus, the use of citric acid should be more closely monitored and regulated. It is advised that a maximum citric acid content be specified by the mixture designer and that samples for slump and strength be required to include the citric acid in the mixture.

With regards to the main issue of concern to the project, no significant cracking was found with or without the addition of fibers. The only visible cracking that occurred was relatively minor. The lack of cracking on all lanes matches the expectation based on the results of laboratory overlay slabs. Because all overlay lanes performed satisfactorily, the addition of fibers was not found to degrade or enhance the cracking performance of overlays. Thus, cracking experienced on previous projects was likely due to lack of compliance with project specifications, construction error, excess citric acid, or all of the above. Importantly, the field trial project relied on a highly experienced and reputable contractor. Unlike on the previous project completed by NC State, this contractor did not add water to the surface in an excessive and uncontrolled manner (Smyl et al., 2016). In the field, the crew knew that they were being watched by both researchers and many more members of the NCDOT than usual. This was not a blind test; the quality of the construction crew and their performance are variables. Additionally, the field trial project was originally scheduled as a standard LMC overlay instead of LMC-VES. VES projects often occur over the course of a single night to avoid impacting traffic during busy hours. In such cases, the time window is much narrower. Construction and inspection crews are under a lot of time pressure to get the work done. In this case, the time pressure was not a factor, increasing the likelihood that the crews completed their work more carefully and thoroughly on this project. Therefore, it is likely that compliance with the relevant specifications and procedures was close to a best-case scenario on the field project. Subsequently, there was no cracking. The overlays were completed in the morning, under relatively constant temperature, when sunset would not affect the setting of the concrete. The usual nighttime casting can have effects on the temperature and subsequently on the cracking of overlays. Based on the field trial, if proper construction procedure is used and weather and temperature are cooperative, then significant cracking should not occur, and no fibers should be needed.

7. Research Findings and Conclusions

The research presented in this report was conducted to investigate possible causes and controls of cracking in LMC-VES bridge deck overlays. Specifically, the potential to add fiber to LMC-VES was studied experimentally in the laboratory and in the field. A full-scale field trial was used to investigate the feasibility of fiber addition at scale and to identify any issues related to fiber and the typical LMC-VES construction process. The findings of this research are summarized below:

- Study of available fiber addition methods for continuous mixing trucks revealed alkali-resistant glass (AR glass) and polyvinyl alcohol (PVA) microfibers of lengths between 0.5 and 1 inches to be viable for inclusion in an LMC-VES mix. Of the two, AR glass was determined to be more compatible with available dispensing technology. A fiber dose of up to 2 lbs. per cubic yard for AR glass was determined to be reasonable for LMC-VES.

- Laboratory material-scale experiments revealed that the inclusion of fibers into LMC-VES at a dosage rate of up to 2 lbs./yard had little effect on the compressive strength. Citric acid had a greater effect on compression strength than did fiber.

- The presence of fibers was found to increase the flexural performance of LMC-VES to a minor degree for the fiber doses tested. The small increase in flexural performance from fiber was sufficient to offset the small corresponding decrease from citric acid.

- The presence of fibers was not found to have a dramatic influence on slump behavior of fresh LMC-VES. The effects of citric acid content on slump were far more dramatic.

- Fibers were shown to enhance the slant shear performance of LMC-VES bonded to ordinary Portland cement concrete bases, likely by improving tension resistance in areas cracked due to local surface roughness.

- When proper NCDOT curing practices are followed, laboratory-scale slabs with LMC-VES overlays demonstrated that restrained shrinkage, bridge deck vibration due to traffic, and sudden temperature changes were not significant drivers of cracking in overlays up to three-inches deep. The addition of fibers and/or low-dose citric acid did not degrade or enhance the cracking performance of overlays in these tests.

- Citric acid, even at low doses, has a measurable effect on the flowability of calcium sulfoaluminate (CSA) cement mortar. Citric acid should be considered more explicitly as part of the LMC-VES mixture design and not listed simply "as needed."
    - The addition of citric acid to LMC-VES was shown to decrease the compressive, chemical bond, and flexural strengths. Decreases were more pronounced at early ages, which is expected from the retarding admixture. Arguably, changes to ultimate strength were insignificant.
    - The addition of citric acid to CSA cement mortar (CSA cement being used in LMC-VES) dramatically increased flowability, even at relatively low dosage rates (under 0.1% by mass of cement). Increases in flowability did not continue to increase with additional increases in citric acid dose, although delays in set time did increase with increasing citric acid. In practical terms, this finding indicates that construction and inspection crews have no way to easily identify the difference between acceptable and extreme amounts of citric acid retarder.
    - Citric acid is commonly added to LMC-VES post-inspection in uncontrolled amounts, "as needed" by the contractor, as allowed by specification.

- On the multi-lane LMC-VES overlay field trial, no significant cracking occurred within five months (the last inspection as of this writing). The addition of fibers did not degrade or enhance the cracking performance of overlays. The selected fibers did not adequately disperse in the trial concrete and were likely ineffective as mixed. The LMC-VES control lane with no fibers performed as well or better than the LMC-VES lanes batched with fibers.

- The selected fiber dispenser did not perform well on the field trial. Deficiencies with the dispenser itself and incompatibilities with the truck hydraulics caused highly imprecise and unreliable fiber addition to the mixture. A second trial that added fiber to the mixer by hand from pre-measured cups was more consistent, but far more labor intensive and impractical for routine use. Adjustments to the fiber dispenser allowed for a more constant rate of fiber addition, but demonstrate that commercially available equipment for adding fibers to volumetric mixing operations is not "off-the-shelf" ready.

- The fibers used for the field trial did not break apart and disperse in fresh concrete as well as did similar fibers by a different manufacturer used in the laboratory work. The sizing (coating) on the two fibers was different, and the way that this sizing behaved when immersed in water also differed. This result demonstrates that any fibers used with LMC-VES need to be specifically qualified and tested for the volumetric mixing process. Fibers demonstrated to be effective in drum mixing are not automatically appropriate for volumetric mixing.

- The field inspection processes were effective at identifying significantly deficient LMC-VES on the jobsite. However, opportunities to improve the field inspection process were identified and are discussed in the following section. Citric acid was always turned off when the trucks were providing initial samples in the inspection area.

- The early age strength of the field-cast LMC-VES varied dramatically over the course of the project within and across truckloads of material. All non-rejected concrete achieved at least 2.5ksi at 3 hours, however, 1 hour strengths for this same concrete varied from 0 psi (not yet set) to over 2.5 ksi. This radical difference in early age strength is likely partially due to the "as needed" addition of citric acid to the mixture. Ambient temperature also plays some role.

- Slump tests performed at regular intervals on samples of LMC-VES being placed on the field trial bridge deck showed values ranging from 3" to 7". Slump values on concrete rejected by inspection were as high as 12".

In summary, if the construction procedures outlined in current NCDOT documents are followed, surfaces are properly prepared, weather conditions are within specification, and limited citric acid is used, then cracking of LMC-VES overlays should not occur. There is a strong likelihood that when significant cracking does develop, it results from incorrect or unwise construction procedures that may include excessive use of citric acid. Improper construction procedure, including excessive citric acid use, likely amplifies the cracking risk caused by factors such as temperature, shrinkage, or vibration.

8. Recommendations

The following items are recommended to reduce the risk of cracking in LMC-VES bridge deck overlays. Proposed updates to the text of PSP 004 are provided in a following section.

- The field sampling and inspection procedure should be adjusted. The LMC-VES mixture varies significantly over a truckload of material, and the current procedure does not well represent the concrete actually placed on the bridge deck.

    - An initial sample of LMC-VES should be taken in the inspection area prior to discharging any concrete on the bridge (as per current practice). This sample should be checked for slump only prior to the truck leaving the inspection area. Concrete checked for slump should not include any citric acid. The purpose of the slump check is to confirm that the baseline concrete mixture, as discharged from the truck, does not include too much water. Mixing citric acid into this initial sample would interrupt this confirmation of water content. The slump sample should be tested immediately in the inspection area, directly at the discharge chute. Time should not be wasted moving the sample to a separate testing area.

        - The limit of 1" variation in slump found in PSP 008 is not relevant if citric acid is employed. Slump should not vary by more than 1" when discharged by the mixer at random intervals, <u>with no citric acid included</u>. PSP 008 should be updated in this area to include the words "with no citric acid included."

        - Inspectors should specifically confirm that each truck wastes at least 3 cubic feet of material in the inspection area prior to sampling for slump to ensure a homogenous mixture is sampled. Using slump to confirm water content on a non-representative and non-homogeneous sample of LMC-VES is not useful. Use of a calibrated square frame similar to that used for verification of concrete volume could be employed.

    - A separate composite sample of LMC-VES should be taken at random from the bridge deck approximately halfway through the truckload of material, after at least 2 cubic yards of material have been discharged (or after half the total discharge if the total discharge will be less than 2 cubic yards). This composite sample of concrete will be used to cast cylinders for compression testing. The composite sample is created by shoveling fresh LMC-VES from the bridge deck into a wheelbarrow within 30 seconds of that concrete being deposited by the mixer, before the concrete is handled, screeded, or finished in any way. The inspector should randomly select the time and location of sampling and should randomly shovel from at least five distinct areas of the fresh pile of LMC-VES that is normally deposited by the mixer on the bridge deck. Sample portions should be taken from the middle portion of a pile of fresh concrete – do not sample concrete from the bottom of a pile that has been contaminated by direct contact with the deck. Note that *ASTM C172: Procedure for Sampling of Freshly Mixed Concrete* includes guidance for sampling from continuous mixers and also from paving mixers. This recommendation is closer to the ASTM method for sampling from paving mixers.

    - The purpose of sampling LMC-VES directly from the bridge deck for concrete strength testing is to determine the concrete strength most likely to be representative of the LMC-VES actually placed on the deck. The LMC-VES sampled in this way will come from a homogenous mixture, and will likely include a representative dose of citric acid. If citric acid is in use, then the concrete sampled from the bridge deck will likely be weaker than that which would have been sampled in the inspection area.

    - Tests for air content should be conducted on the same composite sample of LMC-VES used for casting compression cylinders. The air content determined from this sample will be representative of the air that is in the concrete actually placed on the bridge deck.

- The maximum citric acid content proposed for use by a contractor should be included by that contractor on the submitted LMC-VES mix design. The 3 hour compressive strength data on (6) cylinders required to be submitted with the mix design should include citric acid in the mixture at the maximum proposed dosage.

    - The slump data required to be submitted with the mix design should be performed on the proposed LMC-VES mixture with no citric acid.

