

**COMPREHENSIVE FRAMEWORK FOR STRUCTURAL CONCRETE MIX
OPTIMIZATION: INTEGRATING DIFFERENT AGGREGATE TYPES, GRADATION
TECHNIQUES, AND PASTE CONTENT REDUCTION**

A Thesis Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Sazzadul Shahriar Saykat

August 2025

Copyright © 2025 by Sazzadul Shahriar Saykat

All rights reserved.

ACKNOWLEDGEMENTS

First and foremost, I am deeply grateful to Allah for granting me the strength, patience, and perseverance to pursue and complete this journey. This thesis marks a significant milestone in a remarkable journey that began when I moved from Bangladesh to the United States to pursue graduate study at the University of Tennessee, Knoxville. I am sincerely thankful for the support, guidance, and encouragement I have received along the way.

I would like to express my heartfelt gratitude to my supervisor, Dr. Zhongguo John Ma, for his invaluable guidance, patience, and mentorship throughout my research. His expertise and encouragement have been instrumental in shaping my academic and professional growth.

I am especially grateful to the Tennessee Department of Transportation (TDOT) and its staff for funding this research and providing crucial support throughout my research. Their assistance and collaboration were vital to the successful completion of this work.

Special thanks to Ammar El Hassan and Debalina Ghosh, whose unwavering support and insightful discussions helped me navigate the challenges of my research journey. Thank you to everyone else I researched with: Caleb Napper, Syed Aqib, Saeed Davar, Levi Matthews, Evan Pindrock, Jaden Chin, Sam Steiger, and LaTasha Woodard. My sincere appreciation goes to the professors, advisors, office workers, and custodians at UTK for their kindness and support.

Most importantly, I owe my deepest thanks to my lovely wife, whose unwavering support, love, and belief in me made this achievement possible. Without her by my side, this journey would have been unimaginable. Special thank you to my mother and sister for their wholehearted support from back home in Bangladesh. Their love, prayers, and constant encouragement have always been a source of strength and motivation. Finally, I am grateful to the rest of my family for their love and encouragement. To everyone who has been a part of this journey, thank you for

being the shoulders I could lean on. This accomplishment is as much yours as it is mine.

ABSTRACT

Traditional structural concrete mixes focus on individual aggregate sizes which leads to suboptimal mixtures that require excessive paste content, resulting in increased costs, higher carbon footprint, and potential durability issues. There is limited research on the workability challenges and solutions associated with these mixtures to find the optimal balance when paste content is reduced after optimization. So, there is a need for a systematic approach to find the optimal balance between aggregate optimization and paste content reduction while enhancing or maintaining workability, strength, and durability. Also, understanding the effects of different aggregate types on optimization techniques is needed to help engineers and concrete producers make more informed decisions when selecting materials for specific applications while using optimization techniques. This study investigates the effects of reduced paste content on the performance of optimized concrete mixtures for structural applications, while also examining the influence of different aggregate types on optimization techniques. Four different coarse aggregates (two granite, one limestone, and one gravel) and two fine aggregates (manufactured sand and natural sand) were used for optimized concrete using tarantula curve and coarseness factor chart methods. Optimized mixes were designed with 0%, 10%, and 20% reductions in cementitious content and compared to non-optimized control mixes. The study found that the optimization process led to improved freeze-thaw durability, higher compressive strengths, and better resistance to chloride ion penetration. However, there were some trade-offs, such as increased drying shrinkage due to partial replacement of coarse aggregates with intermediate aggregates. The results also indicate that while natural sand demonstrates superior performance compared to manufactured sand in terms of workability and durability, gravel and granite outperformed other coarse aggregate types by providing better compressive strength. While

optimized mixes with a 20% reduction in paste content exhibited acceptable properties, a 10% reduction is recommended. This is due to the significantly higher demand for admixtures required in the 20% reduction mixes to maintain adequate workability. The 10% reduction strikes a better balance between sustainability, performance, and cost-efficiency, making it a more practical choice for structural concrete applications.

TABLE OF CONTENTS

CHAPTER 1 INTRODUCTION.....	1
CHAPTER 2 LITERATURE REVIEW.....	4
2.1 Overview.....	4
2.2 Optimized Aggregate Gradation (OAG) Methods	5
2.3 Latest Development of Optimized Aggregate Gradation (OAG).....	8
CHAPTER 3 METHODOLOGY	11
3.1 Introduction.....	11
3.2 Materials and Description.....	12
3.3 Aggregate Sampling and Sieving Procedure	18
3.4 Optimization Process	21
3.5 Development of Mix Design	22
3.6 Mix Proportioning	30
3.7 Fresh Concrete Property Testing	34
3.8 Curing Procedure	36
tank that was used for curing.	37
3.9 Hardened Property Testing	37
CHAPTER 4 RESULTS AND DISCUSSIONS	42
4.1 Aggregate Size and Shape Analysis	42

4.2 Class A Optimized & Non-optimized Control Mixtures	45
4.3 Class D/Ds Optimized and Non-optimized Control Mixtures.....	68
CHAPTER 5 CONCLUSIONS.....	86
REFERENCES.....	91
APPENDIX.....	97
VITA.....	99

LIST OF TABLES

Table 2-1 Difference between previous research on optimization.....	10
Table 3-1 Control mixtures provided by TDOT	23
Table 3-2 Class A concrete mixture design (Limestone / Manufactured sand)	26
Table 3-3 Class A concrete mixture design (Limestone / Natural sand).....	27
Table 3-4 Class A concrete mixture design (Crushed gravel / Manufactured sand).....	28
Table 3-5 Class A concrete mixture design (Crushed gravel / Natural sand)	29
Table 3-6 Class D/DS concrete mixture design (#7 Intermediate Aggregate).....	31
Table 3-7 Class D/DS concrete mixture design (#89 Intermediate Aggregate).....	32
Table 4-1 Percentage of flat and elongated particles in coarse aggregates	45
Table 4-2 Fresh concrete properties of optimized mixtures for the small-scale mixtures ...	46
Table 4-3 Fresh concrete properties of optimized and nonoptimized mixtures.....	48
Table 4-4 Class A surface resistivity results	64
Table 4-5 Class A surface resistivity results of comparable mixtures	66
Table 4-6 Fresh concrete properties of optimized and nonoptimized Class D/Ds mixtures	69
Table 4-7 Class D/Ds surface resistivity results	84
Table 4-8 Class D/Ds surface resistivity results of comparable mixtures.....	85
Table A-1 Specific gravity of coarse aggregates.....	98

LIST OF FIGURES

Figure 2-1 Coarseness factor chart	7
Figure 2-2 Tarantula curve limits	8
Figure 3-1 Type IL cement used in the research.....	12
Figure 3-2 Class F fly ash used in the research	13
Figure 3-3 Coarse aggregate samples from different sources.....	15
Figure 3-4 Fine aggregate samples from different sources	16
Figure 3-5 Intermediate aggregate samples from different sources	17
Figure 3-6 Aggregate sampling.....	18
Figure 3-7 Use of splitter to collect representative sample	19
Figure 3-8 Sieve analysis procedure.....	21
Figure 3-9 Drum mixer.....	33
Figure 3-10 Slump test.....	34
Figure 3-11 Unit weight measurement using super air meter bowl.....	35
Figure 3-12 Air content testing using the super air meter	36
Figure 3-13 SAM number testing result for a mixture.....	37
Figure 3-14 Curing tank.....	38
Figure 3-15 Compressive strength test setup.....	38
Figure 3-16 Modulus of Elasticity test setup	39
Figure 3-17 Shrinkage beam placed into a comparator	40
Figure 3-18 Surface resistivity testing.....	41
Figure 4-1 Gradation curve of coarse aggregates	43
Figure 4-2 Gradation curve of fine aggregates.....	44

Figure 4-3 Unit weight of Class A mixture	49
Figure 4-4 Slump test for nonoptimized and optimized mixtures	49
Figure 4-5 Slump of Class A mixtures	50
Figure 4-6 Air content of Class A mixtures	52
Figure 4-7 SAM number results for Class A mixtures	53
Figure 4-8 Effect of different fine aggregates on unit weight	54
Figure 4-9 Effect of different fine aggregates on SAM number	55
Figure 4-10 28 days compressive strength of Class A mixtures	56
Figure 4-11 7 days and 28 days compressive strength results	57
Figure 4-12 Effect of different fine aggregates on compressive strength	59
Figure 4-13 Effect of different coarse aggregates on compressive strength	60
Figure 4-14 MOE results for Class A mixtures.....	61
Figure 4-15 Drying shrinkage results at 28 days.....	62
Figure 4-16 Drying shrinkage results at 28 days, and 56 days	63
Figure 4-17 Surface resistivity of comparable Class A mixtures	67
Figure 4-18 Unit weight of Class D/Ds mixtures	70
Figure 4-19 Slump of Class D/Ds mixtures.....	71
Figure 4-20 Air content of Class D/Ds mixtures	72
Figure 4-21 SAM number results for Class D/Ds mixtures	73
Figure 4-22 Effect of intermediate aggregates on unit weight.....	74
Figure 4-23 Effect of intermediate aggregates on SAM number.....	75
Figure 4-24 28 days compressive strength of Class D/Ds mixtures	76
Figure 4-25 7 days and 28 days compressive strength results for Class D/Ds mixtures.....	77

Figure 4-26 Effect of intermediate aggregates on compressive strength	78
Figure 4-27 Effect of different coarse aggregates on compressive strength	79
Figure 4-28 MOE results for Class D/Ds mixtures	80
Figure 4-29 Drying shrinkage results at 28 days.....	81
Figure 4-30 Drying shrinkage results at 28 days and 56 days	82
Figure A-1 Chemical composition of cement.....	97
Figure A-2 Chemical composition of fly ash.....	98

CHAPTER 1

INTRODUCTION

Concrete remains the most widely used construction material globally, underpinning the infrastructure of modern society. Its versatility, strength, and durability have made it indispensable for structural applications. However, the environmental impact and cost associated with cement production, as well as the increasing demand for sustainable construction, have intensified the need to optimize concrete mix designs for both performance and sustainability (Agarwal et al. 2024). Traditional approaches to structural concrete mix design often focus on individual aggregate sizes and rely on high paste content to achieve workability and strength. This methodology, while effective in the short term, leads to mixtures that are not only costlier but also carry a higher carbon footprint and may exhibit durability issues such as increased permeability, shrinkage, and susceptibility to cracking (Smit & Kearsley, 2015).

