Report No. UT-23.17

VALIDATING AASHTO PP-84 PASTE VOLUME LIMITS FOR SHRINKAGE MITIGATION IN UDOT CONCRETE MIXES

Prepared For:

Utah Department of Transportation
Research & Innovation Division

Final Report
May 2024

RESEARCH

UDOT
Keeping Utah Moving
Utah Department of Transportation - Research Division
4501 South 2700 West - P.O. Box 148410 - SLC,UT 84114-8410

DISCLAIMER

The authors alone are responsible for the preparation and accuracy of the information, data, analysis, discussions, recommendations, and conclusions presented herein. The contents do not necessarily reflect the views, opinions, endorsements, or policies of the Utah Department of Transportation or the U.S. Department of Transportation. The Utah Department of Transportation makes no representation or warranty of any kind, and assumes no liability therefore.

ACKNOWLEDGMENTS

The authors acknowledge the Utah Department of Transportation (UDOT) for funding this research, and the following individuals from UDOT on the Technical Advisory Committee for helping to guide the research:

- Bill Lawrence
- Scott Nussbaum
- Jason Richins
- Curt McCuiston
- Scott Strader
- Bryan Lee
- Kevin Nichol

TECHNICAL REPORT ABSTRACT

1. Report No. UT- 23.17	2. Government Accession No. N/A	3. Recipient's Catalog No. N/A

4. Title and Subtitle
VALIDATING AASHTO PP-84 PASTE VOLUME LIMITS FOR SHRINKAGE MITIGATION IN UDOT CONCRETE MIXES

5. Report Date
October 2023

6. Performing Organization Code

7. Author(s)
Md. Abdullah Al Sarfin, Andrew D. Sorensen

8. Performing Organization Report No.

9. Performing Organization Name and Address
Utah State University
4110 Old Main Hill
Logan, UT 84322-4110

10. Work Unit No.
5H090 26H

11. Contract or Grant No.
19-8052

12. Sponsoring Agency Name and Address
Utah Department of Transportation
4501 South 2700 West
P.O. Box 148410
Salt Lake City, UT 84114-8410

13. Type of Report & Period Covered
Final
Jul 2018 to Jun 2024

14. Sponsoring Agency Code
PIC No. UT18.101

15. Supplementary Notes
Prepared in cooperation with the Utah Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration

16. Abstract

This document presents the findings of an experimental study to evaluate the effect of the paste volume on the Utah Department of Transportation (UDOT) approved concrete mixtures. The AASHTO PP-84-17 provisional specification limits the maximum paste volume to 25%, while the selected UDOT approved mixtures have paste volume over 27%. The selected mixtures and the modified mixtures, with reduced paste volume, are studied to quantify the effect of such reduction on volume stability, shrinkage cracking, fresh, mechanical, and durability properties of concrete. The finding of this research project concludes that at 25% paste volume, the mixtures retain sufficient plasticity. At this limit, the air content, compressive strength, and static modulus of elasticity of the concrete are also comparable to the approved mixtures. The unit weight of the concrete mixtures increases as the paste volume decreases. Irrespective of paste volume, the approved and modified mixtures demonstrate low to very low chloride ion penetrability. At the 25% paste volume, the shrinkage of the mixtures is significantly less compared to the control mixtures with higher paste volume. However, further reduction of paste volume negatively affects some of the fresh and hardened properties of the concrete, such as, workability and compressive strength. In conclusion, based on the findings of this study, the reduction of paste volume of the UDOT-approved mixtures following the AASHTO PP-84 limits is recommended.

17. Key Words
Concrete Paste Volume, Shrinkage Control

18. Distribution Statement
Not restricted. Available through:
UDOT Research Division
4501 South 2700 West
P.O. Box 148410
Salt Lake City, UT 84114-8410
www.udot.utah.gov/go/research

23. Registrant's Seal
N/A

19. Security Classification (of this report) Unclassified	20. Security Classification (of this page) Unclassified	21. No. of Pages 63	22. Price N/A

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

UNIT CONVERSION FACTORS

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. (Adapted from FHWA report template, Revised March 2003)

LIST OF ACRONYMS

ACI	American Concrete Institute
CPV	Cementitious Paste Volume
DOT	Department of Transportation
FHWA	Federal Highway Administration
HPC	High Performance Concrete
HRWR	High-Range Water-Reducers
ITZ	Interfacial Transition Zone
NMAS	Nominal Maximum Aggregate Size
OPC	Ordinary Portland Cement
PLC	Portland Limestone Cement
PCC	Portland Cement Concrete
SCC	Self-Compacting Concrete
SCM	Supplementary Cementitious Materials
UDOT	Utah Department of Transportation

EXECUTIVE SUMMARY

In light of the proposed provisional limits on the paste volume in concrete pavement mixtures as a means of mitigating shrinkage cracking in AASHTO PP 84-17, this project aims to validate Utah Department of Transportation (UDOT) mixtures in order to determine the actual effect on volume stability and cracking potential of the mixtures. The UDOT-approved mixtures for this study, selected in consultation with UDOT, have paste volume over 27%, while the AASHTO PP-84-17 provisional specification limit for maximum paste volume is 25%. This project studies the fresh and hardened properties of selected UDOT approved mixtures as well as modified mixtures with reduced paste volume.

The objectives of this research project are twofold; primarily, determine if the proposed limits affect volume stability and shrinkage cracking in UDOT concrete pavement mixtures, and secondarily, evaluate the effects of paste volume limits on the fresh properties, mechanical properties, and durability properties of UDOT concrete pavement mixtures. This research project evaluates two UDOT-approved pavement mixtures from Geneva Rock Products by consulting with UDOT representatives. Field samples of the mixtures are collected from the batch plant for quality control purposes. Following standard procedure of concrete mixtures, specimens for laboratory investigation are prepared in a controlled environment at the concrete laboratory of Utah State University. The following material properties/behaviors are studied: workability, fresh air content, unit weight, compressive strength, static modulus of elasticity, autonomous shrinkage, and ring shrinkage. Each UDOT concrete pavement mixture is modified to reduce the paste volume in concrete and compared with the control mixtures.

The findings of the study show that the workability of the pavement mixtures is greatly influenced by the amount of paste volume in the freshly mixed concrete. With decreasing amount of paste volume, the concrete starts to lose workability. At a minimum value of 25% of the paste volume, the laboratory mix is sufficiently workable. However, at 23.5% paste volume, the modified pavement mixture loses plasticity. As the workability is reduced, the percentage of surface voids increases. Based on the box test results for workability, the volume of paste can be reduced to a minimum value of 25%. Admixtures dosage can be adjusted to account for any reduced workability of the mixtures.

The fresh air content is affected by the volume of the paste present in the mixtures. When there is less amount of paste available in the mix, the voids between the aggregates are filled up by air voids. Therefore, the air content of the concrete increases with reduced volume of the paste. At a minimum value of 25% of the paste volume, the air content is comparable with the control mixtures. The effect of the paste volume is much higher for mixtures with paste volume less than 25%.

The unit weight of the concrete mixtures increases with decreasing volume of the paste. As less cement paste is available in the mixtures, the spaces are occupied by heavier aggregates, resulting in higher unit weight.

At a minimum value of 25% volume of the paste, the compressive strength, and the static modulus of elasticity of the mixtures are not significantly affected. The compressive strength and the elastic modulus of the mixtures with 25% paste volume is comparable to those of the control mixtures with higher paste volume. The compressive strength, primarily, depends on the water-to-cement ratio, provided that sufficient cement paste is present in the mixtures. However, when the volume of the paste is reduced below 25%, the strength of the mixtures reduces notably.

The surface electrical resistivity test indicates that, irrespective of paste volume, all the mixtures have low to very low chloride ion penetrability. Surface electrical resistivity is found to be the least affected property of the pavement mixtures.

In general, the reduction of paste volume positively affects the shrinkage properties of concrete. The percentage of length change and the shrinkage strain reduce with decreasing volume of the paste. The maximum shrinkage strain and the maximum percentage of length change of the mixtures with 25% paste volume are within the limit recommended by AASHTO PP-84 and UDOT. Overall, the shrinkage in mixtures with 25% paste volume significantly reduces compared to the control mixtures with higher volume of the paste.

The finding of this research program concludes that the paste volume of the UDOT-approved pavement mixtures can be reduced to a minimum value of 25% without negatively affecting the concrete performance. Therefore, it is recommended that the paste volume content of the UDOT-approved pavement mixtures should be reduced following the paste volume limit of AASHTO PP-84.

1.0 INTRODUCTION

1.1 Problem Statement

In light of the proposed provisional limits on the paste volume in concrete pavement mixtures as a means of mitigating shrinkage cracking in AASHTO PP 84-17, this project aims to validate Utah Department of Transportation (UDOT) mixtures in order to determine the actual effect on volume stability and cracking potential of the mixtures. The UDOT-approved mixtures for this study, selected in consultation with UDOT, have paste volume over 27%, while the AASHTO PP-84-17 provisional specification limit for maximum paste volume is 25%. This project studies the fresh and hardened properties of selected UDOT approved mixtures as well as modified mixtures with reduced paste volume.

1.2 Objectives

The objectives of this research project are twofold; primarily, determine if the proposed limits affect volume stability and shrinkage cracking in UDOT concrete pavement mixtures, and secondarily, evaluate the effects of paste volume limits on the fresh properties, mechanical properties, and durability properties of UDOT concrete pavement mixtures.

1.3 Scope

This research project evaluates two UDOT-approved pavement mixtures from Geneva Rock Products by consulting with UDOT representatives. Field samples of the mixtures are collected from the batch plant for quality control purposes. Following standard procedure of concrete mixtures, specimens for laboratory investigation are prepared in a controlled environment at the concrete laboratory of Utah State University. Each UDOT concrete pavement mixture is modified to reduce the paste volume in concrete and compared with the control mixtures.

1.4 Outline of Report

This report consists of six chapters:

- Introduction
- Literature Review
- Research Methods
- Results and Data Analysis
- Conclusions
- Recommendations and Implementation

The first chapter describes the objectives and scope of the project as well as the outline of the report. The second chapter presents a review of the literature on the effect of paste volume on various properties of concrete. The third chapter describes the mixing and testing methods, and relevant standards. Field and laboratory test results are presented and analyzed in the fourth chapter. The last two chapters summarize the findings of this research project and recommendations, respectively.

2.0 LITERATURE REVIEW

2.1 Overview

Reduction of paste volume in concrete can be beneficial due to ascending price of concrete, high demand and decreasing production of fly ash (Black), and for reduction of the carbon footprint of concrete (Kwan and Ling; Ling and Kwan). In addition to these advantages, by reducing cementitious contents of concrete, the shrinkage cracking potential can be reduced. High paste volume leads to higher cracking potential. Concrete shrinks by losing moisture as it hardens and, as a result, tensile stresses start to develop due to restraint from connected structural components and adjoined materials. Once the developed tensile stress exceeds the tensile strength of the material, shrinkage cracks begin to develop. Cracking deteriorates structures' service life, reduces load-carrying capacity, and allows water and various chemical agents to come into contact with reinforcing steel, leading to corrosion. In addition to affecting the properties of hardened concrete, paste volume significantly influences fresh concrete properties. This chapter provides a brief overview of existing literature on the effect of paste volume on fresh and hardened concrete properties as well as a summary of the paste volume requirements in different state DOT specifications.

2.2 Paste Volume and Fresh Concrete Properties

Paste content has a significant effect on the properties of both fresh and hardened concrete. The following sub-sections discuss recent studies on the effect of paste content on workability and air content of fresh concrete.

2.2.1 Workability

American Concrete Institute's CT-18: ACI Concrete Terminology defines workability as the property of fresh concrete or mortar that determines the ease with which it can be mixed, placed, consolidated, and finished to a homogenous condition (ACI). The desired workability of a concrete mixture corresponds to the construction type, placement method, compaction, and finishing methods (Mehta and Monteiro). Factors affecting workability are method and duration of transportation, quantity and characteristics of cementitious materials, slump, gradation, shape and texture of aggregates, entrained air, water content, concrete and ambient air temperature, and admixtures (Kosmatka and Wilson). ASTM C143-15 Standard Test Method for Slump of Hydraulic-Cement Concrete describes a method for assessing the workability of hydraulic cement concrete using a frustum of a cone with 8 in. (200 mm) diameter base, 4 in. (100 mm) diameter top, and 12 in. (300 mm) height (ASTM C143/143M). For various types of construction, different slumps, usually ranging from 2 in. to 4 in. (50 mm to 100 mm), are specified. For example, typically 1 in. to 3 in. (25 mm to 75 mm) slump is specified for pavements placed by mechanical paver (Kosmatka and Wilson). AASHTO PP 84-14 Standard practice for Developing Engineered Concrete Pavement Mixtures specifies a box test to evaluate the workability of concrete paving mixtures. In this method, a cubic wooden box of 1 ft^3 volume with sides or length of 12 in. (300 mm) is used. In addition to measuring the slump, this test method requires reporting of surface voids by comparing to a rubric provided in the specification (AASHTO PP 84). Detailed methodology for the box test is further discussed in Chapter 3.

For a given water content, workability decreases with decreasing cement content. Required workability can be maintained by using higher dosages of admixture such as superplasticizer. Some of the recent findings on concrete workability are summarized as follows:

- For self-compacting concrete, an increase in slump flow is reported with increase in paste volume for a given combination of aggregate with a packing density of 0.68 (Nanthagopalan and Santhanam).

- Yurdakul et al. demonstrated that for plain mixtures without any supplementary cementitious materials (SCM), a minimum of 1.5 times more paste than voids between aggregates is required to achieve a workable mix; below which even a high dosage of high-range water-reducer (HRWR) is not very effective. For mixtures with SCMs, the minimum paste volume is reported to be approximately 1.25 times the volume of voids between aggregates. The spherical morphology of fly ash reduces inter-particle friction and thus reduces minimum paste volume required to maintain workability (Yurdakul, Peter C Taylor, et al.).