    - The air content data required to be submitted with the mix design should be performed on the proposed LMC-VES mixture with any amount of citric acid, up to the proposed maximum, at the option of the contractor. Specify the citric acid content used for this sample in the submittal. The contractor is reminded that air content will be tested for acceptance from concrete selected at random from the bridge deck during LMC-VES placement.

    - Citric acid use in the field cannot exceed the maximum dose included on the proposed mix design. Citric acid use in the field remains "as needed" up to the maximum dose.

    - The reason that citric acid should be more tightly controlled by the PSP is that it seems to have substantial impacts on final overlay quality. Too much retarder may cause too long of a delay in the setting time, contributing to increased risk of cracking and/or delayed strength gain of the overlay.

- Current NCDOT procedures are very effective at preventing cracking in LMC-VES overlays if those procedures are properly implemented. The importance of following these procedures accurately should be clearly conveyed in the pre-construction meeting already required by PSP 004. The Quality Plan already required by PSP 004 should be taken seriously by all involved, including inspection teams.

  - Deck surfaces should be prepared, cleaned, dampened, and cleared of standing water as required. Mixers should be calibrated and maintained as required. Materials should be stored to control moisture contents as required. Ambient temperatures, deck temperatures, and material temperature should be monitored and construction plans adjusted as necessary to make sure all are within acceptable ranges. Casting and finishing should be completed without introducing extra water into the mixture. Curing should be completed as required using <u>fully</u> saturated burlap applied and covered with plastic <u>immediately</u> after the finishing operation. Note that discussions with field personnel indicate it may take up to 24 hours of immersion in water to fully saturate some burlap, particularly new burlap.

- Fibers do not appear to be necessary in LMC-VES overlays for the purposes of controlling cracking. Fibers offered minimal to no performance gains in the experiments conducted in this research and added non-trivial complications to the volumetric mixing process. An argument for including fiber would necessarily start from the assumption that proper LMC-VES construction procedure is not being followed, because cracking did not develop in the laboratory or in the field with proper procedure. In the authors' opinion, the expense of adding fiber to LMC-VES is not justified by the available data. Resources would be better spent further investigating citric acid limits, training inspectors, and working with contractors to ensure that proper construction practices for LMC-VES are followed.

- If further trials with fiber and LMC-VES do occur, a valid combination of fiber, fiber dispenser, and mixing truck need to be qualified and tested as a system before use in the field. A spooled fiber feeder would be worth investigating. Fibers must be proven compatible with volumetric mixing (fiber addition and dispersion) before use.

8.1 Recommendations for Future Research

The laboratory-scale testing reported here used a relatively low dose of citric acid. Additional study to determine the effects of citric acid on CSA cements and LMC-VES at higher dosage would be helpful. In addition, the current study directly investigated the effects of citric acid on flowability only in CSA mortar, without latex or coarse aggregate. Additional study of the effects of citric acid with regards to workability and strength gain over time of LMC-VES, including latex and aggregate, would be helpful for establishing practical maximum limits of citric acid for field use.

9. Technology Transfer Plan

The NCDOT research committee and NCSU research team will meet to discuss the findings of this project. If helpful, the research team can demonstrate the fiber dispensing equipment, fibers themselves, and laboratory mixing methods in person at the laboratory. The research team can also present the findings of this research to other members of the NCDOT and to contractors if necessary. A detailed graduate thesis has been published on this work (Stirewalt, 2021). The research team is in the process of preparing manuscripts for potential publication in refereed journals such as ASCE or TRB. Draft papers will be provided to NCDOT for review.

Other important items for technology transfer are contained within the report itself. A list of currently available fiber dispensers and important details of such can be found in Section A.3.1.3 and Table A-2. Finally, Section 9.1 below provides suggested updates to PSP 004. The suggested additions are shown in red.

9.1 Proposed Updates to PSP 004 (LMC Overlay – Very Early Strength)

The following edits are proposed to PSP 004. Edits are in bold red text within the original text. Not all sections of PSP 004 are reproduced here.

MATERIALS

…

1000-7(A), Line 15 – Replace with the following:
Measure the slump **immediately** after discharge from the mixer.

1000-7(A) – Add the following paragraph**s** to the end of the section:

Submit the LMC-VES mix design, including laboratory compressive strength data for a minimum of six (6) 4-inch by 8-inch cylinders at three (3) hours for very early strength concrete to the Engineer for review. **Specify the maximum allowable citric acid dosage rate for the mix design, and include this maximum dosage of citric acid in the mixture used to cast the cylinders.**

Include test results for the slump of the laboratory mix. **Do not include citric acid in the mixture when testing for slump. Include any desired level of citric acid in the mixture when testing for air, up to the maximum, and specify the dosage used. The contractor is reminded that air content will be sampled from the LMC-VES as placed on the bridge deck.**

Perform laboratory tests in accordance with AASHTO T 22, T 119 and T 152.

…

ONSITE INSPECTION (NEW SECTION)

An onsite quality inspection should be performed by an NCDOT approved inspector. This inspector should measure the slump from each truckload of concrete before any concrete is placed on the bridge deck. No citric acid should be included in the mixture when the slump measurement is performed. Prior to taking a sample for slump testing, at least 3 cubic feet of concrete must be discharged from the truck and disposed of to ensure a homogenous mixture. A slump test should be conducted on each truckload of material. The slump test is to be conducted immediately upon discharge of the sample in the immediate vicinity of the discharge.

A separate composite sample of LMC-VES should be taken at random from the bridge deck approximately halfway through the truckload of material, after at least 2 cubic yards of material have been discharged (or after half the total discharge volume if the total discharge volume will be less than 2 cubic yards). This composite sample of concrete shall be used to cast cylinders for compression strength testing and to check the total air content.

The composite sample is created by shoveling fresh LMC-VES from the bridge deck into a clean wheelbarrow or similar container within 30 seconds of that concrete being deposited by the mixer, before the concrete is handled, screeded, or finished in any way. The inspector should randomly select the time and location of sampling and should randomly shovel from at least five distinct areas of the fresh pile of LMC-VES normally deposited by the mixer on the bridge deck. Sample portions should be taken from the middle of a pile of fresh concrete – do not sample from the bottom of a pile that has been contaminated by direct contact with the deck.

PLACING AND FINISHING

…

Do not place the LMC-VES until the burlap is **fully** saturated and approved by the Engineer. Drain excess water from the wet burlap before placement.

…

Promptly cover the surface with a second layer of clean, wet burlap as soon as the surface will support it without deformation. Wet cure only the surface for a minimum of three (3) hours and until a compressive strength of 2,500 psi is reached. Curing material shall be continually saturated during the wet cure period using a fogging system approved by the Engineer. **The purpose of fogging is to maintain the saturation of the burlap, thus preventing evaporation of moisture from the concrete surface. Fogging over or spraying of water directly onto the fresh concrete surface is prohibited.** The Engineer may require an increase in the minimum cure time when the overlay thickness is greater than 1.5 inches or the ambient temperature remains below 60°F. **The required curing time may also be increased depending on the amount of retarder added.**

…

10. References

Afroughsabet, V., Biolzi, L., & Cattaneo, S. (2019). Evaluation of engineering properties of calcium sulfoaluminate cement-based concretes reinforced with different types of fibers. *Materials,* Vol. 12.

Alhassan, M. A., & Issa, M. A. (2010). Long-term protection of bridge-deck systems with structural latex-modified concrete overlays. *PCI Journal, 55*(3), 122-137. https://10.15554/pcij.06012010.122.137

Alhassan, M., & Suleiman, A. (2012). *Superiority & Constructability of Fibrous Additives for Bridge Deck Overlays.* (No. FHWA-ICT-12-003).Illinois Department of Transportation.

American Association of State Highway and Transportation Officials. (2017). *AASHTO LRFD bridge design specifications (8th edition)* (8th ed.). American Association of State Highway and Transportation Officials.

Amirkhanian, A., & Roesler, J. (2019). *Overview of Fiber-Reinforced Concrete Bridge Decks.* (). Ames, Iowa: Technology Transfer Concrete Consortium.

Andrew, R. (2019). Global CO2 emissions from cement production, 1928–2018. *Earth System Science Data, 11*(4), 1675-1710.

ASTM International. (2015a). *C1116/C1116M-10a(2015) Standard Specification for Fiber-Reinforced Concrete*. West Conshohocken: ASTM International.

ASTM International. (2015b). *C127-15 Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate*. West Conshohocken: ASTM International.

ASTM International. (2015c). *C128-15 Standard Test Method for Relative Density (Specific Gravity) and Absorption of Fine Aggregate*. West Conshohocken: ASTM International.

ASTM International. (2017a). *C172/C172M-17 Standard Practice for Sampling Freshly Mixed Concrete*. West Conshohocken: ASTM International.

ASTM International. (2017b). *C685/C685M-17 Standard Specification for Concrete Made by Volumetric Batching and Continuous Mixing*. West Conshohocken: ASTM International.

ASTM International. (2019a). *C1600/C1600M-19 Standard Specification for Rapid Hardening Hydraulic Cement*. West Conshohocken: ASTM International.

ASTM International. (2019b). *C192/C192M-19 Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory*. West Conshohocken: ASTM International.

ASTM International. (2020a). *C143/C143M-20 Standard Test Method for Slump of Hydraulic-Cement Concrete*. West Conshohocken: ASTM International.

ASTM International. (2020b). *C143/C143M-20 Standard Test Method for Slump of Hydraulic-Cement Concrete*. West Conshohocken: ASTM International.

ASTM International. (2020c). *C1437-20 Standard Test Method for Flow of Hydraulic Cement Mortar*. West Conshohocken: ASTM International.

ASTM International. (2020d). *C882/C882M-20 Standard Test Method for Bond Strength of Epoxy-Resin Systems Used With Concrete By Slant Shear*. West Conshohocken: ASTM International.

ASTM International. (2020e). *D7508/D7508M-20 Standard Specification for Polyolefin Chopped Strands for Use in Concrete*. West Conshohocken: ASTM International.

ASTM International. (2021a). *C39/C39M-21 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*. West Conshohocken: ASTM International.

ASTM International. (2021b). *C78/C78M-21 Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)*. West Conshohocken: ASTM International.

Aulia, T. (2002). Effects of polypropylene fibres on the properties of high strength concretes. *Leipzig Annual Civil Engineering Report, 7*, 43-59.