Recent research has highlighted the critical role of aggregate selection and gradation in optimizing concrete mixtures. Aggregates constitute the bulk of concrete volume and their properties—such as type, size, shape, and gradation—significantly influence the workability, strength, and durability of the final product (Saykat et al. 2025). Well-graded aggregate systems, achieved through advanced techniques like the tarantula curve and coarseness factor chart, have been shown to enhance packing density, thereby reducing the void content and the required paste volume. This not only improves the mechanical properties and durability of concrete but also allows for a reduction in cementitious materials, directly addressing economic and environmental concerns (Liu et al. 2024).

Despite these advancements, there remain significant challenges, particularly in balancing reduced paste content with the need to maintain or enhance workability, strength, and durability.

High paste content can improve early-age workability but often results in increased permeability and reduced tensile strength at later ages, underscoring the importance of minimizing paste while ensuring constructability (Taylor et al. 2012). The use of chemical admixtures, such as high-range water reducers and viscosity-modifying agents, has enabled further reductions in paste content without compromising workability, but the interplay between aggregate optimization and admixture use requires systematic study (Handojo, 2009).

Moreover, the selection of aggregate types—ranging from granite and limestone to gravel and manufactured sands—introduces additional complexity. Each aggregate type imparts unique characteristics to the concrete, influencing not only mechanical performance but also the efficacy of optimization techniques. For instance, high-strength coarse aggregates like granite can yield higher compressive strengths in high-strength concrete, while the effect is less pronounced in normal-strength mixes (Kozul & Darwin, 1997). The interaction between aggregate type, gradation method, and paste content reduction remains underexplored, particularly with respect to workability and durability in structural applications.

To address these gaps, a comprehensive framework is needed that systematically integrates aggregate type selection, advanced gradation techniques, and paste content reduction, all while ensuring that the resulting mixtures meet or exceed performance requirements for workability, strength, and durability. Such a framework would enable engineers and concrete producers to make informed decisions tailored to specific structural applications, optimizing both material usage and long-term performance. Recent studies have demonstrated the utility of holistic optimization procedures that combine experimental data, physics-based models, and probabilistic approaches to minimize global warming potential and cost, while satisfying structural and durability constraints (Ahmad & Alghamdi, 2014).

This study aims to advance the field by investigating the effects of reduced paste content on the performance of optimized concrete mixtures for structural applications, with a particular focus on the influence of different aggregate types and gradation techniques. By employing four distinct coarse aggregates (two granite, one limestone, and one gravel) and two fine aggregates (manufactured sand and natural sand), and applying both the tarantula curve and coarseness factor chart methods, this research seeks to elucidate the optimal balance between aggregate optimization and paste content reduction. Mixes will be evaluated at 0%, 10%, and 20% reductions in cementitious content and compared to non-optimized control mixes, providing a robust dataset to inform future mix design practices. The findings are expected to contribute significantly to the development of more sustainable, cost-effective, and durable structural concrete, aligning with the broader goals of modern civil engineering and sustainable construction.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

Research has shown that 10-18% cement reduction compared to the minimum cement content currently required by the TDOT specification (e.g. Table 604.03-1) can be achieved using aggregate grading optimization (Cook et al. 2015; Sobolev et al. 2015). Nevertheless, mixtures with reduced cementitious materials content frequently demonstrated poor workability and inadequate durability unless proper proportioning of the mixture to maintain the expected workability, overall performance, and long-term durability is ensured (Sobolev et al. 2015). The current concrete mixture design specifications (ACI 211 or DOTs specifications) control aggregate gradation by calling out envelopes for individual fractions sizes, typically coarse and fine aggregates. The major limitation of this approach is that the gradation of the resulting composite blend is not addressed. A well-graded aggregate system (e.g. aggregate with a balanced variety of sizes) contributes to achieving a workable and economical mixture with a minimum amount of water which will have less shrinkage and permeability (Shilstone 1990; Cross 2000; Cook et al. 2013; Ley et al. 2012). The use of gap-graded (e.g. single-sized) aggregate, on the other hand, can result in mixtures that segregate and have poor workability. When mixtures do not possess sufficient workability, it is common to increase the cement and water content of the mixture according to the latest TDOT specification (TDOT, 2021, Section 604.03). This practice can increase cost and decrease the sustainability and durability of concrete (Taylor et al. 2007). Thus, Shilstone (1990) considered the combined aggregate grading analysis as the best means for specifying and selecting mixture proportions. However, there is no guidelines on the optimized/combined aggregates grading or the use of ternary aggregate blends

(e.g., such as those used in asphalt - TDOT Spec. Sec. 903.06.C) for concrete mixtures within Tennessee so far. Multiple theoretical and experimental methods have been developed for aggregate optimization through packing or particle size distribution for concrete mixtures (Fuller and Thompson 1907; Shilstone 1990; Kennedy et al. 1994; Goltermann et al. 1997; Sobolev et al. 2010; Cook et al. 2015). Nevertheless, due to the complexities in aggregate packing and irregularities in shape and texture for different types of aggregates (e.g. limestones vs. gravel and natural sand vs. manufactured sand), there is no standard methodology to account for the contribution of aggregate gradation and packing density on the performance of fresh and hardened concrete. Common tools for aggregate optimization such as the Power 45 curve, Shilstone workability-coarseness chart, and the Haystack limits (8-18% retained) have been criticized for resulting in too dense concrete, poor workability, or not adequate performance (Cook et al. 2013; Ley et al. 2012). The Tarantula curve, which was developed based on a large amount of highway pavement data, has been quickly adopted in the highway pavement industry and state highway agencies. But even with the promising results from this curve, the limits of the Tarantula Curve have been developed based on limited types of aggregates, namely limestones and natural sand.

2.2 Optimized Aggregate Gradation (OAG) Methods

In order to optimize aggregate gradations and enhance concrete performance, numerous techniques have been established. However, which is best for developing an optimal mixture is up for debate. In this study, the following techniques were employed for optimization.

2.2.1 Coarseness Factor Method

The Coarseness Factor approach is an empirical technique that may be used to estimate the fresh concrete mix's workability and to reduce segregation. The Coarseness Factor Chart shows the

relationship between the modified workability factor (WF) and the coarseness factor (CF), which can be calculated using Equations 2-1 and 2-2. In the X axis of the Figure 2-1, workability factor which indicates the amount of sand and cementitious content in the mix is plotted, whereas in the Y axis, coarseness factor which shows the ratio of large to intermediate aggregate in the mix is plotted.

$$\text{Workability factor} = P + \frac{2.5 \cdot (M - 564)}{94}$$

Equation 2.1

$$\text{Coarseness factor} = \frac{R}{S} \cdot 100$$

Equation 2.2

Where,

P = Cumulative percent passing on the number 8 sieve

M = Cementitious material content (lb/yd³)

R = Cumulative percent passing on the number 3/8" sieve

S = Cumulative percent retained on the number 8 sieve

Figure 2-1 displays the coarseness factor chart, which has been divided into five zones. Mixtures in Zone I are gap-graded and have a significant propensity for segregation due to inadequate combined aggregate grading and a lack of intermediate particles. The preferred area on the chart is Zone II which represents a well-graded design for a concrete mixture. Zone III is an expansion of Zone II for 1/2 inch and finer aggregate combinations and also indicates gap grading. A substantial possibility for segregation during consolidation and finishing exists in Zone IV mixtures because of the large number of finer particles present in them. Zone V, sometimes referred to as non-plastic, is composed of mixtures with an excessive amount of coarse material.

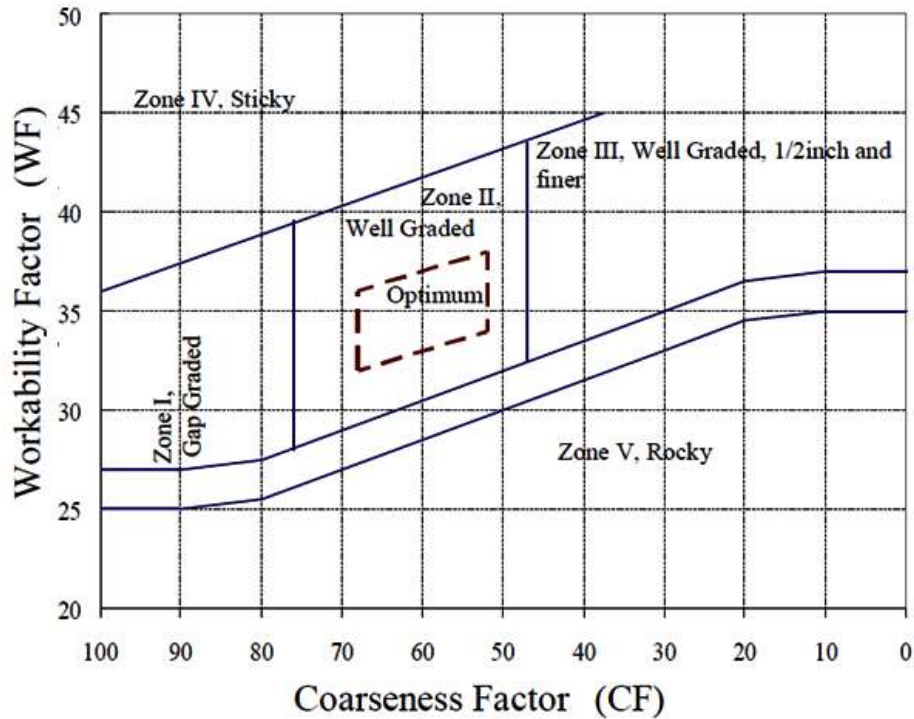


Figure 2-1 Coarseness factor chart

2.2.2 Tarantula Curve

The Tarantula Curve was created as a tool for proportioning aggregate for the majority of concrete applications after four rigorous years of generating over 4,000 mixture designs and trial batching over 800 mixtures (Ley & Cook, 2014). In order to study the effects of varied quantities of aggregates retained on each sieve, it was built utilizing five separate aggregate types from several quarries, generating mixtures with a consistent w/cm ratio, and producing specified gradations. The construction of a suggested framework for the integrated grading of aggregates is the final result of the study endeavor. The suggested framework also offers advice on potential problems that can arise if the gradation curve deviates from it. The optimal aggregate gradation for a concrete mixture is not offered by the Tarantula Curve. However, it gives a range with a variety of gradations so users can produce an ideal aggregate gradation. **Figure 2-2** shows a framework, which is shaped like a Tarantula, hence the name of the method.