- Decreased cementitious paste volume (CPV) results in thinner mortar film thickness around aggregate particles, which reduces workability. Research indicates that CPV can be reduced without compromising workability of concrete if CPV is replaced by fillers and recycled materials to increase mortar film thickness (Chu).

- Chung et al. reported that concrete with low CPV requires high dosage of HRWR to maintain required workability. They demonstrated that for Ordinary Portland Cement (OPC) and Portland Limestone Cement (LPC), the amount of cementitious material can be reduced by 2.4% by volume and maintain plastic properties. By applying blended aggregate techniques, the amount of cementitious material can be reduced by 3.6% by volume (Chung et al.).

Workability is also affected by other constituents of concrete. Water content is the most important factor that affects workability. Increasing water-to-cement ratio increases workability. Within limits, workability or consistency of concrete is independent of aggregate grading and cement content and is only a function of water content (Mehta and Monteiro). Aggregate shape and surface texture, gradation, void content of fine aggregates, and absorption also influence the workability of fresh concrete. In general, recycled aggregate concrete requires more water to achieve the same workability of concrete with conventional aggregates due to their high absorption capacity (Kosmatka and Wilson). Poor workability of concrete is reported when more than 20% of coarse aggregates are retained on a single sieve (Cook et al.; Sokhansefat et al.). Supplemental Cementitious Materials (SCM) like fly ash, slag cement, and calcined clay and shales generally increase workability, while silica fume and metakaolin have an opposite effect (Kosmatka and Wilson). Water-reducing admixtures increase concrete workability for a given water-to-cement ratio (Mehta and Monteiro; Kosmatka and Wilson).

2.2.2 Air Content

Air content is “the volume of air voids in cement paste, mortar, or concrete, exclusive of pore space in aggregate particles, usually expressed as a percentage of total volume of the paste, mortar, or concrete” (ACI). Air entrainment is beneficial for various fresh and hardened concrete properties. Air voids improve the workability of fresh concrete. A small amount of entrained air can also reduce bleeding of fresh concrete. Improved freeze-thaw durability can be achieved for hardened concrete through the use of air-entraining admixtures. A summary of recent literature of air content in concrete follows:

- For a given water-to-cement ratio, air permeability increases with increasing paste content (Mehta and Monteiro; Yurdakul, Peter C. Taylor, et al.).

- Increased sand-to-total aggregate ratio has a positive effect on air content. Increase in maximum size of aggregate can decrease the air content requirement (Kosmatka and Wilson).

- SCM, which increase the fineness of cementitious material content in concrete, generally require higher amount of air entraining admixtures. Fly ash and silica fume reduce air content in cement. (Kosmatka and Wilson).

- A 50% to 100% increase in efficiency of air-entraining admixture can be achieved with the help of water-reducing and set-retarding admixtures, requiring less air-entrainment admixtures. Superplasticizer or HRWR, based on their chemical composition, can either increase or decrease air content (Kosmatka and Wilson).

- Increasing air content decreases the compressive strength of concrete. Kosmatka and Wilson state that a 5% to 6% reduction in compressive strength occurs for each percentage of increase in air content (Kosmatka and Wilson; Mehta and Monteiro).

2.3 Paste Volume and Mechanical Properties of Hardened Concrete

Paste in concrete consists of cement, SCM, water, and admixtures. Normally, the paste constitutes approximately 25% to 40% of the total volume of concrete which coats the aggregates and fills the void space between aggregates. The mechanical properties of concrete are highly dependent on the quality and amount of the paste present in the mix. Therefore, any reduction of paste content in concrete will affect the mechanical properties and shrinkage behavior of the hardened final product. The following sections present some recent findings on the mechanical properties of hardened concrete relevant to this study.

2.3.1 Compressive Strength

A review of existing literature reveals that compressive strength of concrete is not affected by reduction of cement content if the mixture is workable.

- A restricted effect of paste volume on self-compacting concrete strength is reported by Rozière et al. They attribute the slight decrease in compressive strength with increasing paste volume found from their experiment to the opposite effects of the aggregate on the internal structure of concrete and on the interface transition zones in the matrix (Rozière et al.).

- Kolias and Georgiou report decreased compressive strength with increased paste volume. For higher water-to-cement ratio, this effect is more pronounced (Kolias and Georgiou).

- Wassermann et al. report that the strength of concrete compressive strength is independent of cement content for a given water-to-cement ratio. They investigate mixtures with water-to-cement ratios ranging from 0.45 to 0.7 with cement content ranging from 22.6% to 34.7% by volume of concrete. The 28-days compressive strength decreases with increasing water-to-cement ratio, consistent with Abrams' Law (Abrams), but it is not affected by paste content as long as the workability can be maintained by using admixtures (Wassermann et al.).

- Chung et al. report achieving sufficient compressive strength with a minimum paste volume of 23.7% for concrete with both OPC and PLC by using minimized paste volume method. For PLC with blended aggregate technique to enhance aggregate gradation, they report a minimum paste volume of 22.6% while still maintaining adequate strength. (Chung et al.).

- Mapa et al. achieves high strength using low paste mixtures and concludes that the difference in strength among mixes with different paste content is not statistically significant (Mapa et al.).

- It has been reported that by using limestone powder, significant reduction of paste content can be achieved while the concrete performs similar or better in terms of compressive strength (Bentz et al.).

- Yardakul et al. notes improved strength with increasing cementitious content up to a certain limit, beyond which strength is independent of it. That critical limit of minimum paste volume is reported to be about twice the voids content of the aggregate system (Yurdakul, Peter C Taylor, et al.).

- Compressive strength of concrete of all ages is reported to increase when CPV is lowered from 32% to 26% (Chu).
- Piasta and Zarzycki found a significant relation between compressive strength and paste volume for High Performance Concrete (HPC). Compressive strength is observed to increase when cement paste volume decreases for mixtures with water-to-cement ratios from 0.25 to 0.35 for HPC. The authors explain that the interfacial transition zone (ITZ) becomes narrow when the actual water-to-cement ratio is lowered due to the adsorption of water on the aggregate surface, which subsequently dries the paste. This, the authors speculate, may increase the paste-around aggregate and bulk paste strength. As a result, the cement paste-aggregate bond strength and concrete strength are improved. (Piasta and Zarzycki).

2.3.2 Modulus of Elasticity

Along with strength, creep, shrinkage, durability, and the elastic modulus of concrete is a parameter of particular importance for design purposes; especially in strain calculation (Pasko). As volume change of concrete at different stages causes strain in the hardened matrix, researchers are particularly interested in the factors that affect elastic modulus; which represents the concrete’s rigidity. Depending on the compressive strength and aggregate type, the elastic modulus of normal-density concrete varies from 2,000,000 psi to 6,000,000 psi (14,000 MPa to 41,000 MPa) (Kosmatka and Wilson). For concrete, a heterogeneous composite material, modulus of elasticity depends on the volume fraction, density and elastic modulus of constituents and the IZT. The porosity of both aggregate and cement paste matrix influence the elastic modulus as it determines the stiffness of these components and, in turn, controls the ability of concrete to resist deformation. High elastic modulus can be achieved through the use of higher amounts of coarse aggregate. The stress-strain relationship is also influenced by the capillary voids, micro-cracks, and the orientation of calcium hydroxide crystals in the interfacial zones of the concrete matrix (Mehta and Monteiro). As the elastic modulus of hydrated cement paste is lower than that of normal-weight aggregate, higher aggregate content results in a higher elastic modulus of concrete for a given compressive strength (Haranki; Tia et al.; Neville and Brooks). Crouch et al. reported a statistically significant decrease in static elastic moduli of pervious Portland Cement Concrete (PCC) with increased aggregate amount as the higher aggregate content decreases the paste amount of pervious PCC (Crouch et al.). Modulus of elasticity is also reported to increase with increasing concentration of fly ash (Gorninski et al.). In addition to the composition of concrete, the development and final value of modulus of elasticity is also influenced by moisture content as well as the curing and casting temperature (Liu et al.; Shoukry et al.; Safiuddin et al.; Kim et al.).

2.4 Electrical Resistivity of Concrete

Corrosion of steel reinforcing bars (often referred to as rebars), an electrochemical process, embedded in pavement concrete is a major durability issue in certain environments. The presence of deicers can penetrate the corrosion-protective oxide film on steel formed in high pH environments inside concrete. Once the chloride corrosion threshold is reached, the formation of electric cells along steel or between steel bars results in and triggers corrosion by rusting. Rusting reduces the effective cross-sectional area of rebar. In addition to this, induced internal stresses due to the expansive nature of rusting causes spalling of concrete over the reinforcing bars (Kosmatka and Wilson). As a result, the lifespan of concrete structures is significantly reduced. Among other factors, the rate of corrosion is influenced by the electrical resistivity of concrete and, therefore, is a topic of significant research interest. Moisture content as well as chloride and sulfide contamination can affect the electrical resistivity of concrete. Saleem et al. reported that the change in electrical resistivity of concrete with increasing moisture content is insignificant after a certain moisture content. They also found that in near dry concrete, high chloride concentration can significantly increase the rate of reinforcement corrosion, indicating very little influence of moisture content at high salt concentration (Saleem et al.). The type of cement is reported to have a significant effect on resistivity. Medeiros-Junior and Lima concluded that the presence of blast furnace slag and pozzolans results in higher electrical resistivity. For the same type of cement, electrical conductivity is not influenced by the water-to-binder ratio (Saleem et al.). Higher aggregate content and rougher surface texture of aggregate increases concrete resistivity (Azarsa and Gupta). A recent study reported about 28% reduced chloride penetration and 6% increased electrical resistance in air-entrained concrete when bacteria and nutrients are added to the water mixture of concrete. The movement of free ions are obstructed as the pores of the matrix are filled with bacteria-precipitated calcium carbonate; resulting in the aforementioned reduced chloride penetration and increased electrical resistance (Parastegari et al.).

2.5 Paste Volume and Concrete Shrinkage

Concrete undergoes a small change in volume caused by expansion or contraction due to chemical reaction (hydration), temperature gradient, or moisture change. If the deformation of concrete members due to such volume changes is not restrained by connecting members (e.g., foundations, reinforcements, etc.), the change would have little consequence. But as the member is usually restrained, significant tensile stresses develop. Therefore, concrete, being weak in tension, is susceptible to the development of cracks when such tensile stresses exceed the tensile strength of concrete. During the fresh and hardened phase, concrete undergoes several types of shrinkage: chemical shrinkage (early age), plastic shrinkage (early age), autogenous shrinkage (early age), carbonation shrinkage (hardened concrete), and drying shrinkage (hardened concrete) (Kosmatka and Wilson). The following subsections summarize the recent literature that looks into the effects of paste content on drying and autogenous shrinkage. The last subsection also discusses the recent finding of concrete shrinkage in restrained conditions.

2.5.1 Drying Shrinkage

Drying shrinkage occurs when tensile stresses are developed in hardened concrete due to moisture losses. Drying shrinkage, also referred to as free shrinkage, is the actual shrinkage of concrete without any restraint. Some recent findings on the effect of cementitious content and paste volume follow:

- Bissonnette et al. demonstrates a directly proportional relationship between shrinkage and paste volume content while the water-to-cement ratio has a very small effect on drying shrinkage (Bissonnette et al.).

- Increased volume of paste is reported to slightly increase shrinkage of binary and ternary blended concrete (Yurdakul, Peter C. Taylor, et al.).

- For self-compacting concrete (SCC), an almost linear positive relationship between free shrinkage and paste volume is reported by Rozière et al. (Rozière et al.)

- Chung et al. tests specimens from three groups of concrete (OPC with minimum CPV method, PLC with minimum CPV method, and PLC with minimized CPV and blended aggregate method) at up to 182 days for drying shrinkage. Across all groups, they conclude that drying shrinkage decreases with reduced paste volume ranging from 22.4% to 35.0%. They also notice that the third group demonstrates relatively higher drying shrinkage (Chung et al.).

- Wassermann et al. demonstrate that water-reducing admixtures, often used to maintain the workability of mixtures with reduced paste content, can increase shrinkage. Their experimental data suggests that the presence of water reducing admixtures effectively negates the expected free shrinkage reduction from the reduction of cement content for a given water-to-cement ratio. Their research finds little impact on shrinkage by cement content and no trend could be established between the small difference in shrinkage curves for various cement content, when water-to-cement ratio is held constant. They recommend a reevaluation of the requirement for minimum cement content in standards (Wassermann et al.).

- Hu and others conversely report that drying shrinkage is significantly decreased by the addition of superplasticizers in ternary blended concretes with fly ash and slag (Hu et al.).

- Reinforced concrete undergoes less drying shrinkage compared to plain concrete as steel reinforcement restricts drying shrinkage. Mortar is more affected than concrete by paste content. (Kosmatka and Wilson).

Other factors also affect drying shrinkage. High water content, use of accelerators, admixtures, SCM, air entrainment, fibers, evaporation of water, hydration rate, relative humidity, specimen geometry, temperature, curing method, aggregate type and content, and cement type can all influence the drying shrinkage of concrete (Bissonnette et al.; Hansen and Boegh; Kayali et al.; Bisschop and Van Mier; Fathifazl et al.; Carlson; Kosmatka and Wilson; Yalçınkaya and Yazıcı).