Balakumaran, S. S. G., Weyers, R. E., & Brown, M. C. (2017). *Performance of Bridge Deck Overlays in Virginia: Phase I: State of Overlays.* (No. FHWA/VTRC 17-R17). Charlottesville, Virginia: Virginia Transportation Research Council.

Banthia, N., & Gupta, R. (2006). Influence of polypropylene fiber geometry on plastic shrinkage cracking in concrete. *Cement and Concrete Research, 36*(7), 1263-1267. https://10.1016/j.cemconres.2006.01.010

Belhadi, R., Govin, A., & Grosseau, P.Hydration and rheology of sulfoaluminate cements (CSA) in presence of polycarboxylate superplasticizers (PCE) and citric acid. Paper presented at the *15th International Congress on the Chemistry of Cement,* https://hal.archives-ouvertes.fr/hal-02360076

Bentur, A., & Mindess, S. (2007). *Fibre reinforced cementitious composites*. CRC Press.

Branston, J., Das, S., Kenno, S. Y., & Taylor, C. (2016). Influence of basalt fibres on free and restrained plastic shrinkage. *Cement and Concrete Composites, 74*, 182-190.

Burris, L., & Kurtis, K. (2018). Influence of set retarding admixtures on calcium sulfoaluminate cement hydration and property development. *Cement and Concrete Research, 104*, 105-113. https://10.1016/j.cemconres.2017.11.005

Cement Admixtures Association. (2012). *Admixture Technical Sheet – ATS 3* . http://www.admixtures.org.uk/publications/admixture-technical-sheets

Dhand, V., Mittal, G., Rhee, K. Y., Park, S., & Hui, D. (2015). A short review on basalt fiber reinforced polymer composites. *Composites Part B: Engineering, 73*, 166-180.

Earwood, A., & Garbee, C. (2018). *Latex Modified Concrete in NC*. North Carolina: North Carolina Department of Transportation.

Filho, R. D. T., & Sanjuán, M. A. (1999). Effect of low modulus sisal and polypropylene fibre on the free and restrained shrinkage of mortars at early age. *Cement and Concrete Research, 29*(10), 1597-1604. https://10.1016/S0008-8846(99)00136-2

Gartner, E. (2004). Industrially interesting approaches to "low-CO2" cements. *Cement and Concrete Research, 34*(9), 1489-1498. https://10.1016/j.cemconres.2004.01.021

Gwon, S., Jang, S. Y., & Shin, M. (2018). Combined effects of set retarders and polymer powder on the properties of calcium sulfoaluminate blended cement systems. *Materials, 11*(5), 825. https://10.3390/ma11050825

Harsh, S., & Darwin, D. (1986). Traffic-induced vibrations and bridge deck repairs. *Concrete International,* , 36-42.

Hu, Y., Li, W., Ma, S., & Shen, X. (2017). Influence of borax and citric acid on the hydration of calcium sulfoaluminate cement. *Chemical Papers, 71*(10), 1909-1919. https://10.1007/s11696-017-0185-9

Issa, M. A. (2004). *Evaluation and Recommendation of Overlay Materials for the New Mississippi River Bridge.* ().Illinois Department of Transportation.

Issa, M., Alhassan, M., & Ramos, J. (2007). Glass fiber reinforced latex-modified concrete using a volumetric mixer for production overlays. *Concrete International, 29*, 48-52. https://search.proquest.com/docview/198740240

Juenger, M. C. G., Winnefeld, F., Provis, J. L., & Ideker, J. H. (2011). Advances in alternative cementitious binders. *Cement and Concrete Research, 41*(12), 1232-1243. https://www.sciencedirect.com/science/journal/00088846

Khalil, W. (2008). Using citric acid as an admixture and it's influence on some properties of concrete. *Eng. & Tech. Journal, 27*(1), 33-46.

Kim, D., & Park, C. (2013a). Permeability, abrasion, and impact resistance of latex-modified fibre reinforced concrete for precast concrete pavement applications. *Progress in Rubber, Plastics and Recycling Technology, 29*(4), 239-254. https://10.1177/147776061302900403

Kim, D., & Park, C. (2013b). Strength, permeability, and durability of hybrid fiber-reinforced concrete containing styrene butadiene latex. *Journal of Applied Polymer Science, 129*(3), 1499-1505. https://10.1002/app.38861

Kucharavy, D., & De Guio, R. (2011). Application of S-shaped curves. *Procedia Engineering, 9*, 559-572.

Lahne, J., & Preston, F. (2018). *Making Concrete Change: Innovation in Low-carbon Cement and Concrete.* ().

Lee, J., Kim, H., Park, S., Oh, R., Kim, H., & Park, C. (2018). Mechanical properties and durability of latex-modified fiber-reinforced concrete: A tunnel liner application. *Advances in Materials Science and Engineering, 2018*, 1-14. https://10.1155/2018/2134873

Lee, J. J., Song, J., & Kim, H. (2014). Chemical stability of basalt fiber in alkaline solution. *Fibers and Polymers, 15*(11), 2329-2334.

Lee, S., Jeon, M., Cha, S., & Park, C. (2017). Mechanical and permeability characteristics of latex-modified fiber-reinforced roller-compacted rapid-hardening-cement concrete for pavement repair. *Applied Sciences, 7*(7), 694. https://10.3390/app7070694

Majumdar, A. J., & Nurse, R. W. (1974). Glass fibre reinforced cement. *Materials Science and Engineering, 15*(2-3), 107-127.

Manning, D. (1981). *Effects of Traffic-Induced Vibrations and Bridge-Deck Repairs.* (). Washington, D.C.: Transportation Research Board.

North Carolina Department of Transportation. (2018). *Standard Specifications for Roads and Structures*. Raleigh, North Carolina: North Carolina Department of Transportation.

North Carolina Department of Transportation. (2019a). *PSP 003: Latex Modified Concrete Overlay*. Raleigh, North Carolina: North Carolina Department of Transportation.

North Carolina Department of Transportation. (2019b). *PSP 004: Latex Modified Concrete Overlay-Very Early Strength*. Raleigh, North Carolina: North Carolina Department of Transportation.

Oh, R., Kim, D., & Park, C. (2014). Durability performance of latex modified nylon fiber reinforced concrete for precast concrete pavement applications. *Indian Journal of Engineering & Material Sciences, 21*, 49-56.

Oregon Department of Transportation. (2019). *Qualified Products List*. Salem, Oregon: Oregon Department of Transportation.

Park, R., & Jang, J. (1999). Performance improvement of carbon fiber/polyethylene fiber hybrid composites. *Journal of Materials Science, 34*(12), 2903-2910. https://10.1023/A:1004647721380

Ramseyer, C. C., & Myers, D. S. (2009). *Creation of an ODOT Specification for Patching or Overlay of Bridge Decks.* (). Oklahoma City: Oklahoma Department of Transportation. https://hdl.handle.net/11244/299502

Roesler, J., Bordelon, A., Brand, A. S., & Amirkhanian, A. (2019). *Fiber-Reinforced Concrete for Pavement Overlays: Technical Overview.* (No. InTrans Project 15-532). Ames, Iowa: Technology Transfer Concrete Consortium.

Smyl, D., Mohammadian, A., Park, S., Lucier, G., & Pour-Ghaz, M. (2016). *The Use of Fiber Reinforcement in Latex Modified Concrete Overlay.* (No. FHWA/NC/2016-07). Raleigh, North Carolina: North Carolina Department of Transportation.

Song, P., Hwang, S., & Sheu, B. C. (2005). Strength properties of nylon- and polypropylene-fiber-reinforced concretes. *Cement and Concrete Research, 35*(8), 1546-1550. https://10.1016/j.cemconres.2004.06.033

Soroushian, P., & Ravanbakhsh, S. (1999). High-early-strength concrete: Mixture proportioning with processed cellulose fibers for durability. *ACI Materials Journal, 96*(5), 593-599.

Stirewalt, T. (2021). *Cracking Causes and Resistance in Very Early Strength Latex Modified Concrete Overlays with and without Nonmetallic Fibers*

Suksawang, N., Mirmiran, A., & Daniel, Y. (2014). *Use of fiber reinforced concrete for Concrete Pavement slab replacement*. State of Florida Department of Transportation.

Velazco, G., Almanza, J. M., Cortés, D. A., Escobedo, J. C., & Escalante-Garcia, J. I. (2014). Effect of citric acid and the hemihydrate amount on the properties of a calcium sulphoaluminate cement. *Materiales De Construcción (Madrid), 64*(316), 1-8. https://10.3989/mc.2014.03513

Winnefeld, F., & Klemm, S.Influence of citric acid on the hydration kinetics of calcium sulfoaluminate cement. Paper presented at the *1st International Conference on Sulphoaluminate Cement: Materials and Engineering Technology,* 288-308.

Won, J., Kim, J., Lee, S., & Park, C. (2009). Durability of low-heat, ultra rapid-hardening, latex-modified polymer concrete. *Progress in Rubber, Plastics and Recycling Technology, 25*(2), 91-102. https://10.1177/147776060902500201

Won, J., Kim, J., Park, C. -, Kang, J. -, & Kim, H. -. (2009). Shrinkage cracking of styrene butadiene polymeric emulsion-modified concrete using rapid-hardening cement. *Journal of Applied Polymer Science, 112*(4), 2229-2234. https://10.1002/app.29733

Won, J., Kim, J., Lee, S., Lee, S., & Park, S. (2011a). Mix proportion of high-strength, roller-compacted, latex-modified rapid-set concrete for rapid road repair. *Construction and Building Materials, 25*(4), 1796-1800. https://10.1016/j.conbuildmat.2010.11.085

Won, J., Kim, J., Lee, S., Lee, S., & Park, S. (2011b). Performance evaluation of ultra-rapid-hardening roller-compacted concrete with styrene butadiene latex. *Journal of Applied Polymer Science, 121*(1), 196-201. https://https://doi.org/10.1002/app.33500

Yun, K., & Choi, P. (2014). Causes and controls of cracking at bridge deck overlay with very-early strength latex-modified concrete. *Construction & Building Materials, 56*, 53-62. https://10.1016/j.conbuildmat.2014.01.055

Zhang, J., Liu, G., Chen, B., Song, D., Qi, J., & Liu, X. (2014). Analysis of CO2 emission for the cement manufacturing with alternative raw materials: A LCA-based framework. *Energy Procedia, 61*, 2541-2545. https://10.1016/j.egypro.2014.12.041

Appendix A: Literature Review – Inclusion of Fibers in LMC and LMC-VES

This appendix provides an overview of the published literature regarding Latex Modified Concrete-Very Early Strength (LMC-VES) and the fibers that were used to shape the direction of the research.