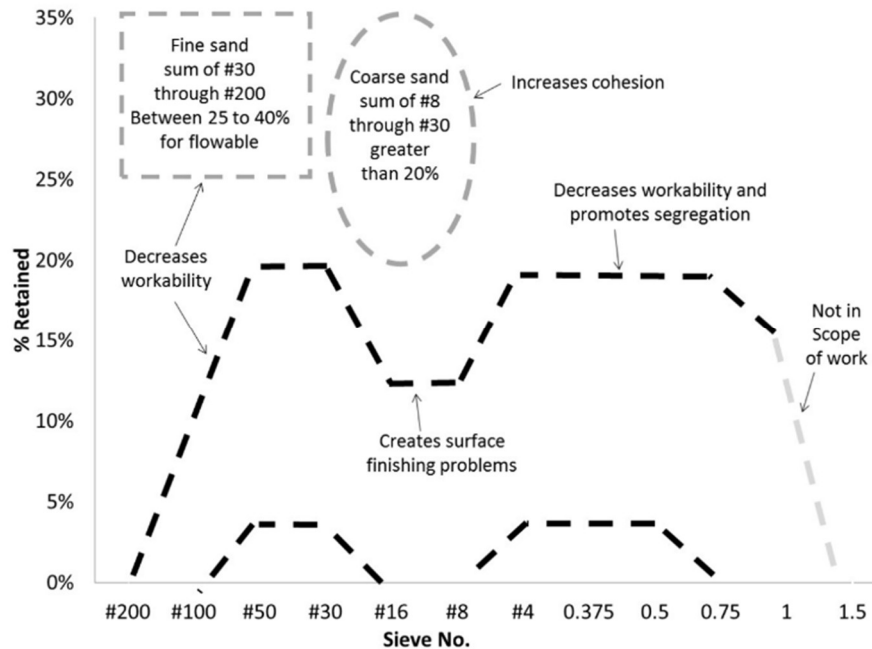


Figure 2-2 Tarantula curve limits

2.3 Latest Development of Optimized Aggregate Gradation (OAG)

An extensive review of literature on optimized aggregate gradation research across various Departments of Transportation (DOTs) revealed significant work by North Carolina DOT (Theilgaard, 2022) and Florida DOT (Chung et al., 2021). A study by Hung-Wen Chung and colleagues from the University of Florida in 2021 investigated the effects of minimized volume in structural concrete using Portland limestone cement and blended aggregates (BA). Their research examined fresh and hardened concrete properties using Type I/II and Type IL cement, focusing on three sets of concretes with varying paste volumes. The study aimed to assess the benefits of concrete with minimal paste volume, explore the BA technique, and evaluate the viability of Type IL cement in structural concrete. The research explored three methods to reduce cementitious material content (CMC) in structural concrete: reduced cement paste volume (CPV), use of type IL cement, and implementation of blended aggregates (BA). The findings indicated that paste volume could be reduced to approximately 27% without compromising

concrete properties and further reduced to 24% using the BA method. Concrete mixtures utilizing the BA approach demonstrated superior performance compared to reference concrete. The combination of Type IL cement and BA proved effective in reducing initial costs and carbon dioxide emissions without sacrificing performance. Theilgaard (2022) conducted research on the Tarantula Curve's application in optimized aggregate gradation concrete mixtures with reduced paste. The study compared 21 optimized aggregate gradation concrete mixtures against 21 non-optimized counterparts. Theilgaard's research demonstrated that cementitious content in concrete mixtures could be reduced by 10% while still meeting NCDOT specification requirements. Although electrical resistivity tests showed increased permeability in optimized aggregate gradation mixtures, this may have been influenced by higher aggregate content, interfacial transition zone (ITZ) effects, and the reduction in cementitious components altering cement paste structure. These studies suggest that optimized aggregate mixtures may lead to concrete with enhanced durability, extended service life, and reduced cracking due to volumetric shrinkage. Additionally, these mixtures offer potential cost savings and reduce greenhouse gas emissions through decreased cement usage. These findings underscore the potential benefits of optimized aggregate gradation in concrete mixtures, aligning with broader industry trends toward more efficient, durable, and sustainable concrete designs. The differences between the two studies are displayed in **Table 2-1**.

Table 2-1 Difference between previous research on optimization

Parameter	(Theilgaard, 2022)	(Chung et al., 2021)
Combined Aggregate Gradation Method	Tarantula Curve	Coarseness Factor (CF) method
Coarse Aggregates Type	Limestone	Limestone
Fine Aggregate Type	Natural sand	Silica sand
Coarse Aggregates size	#67	#57
Intermediate Aggregates size	#89M	#89
Type of Cement	OPC, Type IL(mixtures were not included in the study)	OPC(type I/II), Type IL)
Type of Fly Ash	Class F	Class F
Fly ash replacement	0-30%	20%
w/c ratio	0.37, 0.42, 0.47	0.40
Cementitious material content (CMC)	700 pcy, 650 pcy, 600 pcy	730 pcy

CHAPTER 3

METHODOLOGY

3.1 Introduction

The methodology chapter provides a comprehensive overview of the research approach and experimental procedures employed in this study on optimizing aggregate gradations for concrete mixtures. This chapter is structured to offer a clear and detailed account of the methods used, ensuring reproducibility and scientific rigor.

In the Materials and Description section, a thorough account of all materials used in the study is presented. This includes detailed specifications of the various types of aggregates, cementitious materials, and any admixtures employed. The section aims to provide a clear understanding of the raw materials that form the basis of the concrete mixtures under investigation.

The Optimization Process section delves into the core of the research, detailing the methods and techniques used to optimize aggregate gradations. This may include descriptions of various optimization algorithms, software tools, or empirical methods employed to achieve optimal aggregate blends.

The Development of Mix Design section outlines the process of creating concrete mixtures using the optimized aggregate gradations. It describes the proportioning methods, the rationale behind mixture compositions, and any iterative processes used to refine the designs.

Testing of Fresh Concrete Properties focuses on the methods used to evaluate the workability, consistency, and other relevant properties of the freshly mixed concrete. This section details the specific tests performed, such as slump tests, air content measurements, and any other relevant fresh concrete assessments.

The Preparation and Curing of Test Specimens section provides information on how concrete

samples were prepared, molded, and cured for subsequent hardened concrete testing. This includes details on specimen sizes, curing conditions, and any special handling procedures. Finally, the Testing of Hardened Concrete section describes the methods used to evaluate the performance of the hardened concrete specimens. This encompasses strength tests (compressive, flexural, and tensile), durability assessments (such as permeability and freeze-thaw resistance), and any other relevant hardened concrete property evaluations. Throughout the chapter, emphasis is placed on adherence to standardized testing methods and procedures, ensuring the validity and comparability of results.

3.2 Materials and Description

3.2.1 Cement

For this research, ASTM C595 Portland-limestone Type IL cement was selected as the primary cementitious material for all concrete mixtures. The cement was sourced locally, ensuring consistency throughout the research. To maintain uniformity in the experiments, a sufficient quantity of this cement was stored in the laboratory for the duration of the study. **Figure 3-1** shows the cement sample used in the research.



Figure 3-1 Type IL cement used in the research

The chemical composition of the cement, which plays a crucial role in concrete performance, is detailed in Appendix A. This choice of cement aligns with current industry trends towards more sustainable concrete production, as type IL cement typically has a lower carbon footprint compared to traditional Portland cement.

3.2.2 Fly Ash

In accordance with the TDOT Standard Specification for road and bridge construction (TDOT, 2021), the study incorporated ASTM C618 Class F fly ash as a partial replacement for cement. The researchers utilized a 25% replacement rate by cement mass, which is the maximum allowable percentage under current TDOT specifications. To ensure consistency throughout the experimental program, a sufficient quantity of Class F fly ash was procured at the start of the research. This material was stored in the laboratory for the duration of the study, maintaining its integrity and uniformity. **Figure 3-2** illustrates Class F fly ash used in the research.

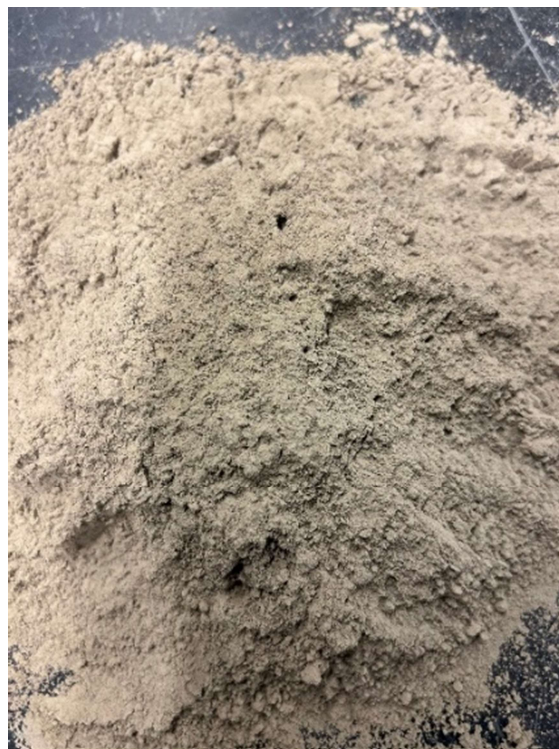


Figure 3-2 Class F fly ash used in the research

The chemical composition of the Class F fly ash, which is crucial for understanding its impact on concrete properties, is presented in Appendix A. The use of fly ash in this study aligns with industry efforts to reduce the environmental impact of concrete production while potentially enhancing certain performance characteristics of the mixtures.