2.5.2 Concrete Shrinkage Under Restrained Conditions

As previously mentioned, if concrete members are not restrained by connections, shrinkage, by itself, would be less concerning. As these members are not allowed to shrink freely, cracks develop, which in turn compromise the strength, serviceability, and durability of the structure. Researchers have attempted to quantify the cracking tendency of concrete and other cement-based materials due to shrinkage under restrained conditions. The most widely used method of drying shrinkage test under restrained conditions is the restrained ring shrinkage test. Weiss assumed that a ring shrinkage specimen can be considered to be an approximate of an infinitely long pavement (Weiss). A Utah Department of Transportation (UDOT) funded project favors ASTM C157 free shrinkage method over AASHTO T334-08 ring shrinkage test due to lack of definitive cracking age or high variability in cracking age (Allahham et al.). They report difficulty in implementation of the restrained ring shrinkage test because of the over-sensitivity of strain gauges. They also point out the time-consuming nature of the test and lack of conclusive results when the specimen does not crack. Their research points to the sensitivity of the test to the surrounding environment, such as ambient temperature and humidity. Therefore, a tightly controlled environment and rings made with a low coefficient of thermal expansion are suggested for such testing. The research group confirm that increased paste content increases shrinkage cracking under restrained conditions. They report no crack for mixes with cement content less than 21% while the specimens with cement content higher than 24% did present cracks (Allahham et al.).

A gap in literature on the effect of paste volume on shrinkage cracking of conventional concrete under restrained conditions should be noted. In light of that and the new requirement for paste volume in the AASTHO PP 84 specification warrant extensive investigation of the restrained shrinkage behavior of UDOT mixes.

2.6 Review of State DOT Requirements on Paste Volume

AASHTO PP 84-18 Standard Practice for Developing Performance Engineered Concrete Pavement Mixtures recognizes that recent innovations in concrete technology have allowed the industry to move toward specifying performance criteria of concrete mixtures to achieve specific requirements. The standard sets the maximum paste volume of concrete to 25% as one of the requirements of proportioning hydraulic cement concrete (AASHTO PP 84).

At present, the Utah Department of Transportation's (UDOT) Standard Specifications for Road and Bridge Construction (2017) do not have any specification regarding paste volume limit (UDOT). This research project is funded by UDOT to validate the AASHTO PP-84 paste volume limit for shrinkage mitigation in UDOT concrete mixes.

3.0 RESEARCH METHODS

3.1 Overview

This section provides an overview of the material properties and UDOT mixture designs that are selected for this study. This section also describes the test methods of mechanical and durability properties of the aforementioned mixtures and the modified mixtures with reduced paste volume, as well as deviations from the corresponding standards, if any.

3.2 Mixture Design and Material Properties

After consulting with UDOT, two mixture designs from Geneva Rock Products are selected as control mixtures for laboratory and field investigations. The mix code for these mixtures are A6583A (M1-C) and A6505AR (M2-C). The mixture designs of the control mixes are provided in Table 3.1.

Table 3.1 Mixture Design of Selected Mixtures (per cubic yard)

Material Description	**Specific Gravity**	**Quantity (lbs.)**	
		M1-C	**M2-C**
Cement Type II-V	3.15	489	489
Fly Ash Type F	2.3	122	122
Coarse Aggregate-1-1/2"x3/4" Washed	2.63	634	-
Coarse Aggregate -3/4"x#4 Washed	2.58	934	1706
Coarse Aggregate - No. 8 Pea Gravel	2.62	232	-
Fine Aggregate-Sand Washed Concrete	2.6	1103	1146
Water	1	258	268.72
Admixture-Daravair 1000	-	18*	5*
Admixture-Zyla 630	-	25*	12*
Admixture ADVA 140	-	-	37*

*In liquid ounces

The materials required for mixing are collected from Geneva Rock Products' Salt Lake City plant. The cement and fly ash used in these mixtures are Type II-V and Type F, respectively. For the A6583A mixture, three types of coarse aggregates are used: rock with aggregate size between 1½-inches and ¾ inches, rock with aggregate size between ¾ inches and 0.187 inches, and ASTM C33 No. 8 pea gravel. In A6505AR, rock with aggregate size between ¾ inches and 0.187 inches is used. For both mixtures, concrete sand is used for fine aggregate. For the A6583A mixture, an air entraining admixture, Daravair 1000 (conforming to ASTM C260 and AASHTO M154), and a water-reducing admixture, Zyla 630 (conforming to ASTM C494, Type A, D, and AASHTO M194 Type A, D), are used. For the A6505AR mixture, a high-range water reducer, ADVA 140(M) (conforming to ASTM C494, Type A, F, and AASHTO M194, type A, F), is used. The design strength for both mixes is 4000 psi. The water-to-cement ratio of M1-C and M2-C are 0.42 and 0.44, respectively. Design properties of the control mixtures are provided in Table 3.2.

Table 3.2 Design Properties of Selected Mixtures

Property	**M1-C**	**M2-C**
Design Strength (psi)	4000	4000
Air Content (%)	6±1	6±1
Unit Weight (lbs./ft^3)	139.8	138.2
Slump (inch)	2±1	4.5±1
w/c ratio	0.42	0.44
Volume of Paste (%)	27.7	28.3

The control mixtures were modified so that the volume of the paste is reduced while the water-to-cement ratios remain constant. Each of the control mixtures are modified into two mixtures: with 25% paste volume (M1-25 and M2-25) and 23.5% paste volume (M1-23 and M2-23). The mixture design of the modified mixtures is given in Table 3.3.

Table 3.3 Mixture Design of Modified Mixtures (per cubic yard)

Material Description	Quantity (lbs.)			
	M1-25	**M1-23**	**M2-25**	**M2-23**
Cement Type II-V	442.4	415.1	432.97	406.8
Fly Ash Type F	110.3	103.6	108.03	101.5
Coarse Aggregate-1-1/2"x3/4" Washed	660	674.7	-	-
Coarse Aggregate -3/4"x#4 Washed	972.2	994	1801.56	1841
Coarse Aggregate - No. 8 Pea Gravel	241.5	246.9	-	-
Fine Aggregate-Sand Washed Concrete	1148.2	1173.8	1210.19	1236.7
Water	233.4	219	237.6	223.2
Admixture-Daravair 1000	16.3*	15.3*	4.4*	4.2*
Admixture-Zyla 630	22.6*	21.2*	10.6*	10*
Admixture ADVA 140	-	-	32.8*	30.8*

*In liquid ounces

3.3 Mixing and Casting Procedure

For the field study phase of the project, cylindrical specimens for compressive strength and electrical resistivity testing are collected and prepared from UDOT pours from Geneva Rock’s Salt Lake City batch plant. The air content of the fresh concrete is measured in the field. For logistical limitations, drying and restrained ring shrinkage specimens are not prepared in the field.

For the preparation of specimens for the laboratory test program, the coarse and fine aggregates are air-dried. Mixing is done in a rotating drum mixer of 3 cubic feet capacity. The mixing sequence is as follows:

1. Rinse the mixer and remove the excess water.
2. Blend the coarse and fine aggregates thoroughly in the mixer.
3. Add one-third of the mixing water to the aggregate blend. Run the mixer until the aggregates are coated with the added water.
4. Add half of the cement and the fly ash. While the mixer is running, slowly add one-third of the mixing water to the blend. Run the mixer until the aggregates are coated with cement and fly ash.

5. Add the rest of the cement and fly ash to the mixer. Slowly add remaining mixing water.
6. Keep mixing until the desired consistency is achieved.
7. Immediately after the mixing is done, perform the air content, workability, and unit weight measurement.
8. Cast the cylindrical and shrinkage specimens as per the corresponding testing standards.

3.4 Testing Methods

The following subsections provide a summary of the test methods for fresh hardened concrete samples and specimens. Any adjustments deemed necessary are also discussed.

3.4.1 Workability

The workability of the fresh concrete mixtures is evaluated by performing a box test as specified in AASHTO PP 84. This test is performed using a wooden formed box of 1-ft^3 volume made of 0.5-inch plywood. The length, width, and height are 12 inches. The box is held using pipe clamps.

Figure 3.1 Box Test Setup

Figure 3.2 Air Content Test Apparatus

The mixture is hand scooped into the box up to a height of 9.5 inches. The mixture is then consolidated using a vibrator. The vibrator is vertically inserted into the mixture to the bottom of the box for 3 seconds and then raised up at a rate of 3 seconds. The clamps and the side wall forms are then immediately removed. The surface voids are reported using the rubrics provided in the standard. The slump is reported by placing a straight-edge at a corner and horizontally using a tape measure to find the length of the highest extruding point (AASHTO PP 84). The workability of laboratory mixed concrete is measured only. The box test setup for workability is shown in Figure 3.1.

3.4.2 Fresh Air Content

The air content of a freshly mixed concrete sample is measured using ASTM C231 with a Type B meter. In this method, a known volume of air at a known pressure in a sealed chamber is compared with the unknown volume of air in the concrete sample. The pressure gauge dial is calibrated to show the percentage of air based on the observed pressure when volume of air in the two chambers is equalized (AASHTO T152; ASTM C231/C231M). The air content of both the field and lab samples are measured. The air content test setup for freshly mixed concrete is shown in Figure 3.2.

3.4.3 Unit Weight

The unit of fresh concrete is measured according to the ASTM C138 standard (ASTM C138/C138M). The measuring bowl of air meter of 0.25 ft^3 as described in ASTM C231 is used. The net mass of the fresh concrete is calculated by subtracting the mass of the measuring bowl.

Figure 3.3 Unit Weight Measurement Bucket

Density is calculated by dividing the net mass of concrete by the volume of the measuring bowl. Only the unit weight of fresh concrete mixed in the laboratory is measured. The unit weight test setup is shown in Figure 3.3.

3.4.4 Compressive Strength Test

The compressive strength tests are performed at 28 days according to the ASTM C39 standard specification (ASTM C39/C39M). Three cylindrical specimens are tested for each mixture. Each specimen is capped with neoprene capping and is tested using a servo-controlled universal testing machine at a loading rate of 35±7 psi. For mixtures with nominal maximum aggregate size (NMAS) of 1½ inches and for mixtures with NMAS of ¾ inches, 6 inches and 4 inhes, cylindrical specimens are prepared following the ASTM C31 standard specification (ASTM C39/C39M). The compressive strength test setup is shown in Figure 3.4.

Figure 3.4 Compressive Strength Test Setup

3.4.5 Static Modulus of Elasticity Test

The static modulus of elasticity test is performed in accordance with the ASTM C469 specification. Each cylinder is fitted with a compressometer with a digital indicator to record the deformation of the cylinder at specified loads. The specimens are loaded in uniaxial compression up to a stress of approximately 40% of the peak strength. Deformation at 10% and 20% peak stresses are recorded as well. The peak stress is the average strength of the three cylinders tested for compressive strength. The average static elastic modulus of three cylindrical specimens are reported (ASTM C469/C469M). The static modulus of elasticity test setup is shown in Figure 3.5.

3.4.6 Surface Electrical Resistivity Test

Surface electrical resistivity test is performed according to the AASHTO T358 test method. This test method measures the resistivity of concrete cylinders by using a 4-pin Wenner probe array. The testing apparatus, Surf by Giatec Scientific, applies alternating current potential difference across the outer pins of the Wenner array. This causes current to flow through the concrete specimen. The resulting potential difference between the two inner pins is recorded.

Figure 3.5 Static Modulus of Elasticity Test Setup

Figure 3.6 Surface Electrical Resistivity Test Setup

Similar measurements are recorded by rotating the specimens 90°. The apparatus calculates the resistivity in four perpendicular directions. The average resistivity measurement is reported. AASHTO T358 provides a table (shown in Table 3.4) that relates surface resistivity to the chloride ion penetration (AASHTO T 358). The surface electrical test setup is shown in Figure 3.6.

Table 3.4 Relation Between Chloride Ion Penetration and Surface Resistivity of Concrete

Chloride Ion Penetration	**Surface Resistivity Test**	
	4×8 inches Cylinder (kΩ-cm) a = 1.5	**6×12 inches Cylinder (kΩ-cm) a = 1.5**
High	<12	<9.5
Moderate	12-21	9.5-16.5
Low	21-37	16.5-29
Very Low	37-254	29-199
Negligible	>254	>199

a = Wenner probe tip spacing

3.4.7 Drying Shrinkage Test

The drying shrinkage of concrete specimens are measured in accordance with ASTM C157. Three prismatic specimens of 3×3×16 inch, with 15-inch gage length, are cast in two lifts. Each layer is rodded 25 times in accordance with ASTM C192 (ASTM C192/C192M).

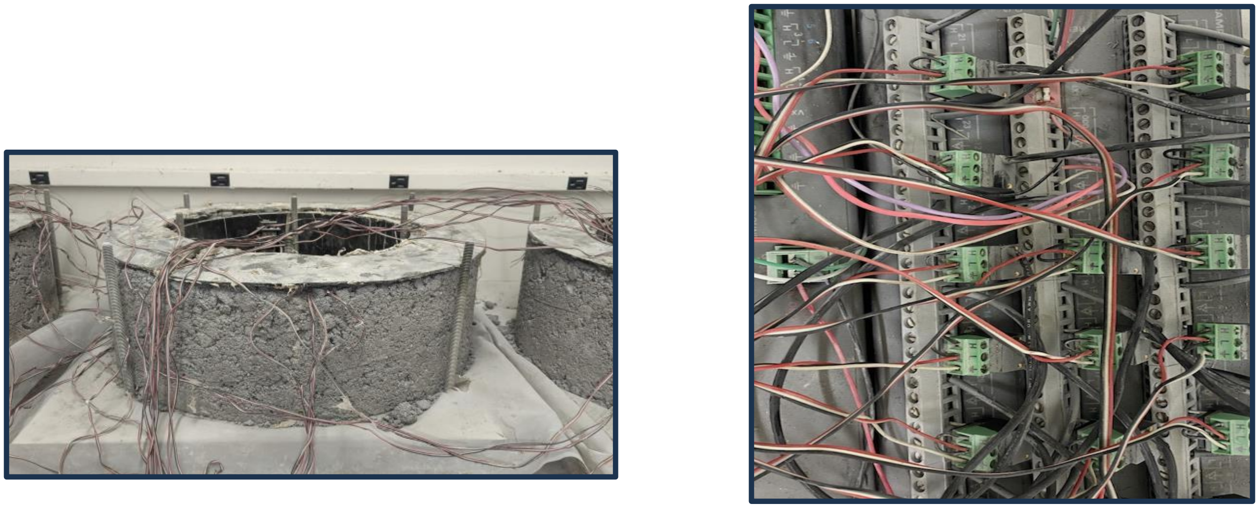
The specimens are demolded 24 hours after casting and air-cured at 73°F±3°F and relative humidity of 50±4%. The specimens are tested at 4, 7, 14, 28, and 56 days. The length change over the testing period and the shrinkage strain at the 28th day are reported (ASTM C157/C157M). The drying shrinkage test setup is shown in Figure 3.8.