A.1 Fibers in Current Design Specifications

A.1.1 North Carolina DOT Design Specifications

The only mention of fiber in the current NCDOT Specifications appears in section 1077-7B. This section addresses using synthetic macrofibers to replace welded wire reinforcement. It requires that the fibers be made of virgin polyolefins (polyethylene and polypropylene), and measure greater than or equal to 1 ½" in length. Additionally, it requires all fibers have "an aspect ratio (length divided by the equivalent diameter of the fiber) between 45 and 150, a minimum tensile strength of 40 ksi…and a minimum modulus of elasticity of 400 ksi" (North Carolina Department of Transportation, 2018). There are no current NCDOT specifications for fibers in LMC-VES bridge deck overlays.

A.1.2 Design Specifications from Other States

To the best knowledge of the authors, no US states require fibers to be used in LMC-VES deck overlays. However, in order to reduce cracking, some states, such as California, Delaware, Minnesota, and Oregon, require that all concrete bridge decks include fiber in their mixture designs (Amirkhanian & Roesler, 2019).

California requires 1 lb/yd^3 of polymer microfibers and 3 lb/yd^3 of polymer macrofibers for all concrete bridge decks. Delaware specifies 1.5 lb/yd^3 of reinforcing fibers (nonferrous) for bridge decks. Minnesota specifies 4.5 lb/yd^3 of non-metallic Type III Fibers for bridge decks (Amirkhanian & Roesler, 2019). Type III Fibers are alkali resistant synthetic fibers, including polyolefin fibers (ASTM International, 2015a). Oregon specifies fiber by specific product, generally requiring 1.0 to 1.5 lb/yd^3 of synthetic microfiber or 5.0 to 7.0 lb/yd^3 of synthetic macrofiber (Oregon Department of Transportation, 2019).

A.2 Fiber Types

A.2.1 Polypropylene Fibers

Polypropylene and general polyolefin fibers are the fibers most frequently specified by US state DOTs (Amirkhanian & Roesler, 2019). Traditionally, polyolefin and polypropylene are thought of as different fiber types, however, polypropylene is a long-chain synthetic polymer that is part of the polyolefin family. Polyolefins also include polyethylene fibers among others (ASTM International, 2020d). As such, fibers labeled as "polyolefin" are often proprietary blends and were not considered in this study.

Polypropylene fibers are low cost and have high alkali resistance (Bentur & Mindess, 2007). Aulia found that polypropylene fibers could improve the ductility, residual strength, and fracture energy of high strength concrete (Aulia, 2002). However, they also form a poor bond with cement paste, experience sensitivity to oxygen and sunlight, and have a low modulus of elasticity (Bentur & Mindess, 2007). As such, polypropylene fibers are considered non-structural secondary reinforcement. Their main functionality comes when the concrete is still at an early stage in the curing process (Ramseyer & Myers, 2009). Once the concrete hardens, the modulus of the concrete overtakes that of the polypropylene, decreasing their functionality in uncracked segments (Bentur & Mindess, 2007). If hardened concrete does crack, polypropylene fibers still have an impact (Ramseyer & Myers, 2009).

One of the main advantages of polypropylene is its effectiveness in reducing early age cracking, including plastic shrinkage cracking (Filho & Sanjuán, 1999). Aulia stated that polypropylene fibers could "reduce the early plastic shrinkage cracking by enhancing the tensile capacity of the early age concrete to resist the typical volume changes" (Aulia, 2002). Kim and Park tested and compared properties of latex modified concrete reinforced with polypropylene, polyvinyl alcohol (PVA), and nylon. Polypropylene decreased the permeability and abrasion rate and increased the impact resistance relative to plain LMC. However, PVA and nylon fibers performed better in all three categories, which was attributed to those fibers being hydrophilic while polypropylene is hydrophobic (Kim & Park, 2013a).

A.2.2 Polyvinyl Alcohol (PVA) Fibers

PVA fibers are synthetic fibers that have higher stiffness and strength compared to most other synthetics (Roesler et al., 2019). The elastic modulus of PVA is similar in value to the modulus of most concrete (Bentur & Mindess, 2007). Therefore, PVA fibers have a greater pre-crack effect in hardened concrete than do polypropylene fibers, whose modulus is much lower. In addition to having relatively high strength and modulus (for a synthetic), PVA fibers also bond better with concrete than do other synthetic fibers. This bonding performance comes from water absorption (hydrophilic behavior). The bond is so great that PVA fibers tend to rupture instead of pulling out.

A few studies have investigated the use of PVA fibers in LMC. Lee, Jeon, Cha, & Park found that addition of PVA fibers to LMC-VES reduced the chloride ion penetration while increasing the flexural strength, tensile strength, abrasion resistance, and impact resistance. However, in these tests, macrosynthetic polyolefin performed superiorly in every category except abrasion. The increased abrasion resistance of the PVA reinforced LMC-VES was attributed to its hydrophilic behavior. The lower performance in the other tests is expected because the PVA fibers used were designed for durability and cracking control rather than for increasing structural performance of the concrete (Lee et al., 2017).

A.2.3 Nylon Fibers

Nylon fibers are a lower cost alternative to PVA. The biggest difference between the two is that the modulus of elasticity of nylon is much lower than that of PVA, sometimes by an order of magnitude (Bentur & Mindess, 2007). Like PVA, nylon is hydrophilic, giving excellent bonding capacity (Kim & Park, 2013a). Bonding is facilitated by the absorption of water and the subsequent hydrogen bonding that develops between the nylon and the concrete, which acts to reduce the presence of pores around the fiber (Oh et al., 2014). Contrarily, Bentur and Mindess reported that nylon has a relatively low strength of bond with cement (2007), so the literature on bonding of nylon with concrete is conflicted. It is likely that specific proprietary coatings (sizing) on specific fibers may have a big influence on fiber bond. Sizing is typically not specified by a fiber manufacturer and is rarely discussed on technical data sheets.

A potential issue with nylon is that of balling in regular cement concrete (tangling during mixing and not dispersing throughout the fresh concrete). Nylon is particularly susceptible to balling when it gets wet and can ball at a volume fraction as low as 0.1% (Suksawang et al., 2014). However, Oh, Kim, and Park theorized that the addition of latex improves the dispersion of nylon fibers, and likely reduces the tendency of balling (Oh et al., 2014).

Song, Hwang, and Sheu did a comparative study of nylon and polypropylene fibers in regular (non-LMC) concrete. They found that the nylon reinforcement dispersed better. The dispersion, along with the increase in tensile strength from polypropylene to nylon, caused the concrete to perform better in terms of crack interception (amount of fiber crossing a crack), tensile strength, and modulus of rupture. In the modulus of rupture tests, the nylon fibers absorbed a greater amount of energy by stretching more than polypropylene. This trend was attributed by the study authors to a high-quality bond between nylon and cement. Additionally, these authors found that nylon fiber reinforced concrete (FRC), even at a smaller volume fraction, had a significantly smaller total crack area than did polypropylene FRC, at least in shrinkage testing. In impact resistance tests, while nylon FRC was somewhat superior to polypropylene FRC at the first cracking strength, the nylon specimens significantly outperformed the polypropylene specimens at ultimate failure (Song et al., 2005). This result demonstrates the potential of nylon to provide enhanced strength post cracking.

A.2.4 Alkali-Resistant Glass Fibers

Alkali-Resistant Glass Fiber (ARGF) is another option for fiber type. A big advantage of ARGF is that it can be purchased in a roving compatible with mobile mixer choppers (Alhassan & Issa, 2010). Adding fiber to a volumetric mixer by chopping, as will be discussed in detail in Section A.3.1.1, is advantageous because the method generally allows for a more consistent distribution of fibers (Issa, Mohsen et al., 2007). Additionally, the specific gravity of glass is close to that of concrete, so glass fibers are not as prone to balling, floating, or air entrapment as are their synthetic counterparts (Issa et al., 2007).

There are downsides to ARGF as well. The properties of concrete reinforced with ARGF often change with exposure to water and weathering, resulting in more brittle failure modes in aged concrete with reductions in ultimate strength and maximum strain. However, the inclusion of latex in the concrete has been shown to decrease the loss of strength sometimes observed with glass fiber (Bentur & Mindess, 2007).

Another potential downside of glass fiber was outlined by Suksawang, Mirmiran, and Daniel who noted that, in regular Portland cement concrete, stiffer fibers such as glass are poor at resisting early age cracking in the fresh concrete and can often initiate cracking themselves (Suksawang et al., 2014). The contrary conclusion was drawn by Issa who suggested that glass fiber can actually reduce the tendency for shrinkage cracks (Issa, Mohsen A., 2004), so the literature is conflicted on this issue. To the best knowledge of the authors, this phenomenon has not yet been tested in LMC. Additionally, while ARGF has been studied as secondary reinforcement for concrete, it has not been significantly applied to pavements (Roesler et al., 2019).

A.2.5 Other Fibers

Other fibers were considered for use but were found to offer performance levels below the standards of the primary fibers reviewed in this chapter. Polyethylene is a relatively tough fiber with high strength, stiffness, and elongation at breaking (Park & Jang, 1999). Polyethylene is part of the polyolefin family (ASTM International, 2020d), but it has not been the subject of much independent research. Polyethylene is chemically inert (Park & Jang, 1999), which is disadvantageous for structural applications. Additionally, it can be prone to balling (Roesler et al., 2019).

Another fiber type considered was basalt. Basalt has high strength, a good elastic modulus, and good mechanical and physical properties (Dhand et al., 2015). However, while basalt fibers have a relatively stable weight retention in the alkali environment of concrete, they can lose the majority of their tensile strength in alkali environments, at least as reported by some researchers (Lee, Jung Jin et al., 2014). In this sense, basalt may be acceptable for short term prevention of cracking, but may not stop the long-term propagation of cracks (Branston et al., 2016). Other reports suggest that basalt does not work well for early age shrinkage and cracking (Suksawang et al., 2014). Due to these issues, basalt fibers have not been applied to fiber reinforced concrete pavements (Roesler et al., 2019). In general, few studies have been completed on basalt fibers mixed with concrete, and the topic of basalt fiber in concrete should be considered an open area of research. For these reasons, including basalt was deemed too risky for the current study.

Table A-1: Summary of Fiber Properties Reported in the Literature.