3.2.3 Coarse Aggregate

In this study, researchers intentionally selected a diverse array of coarse aggregates to capture the broad geological differences present throughout Tennessee. The rationale behind this approach was to ensure that findings regarding aggregate optimization would be broadly applicable across different regions of the state, each of which may possess unique aggregate sources and properties. By considering this geological variety, the study aims to provide recommendations and insights that are relevant to a wide range of local contexts within Tennessee. For Class A concrete mixtures, six distinct #57 coarse aggregate samples were utilized:

1. Three limestone samples [Limestone 1 (LS1), Limestone 2 (LS2), and Limestone 3 (LS3)]
2. Two granite samples [Granite 1 (GR1) and Granite 2 (GR2)]
3. One gravel sample [Gravel 1 (GV1)]

These aggregates were sourced from various regions throughout Tennessee, ensuring a comprehensive evaluation of optimization effects across the state's diverse geological landscape.

For Class D/Ds concrete mixtures, a subset of these aggregates was employed:

1. LS1
2. GR2
3. GV1

Figure 3-3 shows a visual representation of all the coarse aggregate samples used in this study.

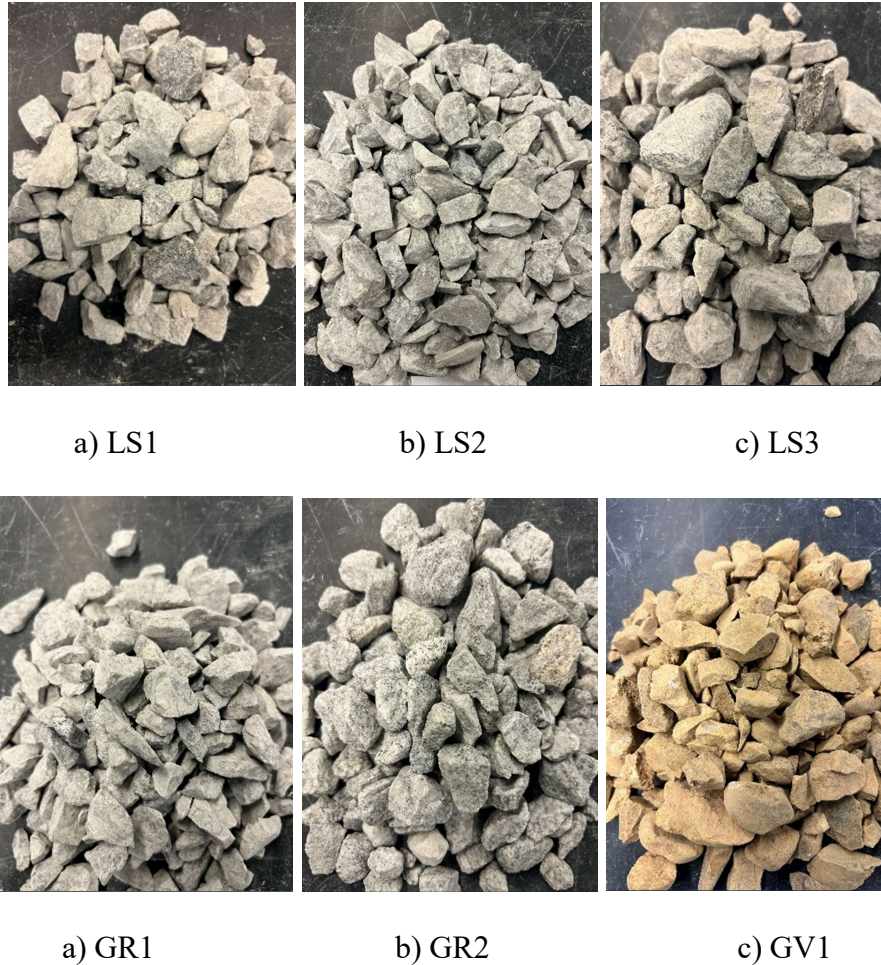


Figure 3-3 Coarse aggregate samples from different sources

3.2.4 Fine Aggregate

For Class A mixtures, the researchers employed a natural sand sample and a manufactured sand sample. These samples were sourced from different regions within the state, providing a representative cross-section of fine aggregates available in Tennessee. In the case of Class D/Ds mixtures the study focused solely on natural sand. **Figure 3-4** presents visual documentation of the fine aggregate samples used in this study. This careful selection of fine aggregates allows for a comprehensive analysis of how different sand types influence the performance of optimized gradation concrete mixtures especially Class A mixtures, particularly in the context of Tennessee's specific construction needs and material availability.



a) Manufactured sand

b) Natural Sand

Figure 3-4 Fine aggregate samples from different sources

3.2.5 Intermediate Aggregate

The research team introduced intermediate-sized aggregates into the concrete mixes as a strategy for optimizing overall mixture performance. Specifically, for the Class A concrete mixtures, they used #7 sized intermediate aggregates, which are slightly smaller than the primary #57 coarse aggregates. Importantly, these #7 aggregates were obtained from the same suppliers that provided the respective coarse aggregates for each mix. By sourcing both aggregate types from the same producers, the researchers ensured a higher degree of consistency. However, for Class D/Ds mixtures a more varied approach was adopted, using both #7 and #89 sized intermediate aggregates. This decision allowed for a more comprehensive exploration of gradation optimization possibilities in bridge deck applications. It's noteworthy that the LS1 producer did not manufacture #89 intermediate aggregate. Consequently, the researchers were unable to include #89 aggregate in the LS1 Class D/Ds mixtures, highlighting a practical limitation in material availability. **Figure 3-5** provides a visual representation of the intermediate aggregates procured from various regions across Tennessee.

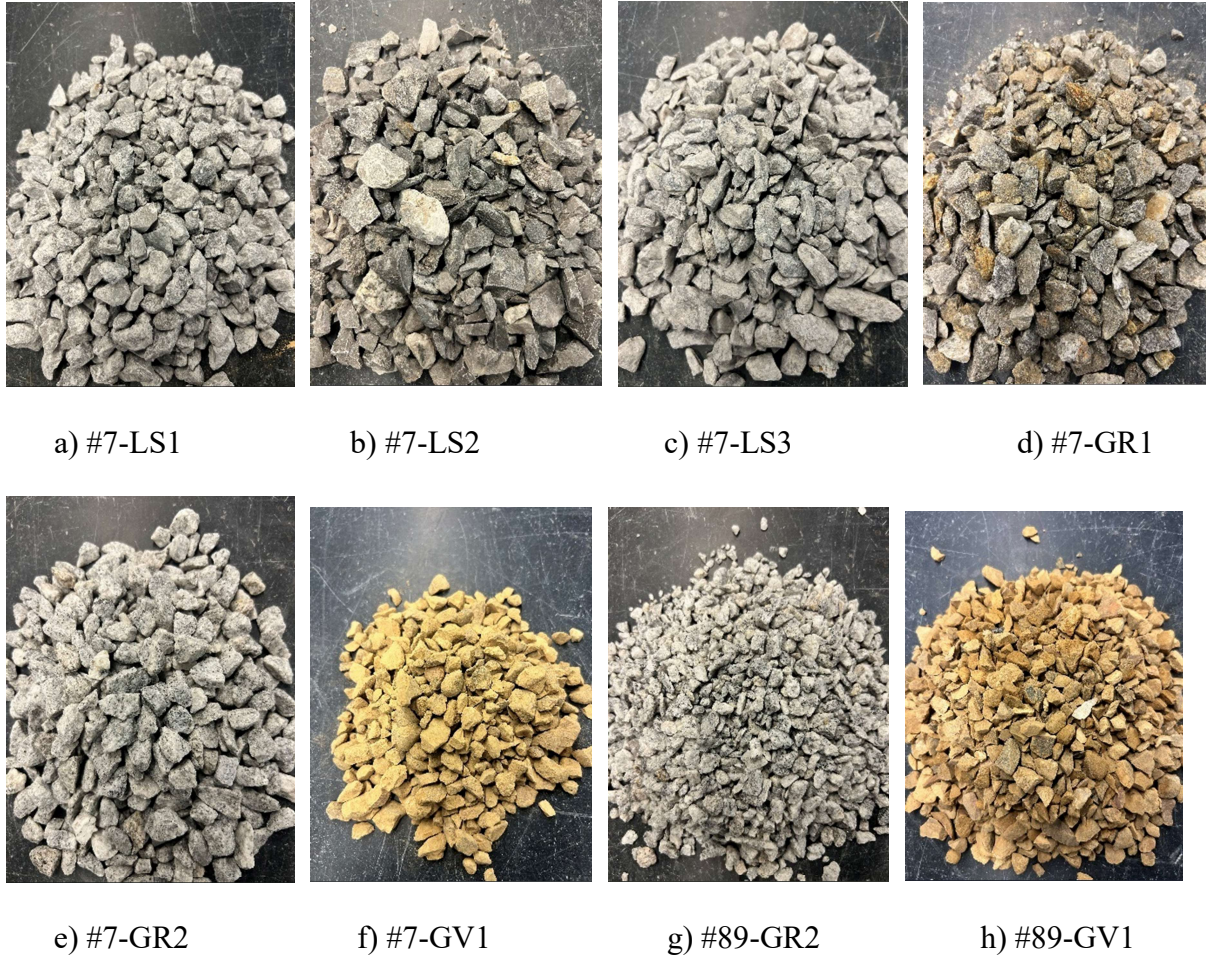


Figure 3-5 Intermediate aggregate samples from different sources

3.2.6 Chemical Admixture

In this research, two specific commercial admixtures were utilized to enhance the properties of Class A and Class D/Ds concrete mixtures:

1. Air Entraining Admixture (AEA): AE 200
2. Mid-range Water Reducing Admixture (WRA): Polyheed 900

The inclusion of these admixtures was crucial in achieving the targeted slump and air content values for both the optimized and non-optimized control concrete mixtures. The AEA helps create a stable air void system in the concrete, which is essential for improving freeze-thaw resistance and workability. The mid-range WRA allows for a reduction in water content while

maintaining or improving workability, potentially leading to higher strength and durability.