(a) (b)

Figure 3.8 (a) Drying Shrinkage Specimens, (b) Drying Shrinkage Specimen Mount on the Length Comparator

3.4.8 Restrained Ring Shrinkage Test

Restrained ring shrinkage test determines the resistance to cracking due to restrained shrinkage of concrete specimens. This test is performed following the AASHTO T334 and ASTM C1581 standard (ASTM C1581/C1581M; AASHTO T 334). Following these standards,



(a) (b)

Figure 3.7 (a) Restrained Ring Shrinkage Specimens, (b) Data Acquisition System

two concrete rings with 12-inch inside and 18-inch outside diameters and of 6 inches in height are cast around a steel ring. Strain gauges are attached to the inside wall of the steel rings. Using a Campbell Scientific CR1000 datalogger, strain measurements are taken at 10-minute intervals. The specimens are monitored for any visual cracking or any drop of strain in the steel ring in excess of 30 microstrain. In accordance with ASTM C1581, the test is terminated on the 28th day if no cracking or drop in strain is observed. The setup is shown in Figure 3.7.

4.0 RESULTS AND DATA ANALYSIS

4.1 Overview

This chapter presents the results of field and laboratory investigations to quantify the fresh properties, mechanical properties, volume stability, and durability of the selected control and modified mixtures. The tests include workability, air content, unit weight, compressive strength, static elastic modulus, surface electrical resistivity, and drying and restrained ring shrinkage. The results are discussed in detail accompanied by relevant plots and tables. A summary of the performance of the mixtures, based on the test results, is provided at the end of the chapter.

4.2 Workability

The box test, specified in the AASHTO PP-84, is performed to evaluate the workability of the mixtures. In this test, along with the slump of the mixture, the surface voids can be evaluated by comparing the mixture with a rubric provided in AASHTO PP-84.

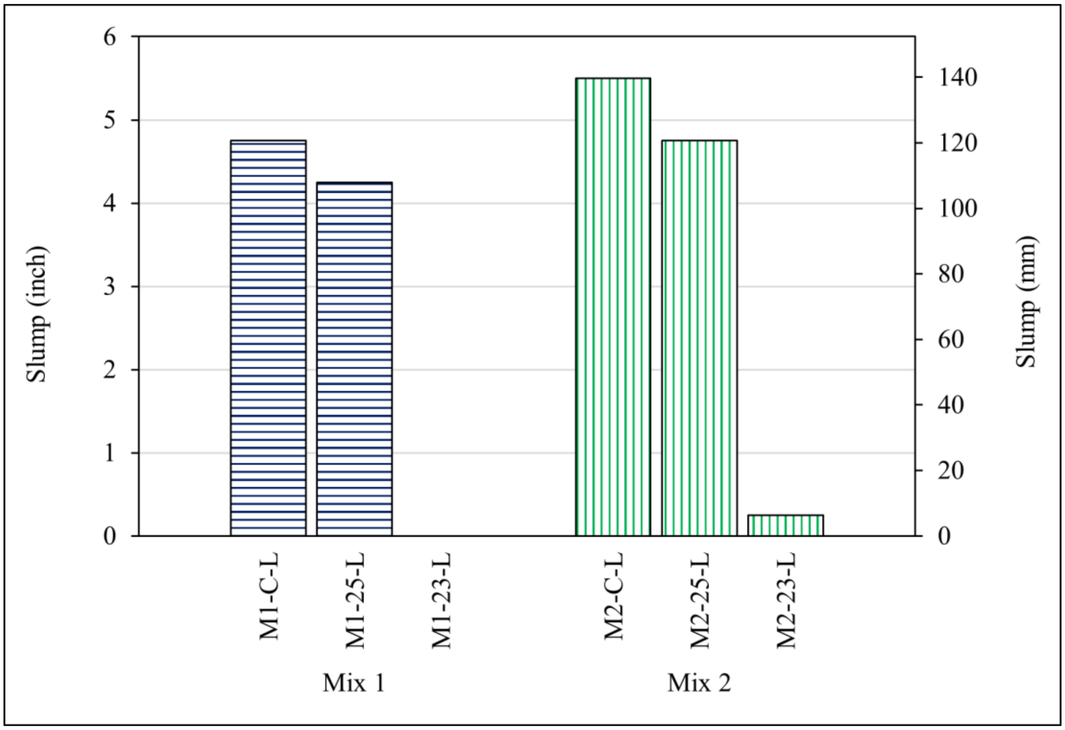
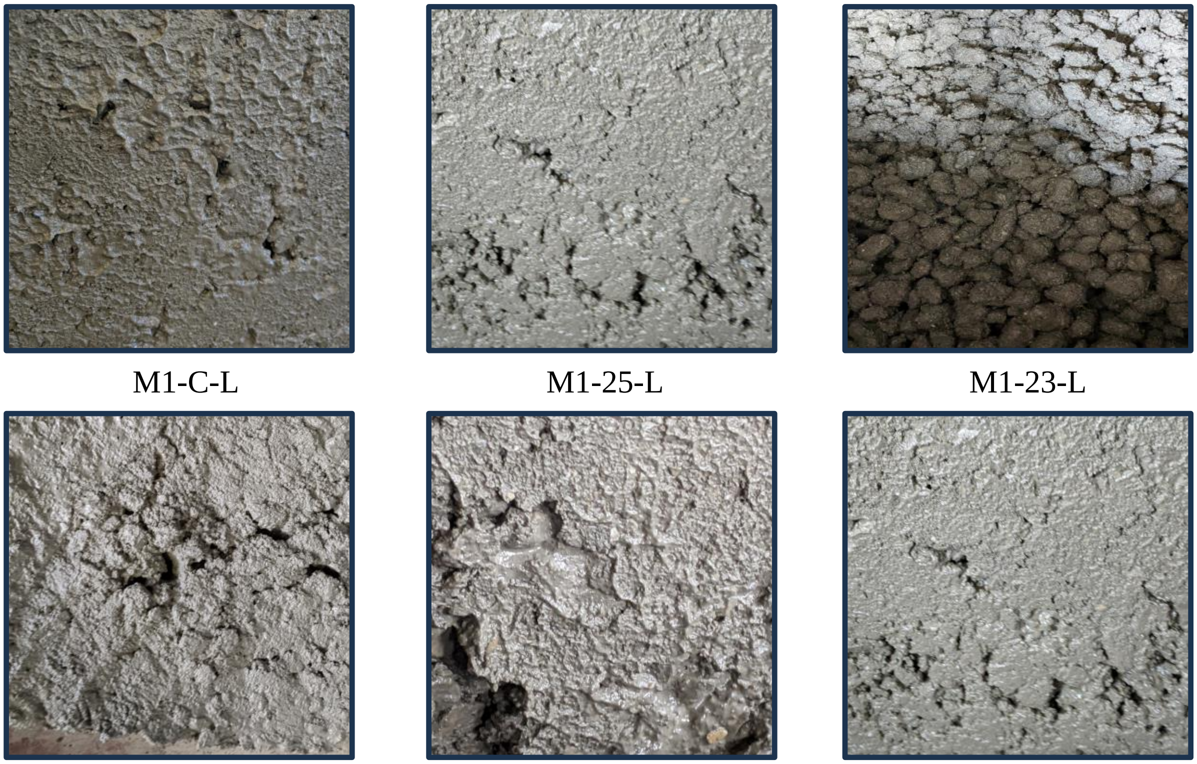


Figure 4.1 Box Slump Test Results

The slump test results are presented in Figure 4.1. The letters ‘L’ and ‘F’ at the end of the mixture’s designations indicate laboratory or field samples, respectively. The workability of the mixtures varies greatly with the amount of paste in the mixtures. For the control mixtures, which have the highest paste volume, the slump is the highest. The workability of the mixtures slightly reduces as the volume of the paste is reduced. For M1 and M2 mixtures, the slump is reduced by 10.5% and 13.6%, respectively, as the paste volume is reduced from 27.7% and 28.3% to 25%, respectively. The workability of the mixtures greatly reduces as the paste volume is reduced to 23.5%. The loss of workability is more noticeable for the M1-23-L mixtures as from visual inspection the mixtures are found to have sufficient paste to coat the aggregates. M1-23-L and M2-23-L mixtures have 0 and 0.25-inches slump, respectively.

Figure 4.2 shows the surface voids of the mixtures obtained from the box test. According to the rubrics provided in AASHTO PP 84, the surface voids of the M1-C-L mixtures are less than 10 percent. This mixture also has the highest slump. M1-25-L, M2-C-L, M2-25-L, and M2-23-L mixtures have voids between 10 to 30 percent. The least workable mixture, M1-23-L, has more than 50 percent overall surface voids.



M1-C-L M1-25-L M1-23-L

M2-C-L M2-25-L M2-23-L

Figure 4.2 Surface Voids of the Control and Modified Mixtures

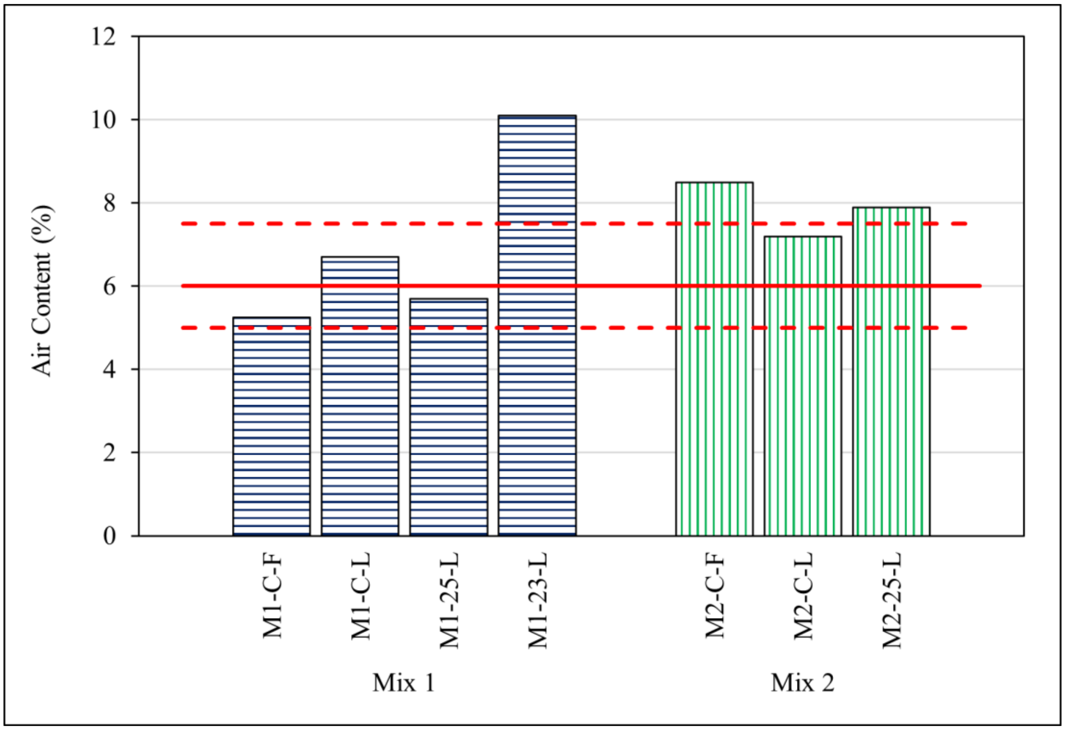


Figure 4.3 Air Content of the Control and Modified Mixtures. The Red Line Marks the Design Air Content. The Dashed Line Marks the Tolerance of the Design Air Content

4.3 Fresh Air Content

A minimum air entrainment is recommended, primarily, to improve the freeze-thaw durability of concrete exposed to freezing water and deicing salts. Both of the selected control mixtures use air entraining admixture, conforming to ASTM C260, to entrain a sufficient amount of air in the fresh concrete. The design air content of both control mixtures is 6 (+1.5/-1.0). The air content of the field samples for M1 and M2 mixtures is 5.25 and 8.5, respectively. The air content of the field sample of the M2 mixture is slightly higher than the target design value. The air content of the control and modified mixtures mixed in the laboratory, M1-C-L, M1-25-L, M1-23-L, M2-C-L, and M2-25-L is 6.7, 5.7, 10.1, 7.2, and 7.9, respectively. The air content of the M2-23-L could not be measured as the pressure in the air chamber never stabilized. Although the air contents of control and modified mixtures with 25% paste volume are close to the design value, they exceed the design tolerance for the M1-23-L mixture. This result can be explained by the mechanism of entrapped air in concrete. Whether or not air-entraining agents are used, air in