Fiber	Chemical Composition	Specific Gravity	Tensile Strength (ksi)	Elastic Modulus (ksi)	Elongation at Break (%)
Polypropylene	$(C_3H_6)_x$	0.9-0.95[b]	65-110 [b]	510-1450 [b]	15-25 [b]
PVA	$(C_2H_4O)_x$	1.3 [b]	115-220 [b]	4200-5220 [b]	5.7 [b]
Nylon	$(C_{12}H_{22}N_2O_2)_x$	1.14 [b]	110-145 [b]	595-755 [b]	16-20 [b]
AR Glass	71% SiO_2, 11% K_2O+Na_2O, 16% ZrO_2, 1% Al_2O_3, 1% Li_2O [a]	2.78 [b]	363 [b]	10150 [b]	3.6 [b]

a: (Majumdar & Nurse, 1974) b: (Bentur & Mindess, 2007)

A.3 Fiber Addition

A.3.1 Fiber Addition Method

As discussed in the early sections of Appendix A, there are two main forms in which fibers can be procured: spooled and precut. Equipment is commercially available to allow volumetric truck mixers the capability to handle either precut or spooled fiber (personal communication with vendors, October 2019).

A.3.1.1 Spooled Fibers

Spooled fiber feeders for mobile mixers have been around for longer than their precut counterparts (Issa et al., 2007). Of the fibers discussed, only AR glass fibers are available in a spooled roving. The fiber roving is chopped to the required length by the feeder equipment and is added to the concrete mixing auger via a pipe and a pressurized airline (Alhassan & Suleiman, 2012). The chopping system helps to prevent balling, floating, and air entrapment by distributing the fibers consistently and uniformly into the mixing auger (Issa et al., 2007).

There are some limitations to using a spooled fiber feeder. The allowable lengths of fibers are limited between ½” and 1” (Issa et al., 2007). In addition to the length requirements and only being applicable for AR glass fiber, one of the main drawbacks is that the system is limited in terms of maximum dosage rates. Some sources listed a maximum possible dosage rate of about 2 lb/yd^3 (Alhassan & Suleiman, 2012). Given the high specific gravity of glass fibers, this dosage rate works out to a volume fraction of approximately 0.045%. In tests reported in the literature, this dosage rate did provide a 10% reduction in shrinkage from regular LMC, although it did not improve the strength (Issa et al., 2007). An investigation of the available fiber dispensers reveals that the maximum dosage rate can be higher than two pounds per cubic yard, but depends on the output speed of the continuous mixing truck. For a truck with a running output of 15 cubic yards per hour, the maximum fiber dosage with a spooled system would be around 8 pounds per cubic yard.

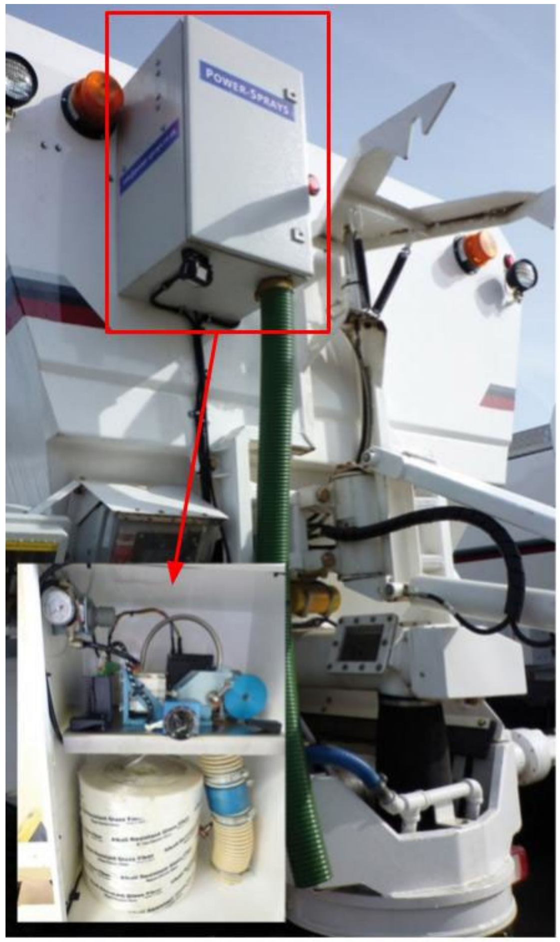


Figure A-1: Spooled Fiber Feeder.

Image Courtesy Power Sprays Ltd

A.3.1.2 Precut Fibers

All of the fibers discussed above, including some forms of AR glass, are commercially available as precut fibers in a variety of lengths. Equipment is also available to add precut (or "pre-chopped") fiber to a volumetric mixer. This equipment is essentially a small hopper that adds fibers at a prescribed rate through a tube into the mixing auger. These fiber feeder systems are reported by vendors and contractors to be reasonably accurate and can give a constant distribution of fibers, however, they fall behind fiber choppers in this regard. The allowable fiber lengths tend to be in the range of 3/8" to 1 ¼" (personal communication, October 2019).

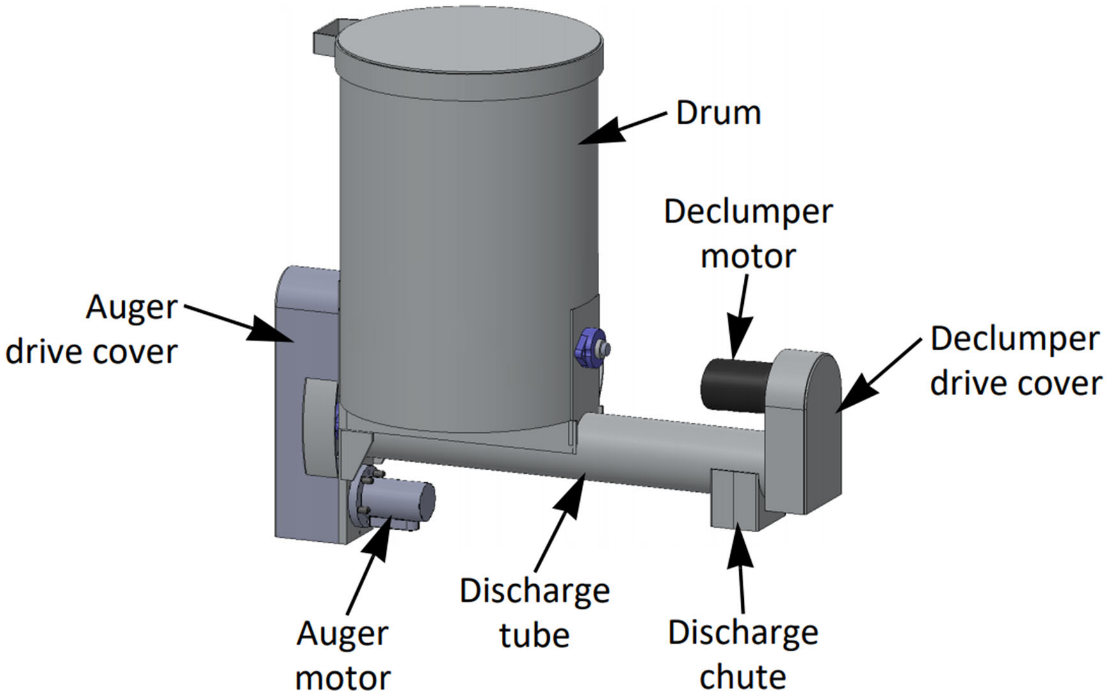


Figure A-2: Precut Fiber Feeder.

Image Courtesy Forta Corporation

A.3.1.3 Current Fiber Dispenser Technology

A summary of commercially available fiber dispensers found by the researchers is shown in Table A-2. These products were compiled from web searches and personal correspondence with truck manufacturers, contractors, and the system manufacturers. The prices listed are approximate at the time of the correspondence. This list is not comprehensive and does not exclude the possibility that other fiber dispensers may be available. Maximum outputs were given as reported by the manufacturers. However, minimum outputs were not typically listed by equipment manufacturers. Minimums as well as maximums are important for LMC-VES overlay work because the volumetric mixing trucks are often operating at a slow speed. Possible dosages are calculated by dividing the dispenser output in pounds per minute by the truck output speed in cubic yards per minute.

Table A-2: Available Fiber Dispensers.

Product Name	Company	Roving or Precut	Fiber Type	Capacity (lb)	Max Output (lb/min)	Lengths	Price	Website/Info
Rover	Forta	Roving	AR-Glass	42	2	3/4"	$ 1,950.00	http://www.fiberfeeders.com/products/rover-concrete/
Ranger	Forta	Precut	AR-Glass	40 or 80	1 to 6	1/2"	$ 1,950.00	http://www.fiberfeeders.com/products/ranger-concrete/
Fiber Dispenser	Zimmer-man	precut	Polypropylene (yes), PVA (most likely), Nylon (no)	Not Listed	3	1/2" to 1 1/4"	$ 7,300.00	https://www.zimmermanindustries.com/gunite-and-shotcrete-mixer/
AR Glass Fiber Dispensing System	Spray Tech	Roving	AR-Glass	40	Not Listed	1/2 or 3/4 or 1	Not Listed	http://www.spraytechne.com/GFRCequipment/Dispensers/VM%20Fiber%20Feeder%20SprayTech%20Version.pdf
AR Glass Fiber Dispensing System	Power Sprays	Roving	AR-Glass	44	2.5	1/4 or 1/2	$ 4,385.00	Would Require Shipping from the UK

A.3.2 Fiber Size

Synthetic fibers are usually broken down by size categories: macrofiber and microfiber. Macrofiber has a linear density of greater than or equal to 580 denier (equivalent to a diameter of 0.3 mm); microfiber has a linear density less than 580 denier (ASTM International, 2020d). Macrofibers are structural and are used to carry load, resisting both early and late age cracking (Alhassan & Suleiman, 2012). Additionally, at high dosages, macrofibers can increase ultimate strength (Lee et al., 2017) by hindering crack propagation and generation (Lee et al., 2018).

Lee, Jeon, Cha, and Park found that, for rapid hardening LMC, macrofibers were good for mechanical characteristics, such as impact resistance, while microfibers were good for cracking performance and reducing chloride ion penetration (Lee et al., 2017). Microfibers are generally used to hinder the propagation and generation of microcracks (Lee et al., 2018), specifically for early age cracking (Alhassan & Suleiman, 2012). Microfibers have also been shown to increase the durability of concrete (Lee et al., 2017).

While some sources suggested a hybrid fiber (macrofiber and microfiber mixed together) due to their ability to suppress both micro and macro cracks (Amirkhanian & Roesler, 2019; Lee et al., 2018), the hybrid approach has practical limitations. While the market offers no shortage of precut hybrid fibers, these all appear to be proprietary blends – a problem for DOT specifications. It would be theoretically possible to custom blend macrosynthetic and microsynthetic fibers in the continuous mixing process, however, this approach would be impractical as it would require the volumetric mixer be equipped with two separate fiber attachments. As such, hybrid and blended fiber types were not considered for this research.