3.3 Aggregate Sampling and Sieving Procedure

3.3.1 Aggregate Sampling

To ensure accurate and representative aggregate sampling for this study, a systematic procedure was employed. Aggregates were initially collected in bags or buckets, with each sample representing a specific size category. To create a uniform blend, all aggregates of the same size were combined into a 30-foot-long pile. This pile was then divided into eight equal sections, each measuring 3 feet 9 inches, and stored separately. **Figure 3-6** shows an image of the pile for one of the aggregate samples.



Figure 3-6 Aggregate sampling

From the initial set of sections, representative aggregates were carefully selected from two different sections. These selected aggregates were then thoroughly mixed together to promote uniformity and eliminate any potential inconsistencies in composition. The goal of this mixing process was to ensure that the resulting mass of aggregate was as homogeneous as possible, thereby improving the reliability of subsequent testing.

To obtain smaller, consistent portions from this mixed aggregate, a mechanical splitter was employed, as shown in **Figure 3-7**. This device divided the material in a systematic and unbiased manner, resulting in three representative samples of approximately equal mass and composition. Each of these three samples was then subjected individually to a detailed sieve analysis in accordance with standard testing procedures. This analysis was undertaken to accurately determine the particle size distribution within each sample, providing important data on the gradation characteristics of the aggregate mixture.



Figure 3-7 Use of splitter to collect representative sample

The average results from these three sieve analyses provided the basis for optimizing aggregate gradation. This methodical approach ensures that the aggregate samples used in the study accurately reflect the materials' characteristics, enabling reliable optimization and performance evaluation.

3.3.2 Sieve Analysis Procedure

Sieve analysis is an important process in aggregate optimization for concrete due to its ability to determine the particle size distribution of aggregates. For Class A concrete, the first stage of testing involves collecting limestone aggregates (coarse, fine, and intermediate) from three different producers from Tennessee Regions 1, 2, and 3. As aggregate optimization closely depends on the gradation of the aggregate, sieve analysis was done using ASTM E11 sieve series and following ASTM C 136. About 40 sieves, from 1.5” to #200, were used for sieve analysis of each aggregate. Sieve analysis procedure, which was followed, is discussed below:

- A bag/ bucket was picked to collect samples for sieve analysis.
- A splitter was used to take representative samples from that bag/ bucket following ASTM C702.
- After collecting representative samples, aggregates were put in an oven for drying.
- Dry samples were first cooled after removing from the oven and then weighted.
- All 40 sieves were arranged accordingly.
- A mechanical sieve shaker was used for sieving.
- Finally retained aggregates in each sieve were weighed using a scale.

Figure 3-8 below illustrates the entire process:

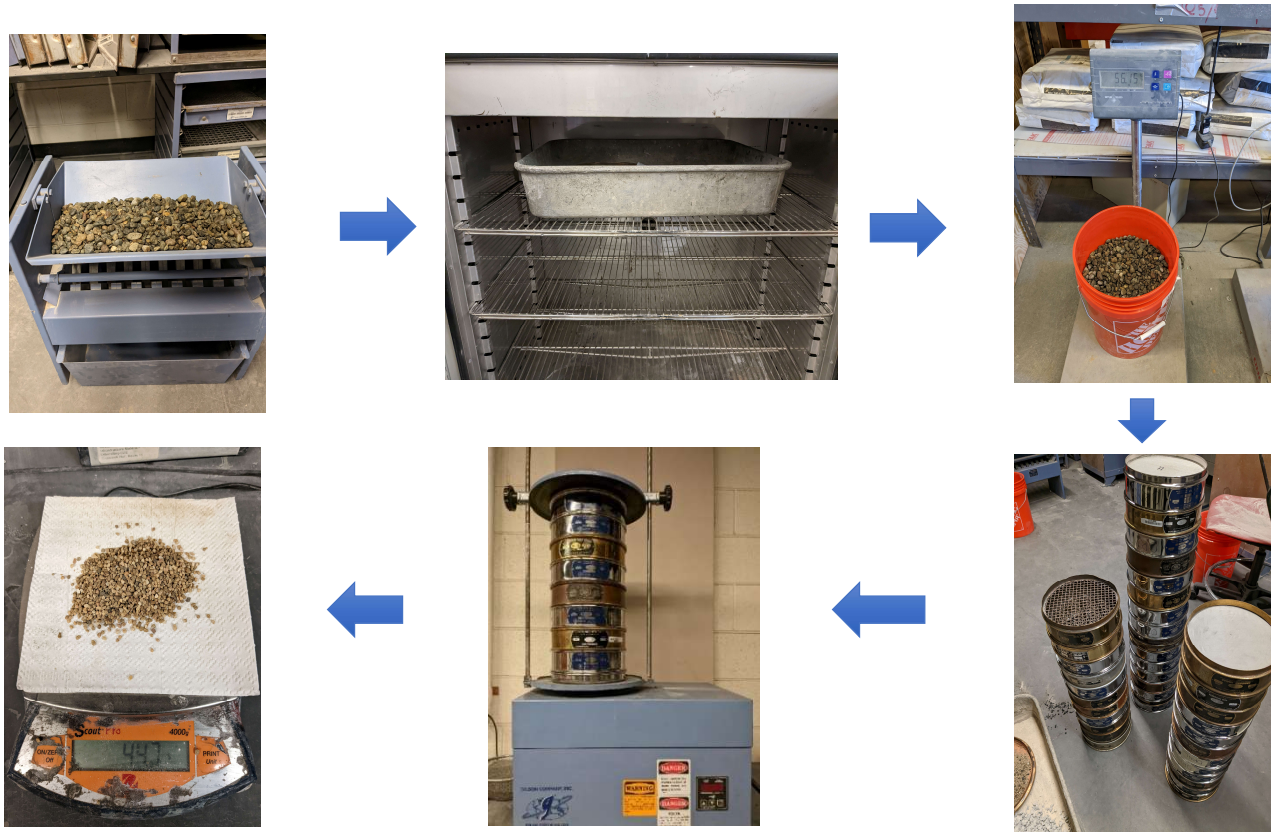


Figure 3-8 Sieve analysis procedure

3.4 Optimization Process

Aggregate gradation was optimized using both Tarantula Curve method and Coarseness factor chart method. An Excel sheet was developed to optimize aggregate using these two methods.

Detailed figures illustrating the step-by-step optimization process are included in Appendix B for reference. The aggregate optimization process is described below:

- **Step -1: Input Sieve Analysis data**

As the first step in the optimization process, the results of every sieve analysis performed on the coarse, intermediate, and fine aggregates used in the mix were entered into the excel sheet.

- **Step -2: Calculate Combined Aggregate Gradation**

Using each of the aggregate sieve analysis results, combined aggregate gradation was calculated.

Graph for the combined aggregate gradation was also plotted.

- **Step -3: Determine the % Volume of the Aggregates to Fit within the Limit of Tarantula Curve**

The volume of the aggregates was calculated after determining the combined aggregate gradation and was fitted within the limits of the tarantula curve. The specific gravity of each component of the concrete mix was recorded on the chart. For each mix design, the mixture components to yield a total of 27.0 cubic feet of concrete were determined.

- **Step -4: Check Constraints for Tarantula Curve**

After completing mix design calculations, all the constraints were checked. The tarantula curve limit for the aggregate retained quantity in each sieve for combined aggregate gradation was the initial constraint to be checked. Other constraints for structural concrete applications were coarse and fine sand percentages as shown below.

- **Step -5: Check the value with the Coarseness Factor Chart**

The mix design was checked on the coarseness factor chart to identify which zone it falls within as the last step of theoretical optimization before testing. The coarseness factor and workability factor were computed. Target mix designs were located in zone II's optimum zone, which is the well-graded zone.

3.5 Development of Mix Design

Table 3-1 below shows typical existing TDOT approved concrete mixtures by Classes based on TDOT database. These mixtures were used as control mixtures (non-optimized) for Class A and Class D/DS. The water cementitious ratio for these mixtures ranges between 0.40 to 0.45. The cementitious material content ranges between 564 – 620 lb/yd³, and the estimated paste volume content ranges between 25.5-27.1 %.

Table 3-1 Control mixtures provided by TDOT

Mixture Class	A (75% Cement+25% Fly Ash)	A (100% Cement)	D/DS
Cement Type	Type I	Type I	Type I
Cement content	423	564	496
Class F-Ash	141 (25%)	-	124 (20%)
# 57 stone	1825	1800	1800
Coarse Limestone	LR1-C2	LR2-C2	-
Coarse Granite	-	-	GR1
Natural sand	-	1261	1170
Manufactured sand	1349	-	-
Design Air %	6	6	7
Water	254.40	250	250
Air admixture	Per MFG	Per MFG	Per MFG
w/cm ratio	0.45	0.44	0.40
Estimated Paste Volume	26.4%	25.5%	27.1%
Sand ratio by volume	42.7%	41.8%	40%
T. Unit Weight, PCF	147.9	143.5	142
Required strength, 28 Days (psi)	3000	3000	4000
Actual strength, psi	AVG= 5649 Min=3210 Max=8400	AVG= 5564.2 Min=4030 Max=7520	AVG= 6142 Min=4490 Max=8100

*Constituent quantities are provided in lb/ yd³

The estimated volume of cementitious paste in each concrete mixture was calculated using the minimum required total content of cementitious materials in combination with the maximum allowable water-to-cementitious materials (w/cm) ratio. This approach ensured that the paste volume would meet structural and durability requirements while minimizing excess use of materials. To establish a baseline for comparison, a set of control mixtures was reproduced using Type II portland-limestone cement. These control mixes were based on previously designed, batched, and tested concrete mixtures provided by the TDOT, serving as a preliminary data set reflecting existing standards and performance expectations.

Building upon these control mixtures, a series of companion concrete mixes were developed to explore possibilities for material optimization. These new designs employed the Tarantula Curve and the Shilstone workability-coarseness chart—two widely recognized tools for optimizing aggregate gradation. The goal was to improve aggregate packing and internal stability in the mixtures, enabling a consistent reduction in paste volume without compromising workability or mechanical performance.