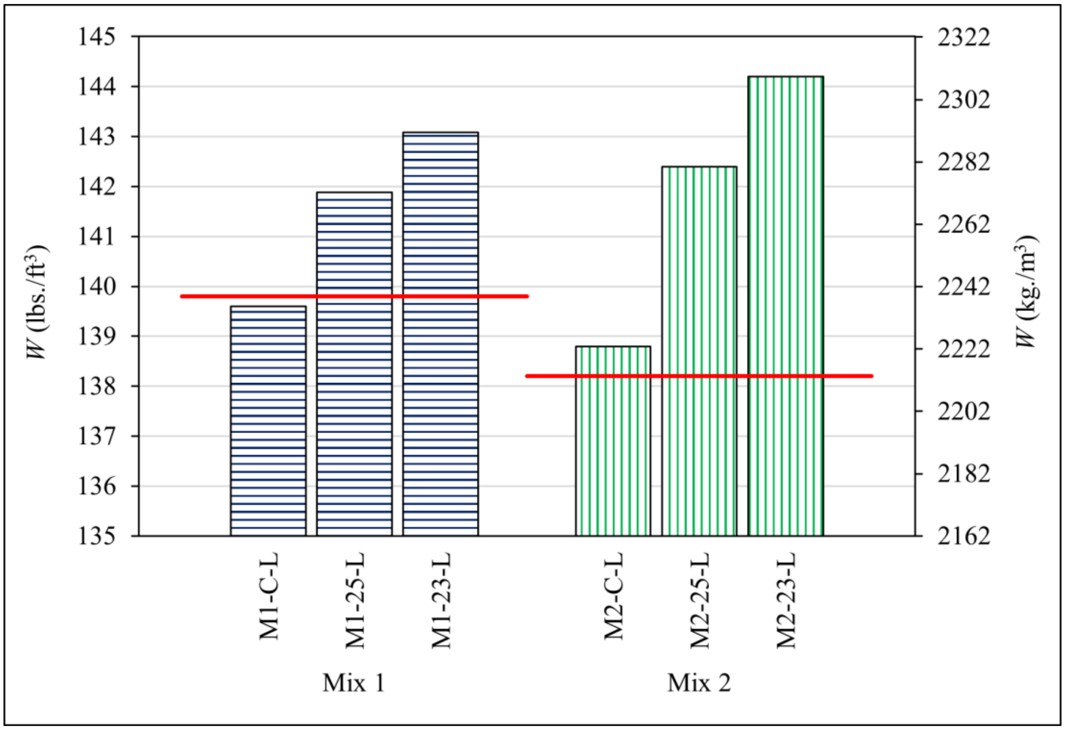


Figure 4.4 Unit Weight of the Control and Modified Mixtures. The Red Line Marks the Design Unit Weight of the Control Mixture

concrete is entrapped in the intergranular spaces in the cement and aggregate as well as during the mixing process, a large portion of which remains within the air bubbles (Mielenz et al.). In the absence of sufficient cement paste to fill the intergranular spaces, these spaces are occupied by an air void which increases the air content at lower paste volume.

4.4 Unit Weight

Unit weight of concrete can be used to determine the density of concrete. Unit weight varies with the amount of paste in the concrete mix as the paste volume affects the overall composition and density of concrete. Figure 4.4 presents the unit weight of the control and modified mixtures. The unit weight of concrete increases as the paste volume decreases. As the amount of paste in the mixtures decreases, the volume of less dense water is replaced by the heavier coarse and fine aggregates. For M1 mixes, the unit weight of modified mixtures with 25% and 23.5% paste volume increases by 1.6% and 2.5%, respectively. For M2 mixes, unit weight increases by 2.6% and 3.9%, respectively. The nominal maximum aggregate size (NMAS) of the M1 and M2 mixtures are 1½-inches and ¾ inches, respectively. As the M2 mixes contain smaller aggregates, aggregates fill up the voids more effectively, resulting in a denser concrete.

4.5 Compressive Strength

According to Abrams' water/cement ratio law, the strength of workable concrete depends solely on the water-to-cement ratio (Abrams). As the modified and control mixtures have the same water-to-cement ratio, the strength of the concrete should be comparable. Any reduction in compressive strength in modified mixtures can be attributed to the loss of workability and insufficient amount of paste available to coat the aggregate resulting in poor bond between the cement paste and aggregates.

The compressive strength test results are provided in Figure 4.5. The compressive strength of the M1 mixtures prepared at the batch plant (field samples) closely matches the strength of the laboratory mixtures. On the other hand, the laboratory-mixed M2 control mixture

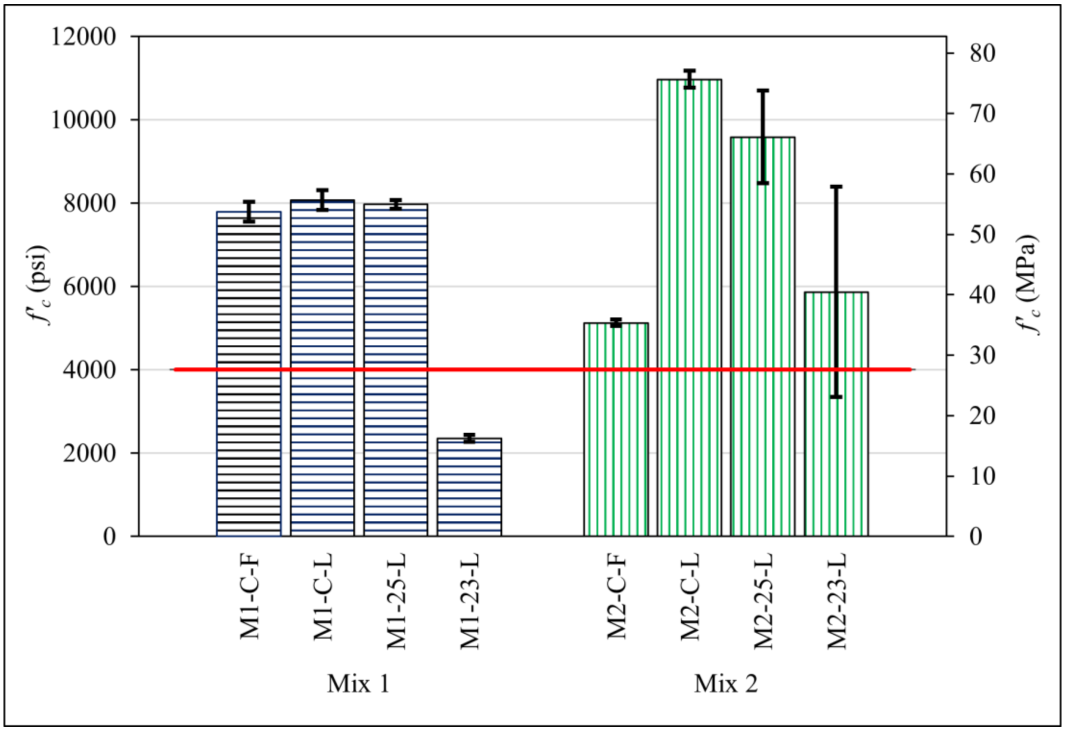


Figure 4.5 Compressive Strength of Field and Laboratory Mixtures. The Red Line Marks the Design Compressive Strength of Control Mixtures

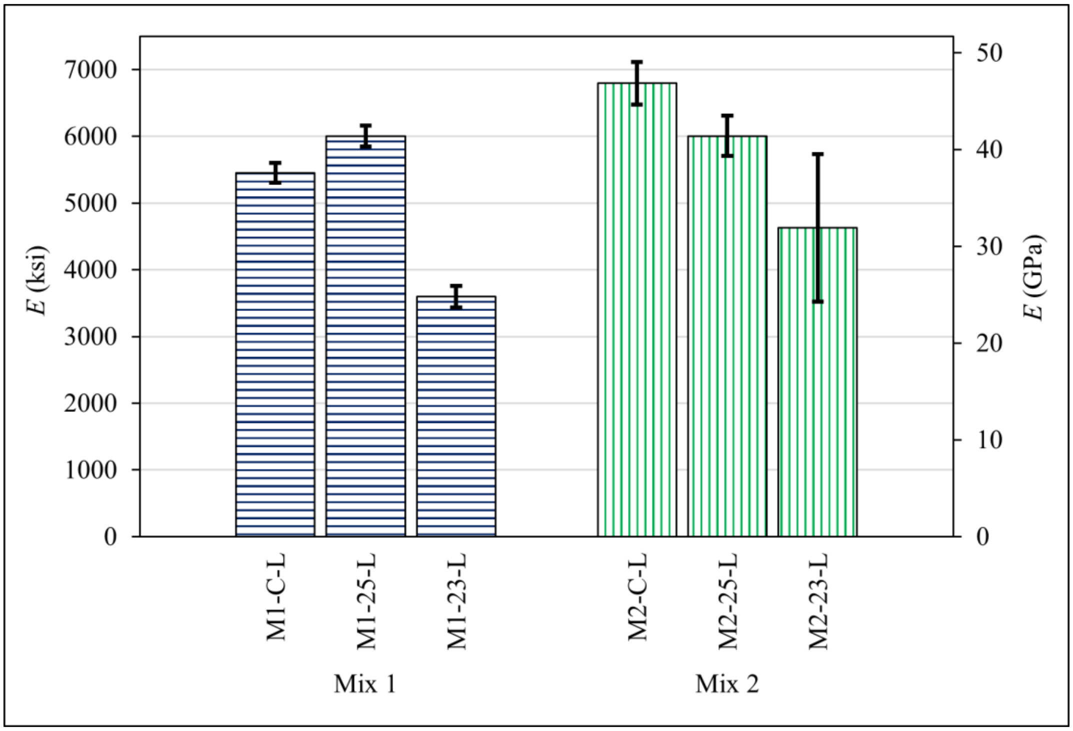


Figure 4.6 Static Modulus of Elasticity Test Results

has about two times higher compressive strength compared to the field samples. This can be attributed to more stringent quality control maintained in the laboratory.

The strength of the modified mixtures with 25% paste volume is significantly higher than the design strength of 4,000 psi. The M1-C-L and M1-25-L mixtures have similar compressive strength. On the other hand, the compressive strength of the M2-25-L mixture is slightly lower than the compressive strength of the control mixtures (10,972 psi and 9589.7 psi, respectively). The M2 batches have smaller NMAS which leads to more aggregate surface to coat by less amount of paste available in the modified mixture resulting in slightly reduced compressive strength. Nevertheless, it is concluded that the volume of paste in these pavement mixtures can be safely reduced without sacrificing compressive strength.

The mixtures with 23.5% paste volume have significantly lower compressive strengths. As evident from the box test, these mixtures are not sufficiently workable due to the reduced amount of paste available. The higher standard deviations of M1-23-L and M2-23-L indicate that although some specimens may show strength higher than the design strength, the mixtures lack consistency.

4.6 Static Modulus of Elasticity

The static modulus of elasticity in compression is defined as the ratio of the normal compressive stress to the corresponding strain below the proportional limit. The static modulus of elasticity test results is presented in Figure 4.6. This test is performed on the laboratory-mixed specimens only. No significant decrease or increase in elastic modulus is observed for mixtures with 25% paste volume. However, at 23.5% paste volume the elastic modulus is significantly lower compared to the control mixtures. At lower paste volume, less amount of cement paste is available to coat aggregates resulting in poor bonding between the mortar and the aggregates. This results in decreased elastic modulus.

4.7 Surface Electrical Resistivity

Surface electrical resistivity of concrete is the measure of the material's capability to withstand the transfer of ions subjected to an electrical field and an indicator of concrete's chloride ion penetrability. Figure 4.7 shows the surface electrical resistivity test results. All the

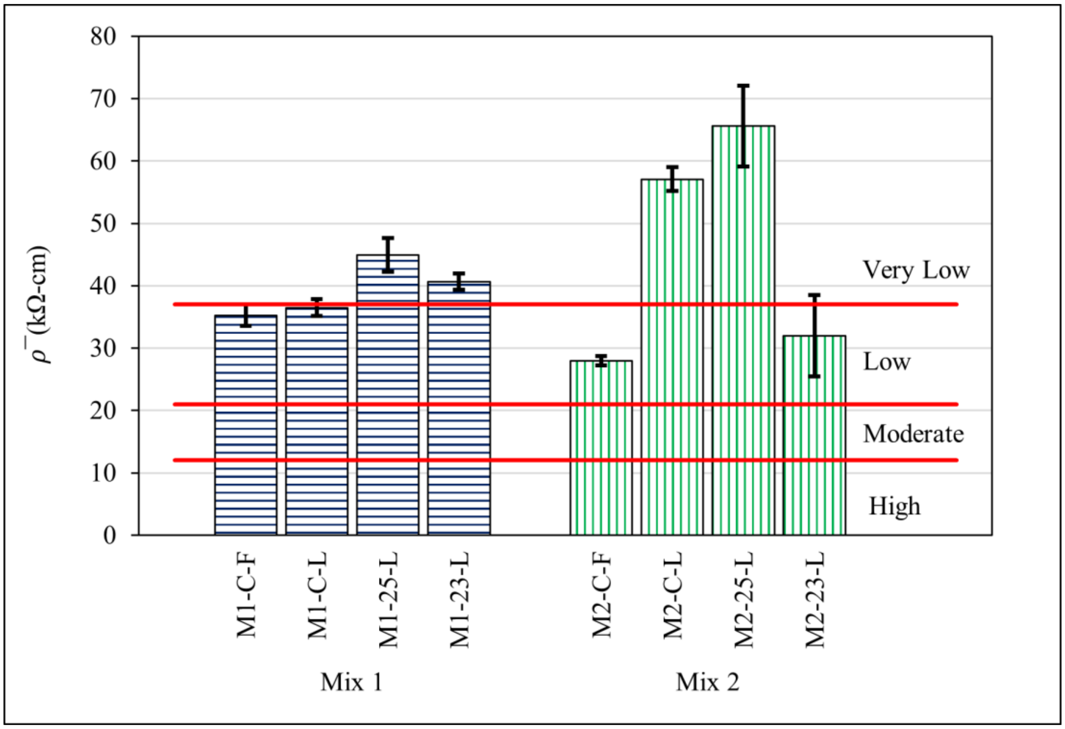


Figure 4.7 Surface Electrical Resistivity Test Result. The Red Lines Mark Different Levels of Chloride Ion Penetrability

mixtures show low to very low chloride ion penetrability as the surface electrical resistivity for all mixtures are over 21 kΩ-cm.