A.3.3 Geometric Properties

Fiber aspect ratio (length divided by the equivalent fiber diameter) plays a major role in concrete performance. Generally, the higher the aspect ratio, the better the performance of the concrete (Kim & Park, 2013a). As reported by Banthia and Gupta, increasing the length and decreasing the denier (which increases the aspect ratio) subsequently increased the capacity of polypropylene fibers to resist plastic shrinkage cracking (Banthia & Gupta, 2006). However, if the aspect ratio is too high, the fiber will ball in the mixer, causing the overall performance to decrease (Kim & Park, 2013a). Kim and Park used synthetic fibers with aspect ratios of 400 and 461 in their fiber reinforced LMC tests. Alhassan and Issa used glass fibers with an aspect ratio of 90 (Alhassan & Issa, 2010).

Fiber length is also an important factor. Fibers need a development length on either side of a crack to provide resistance to crack propagation. The longer the length of the fiber, the higher the likelihood that it will be adequately developed on both sides of a crack (but the higher the likelihood that it will ball in the mixer). For fibers in bridge decks, Alhassan and Suleiman suggested a minimum length of 0.75 inches and a maximum length of 1.75 inches (Alhassan & Suleiman, 2012).

A.3.4 Fiber Dosage

Fiber dosage has major effects on concrete properties. Having too little fiber does not allow for the cracking resistance benefits to take full effect (or any effect). If the fiber dosage is too high, the dispersion of fiber decreases, causing balling. Balling is when fibers clump together during mixing, a phenomenon causing pores at the interface between the cement matrix and the fiber (Oh et al., 2014). Balling leads to reduced workability and to concerns about finishing the concrete (Alhassan & Suleiman, 2012). Luckily, the presence of latex improves fiber dispersion (Oh et al., 2014), allowing for a slightly higher fiber dosage than would be possible in equivalent non-latex concrete.

Fiber dosage is often specified by weight of fiber per cubic yard of concrete, or by a volume fraction, which is the ratio of the fiber volume to the total volume of concrete. Roesler, Bordelon, Brand, and Amirkhanian suggested that, in general, synthetic macrofibers should be prescribed at a volume fraction of 0.27% to 0.38% (Roesler et al., 2019). On the other hand, when testing macrofibers in LMC, Lee et al. used volume fractions of 0%, 0.25% 0.5% and 1.0%. They found that flexural strength increased and chloride ion permeability decreased with increasing fiber content, with 1.0% volume fraction providing the best results (Lee et al., 2018). This result matches the theory put forth by Oh, Kim, and Park.

Dosage in microfibers is somewhat material dependent. Current practice for bridge decks (of all concrete types) is to use between 0.2% and 1% volume percentage of polypropylene (Amirkhanian & Roesler, 2019). However, for the same application, Roesler, Bordelon, Brand, and Amirkhanian suggested an increase from current practice, recommending between 0.5% and 1% by volume for polypropylene and 0.5% to 4% by volume for PVA (Roesler et al., 2019). Alhassan and Suleiman suggested an upper limit of 3 lb/yd^3 in all bridge decks for both polypropylene (~0.13% by volume) and nylon (~0.10% by volume) due to the tendency for balling and clumping (Alhassan & Suleiman, 2012). Bentur and Mindess suggested using 0.1% polypropylene by volume for general concrete, indicating that even at that small volume fraction, the fiber was effective at reducing plastic shrinkage cracking (Bentur & Mindess, 2007). In their tests of PVA, polypropylene, and nylon fiber in LMC, Kim and Park used a 0.1% volume fraction (Kim & Park, 2013a). Similarly, Lee, Jeon, Cha, and Park used 0.1% volume fraction in their tests of polyolefin macrofiber and PVA microfiber. Thus, the literature is far from reaching a consensus on ideal fiber dosage rates. For each individual dispenser, the practical minimum and maximum dosage rate can be calculated by dividing the minimum and maximum fiber dispenser rate (found in Table A-2) by the continuous truck concrete output in cubic yards per minute.

Appendix B: Laboratory Mixing Method

B.1 Introduction

This appendix outlines a continuous mixing method developed for the laboratory mixing of concrete representative of the full-scale volumetrically batched continuous mixing process. This mixing method was successfully used throughout the testing described in Chapters 3 and 5. The required equipment, material preparation, and mixing method are presented in this chapter.

B.2 Background

Continuous mixing is a process in which concrete batching and mixing take place simultaneously. Metered amounts of raw materials feed the inlet of a mixing auger and fresh concrete is dispensed from the outlet of the auger. A continuous mixer draws from stores of different materials in set proportions to produce fresh concrete as it is needed. Mixing can be stopped and restarted as required. The continuous mixing process is often used in field applications with latex-modified concrete, rapid hardening concrete, controlled low strength material (flowable fill), and sometimes ordinary Portland cement concrete. Rapid setting concrete, or other concrete that loses workability quickly, can be difficult or impossible to batch and mix in the traditional sequential process where concrete is batched, mixed/transported, and then placed. For field placement, large-scale continuous mixing equipment is commercially available that can deliver production rates of 50 cubic yards per hour or more. In a laboratory setting, however, large production rates are usually undesirable. Conducting research on materials such as LMC-VES often requires that many small trial or sample batches of concrete be produced in rapid succession. The concrete used in the lab should be as representative as possible of the concrete used in the field, including the mixing process. When lab-mixed material is not representative of field mixing processes, laboratory test results may be unreliable or unrealistic for use. Past experiments involving rapid hardening Calcium Sulfoaluminate (CSA) cement have often used material batched and mixed in a small drum or mortar mixer (Alhassan & Suleiman, 2012; Smyl et al., 2016) or rotating pan mixer (Afroughsabet et al., 2019). Laboratory mixing and casting is often rushed as some of these materials set in as little as 5 to 10 minutes after the addition of water. In these examples (and many others), the laboratory mixing method is substantially different from the field mixing method.

Current mixing methods tend to be based on ASTM C192: Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory (ASTM International, 2019b). In addition to drum mixers, this method also allows for revolving pan, revolving paddle, and tilting mixers. However, none of this equipment mixes continuously, and all are less than ideal for mixing modest-sized batches of rapidly hardening concrete. To combat the problem of quick setting while mixing, retarders are often used. For example, Smyl et al. used citric acid to counteract the rapid-hardening nature of CSA concrete (Smyl et al., 2016). Won et al. added a retarder for similar reasons (Won, Kim, Lee et al., 2009). The addition of retarder can further decrease the similarity between the lab-mixed concrete and the field-mixed concrete it is trying to represent. Other problems encountered with existing laboratory mixing methods include material hardening in the drum, time constraints of testing, and workability concerns. Because of these issues, a volumetrically based laboratory-scale continuous mixing method would be desirable for experimental work with materials such as LMC-VES and others that require continuous mixing. Such a mixing method has been developed and is presented in this appendix.

B.3 Summary of the Laboratory Continuous Mixing Procedure

Continuously mixed concrete, in the case of trials of LMC-VES, was manufactured in the laboratory as follows:

1. Dry materials (cement, sand, aggregate, and fibers if required) were pre-blended in the right proportions in a separate drum mixer. Care was taken to use only oven-dry aggregates, to avoid introducing any water into the dry mixture, and to handle the mixture gently to prevent segregation after dry blending. The pre-blended dry mixture was loaded into the hopper of a small continuous mixer.
2. Latex and water were pre-blended in a separate container to the right ratio. If required, citric acid (or other additives) were be added to this liquid mixture. The pre-blended liquid mixture was fed to the small continuous mixer via an electric pump and hose.
3. The continuous mixer was used to mix the pre-blended dry inputs with the pre-blended liquid inputs. Mixing was continuous, representative of the field mixing process for LMC VES, and could be started and stopped as required to cast test specimens. Specimens were always cast with fresh concrete from the output of the mixing auger, as would be typical in a field mixing process.

Details of this small-scale continuous mixing process for laboratory use are outlined in the sections below.

B.4 Mixer and Apparatus Requirements

This mixing method is based on a modified commercially available small continuous mixer, as shown in Figure B-1 through Figure B-4. The mixer must have a liquid inlet, a hopper, a hopper cover, a liquid pressure regulator, a flow regular, a solenoid, a mixing auger, and an auger speed regulator. Inclusion of a flow meter, T-strainer, and drain valves is helpful. In addition to the mixer, a submersible pump, hose, and container with a lid (such as a trashcan) are required if liquid latex or soluble admixtures will be included with the mixing water. A separate drum mixer is required to pre-blend dry materials prior to volumetric mixing. A large oven is needed for drying aggregates prior to blending.

Figure B-1: Continuous Mixer Overview.

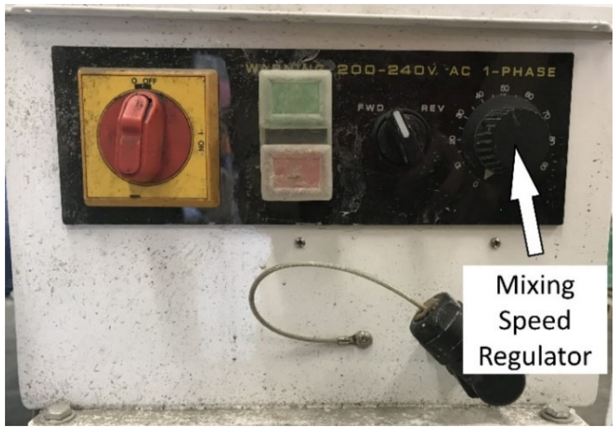


Figure B-2: Mixer Control Panel.

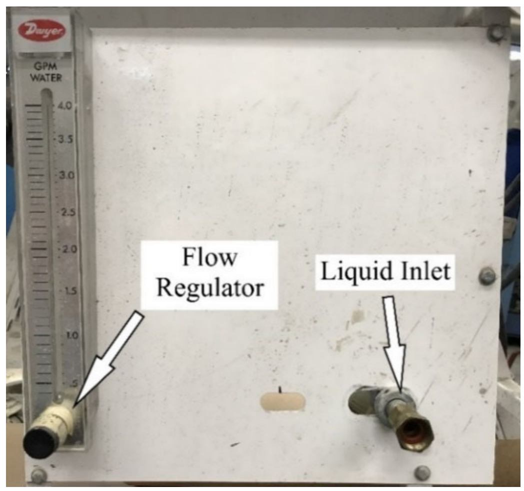


Figure B-3: Liquid Control Panel.