In this study, four key parameters were identified and systematically varied to evaluate their impact on overall mixture behavior. These included: the total content of cementitious materials, serving as the primary binder component; the percentage of fly ash used to replace portland cement, which affects long-term durability and sustainability; the type and shape of coarse aggregate (including limestone, granite, and gravel); and the type and shape of fine aggregate, specifically differentiating between natural sand and manufactured sand. These variables were carefully selected and controlled to replicate mixture compositions typically used in TDOT projects, with a specific focus on performance classes such as Class A and Class D/DS concrete.

➤ **Class A Mixtures: (36 optimized mixtures and 12 non-optimized mixtures)**

The reference concrete mix to be evaluated is TDOT Class A concrete with w/cm of 0.45, and total cementitious materials content (75% Type II and 25% Class F Fly Ash) of 564 lb/cy. The estimated cementitious paste volume of the reference mixtures is 25.4-26.4 %. Mixtures are designed with six coarse aggregate types, #7 or #89 as intermediate aggregate, and two fine aggregate types (natural sand and manufactured sand). The mixture parameters (type of coarse and fine aggregates) are selected to represent typical Class A mixtures within Tennessee.

Candidate mixtures were designed to meet the Tarantula Curve limits with consideration to Shilstone workability-coarseness chart to optimize the aggregate gradation of concrete mixtures with a uniform paste reduction. The mixtures are developed to represent:

- 0% Cementitious Reduction (564 lb/yd³); estimated paste volume = 26.4%
- 10% Cementitious Reduction (508 lb/yd³); estimated paste volume = 23.7%
- 20% Cementitious Reduction (451 lb/yd³); estimated paste volume = 21.1%

Tables 3-2 to 3-5 show the preliminary details of mixture designs of Class A concrete. **Table 3-2** shows mixture designs with limestone and manufactured sand, and **Table 3-3** shows mixture designs with limestone and natural sand. **Tables 3-4 and 3-5** show duplicated mixtures with gravel and granite in lieu of limestone.

The Mixture ID is identified as **AA-BB-CC-DD**, and defined as (e.g A-LS1-MS-0):

AA= Mixture TDOT Class (A and D/DS)

BB= Type of coarse aggregate [limestone (LS1,LS2,...), Gravel (GV1,GV2,...), or Granite (GR1,GR2,...)]

CC=Type of fine aggregate [Manufactured Sand (MS) or Natural sand (NS)]

DD= Cementitious content reduction (0%, 10%, or 20%) or Nonoptimized control mixtures (N)

Table 3-2 Class A concrete mixture design (Limestone / Manufactured sand)

	Limestone 1 (LR1-C1)			Limestone 2 (LR2-C1)			Limestone 3 (LR3-C1)		
Mixture ID	A- LS1- MS-0	A- LS1- MS- 10	A- LS1- MS- 20	A- LS2- MS-0	A- LS2- MS- 10	A- LS2- MS- 20	A- LS3- MS-0	A- LS3- MS- 10	A- LS3- MS- 20
Cementitious content	564	508	451	564	508	451	564	508	451
Cement	423	381	338	423	381	338	423	381	338
Fly Ash	141	127	113	141	127	113	141	127	113
Coarse # 57 stone	1100	1140	1180	1020	1060	1100	905	945	985
Intermediate # 7 stone	710	741	772	785	817	850	900	932	964
Manufactured sand	1335	1385	1435	1335	1385	1435	1335	1385	1435
Design Air %	6	6	6	6	6	6	6	6	6
Water	253.8	228.6	203.0	253.8	228.6	203.0	253.8	228.6	203.0
AEA (oz/cwt)	0.75	0.60	0.40	0.75	0.60	0.40	0.75	0.60	0.40
WRA (oz/cwt)	0.61	2.69	14.17	0.00	2.15	17.20	0.81	2.78	16.19
w/cm ratio	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Sand ratio by volume	42.7%	42.7%	42.7%	42.7%	42.7%	42.7%	42.7%	42.7%	42.7%

*Constituent quantities are provided in lb/ yd³

Table 3-3 Class A concrete mixture design (Limestone / Natural sand)

	Limestone 1 (LR1-C2)			Limestone 2 (LR2-C1)			Limestone 3 (LR3-C1)		
Mixture ID	A- LS1- NS-0	A- LS1- NS-10	A- LS1- NS-20	A- LS2- NS-0	A- LS2- NS-10	A- LS2- NS-20	A- LS3- NS-0	A- LS3- NS-10	A- LS3- NS-20
Cementitious content	564	508	451	564	508	451	564	508	451
Cement	423	381	338	423	381	338	423	381	338
Fly Ash	141	127	113	141	127	113	141	127	113
Coarse # 57 stone	1100	1140	1180	1010	1050	1090	900	940	980
Intermediate # 7 stone	707	735	763	795	823	850	902	930	958
Natural sand	1270	1320	1370	1270	1320	1370	1270	1320	1370
Design Air %	6	6	6	6	6	6	6	6	6
Water	253.8	228.6	203.0	253.8	228.6	203.0	253.8	228.6	203.0
AEA (oz/cwt)	0.75	0.60	0.40	0.75	0.60	0.40	0.75	0.60	0.40
WRA (oz/cwt)	0.97	3.58	16.19	1.62	2.15	20.24	0.00	4.47	20.24
w/cm ratio	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Sand ratio by volume	42.7%	42.7%	42.7%	42.7%	42.7%	42.7%	42.7%	42.7%	42.7%

*Constituent quantities are provided in lb/ yd³

Table 3-4 Class A concrete mixture design (Crushed gravel / Manufactured sand)

	Gravel 1 (GV1-C1)			Granite 1 (GR1-C1)			Granite 2 (GR2-C1)		
Mixture ID	A- GV1- MS-0	A- GV1- MS- 10	A- GV1- MS- 20	A- GR1- MS-0	A- GR1- MS- 10	A- GR1- MS- 20	A- GR2- MS-0	A- GR2- MS- 10	A- GR2- MS- 20
Cementitious content	564	508	451	564	508	451	564	508	451
Cement	423	381	338	423	381	338	423	381	338
Fly Ash	141	127	113	141	127	113	141	127	113
Coarse # 57 stone	1220	1265	1310	945	985	1025	900	940	980
Intermediate # 7 stone	475	500	525	850	880	910	813	843	872
Manufactured sand	1335	1385	1435	1335	1385	1435	1270	1320	1370
Design Air %	6	6	6	6	6	6	6	6	6
Water (lb/cy)	253.8	228.6	203.0	253.8	228.6	203.0	253.8	228.6	203.0
AEA (oz/cwt)	0.75	0.60	0.40	0.75	0.60	0.40	0.75	0.60	0.40
WRA (oz/cwt)	0.00	6.26	20.25	1.94	7.16	14.17	2.43	3.58	16.19
w/cm ratio	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Sand ratio by volume	42.7%	42.7%	42.7%	42.7%	42.7%	42.7%	42.7%	42.7%	42.7%

*Constituent quantities are provided in lb/ yd³

Table 3-5 Class A concrete mixture design (Crushed gravel / Natural sand)

	Gravel 1 (GV1-C2)			Granite 1 (GR1-C2)			Granite 2 (GR2-C2)		
Mixture ID	A- GV1- NS-0	A- GV1- NS-10	A- GV1- NS-20	A- GR1- NS-0	A- GR1- NS-10	A- GR1- NS-20	A- GR2- NS-0	A- GR2- NS-10	A- GR2- NS-20
Cementitious content	564	508	451	564	508	451	564	508	451
Cement	423	381	338	423	381	338	423	381	338
Fly Ash	141	127	113	141	127	113	141	127	113
Coarse # 57 stone	1270	1310	1350	1011	1050	1090	1060	1100	1140
Intermediate # 7 stone	422	450	477	780	810	840	653	682	712
Natural sand	1270	1320	1370	1270	1320	1370	1270	1320	1370
Design Air %	6	6	6	6	6	6	6	6	6
Water	253.8	228.6	203.0	253.8	228.6	203.0	253.8	228.6	203.0
AEA (oz/cwt)	0.75	0.60	0.40	0.75	0.60	0.40	0.75	0.60	0.40
WRA (oz/cwt)	0.00	2.69	14.17	4.86	12.52	28.34	3.24	7.16	20.24
w/cm ratio	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Sand ratio by volume	42.7%	42.7%	42.7%	42.7%	42.7%	42.7%	42.7%	42.7%	42.7%

*Constituent quantities are provided in lb/ yd³

➤ **Class D/DS Mixtures: (15 optimized mixtures and 3 nonoptimized control mixtures)**

The reference concrete mix to be evaluated is TDOT Class D/DS concrete with w/cm of 0.40 and total cementitious materials content (75% Type II and 25% Class F Fly Ash) of 620 lb/cy. The estimated cementitious paste volume of the reference mixture is 27.1%. Mixtures are designed with three different coarse aggregate types (#57 crushed limestone, 57# crushed granite, and #57 crushed gravel), intermediate aggregate(#7 and #89), and natural sand as fine aggregates. The mixture parameters (type of coarse and fine aggregates) are selected to represent typical Class A mixtures within Tennessee.

Candidate mixtures were designed to meet the Tarantula Curve limits with consideration to Shilstone workability-coarseness chart to optimize the aggregate gradation of concrete mixtures with a uniform paste reduction. The mixtures are developed to represent:

- 0% Cementitious Reduction (620 lb/yd³); estimated paste volume = 27.1%
- 10% Cementitious Reduction (559 lb/yd³); estimated paste volume = 24.5%
- 20% Cementitious Reduction (496 lb/yd³); estimated paste volume = 21.7%

Tables 3-6 and 3-7 show the details of the mixture designs of Class D/DS concrete mixture.

Table 3-6 shows mixtures with (limestone, gravel, and granite) + natural sand and #7 stone as an intermediate aggregate. **Table 3-7** shows duplicated mixtures using #89 as intermediate aggregate in lieu of #7 stone. Trial batch mixtures were performed to determine optimum admixtures dosages before every production mixture.