Lower chloride ion penetrability indicates a dense and compact structure with finer pore networks. Thus, the movement of the chloride ions is restricted through the concrete reducing the risk of corrosion of embedded steel reinforcement.

4.8 Drying Shrinkage Test

Drying shrinkage specimens are cast and tested as described in Chapter 3 and presented in Figure 4.8. Insufficient paste and resulting loss in workability of the M2-23-L mix made it difficult to properly consolidate the fresh concrete in prismatic molds. As a consequence, the gauge studs in these specimens came out during demolding and the specimens are discarded. For the same reason, one specimen from each of M1-23-L and M2-25-L were discarded.

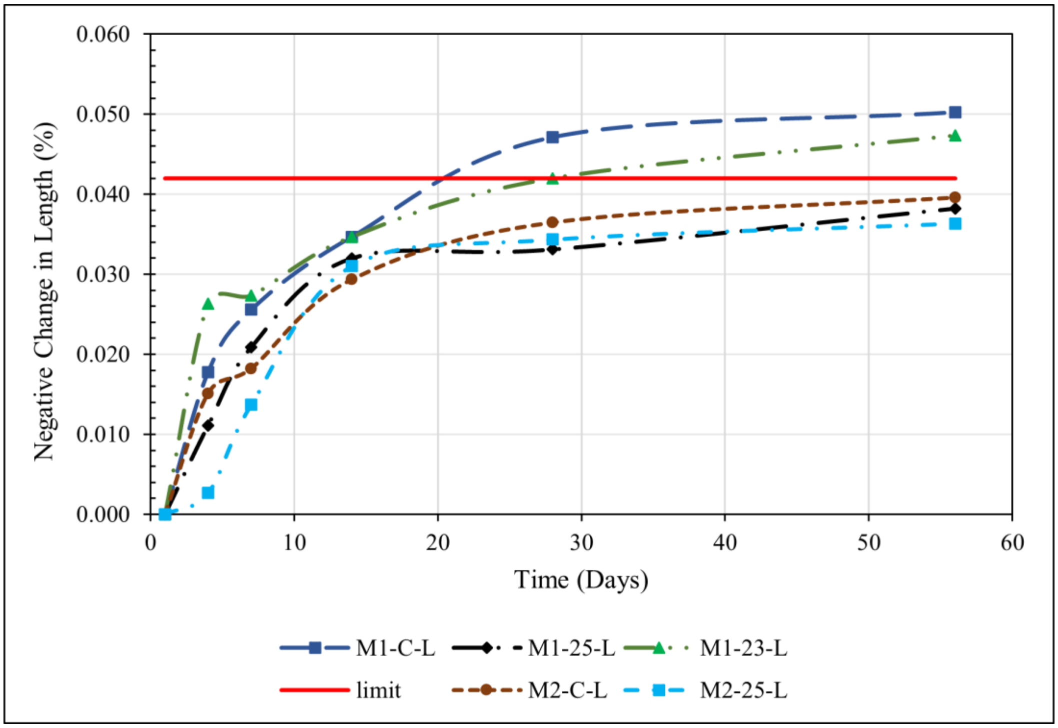


Figure 4.8 Drying Shrinkage of Control and Modified Mixtures. (a) The Red Line Marks the Maximum Percent Shrinkage at 28 Days Specified in 2022 Standard Specifications for Road and Bridge Construction by Utah Department of Transportation

The specimens are tested and measurements reported until the 56th day. As expected, high initial shrinkage is observed for all specimens. The 2022 Standard Specifications for Road and Bridge Construction by UDOT specifies a maximum shrinkage of 0.042% for AA(P) at 28 days. The shrinkage of the mixes, except M1-C-L, are below this limit and therefore satisfy this requirement. The reduction of paste volume clearly has a positive effect on the drying shrinkage potential as with decreasing paste volume, the shrinkage also decreases. One exception is M1-23-L, which experiences higher shrinkage compared to M1-25-L. Free shrinkage strain of the mixtures is presented in Figure 4.9. All the mixtures, except M1-Cl-L, demonstrate lower shrinkage strain than the prescribed limit of 420 microstrain (AASHTO PP 84).

As concrete hardens, the loss in moisture causes concrete to shrink. One of the most important and the most controllable factors affecting the drying shrinkage is the water available in concrete. During the hydration of cement, about half of the water is used for chemical reactions. Part of the excess water is expelled in the bleeding phase. The remaining water contributes to drying shrinkage (Kosmatka and Wilson). Therefore, reduction in paste volume (i.e., controlling the available water in concrete), decreases free shrinkage potential.

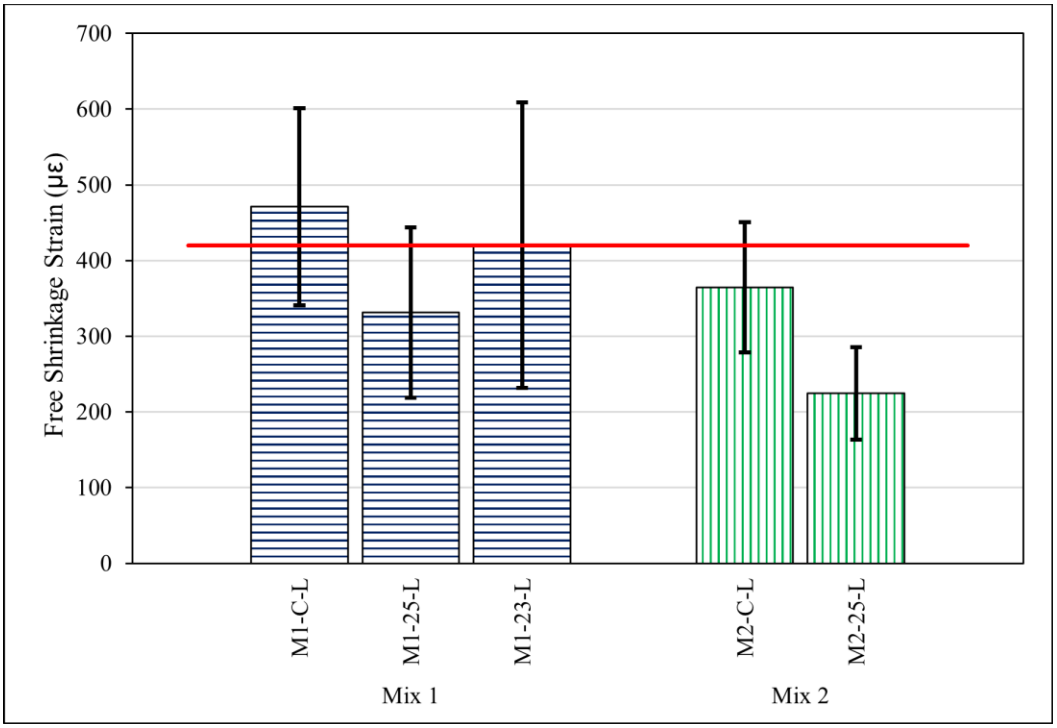


Figure 4.9 Free Shrinkage Strain of Control and Modified Mixtures. The Red Line Marks the Maximum Unrestrained Volume Change Specified in AASHTO PP 84-18

4.9 Restrained Ring Shrinkage

In the restrained ring shrinkage experiment, as the concrete around the steel ring hydrates and shrinks, the steel ring is strained which is measured with strain gauges which are recorded by a data-logger. The resulting compressive strain in steel ring due to shrinkage plots is presented in Figure 4.10 and Figure 4.11. The plots show that the strain in the steel rings increases as the concrete hardens. The cracking due to shrinkage is identified by visual inspection or when a drop in excess of 30 microstrain is registered.

Both of the specimens of M1-C-L and M1-23-L, and one of the two specimens of M1-25-L cracks within the testing period as indicated by the drop shown in Figure 4.10. For the M1-C-L and M1-25-L specimens, the strain in the steel ring gradually increases with time and then a sudden drop associated with cracking is observed. However, for the M1-23-L specimens, the strain gradually increases until approximately three weeks into the experiment. Then the strain starts to increase rapidly followed by cracking and decrease in strain. At the end of the testing period, visual cracking is only observed in the second M1-25-L specimen. The average crack width of this specimen is 0.0059 inch, measured with a crack-width microscope. None of the specimens, either control or modified, prepared for M2 mixtures cracked during the testing period. The strain in the steel rings gradually increases over time without any decrease in strain. The number of days to crack of the restrained ring shrinkage specimens is provided in Table 4.1.

Table 4.1 Number of Days to Crack for Restrained Ring Shrinkage Specimens

Mixtures ID	Specimen 1	Specimen 2
M1-C-L	27.75	28.5
M1-25-L	No crack	23.75
M1-23-L	26.75	26.75
M2-C-L	No crack	No crack
M2-25-L	No crack	No crack
M2-23-L	No crack	No crack

The maximum strain in the steel ring indicates the extent of the shrinkage in the concrete. The greater the strain in the ring, the higher the shrinkage in concrete. Figure 4.12 presents the maximum shrinkage strain in the steel rings induced by the specimen. Note that the plot shows the maximum strain in any of the specimens of a particular mixture, not the average maximum strain of two specimens of the same mixture. The M1-C-L and M1-25-L specimens registered similar maximum strain—the latter registers slightly lower strain. The M1-23-L specimen induced the maximum strain of all the specimens, which is an anomaly compared to the rest of the mixtures. This anomaly can be attributed to (a) the mixtures with 23.5% paste volume were hard to work with due to lack of workability and difficulty to achieve a consistent mix, and (b) a sudden increase in strain before cracking as shown in Figure 4.10. For the M2 control and modified mixtures, the maximum strain reduces as the volume of the paste decreases. Overall, the decreased amount of the paste volume reduces the compressive strain in the steel ring caused by the restrained ring shrinkage specimens.

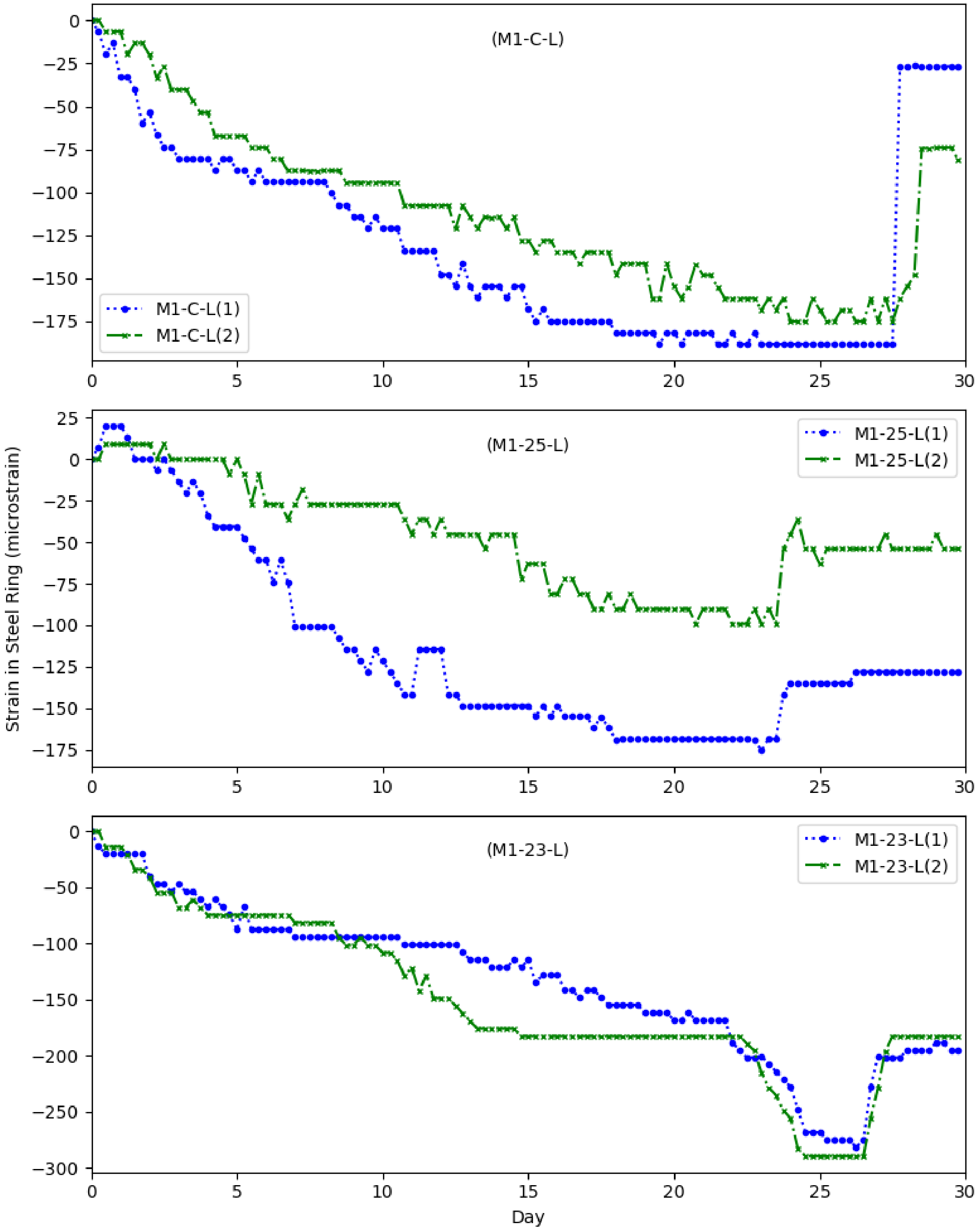


Figure 4.10 Average Strain in Steel Ring for Control and Modified Mixtures of M1 Mix