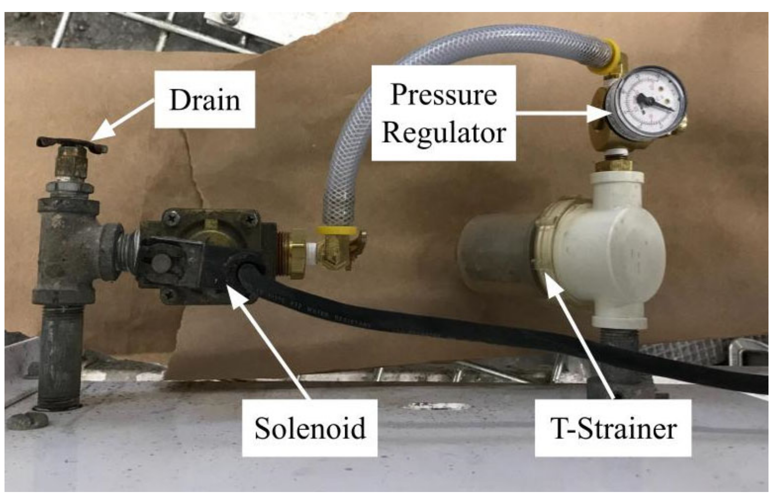


Figure B-4: Liquid System (Behind Liquid Control Panel).

B.4.1 Mixer Adjustments

Commercially available small-scale continuous mixers pull dry material from a single hopper and are usually configured to receive water from a standard garden hose. An adjustable-speed electric motor typically drives a feed auger and a mixing auger. Liquid is introduced to the mixing auger through an adjustable flow control valve and an electronic solenoid valve that starts and stops the liquid flow as the operator starts and stops mixing. As commonly configured, small continuous mixers present some challenges for laboratory use with materials such as LMC-VES. These small mixers draw material from a single hopper whereas typical continuous concrete mixing truck has separate hoppers for sand, coarse aggregate, and cement. The small mixers do not have a provision for introducing liquid latex or other liquid and soluble admixtures to the mixture when required.

As such, the commercially available volumetric mixer was modified in the following ways to facilitate laboratory use with LMC-VES:

1. The hopper was extended to allow loading sufficient amounts of pre-blended dry materials.
2. The mixer was angled to slope the mixing auger downward, thus preventing any moisture from contacting the dry material in the bottom of the hopper.
3. A pressure regulator was added to the liquid inlet to improve the flow rate accuracy of the liquid system. Relatively minor changes to liquid input pressure can have large changes in flow rate. Introducing the pressure regulator significantly reduced flow rate variability and improved mixing accuracy.
4. A strainer and drain valves were added to the liquid system to facilitate using a blend of latex and water with the system. Drain valves enabled convenient and thorough flushing of the liquid system after use, and the strainer kept solid particles of latex from clogging the solenoid and flow meter.

B.5 Material Preparation

B.5.1 Aggregates

All aggregates should be dried so water does not react prematurely with cement. The aggregates may be dried in an oven, in large quantities via evaporation (such as in an environmental chamber as shown in Figure B-5), or through other methods. If aggregates are dried by any method besides in an oven, a representative sample should be tested for moisture content prior to subsequent dry blending. This sample should be dried in an oven at a temperature of 110 ± 5 °C (230 ± 9 °F) as specified in ASTM C127 Section 8.1 (ASTM International, 2015b) and ASTM C128 section 9.2.3 (ASTM International, 2015c). The change in weight of the aggregate sample should be less than 10% of the aggregate absorption capacity, as shown in Equation (B-1), where A is the absorption capacity of the aggregate, w_1 is the weight of the aggregate and container before being placed in the oven, w_2 is the weight of the aggregate and container after being placed in the oven, and w_c is the weight of the container. The absorption capacity (A) should be recorded for each aggregate, as it is important in the next step of the calculations. A_F refers to the absorption capacity of fine aggregate, and A_C refers to the absorption capacity of coarse aggregate.

$$\frac{w_1 - w_2}{w_2 - w_c} * 100\% \leq 0.1 * A(\%) \tag{B-1}$$

Figure B-5: Drying Aggregates by Evaporation in a Large Environmental Chamber.

B.5.2 Pre Mixing

Adjust the mixture design to account for the dryness of the aggregates. The calculations should follow Equation (B-2 a, b, and c), where W_F is the saturated surface dry (SSD) weight of fine aggregate, W_C is the SSD weight of coarse aggregate, $W_{F,D}$ is the dry weight of fine aggregate, $W_{C,D}$ is the dry weight of coarse aggregate, W_W is the weight of mixing water, and W_{WT} is the weight of total water. All weights should be on a per cubic yard of concrete basis.

$$W_{F,D} = \frac{W_F}{(1 + A_F)} \tag{B-2 a}$$

$$W_{C,D} = \frac{W_C}{(1 + A_C)} \tag{B-2 b}$$

$$W_{WT} = W_W + W_{F,D} * A_F + W_{C,D} * A_C \tag{B-2 c}$$

Determine the weight of solids and liquid per cubic yard of concrete (W_S and W_L respectively), as shown in Equation (B-3 a and b). Weight of solids includes the weights of dry fine aggregate ($W_{F,D}$), dry coarse aggregate ($W_{C,D}$), cement (W_{Ce}), insoluble admixtures as defined by ASTM C192 Section 7.5 (ASTM International, 2019b) (W_{SA}), and fibers (W_{Fi}). Weight of liquids includes the weights of total water (W_{WT}), other liquids such as latex (W_{OL}), and water-soluble and liquid admixtures, as defined by ASTM C192 Section 7.5 (ASTM International, 2019b) (W_{LA}).

$$W_S = W_{F,D} + W_{C,D} + W_{Ce} + W_{SA} + W_{Fi} \tag{B-3 a}$$

$$W_L = W_{WT} + W_{OL} + W_{LA} \tag{B-3 b}$$

Determine the required mixing amount by weight. This amount should be based on the amount of concrete required by the intended test specimens. An allowance for at least 25% extra should be made. Based on this amount, determine an intended weight of dry mixture (DM_T) and of liquid mixture (LM_T), as shown in Equation (B-4 a and b), where W_T is the weight of mixing amount. Additional weight for each mixture should account for the necessary amount of unmixed material that will remain in the hopper (solid) and container (liquid) to maintain material rates.

$$DM_T \geq W_T * \frac{W_S}{W_S + W_L} \tag{B-4 a}$$

$$LM_T \geq W_T * \frac{W_L}{W_S + W_L} \tag{B-4 b}$$

Determine the dry mixture weight of fine aggregate, coarse aggregate, cement, insoluble admixtures, and fibers using Equation (B-5). Once again, calculations for aggregates should be based on their dry weight and not their SSD weight.

$$DM_x = \frac{W_x}{W_S} * DM_T \tag{B-5}$$

Determine the liquid mixture weight for total water, liquid and soluble admixtures, and other liquids using Equation (B-6).

$$LM_x = \frac{W_x}{W_L} * LM_T \tag{B-6}$$

B.5.3 Dry Mixing

Completely dry the interior of a drum mixer. Using a scale, weigh out the dry mixture component weights as determined from Equation (B-5). All dry components should be placed in the drum mixer, as shown in Figure B-6. The mixer should then be covered to prevent excess silica dust. The drum mixer should be run until the dry mixture has become homogeneous, as seen in Figure B-7. The resulting mixture should then be loaded into the continuous mixer hopper. Throughout this process, all participants should use appropriate dust control measures and should wear appropriate personal protective equipment to minimize exposure to silica dust. A shop vacuum fitted with a fine dust bag is helpful to control airborne dust.

Figure B-6: Dry Materials in Drum Mixer before Dry Mixing.

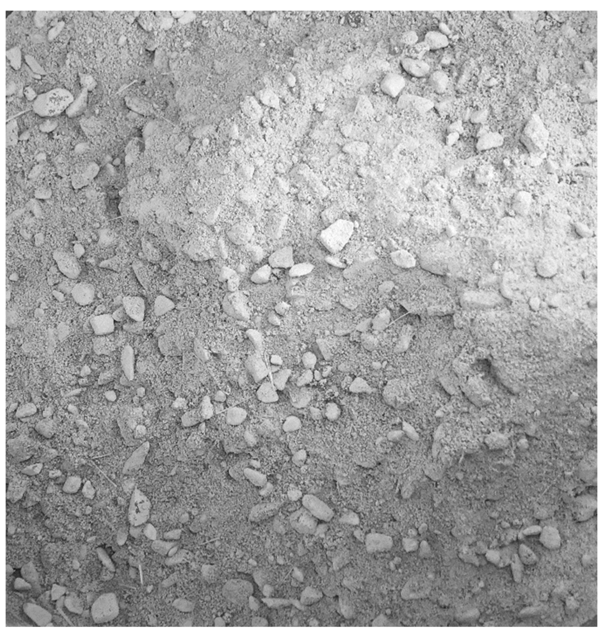


Figure B-7: Homogeneous Dry Material.

B.5.4 Liquid Mixing

Using a scale, weigh out the liquid mixture component weights as determined from Equation (B-6). All components should be placed in the lidded container and mixed thoroughly.

B.6 Mixer Preparations

The continuous mixer should be set up to prevent liquid from flowing back into the hopper. One possible method is to incline the mixer (as shown in Figure B-8). On the day of mixing, the continuous mixer should be calibrated for both liquid and solid output individually; this step is especially important if the mixer does not have a flow meter. The method proposed here uses the rate of liquid output to calculate the rate of solid output. Alternatively, the operator may start by selecting the solid output rate and then calculating the liquid output rate.