3.6 Mix Proportioning

In a controlled laboratory environment, all concrete mixtures were prepared using a three-cubic-foot capacity concrete drum mixer, as shown in **Figure 3-9**. The use of this mixer ensured consistent mixing conditions and uniformity across all batches.

Table 3-6 Class D/DS concrete mixture design (#7 Intermediate Aggregate)

	Limestone 1 (LR1-C2)			Gravel (GV1-C2)			Granite 2 (GR2-C2)		
Mixture ID	D-LS1-NS-0	D-LS1-NS-10	D-LS1-NS-20	D-GV1-NS-0	D-GV1-NS-10	D-GV1-NS-20	D-GR1-NS-0	D-GR1-NS-10	D-GR1-NS-20
Cementitious content	620	559	496	620	559	496	620	559	496
Cement	465	419	372	465	419	372	465	419	372
Fly Ash	155	140	124	155	140	124	155	140	124
Coarse # 57 stone	1102	1140	1185	1330	1386	1440	1070	1110	1150
Intermediate # 7 stone	713	750	780	396	410	427	704	735	765
Natural sand	1175	1222	1272	1157	1205	1255	1175	1222	1272
Design Air %	7	7	7	7	7	7	7	7	7
Water	248.0	223.6	198.4	248.0	223.6	198.4	248.0	223.6	198.4
AEA (oz/cwt)	0.40	0.00	0.00	0.40	0.00	0.00	0.50	0.20	0.00
WRA (oz/cwt)	13.30	22.94	42.48	8.87	14.75	27.70	9.60	15.56	26.78
w/cm ratio	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Sand ratio by volume	40.6%	40.6%	40.6%	40.0%	40.0%	40.0%	40.0%	40.0%	40.0%

*Constituent quantities are provided in lb/ yd³

Table 3-7 Class D/DS concrete mixture design (#89 Intermediate Aggregate)

	Gravel (GV1-C2)			Granite 2 (GR2-C2)		
Mixture ID	D- GV1- NS-0	D- GV1- NS-10	D- GV1- NS-20	D- GR1- NS-0	D- GR1- NS-10	D- GR1- NS-20
Cementitious content	620	559	496	620	559	496
Cement	465	419	372	465	419	372
Fly Ash	155	140	124	155	140	124
Coarse # 57 stone	1398	1445	1502	1197	1245	1293
Intermediate #89 stone	320	345	360	553	573	593
Natural sand	1165	1210	1260	1198	1248	1298
Design Air %	7	7	7	7	7	7
Water (lb/cy)	248.0	223.6	198.4	248.0	223.6	198.4
AEA (oz/cwt)	0.40	0.00	0.00	0.50	0.20	0.00
WRA (oz/cwt)	2.96	9.83	25.86	8.13	15.73	36.94
w/cm ratio	0.40	0.40	0.40	0.40	0.40	0.40
Sand ratio by volume	40.2%	40.2%	40.2%	40.8%	40.8%	40.8%

*Constituent quantities are provided in lb/ yd³



Figure 3-9 Drum mixer

For Class A concrete, in each batch six cylinders (4 in x 8 in) for compressive strength, three cylinders (4 in x 8 in) for surface resistivity, and three beams (3 in x 3 in x 11.25 in) for shrinkage were cast. An outline of the mixing procedure is as follows:

- The mortar was initially put on as a buttery coating to the concrete mixer. The butter mixtures were weighed out in proportion to the batch of concrete. This is done to make up for the mortar that is lost from sticking to the mixer's side. The aggregates were then added after starting the mixer.
- Then, all of the cementitious material was added after mixing the mixture with 75% of the entire amount of water for one minute with air entraining admixtures.
- The water-reducing additive was injected with the rest of the water into the concrete while it had been mixing for another three minutes. Then the mixer was turned off to scrape and the concrete was allowed to rest for three minutes. The mixer was then turned on and left running for an extra two minutes.
- The next step was to assess the concrete to see if it was adequate or if more water-reducing additive was required.

3.7 Fresh Concrete Property Testing

Slump, air content, SAM number, and unit weight were among the fresh concrete property tests conducted to ensure that each mixture met the requirements for satisfactory performance. The next sections provide a description of the steps and criteria that were followed to collect the outcomes of the fresh concrete tests.

3.7.1 Slump

According to ASTM C143, slump testing was performed on every batch of concrete. The required slump for Class A concrete was 3 ± 1 inch according to the TDOT specifications. It was a priority to maintain this value, however, the most important parameter was to maintain the w/cm ratio and workability. **Figure 3-10** shows the on-field slump testing for the fresh concrete.

3.7.2 Unit Weight

Unit weight was measured immediately after completing the mixing according to ASTM C138. The SAM bucket was used to determine the unit weight. The unit weight measurements in the laboratory were conducted using the super air meter bowl, as depicted in **Figure 3-11**.



Figure 3-10 Slump test



Figure 3-11 Unit weight measurement using super air meter bowl

3.7.3 Air Content

A modified Type B pressure meter named as super air meter was used for the air content testing in accordance with ASTM C231 (ASTM 2017). A smaller air content range was determined and implemented in order to ensure consistency between mixtures and to avoid performance changes due to large differences in entrained air content between mixtures. For Class A concrete according to TDOT specifications, air content needs to be within the 6 ± 2 % limit. **Figure 3-12** illustrates the air content testing process conducted utilizing the super air meter.

3.7.4 SAM Number

The Super Air Meter is also used to determine SAM number according to AASHTO T395. This air meter, a modified version of the conventional pressure technique, takes around 10 minutes to measure the bubble size and volume in wet concrete. This guarantees that mixed concrete has



Figure 3-12 Air content testing using the super air meter

more uniform air volume and is freeze-thaw resistant. The SAM test is carried out similarly to the ASTM C231 air content test using a Type B pressure meter. The test is managed by a program in the digital dial gauge positioned at the top of the device, and the SAM device can withstand higher pressures. After completing the test, SAM number result can be determined which suggests the distribution of air voids in the mix. The recommended SAM number value is less than 0.20, but any mix with a SAM number less than 0.30 is acceptable (Minnesota Department of Transportation, 2023). **Figure 3-13** displays the result of a SAM Number testing that was performed in the lab.

3.8 Curing Procedure

After demolding, all the cylinders and beams are placed into a curing tank where the temperature can be controlled according to the ASTM C511. In accordance with the testing standard, specimens were taken out of curing for testing at the proper age. **Figure 3-14** shows the curing



Figure 3-13 SAM number testing result for a mixture

tank that was used for curing.

3.9 Hardened Property Testing

3.9.1 Compressive Strength

Compressive strength tests were performed on 4-inch by 8-inch cylindrical specimens in accordance with ASTM C39 at 7 and 28 days. These tests are crucial for determining the concrete's ability to withstand loads and are a primary indicator of concrete quality. The TDOT specifications require a minimum compressive strength of 3000 psi for Class A concrete and 4000 psi for Class D/Ds concrete. **Figure 3-15** illustrates the compression testing process on a sample cylinder.

3.9.2 Modulus of Elasticity

The modulus of elasticity, a measure of concrete's stiffness, was determined following ASTM



Figure 3-14 Curing tank



Figure 3-15 Compressive strength test setup

C469 guidelines. This property is particularly important for structural applications as it affects the concrete's deformation under load. The same cylinders used for compressive strength testing were utilized for modulus of elasticity measurements, employing an extensometer to capture precise deformation data. **Figure 3-16** depicts the setup for modulus of elasticity testing.

3.9.3 Drying Shrinkage

Drying shrinkage was evaluated using the procedures outlined in ASTM C157. This test involved wet-curing samples in lime water for 7 days in a temperature-controlled environment, followed by periodic measurements using a length comparator at 28 days and 56 days. After the initial curing period, samples were transferred to an environmental chamber with controlled



Figure 3-16 Modulus of Elasticity test setup

conditions to simulate real-world exposure. **Figure 3-17** shows a shrinkage prism being measured in the comparator.

3.9.4 Surface Resistivity

The surface resistivity test, conducted in accordance with AASHTO T 358, provides a rapid assessment of concrete's resistance to chloride ion penetration. This non-destructive test is particularly relevant for evaluating the durability of concrete in environments exposed to deicing salts or marine conditions. A Resipod concrete resistivity meter, as shown in **Figure 3-18**, was used to perform these measurements.



Figure 3-17 Shrinkage beam placed into a comparator



Figure 3-18 Surface resistivity testing

CHAPTER 4

RESULTS AND DISCUSSIONS

This chapter presents results of the fresh, hardened and durability properties of optimized and non-optimized Class A & Class D/Ds concrete mixtures. The fresh properties examined included slump, unit weight, air content, and the SAM number. In addition to the fresh property assessments, a series of tests on hardened properties were performed. The hardened property tests included measurements of compressive strength, modulus of elasticity, drying shrinkage, and surface resistivity. Compressive strength tests were conducted at both 7 and 28 days, while the modulus of elasticity was measured at 28 days. Drying shrinkage assessments were carried out at 7, 28, and 56 days. For electrical resistivity, data were collected at 28, 56, and 90 days.

4.1 Aggregate Size and Shape Analysis

Six distinct coarse aggregates and two fine aggregates were examined to focus on two critical aspects of aggregate characterization: gradation through sieve analysis and particle morphology through shape analysis. These examinations provide essential insights into the physical properties and distribution characteristics of the selected aggregates, forming a fundamental basis for understanding their potential performance in concrete applications.

4.1.1 Sieve Analysis

A comprehensive gradation analysis was conducted on the aggregates following ASTM C 136 standards, utilizing the ASTM E11 sieve series. **Figure 4-1** shows the gradation curve of the six coarse aggregates used for the mixtures. The gradation curves reveal distinct characteristics among the aggregates, with GR1 exhibiting the coarsest gradation as evidenced by its rightmost position on the graph and its steeper curve starting at around 0.2 inches. In contrast, LS2 demonstrates the finest gradation among all aggregates, as shown by its leftmost position in the

particle size distribution, beginning at smaller sieve sizes. The remaining four aggregates (LS1, LS3, GV, and GR2) show remarkably similar gradation patterns, clustering together in the middle of the graph.