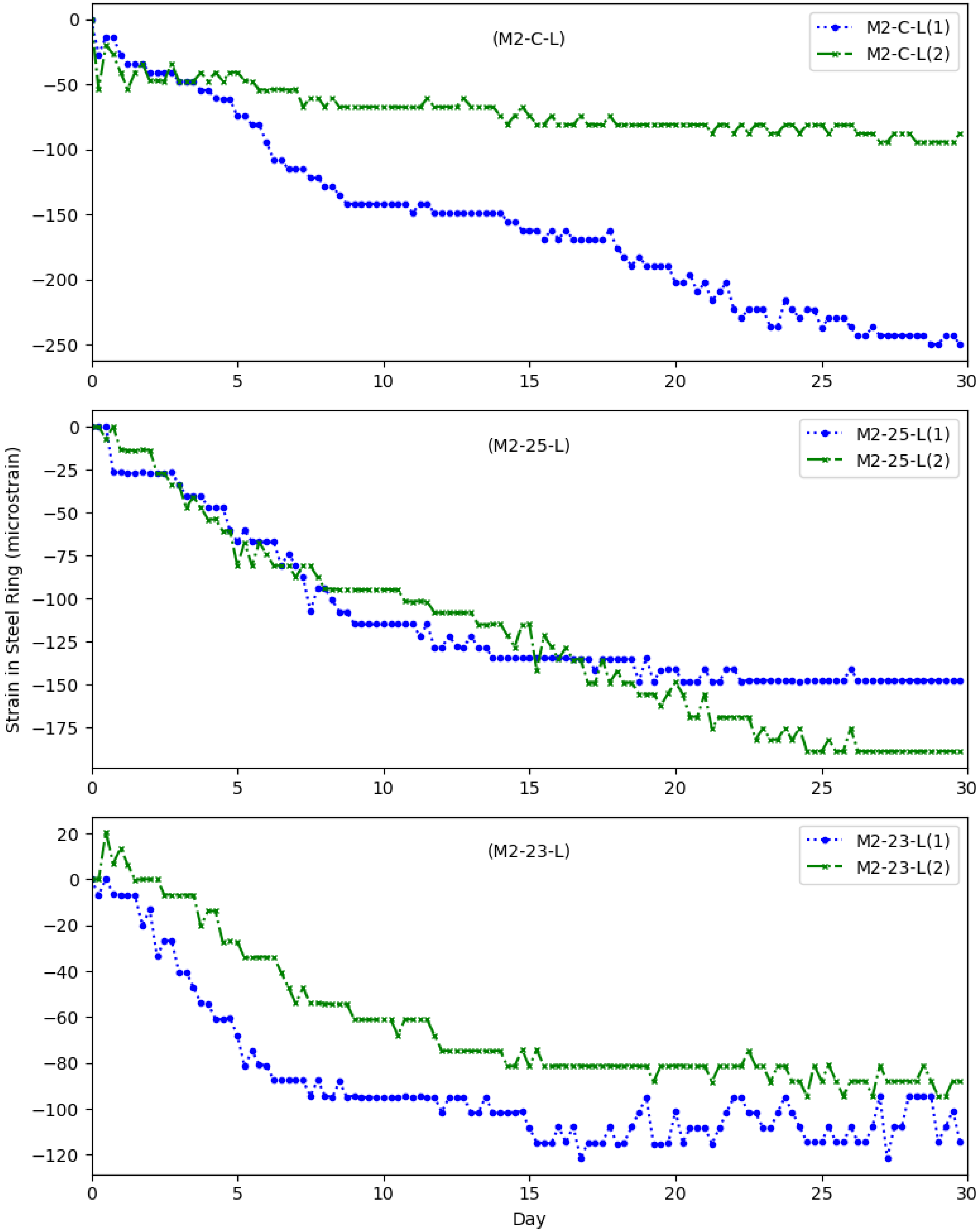


Figure 4.11 Average Strain in Steel Ring for Control and Modified Mixtures of M2 Mix

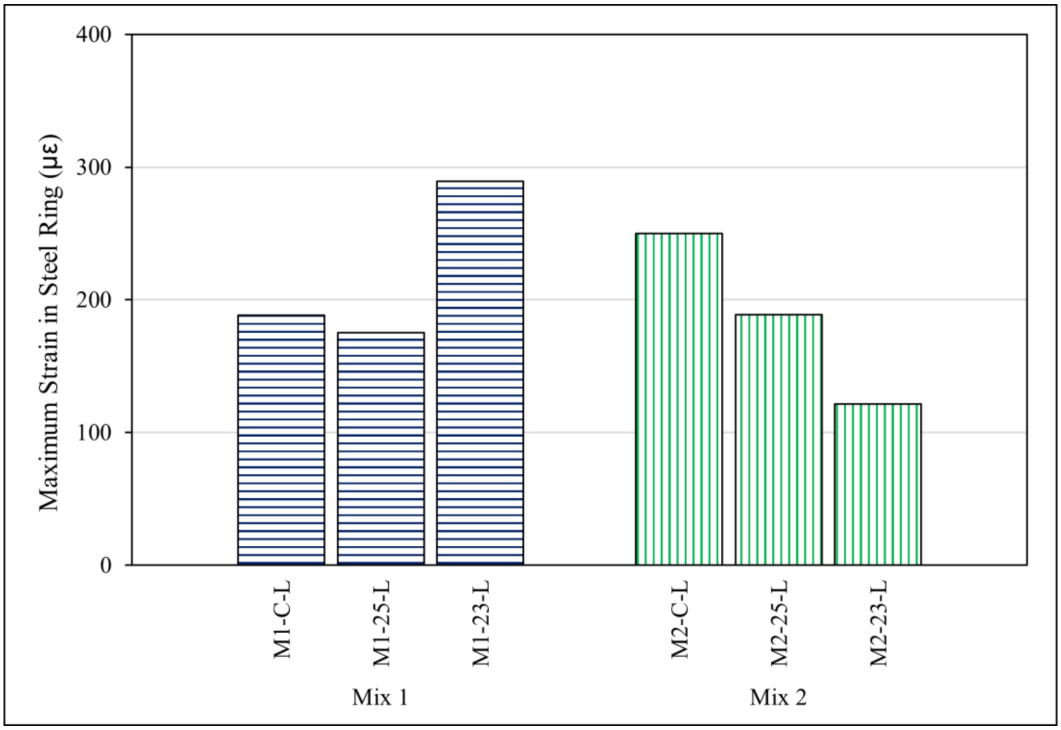


Figure 4.12 Maximum Strain in Steel Ring for Restrained Ring Shrinkage Specimens

4.10 Summary

In this chapter, the field and laboratory test results are presented and discussed. The testing program encompasses fresh, mechanical, durability, and volume stability properties of the control and modified mixtures. Based on the experimental results, it can be concluded that the paste volume of the UDOT-approved pavement mixtures can be reduced to 25% without sacrificing workability, mechanical, durability, and shrinkage properties of the concrete.

5.0 CONCLUSIONS

5.1 Summary

This research program investigates the effect of paste volume reduction in UDOT-approved pavement mixtures. The following sections of this chapter present the key findings of this research program, the summary of the results, and the limitations of the findings.

5.2 Findings

Workability: The workability of the pavement mixtures is greatly influenced by the amount of paste volume in the freshly mixed concrete. With decreasing amount of paste volume, the concrete starts to lose workability. At up to 25% of the paste volume, the laboratory mix is sufficiently workable. However, at 23.5% paste volume, the modified pavement mixture loses plasticity. As the workability is reduced, the percentage of surface voids increases. Based on the box test results for workability, the volume of paste can be reduced to a minimum value of 25%. Admixtures dosage can be adjusted to account for any reduced workability of the mixtures.

Fresh Air Content: The fresh air content is affected by the volume of the paste present in the mixtures. When there is less amount of paste available in the mix, the voids between the aggregates are filled up by air voids. Therefore, the air content of the concrete increases with reduced volume of the paste. At up to 25% of the paste volume, the air content is comparable with the control mixtures. The effect of the paste volume is much higher for mixtures with paste volume less than 25%.

Unit Weight: The unit weight of the concrete mixtures increases with decreasing volume of the paste. As less cement paste is available in the mixtures, the spaces are occupied by heavier aggregates, resulting in higher unit weight.

Compressive Strength and Static Modulus of Elasticity: At a minimum value of 25% volume of the paste, the compressive strength and the static modulus of elasticity of the mixtures are not significantly affected. The compressive strength and the elastic modulus of the mixtures with 25% paste volume are comparable to those of the control mixtures with higher paste volume. The compressive strength, primarily, depends on the water-to-cement ratio, provided that sufficient cement paste is present in the mixtures. However, when the volume of the paste is reduced below 25%, the strength of the mixtures reduces notably.

Surface Electrical Resistivity: The surface electrical resistivity test indicates that, irrespective of paste volume, all the mixtures have low to very low chloride ion penetrability. Surface electrical resistivity is found to be the least affected property of the pavement mixtures.

Shrinkage: In general, the reduction of paste volume positively affects the shrinkage properties of concrete. The percentage of length change and the shrinkage strain reduce with decreasing volume of the paste. For 25% paste volume, the reduction in shrinkage strain of the drying shrinkage specimens is 29.7% and 38.4% for M1-25-L and M2-25-L mixtures, respectively, compared to the control mixtures. Similar observations are made for restrained ring shrinkage specimens. The maximum strains of M1-25-L and M2-25-L are reduced by 7% and 24.5%, respectively, compared to the control mixtures. The maximum shrinkage strain and the maximum percentage of length change of the mixtures with 25% paste volume are within the limit recommended by AASHTO PP-84 and UDOT. Overall, the shrinkage in mixtures with 25% paste volume significantly reduces compared to the control mixtures with higher volume of the paste.

5.3 Limitations and Challenges

One limitation of this research study is that the majority of the tests are performed on laboratory-prepared specimens. These specimens are prepared and tested in controlled environments. The actual circumstances of the batch plant and site are not considered. Another challenge and limitation is the difficulty of preparing specimens in the field. Only fresh air content, compressive strength, and surface electrical resistance of the field samples were measured. Due to logistical limitation, no shrinkage specimens of field samples were tested.

6.0 RECOMMENDATIONS AND IMPLEMENTATION

6.1 Recommendations

The finding of this research study concludes that the paste volume of the UDOT-approved pavement mixtures can be reduced to a minimum value of 25%. The reduction of the paste volume to 25% does not negatively affect the fresh, mechanical, and durability properties of concrete. It has been observed that the shrinkage strain and percentage of length change of the mixtures with 25% paste volume are notably lesser than the control mixtures with higher paste volume. Therefore, it is recommended that the paste volume content of the UDOT-approved pavement mixtures should be reduced following the paste volume limit of AASHTO PP-84.

6.2 Implementation Plan

UDOT standards for design and construction should be modified to allow a minimum paste volume value of 25%.

REFERENCES

AASHTO PP 84. *Standard Practice for Developing Performance Engineered Concrete Pavement Mixtures*. American Association of State Highway and Transportation Officials, 2018.

AASHTO T 334. *Standard Method of Test for Estimating the Cracking Tendency of Concrete*. 2008.

AASHTO T 358. *Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration*. 2021.

AASHTO T152. *Standard Method of Test for Air Content of Freshly Mixed Concrete by the Pressure Method*. 2019.

Abrams, Duff Andrew. *Design of Concrete Mixtures*. Vol. 1, Structural Materials Research Laboratory, 1918.

ACI. *CT-18: ACI Concrete Terminology*. American Concrete Institute, 2018.

Allahham, Jafar, et al. *Review and Specification for Shrinkage Cracks of Bridge Decks*. University of Utah. Dept. of Civil and Environmental Engineering, 2016.

ASTM C138/C138M. *Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete*. 2017.

ASTM C143/143M. *Standard Test Method for Slump of Hydraulic-Cement Concrete*. ASTM International, 2015.

ASTM C157/C157M. *Standard Test Method for Length Change Of Hardened Cement Mortar And Concrete*. 2014.

ASTM C1581/C1581M. *Standard Test Method for Determining Age at Cracking and Induced Tensile Stress Characteristics of Mortar and Concrete under Restrained Shrinkage*. 2009.

ASTM C192/C192M. *Standard Practice for Making and Curing Concrete Test Specimens in the*

Laboratory. 2015.

ASTM C231/C231M. *Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method*. 2014.

ASTM C39/C39M. *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*. 2018.

ASTM C469/C469M. *Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression*. 2014.

Azarsa, Pejman, and Rishi Gupta. "Electrical Resistivity of Concrete for Durability Evaluation: A Review." *Advances in Materials Science and Engineering*, vol. 2017, Hindawi, 2017.

Bentz, Dale P., et al. "Minimizing Paste Content in Concrete Using Limestone Powders–Demonstration Mixtures." *NIST Technical Note*, vol. 38, 2016.

Bisschop, J., and J. G. M. Van Mier. "Effect of Aggregates on Drying Shrinkage Microcracking in Cement-Based Composites." *Materials and Structures*, vol. 35, no. 8, Springer, 2002, pp. 453–61.

Bissonnette, Benoît, et al. "Influence of Key Parameters on Drying Shrinkage of Cementitious Materials." *Cement and Concrete Research*, vol. 29, no. 10, Elsevier, 1999, pp. 1655–62.

Black, Alison Premo. *Production and Use of Coal Combustion Products in the U.S.* American Road & Transportation Builders Association', 2015, p. 28.

Carlson, Roy W. "Drying Shrinkage of Concrete as Affected by Many Factors." *American Soc Testing & Materials Proc*, 1938.

Chu, S. H. "Effect of Paste Volume on Fresh and Hardened Properties of Concrete." *Construction and Building Materials*, vol. 218, Elsevier, 2019, pp. 284–94.

Chung, Hung-Wen, et al. "Evaluation of Pavement Concrete with Low Paste Volume Using Portland Limestone Cement." *ACI Materials Journal*, vol. 117, no. 2, 2020.

Cook, Marllon Daniel, et al. “Impacts of Coarse-Aggregate Gradation on the Workability of Slip-Formed Concrete.” *Journal of Materials in Civil Engineering*, vol. 30, no. 2, American Society of Civil Engineers, 2018, p. 4017265.