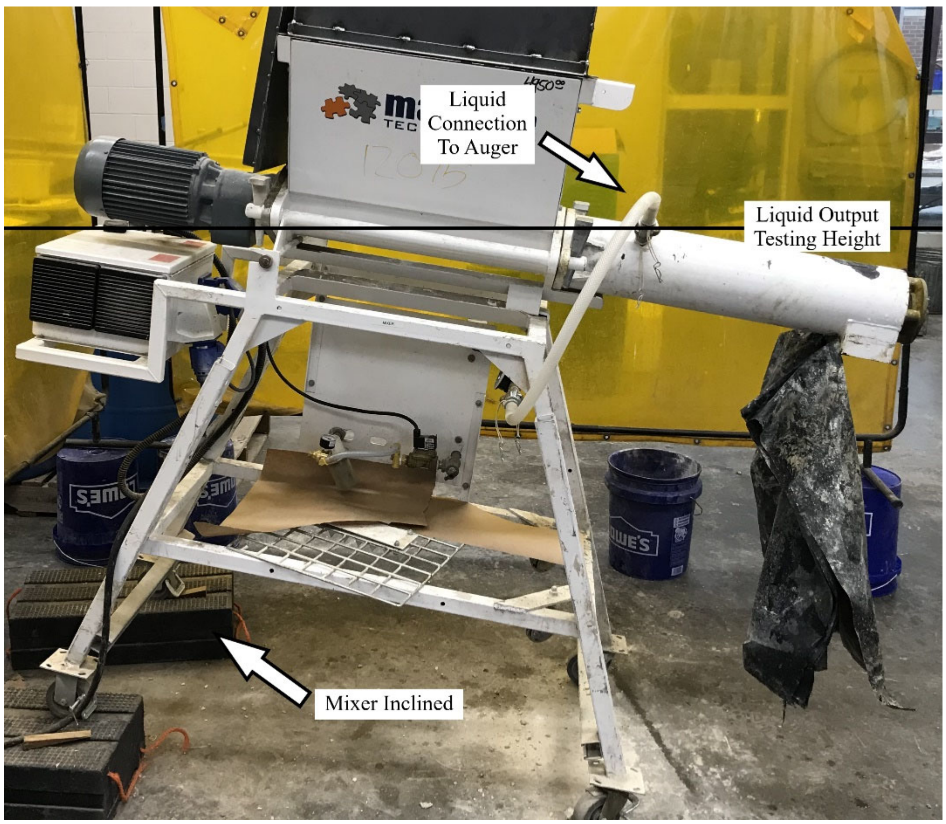


Figure B-8: Inclined Continuous Mixer.

B.6.1 Liquid Output Testing

Set a target rate of liquid for the mixer in pounds per minute. Set the flow regulator to the desired level and then measure the weight of the liquid output until it has run for at least 90 seconds and output at least 10 pounds. Due to the low pressures required by the system, it is very important to measure the liquid output at the height where the liquid will enter the auger (shown in Figure B-8). The rate should be calculated by dividing the output weight by the run time. While it is acceptable to test at different flow regulator settings, the final selected setting should be tested at least three times. The rate of liquid output will be the average of all rates measured at that flow regulator setting. The final average output was found to be reasonable when the maximum percent difference between the three measurements was below 3%.

B.6.2 Solid Output Testing

After testing the rate of liquid output (R_L), calculate the necessary solid output rate (R_S) using Equation (B-7).

$$R_S = R_L * \frac{W_S}{W_L} \tag{B-7}$$

Adjust the auger speed to match the required rate of solid output and then measure the solid output weight over the course of at least 20 seconds and an output of at least 15 pounds. Once again, the rate should be calculated by dividing the output weight by the run time, and the final auger speed setting should be tested at least three times. The final average rate was found to be reasonable when it fell within 3% of the rate calculated using Equation (B-7).

B.6.3 Mixing Technique

Connect the liquid input to the auger and start the pump. Using the flow regulator setting and auger speed previously determined, run the mixer. The first portion of material should be discarded until the concrete mixture has become homogenous (Figure B-9). The amount of discarded material will vary depending on details such as whether the connecting hoses are empty or full at the start of mixing, and whether any residual dry inputs remain in the mixing auger. The resulting mixture should be a homogeneous, well mixed concrete (Figure B-10). During the mixing process, it is acceptable for the operator to stop and start the mixer as needed. However, long pauses (on the order of several minutes) should be avoided to prevent concrete from setting in the mixer auger. After the specimens have been cast, the pump should be stopped, and the liquid input disconnected. The auger, auger housing, and any other surface that the wet concrete touched should be washed immediately and set to dry (Figure B-11). The liquid system should be drained (Figure B-12). If any substance other than water was included in the mixing liquid, run water through the system several times (Figure B-13) and flush the system through the drains. Any excess liquids, such as latex, should be disposed of properly.

Figure B-9 (a and b): Discarded Material.

Figure B-10: Fully Mixed Concrete.

Figure B-11: Cleaning Auger.

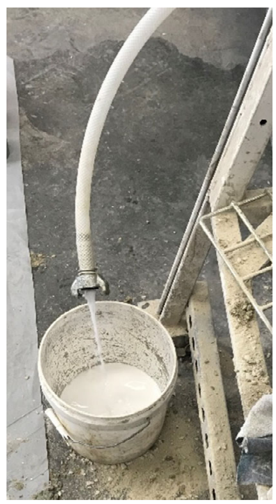


Figure B-12: Draining Liquid System.

Figure B-13: Flushing Liquid System.

B.7 Conclusions on Laboratory Mixing System

A new method for continuously mixing small batches of concrete in a testing laboratory is described that is representative of field-mixed volumetric concrete. The method allowed for using less excess retarder than traditional mixing laboratory methods, and enabled testing and casting of a given portion of material to be completed close to the start of mixing. This method was been used successfully throughout the current research. More study will be necessary to determine if standard deviation allowances and difference limits should be the same for this method as for ASTM C685: Standard Specification for Concrete Made by Volumetric Batching and Continuous Mixing (ASTM International, 2017b) or for ASTM C192 Section 10 and other specifications (ASTM International, 2019b).

Appendix C: Overview of the Overlay Construction Process

The overlay construction process begins with a preparation of the bridge deck surface. All deteriorated, delaminated, and unsound concrete is removed from the top layer of the bridge deck. It is important for all concrete contaminated by chloride ions to be removed. One of the main purposes of the overlay is to protect rebar in the bridge deck from corrosion. If the overlay is performed over concrete that is already contaminated, then deterioration can still continue. Additionally, any structural cracks in the substrate must be removed (chipped out) or repaired (epoxy injected), otherwise, they will propagate through the overlay. In North Carolina, it is common to remove the concrete down to the first layer of rebar or to a maximum of two inches below the final bridge deck surface. However, larger depths of material must sometimes be removed based on the depth of chloride ion penetration. In North Carolina, as well as many other states, concrete is often removed via a process called hydro demolition (often abbreviated as hydro demo), as shown in Figure C-1. The hydro demo process removes deleterious concrete and chlorides, cleans any exposed rebar, and provides a scarified surface for the overlay to bond to. Afterwards, the surface is cleaned, and loose aggregates are removed. Before casting, the deck surface is soaked and saturated for at least two hours and covered with a white opaque polyethylene sheeting (to prevent evaporation and to reflect heat from the surface). All standing water is removed before casting, but the surface should be damp when contacted by the fresh overlay concrete (North Carolina Department of Transportation, 2019b).

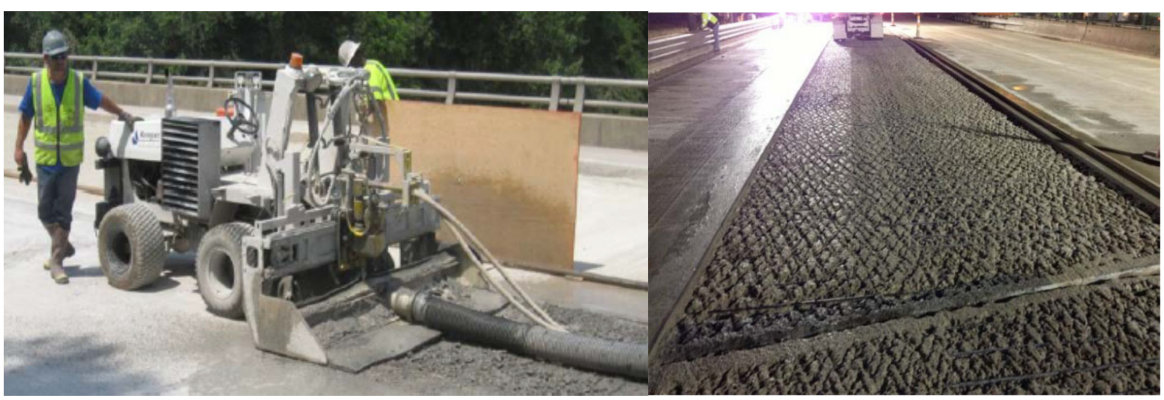


Figure C-1: Hydro Demo and Resulting Surface.
Photo Courtesy (Earwood & Garbee, 2018)

Both LMC and LMC-VES require a mobile continuous mixer, commonly referred to as a volumetric mixer, as opposed to a standard drum mixer truck. A continuous mixer has different hoppers and tanks to store fine aggregates, coarse aggregates, cement, water, and admixtures. The mixer batches and mixes concrete simultaneously, introducing each individual material into a mixing auger at a prescribed rate to result in the final designed mixture. This process allows for concrete to be mixed as needed, leaving a much shorter length of time between the addition of water to cement and the final concrete placement. Continuous mixers must be calibrated for a specific mixture design a few days in advance of the date of casting. At the beginning of each truckload of concrete, material rates are adjusted to allow for the concrete to reach the desired homogeneous mix. The concrete from this initial startup and adjustment period is usually poured into a waste area.

Inspection of the fresh concrete for an overlay is supposed to be completed after a homogeneous mixture has been achieved and before any concrete is placed on the bridge deck. In North Carolina, inspectors measure the slump and air content of LMC-VES and make six 4” x 8” cylinders to be tested for compressive strength three hours later (North Carolina Department of Transportation, 2019b). Inspection is completed on each truckload of concrete prior to the truck depositing any concrete on the bridge deck. After inspection is complete, concrete is deposited from the mixer auger of the volumetric truck directly on the saturated bridge deck. The concrete is spread, vibrated, screeded, and finished, usually using a Bidwell machine, as shown in Figure C-2. A layer of saturated burlap is placed about 5 feet behind the final screed. A second layer of burlap and white opaque polyethylene sheeting are then placed on top to provide a wet cure. The concrete is wet cured for at least three hours (North Carolina Department of Transportation, 2019b). In the case of LMC-VES, it is permissible to open the overlay to traffic directly after the wet cure is finished. The overlay process is generally completed one lane at a time to allow for a shorter interval between mixing of concrete and beginning of curing. When the process is properly carried out, only about 15 minutes should elapse between the time the concrete leaves the mixer and the time the finished fresh overlay is covered with wet burlap. After all lanes have been completed, the overlay surface is grooved within a week (North Carolina Department of Transportation, 2019b).

Figure C-2: Placing, Vibrating, Screeding, and Finishing.
Photo Courtesy (Earwood & Garbee, 2018)