Crouch, L. K., et al. “Aggregate Effects on Pervious Portland Cement Concrete Static Modulus of Elasticity.” *Journal of Materials in Civil Engineering*, vol. 19, no. 7, American Society of Civil Engineers, 2007, pp. 561–68.

Fathifazl, Gholamreza, et al. “Creep and Drying Shrinkage Characteristics of Concrete Produced with Coarse Recycled Concrete Aggregate.” *Cement and Concrete Composites*, vol. 33, no. 10, Elsevier, 2011, pp. 1026–37.

Gorninski, Jane Proszek, et al. “Study of the Modulus of Elasticity of Polymer Concrete Compounds and Comparative Assessment of Polymer Concrete and Portland Cement Concrete.” *Cement and Concrete Research*, vol. 34, no. 11, Elsevier, 2004, pp. 2091–95.

Hansen, Torben C., and Erik Boegh. “Elasticity and Drying Shrinkage Concrete of Recycled-Aggregate.” *Journal Proceedings*, vol. 82, no. 5, 1985, pp. 648–52.

Haranki, Boris. *Strength, Modulus of Elasticity, Creep and Shrinkage of Concrete Used in Florida*. University of Florida Gainesville, 2009.

Hu, Xiang, et al. “Drying Shrinkage and Cracking Resistance of Concrete Made with Ternary Cementitious Components.” *Construction and Building Materials*, vol. 149, Elsevier, 2017, pp. 406–15.

Kayali, O., et al. “Drying Shrinkage of Fibre-Reinforced Lightweight Aggregate Concrete Containing Fly Ash.” *Cement and Concrete Research*, vol. 29, no. 11, Elsevier, 1999, pp. 1835–40.

Kim, Jin-Keun, et al. “Effect of Temperature and Aging on the Mechanical Properties of Concrete: Part I. Experimental Results.” *Cement and Concrete Research*, vol. 32, no. 7, Elsevier, 2002, pp. 1087–94.

Kolias, S., and C. Georgiou. “The Effect of Paste Volume and of Water Content on the Strength and Water Absorption of Concrete." *Cement and Concrete Composites*, vol. 27, no. 2, Elsevier, 2005, pp. 211–16.

Kosmatka, Steven H., and Michelle L. Wilson. *Design and Control of Concrete Mixtures*. 15th ed., Portland Cement Association, 2011.

Kwan, A. K. H., and S. K. Ling. "Lowering Paste Volume of SCC through Aggregate Proportioning to Reduce Carbon Footprint." *Construction and Building Materials*, vol. 93, Elsevier, 2015, pp. 584–94.

Ling, S. K., and A. K. H. Kwan. "Adding Limestone Fines as Cementitious Paste Replacement to Lower Carbon Footprint of SCC." *Construction and Building Materials*, vol. 111, Elsevier, 2016, pp. 326–36.

Liu, Bao Dong, et al. "Effect of Moisture Content on Static Compressive Elasticity Modulus of Concrete." *Construction and Building Materials*, vol. 69, Elsevier, 2014, pp. 133–42.

Mapa, D. G., et al. "Effects of Reduced Paste Content and Base Restraint on Young Concrete Pavement." *ACI Materials Journal*, vol. 115, no. 5, 2018.

Mehta, P. Kumar, and Paulo J. M. Monteiro. *Concrete Microstructure, Properties and Materials*. 2017.

Mielenz, Richard C., et al. "Orgin, Evolution, and Effects of the Air Void System in Concrete. Part 1-Etrained Air in Unhardend Concrete." *Journal Proceedings*, vol. 55, no. 7, 1958, pp. 95–121.

Nanthagopalan, Prakash, and Manu Santhanam. "Experimental Investigations on the Influence of Paste Composition and Content on the Properties of Self-Compacting Concrete." *Construction and Building Materials*, vol. 23, no. 11, Elsevier, 2009, pp. 3443–49.

Neville, Adam M., and Jeffrey John Brooks. *Concrete Technology*. Longman Scientific & Technical England, 1987.

Parastegari, Niloofar, et al. "Use of Bacteria to Improve Electrical Resistivity and Chloride

Penetration of Air-Entrained Concrete." *Construction and Building Materials*, vol. 210, Elsevier, 2019, pp. 588–95.

Pasko, Thomas J. "Pavements: Past, Present, and Future." *Concrete International*, vol. 20, no. 5, 1998, pp. 47–52.

Piasta, Wojciech, and Bartlomiej Zarzycki. "The Effect of Cement Paste Volume and w/c Ratio on Shrinkage Strain, Water Absorption and Compressive Strength of High Performance Concrete." *Construction and Building Materials*, vol. 140, Elsevier, 2017, pp. 395–402.

Rozière, Emmanuel, et al. "Influence of Paste Volume on Shrinkage Cracking and Fracture Properties of Self-Compacting Concrete." *Cement and Concrete Composites*, vol. 29, no. 8, Elsevier, 2007, pp. 626–36.

Safiuddin, Md, et al. "Effects of Medium Temperature and Industrial By-Products on the Key Hardened Properties of High Performance Concrete." *Materials*, vol. 8, no. 12, Multidisciplinary Digital Publishing Institute, 2015, pp. 8608–23.

Saleem, M., et al. "Effect of Moisture, Chloride and Sulphate Contamination on the Electrical Resistivity of Portland Cement Concrete." *Construction and Building Materials*, vol. 10, no. 3, Elsevier, 1996, pp. 209–14.

Shoukry, Samir N., et al. "Effect of Moisture and Temperature on the Mechanical Properties of Concrete." *Construction and Building Materials*, vol. 25, no. 2, Elsevier, 2011, pp. 688–96.

Sokhansefat, Ghazal, et al. "Investigation of Concrete Workability through Characterization of Aggregate Gradation in Hardened Concrete Using X-Ray Computed Tomography." *Cement and Concrete Composites*, vol. 98, Elsevier, 2019, pp. 150–61.

Tia, Mang, et al. *Modulus of Elasticity, Creep and Shrinkage of Concrete*. 2005.

UDOT. *Standard Specifications For Road and Bridge Construction*. 2017.

Wassermann, R., et al. "Minimum Cement Content Requirements: A Must or a Myth?" *Materials and Structures*, vol. 42, no. 7, Springer, 2009, pp. 973–82.

Weiss, William Jason. *Prediction of Early-Age Shrinkage Cracking in Concrete Elements*. 1999.

Yalçınkaya, Çağlar, and Halit Yazıcı. “Effects of Ambient Temperature and Relative Humidity on Early-Age Shrinkage of UHPC with High-Volume Mineral Admixtures.” *Construction and Building Materials*, vol. 144, Elsevier, 2017, pp. 252–59.

Yurdakul, Ezgi, Peter C Taylor, et al. “Effect of Paste-to-Voids Volume Ratio on the Performance of Concrete Mixtures.” *Journal of Materials in Civil Engineering*, vol. 25, no. 12, American Society of Civil Engineers, 2013, pp. 1840–51.

Yurdakul, Ezgi, Peter C. Taylor, et al. “Effect of Water-to-Binder Ratio, Air Content, and Type of Cementitious Materials on Fresh and Hardened Properties of Binary and Ternary Blended Concrete.” *Journal of Materials in Civil Engineering*, vol. 26, no. 6, American Society of Civil Engineers, 2014, p. 4014002, doi:10.1061/(asce)mt.1943-5533.0000900.

APPENDIX A: EXPERIMENTAL RESULTS OF FIELD AND LABORATORY SAMPLES

This section provides experimental data obtained from the testing of field and laboratory samples. The experiments include workability, fresh air content, unit weight, compressive strength, static modulus of elasticity, surface electrical resistivity, drying, and restrained ring shrinkage.

Table A.1 Box Slump Test Result from Laboratory Mixtures

Batch Id	Slump (inch)	Slump (mm)
M1-C-L	4.75	120.65
M1-25-L	4.25	107.95
M1-23-L	0.00	0.00
M2-C-L	5.50	139.70
M2-25-L	4.75	120.65
M2-23-L	0.25	6.35

Table A.2 Fresh Air Content Test Results of Field and Laboratory Samples

Batch Id	Fresh Air Content (%)
M1-C-F	5.25
M1-C-L	6.70
M1-25-L	5.70
M1-23-L	10.10
M2-C-F	8.5
M2-C-L	7.20
M2-25-L	7.90
M2-23-L	NA

Table A.3 Unit Weight Test Result from Laboratory Mixtures

Batch Id	Unit Weight (lbs./ft^3)	Unit Weight (kg./m^3)
M1-C-L	139.60	2236.18
M1-25-L	141.88	2272.70
M1-23-L	143.08	2291.93
M2-C-L	138.80	2223.37
M2-25-L	142.40	2281.03
M2-23-L	144.20	2309.87

Table A.4 Compressive Strength Test Results of Field and Laboratory Specimens

Batch Id	Compressive Strength		Average Compressive Strength		Standard Deviation	
	(psi)	(MPa)	(psi)	(MPa)	(psi)	(MPa)
M1-C-F	7707 7606.5 8057.6	53.1 52.4 55.6	7790.4	53.7	236.8	1.6
M1-C-L	8060 7841 8313	55.6 54.1 57.3	8071.3	55.6	236.2	1.6
M1-25-L	7855 8011 8055	54.2 55.2 55.5	7973.7	55	105.1	0.7
M1-23-L	2330 2290 2442	16.1 15.8 16.8	2354	16.2	78.8	0.5
M2-C-F	5068.2 5096.7 5219.5	34.9 35.1 36	5128.1	35.4	80.4	0.6
M2-C-L	10770 11168 10978	74.3 77 75.7	10972	75.6	199.1	1.4
M2-25-L	8904 10866 8999	61.4 74.9 62	9589.7	66.1	1106.4	7.6
M2-23-L	3970 8731 4904	27.4 60.2 33.8	5868.3	40.5	2522.7	17.4

Table A.5 Static Elastic Modulus of Elasticity Test Results of Laboratory Specimens

Batch Id	Compressive Strength		Average Compressive Strength		Standard Deviation	
	(ksi)	(GPa)	(ksi)	(GPa)	(ksi)	(GPa)
M1-C-L	5283.7 5523.9 5549.2	36.4 38.1 38.3	5452.3	37.6	146.5	1.0
M1-25-L	5911.9 5908.7 6185.4	40.8 40.7 42.6	6002	41.4	158.8	1.1
M1-23-L	3782.5 3519.9 3490.6	26.1 24.3 24.1	3597.7	24.8	160.8	1.1
M2-C-L	6569.3 7019.5	45.3 48.4	6794.4	46.8	318.3	2.2
M2-25-L	5961.9 5727.3 6325.9	41.1 39.5 43.6	6005.1	41.4	301.6	2.1
M2-23-L	3847.4 5412.2	26.5 37.3	4629.8	31.9	1106.5	7.6

Table A.5 Surface Electrical Resistivity Test Results of Field and Laboratory Specimens

Batch ID	Specimen No	$\bar{\rho}$ (kΩ-cm)				Average $\bar{\rho}$ (kΩ-cm)	Standard Deviation (kΩ-cm)
M1-C-F	1	33.1	33.2	33.8	33.5	35.28	1.74
	2	34.9	35.2	35.2	34.7		
	3	37.6	37.1	37.5	37.5		
M1-C-L	1	35.8	35.3	35.1	34.3	36.48	1.33
	2	36.2	36.9	37.2	36.2		
	3	37.5	36.5	39.3	37.5		
M1-25-L	1	43.5	44.3	39.1	40.5	44.91	2.71
	2	46.8	47.1	47.9	47.36		
	3	45.5	45.6	45.5	45.7		
M1-23-L	1	41.6	42.9	41.5	42.9	40.63	1.28
	2	39.7	39.3	40.1	40.5		
	3	39.4	40	39.8	39.9		
M2-C-F	1	27.1	27.1	27.7	27.6	27.99	0.73
	2	28.7	28.6	28.6	28.3		
	3	27.1	27.4	29	28.7		
M2-C-L	1	56.3	59.6	56.5	56.3	57.08	1.90
	2	55.5	56.2	54.3	56.9		
	3	56.4	56.5	60.6	59.8		
M2-25-L	1	65	62.9	64.1	68.5	65.62	6.47
	2	64	83.2	58.3	58		
	3	68	66.6	66.6	62.2		
M2-23-L	1	47.7	39.6	31.1	36.6	31.97	6.54
	2	32.6	27.2	26.2	25.9		
	3	26.6	27.6	31.8	30.7		

Table A.6 Average Length Change Due to Drying Shrinkage of Laboratory Specimens

Time (Days)	Average Length Change of Specimen, ΔL_x (%)					
	M1-C-L	**M1-25-L**	**M1-23-L**	**M2-C-L**	**M2-25-L**	**M2-23-L**
1	0.00000	0.00000	0.00000	0.00000	0.00000	NA
4	0.01778	0.01111	0.02633	0.01511	0.00267	NA
7	0.02556	0.02089	0.02733	0.01822	0.01367	NA
14	0.03467	0.03200	0.03467	0.02933	0.03100	NA
28	0.04711	0.03311	0.04200	0.03644	0.03433	NA
56	0.05022	0.03822	0.04733	0.03956	0.03633	NA

Table A.7 Free Shrinkage Strain of Laboratory Specimens

Batch ID	Average Shrinkage Strain (microstrain)	Standard Deviation (microstrain)
M1-C-L	471.11	130.36
M1-25-L	331.11	112.41
M1-23-L	420.00	188.56
M2-C-L	364.44	85.98
M2-25-L	224.44	61.28
M2-23-L	NA	NA

Table A.8 Maximum Strain in Steel Ring for Restrained Ring Shrinkage Laboratory Specimens

Batch ID	Maximum Strain in Steel Ring (microstrain)
M1-C-L	471.11
M1-25-L	331.11
M1-23-L	420.00
M2-C-L	364.44
M2-25-L	224.44
M2-23-L	NA