Figure 4-2 illustrates the comparison of particle size distribution between natural sand and manufactured sand as fine aggregates. The natural sand exhibits a steeper curve in the middle range, particularly between 0.02-inch and 0.04-inch sieve sizes, indicating a more uniform particle size distribution in this range. It shows a gradual S-shaped curve, with approximately 70% of particles passing through the 0.04-inch sieve. In contrast, the manufactured sand displays a more gradual, linear increase across most sieve sizes, suggesting a more even distribution of particle sizes. It shows a slightly higher percentage of finer particles below 0.02 inch compared to natural sand. In conclusion, both types of fine aggregates have distinct characteristics based on their particle size distributions, which will influence their performance in construction applications.

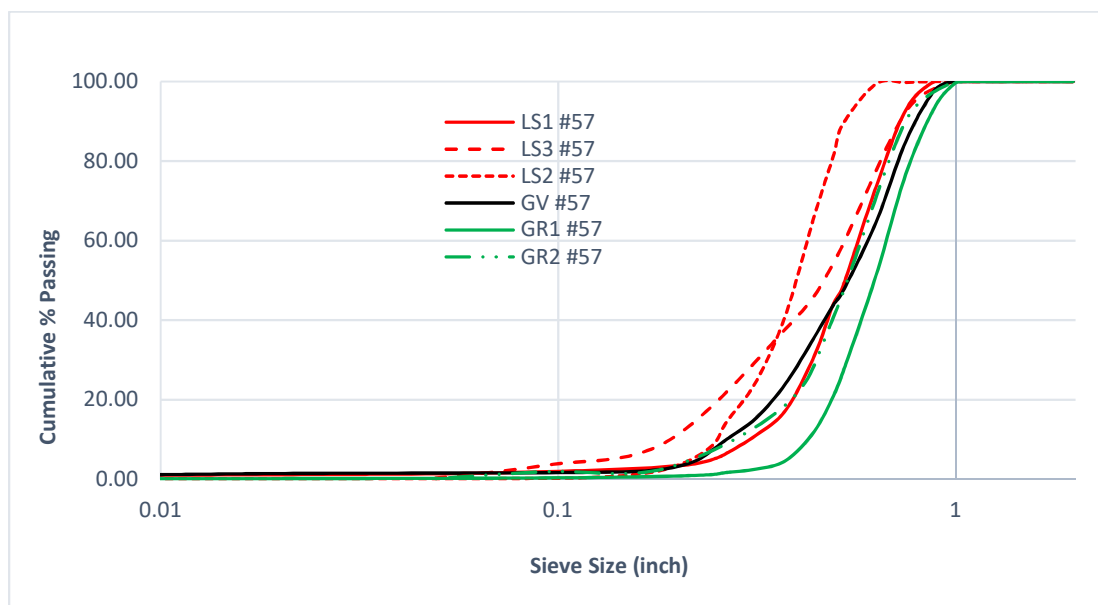


Figure 4-1 Gradation curve of coarse aggregates



Figure 4-2 Gradation curve of fine aggregates

4.1.2 Shape Analysis

The shape analysis results for different coarse aggregates, based on the flat and elongated particle percentages determined using ASTM D4791 (1:2 ratio), provide insight into the particle geometry of the aggregates. **Table 4-1** shows the flat and elongated particle percentages for the coarse aggregates. The flat and elongated particle percentages for the limestone aggregates (LS1, LS2, and LS3) are relatively similar, ranging from 11.50% to 12.67%. GR1 has a significantly higher percentage of flat and elongated particles (20.50%), which could negatively affect the workability of concrete mixtures, as such particles tend to align during compaction, leading to potential weaknesses in the structure (Polat et al., 2013). The gravel aggregate (GV1) has the lowest percentage of flat and elongated particles at 5.33%, suggesting that it has the most favorable shape characteristics among all the aggregates tested.

Table 4-1 Percentage of flat and elongated particles in coarse aggregates

Aggregate	Flat & Elongated (%)
LS1	12.33
LS2	11.50
LS3	12.67
GR1	20.50
GR2	10.00
GV1	5.33

4.2 Class A Optimized & Non-optimized Control Mixtures

A thorough evaluation was conducted on various concrete mixtures using a rheometer to analyze their fresh properties, such as slump, unit weight, air content, and SAM number. In addition, compressive strength tests were carried out at the 7-day to assess early strength development. The results of these assessments were analyzed to identify the most promising mixture designs for upscaling. The chosen mixtures were then produced on a larger scale with the use of a drum mixer, ensuring compliance with established standards for both fresh and hardened property testing. The fresh property tests included measurements of slump, unit weight, air content, and SAM number, while the hardened property tests covered compressive strength, modulus of elasticity, drying shrinkage, and surface resistivity.

4.2.1 Fresh Property Results

This section presents the outcomes of experimental evaluations conducted on fresh concrete for small scale and upscale mixtures. Key parameters including the SAM number, unit weight, slump, and air content were measured for Class A concrete mixtures. The results, summarized in **Table 4-2**, highlight the comparative performance of the small-scale mixtures, demonstrating variations in key properties between optimized mixtures.

Table 4-2 Fresh concrete properties of optimized mixtures for the small-scale mixtures

Mixture ID	Slump (inch)	Unit Weight (pcf)	Air Content (%)	SAM Number
A-LS1-MS-0	3.25	154.8	2.2	0.17
A-LS1-MS-10	4.00	146.6	2.6	N. Err
A-LS1-MS-20	4.00	144.0	5.9	N. Err
A-LS1-NS-0	3.50	144.8	6.3	0.26
A-LS1-NS-10	2.50	143.3	5.2	0.28
A-LS1-NS-20	4.50	145.2	7.2	0.36
A-LS2-MS-0	2.25	144.3	3.9	0.33
A-LS2-MS-10	3.00	149.3	5.4	0.14
A-LS2-MS-20	2.50	149.8	4.2	0.40
A-LS2-NS-0	3.00	146.5	4.1	0.54
A-LS2-NS-10	3.50	142.7	5.0	0.41
A-LS2-NS-20	6.50	145.1	7.3	0.27
A-LS3-MS-0	4.00	144.1	8.0	0.17
A-LS3-MS-10	3.00	143.9	7.8	0.19
A-LS3-MS- 20	7.00	144.7	4.2	0.49
A-LS3-NS-0	3.75	143.8	6.8	0.19
A-LS3-NS-10	3.50	140.5	6.8	0.30
A-LS3-NS-20	3.75	143.3	7.7	0.18

Table 4-3 presents a comprehensive summary of the results obtained from the upscaled mixtures, offering a clear comparison of their performance. The data reveals notable differences in critical properties between the optimized and non-optimized control mixture designs. These variations provide valuable insights into the effectiveness of the optimization process and its impact on concrete performance. A thorough analysis and interpretation of these findings will be presented in the subsequent sections of this report, allowing for a deeper understanding of these results.

4.2.1.1 Unit Weight

The average unit weight of non-optimized Class A concrete mixtures was determined to be 141.6 pcf. Following the optimization of aggregate gradation, the unit weight experienced a slight increase, averaging 141.8 pcf. Individual mixture values ranged from 135.4 to 149.8 pcf when scaled up and mixed using a drum mixture. The optimal aggregate gradation mixtures for initial batches mixed with the rheometer had an average of 144.8 pcf and a range of 140.5 to 154.8 pcf.

Figure 4-3 illustrates the variations in unit weight among the different upscaled mixtures.

Generally, non-optimized control mixtures exhibited lower unit weights compared to optimized mixtures. It was anticipated that optimization of aggregate packing density would lead to an increase in unit weight; however, some mixtures did not follow this trend. This anomaly is likely attributed to the higher air content observed in these mixtures, which offset the expected increase in unit weight.

4.2.1.2 Slump

According to TDOT specifications, the desired slump for mixtures in this research for Class A concrete is 3 ± 1 inches. **Figure 4-4** shows slump tests conducted in the lab for nonoptimized and optimized mixtures.

Table 4-3 Fresh concrete properties of optimized and nonoptimized mixtures

Mixture ID	Slump (inch)	Unit Weight (pcf)	Air Content (%)	SAM Number
A-LS1-MS-N	5.00	143.7	6.9	0.43
A-LS1-MS-0	3.75	149.8	5.9	0.09
A-LS1-MS-10	5.00	147.2	7.1	0.16
A-LS1-MS-20	3.50	146.1	7.9	0.14
A-LS2-NS-N	2.25	145.2	6.0	0.28
A-LS2-NS-0	3.50	143.4	7.0	0.24
A-LS2-NS-10	3.50	144.2	7.1	0.17
A-LS2-NS-20	2.50	143.9	6.7	0.27
A-GV1-MS-N	3.00	135.6	6.4	0.57
A-GV1-MS-0	2.25	137.4	6.7	0.44
A-GV1-MS-10	2.25	137.2	6.6	0.44
A-GV1-MS-20	3.00	137.2	7.9	0.24
A-GV1-NS-N	4.25	135.4	6.0	0.49
A-GV1-NS-0	2.75	136.2	5.6	0.43
A-GV1-NS-10	2.50	136.6	5.9	0.28
A-GV1-NS-20	3.25	139.0	8.0	0.12
A-GR1-MS-N	3.00	143.6	4.8	0.54
A-GR1-MS-0	3.75	144.1	7.9	0.23
A-GR1-MS-10	3.00	143.2	8.0	0.11
A-GR1-MS-20	3.50	142.4	8.1	0.09
A-GR1-NS-N	2.25	145.3	4.8	0.42
A-GR1-NS-0	2.50	145.3	5.2	0.44
A-GR1-NS-10	2.25	142.4	7.4	0.16
A-GR1-NS-20	4.00	140.6	8.0	0.19
A-GR2-MS-N	3.00	142.6	7.0	0.22
A-GR2-MS-0	3.50	141.6	7.5	0.19
A-GR2-MS-10	2.75	142.2	7.9	0.11
A-GR2-MS-20	4.00	141.0	8.5	0.19
A-GR2-NS-N	3.00	141.2	5.3	0.33
A-GR2-NS-0	3.25	143.0	5.6	0.26
A-GR2-NS-10	2.75	142.0	6.1	0.31
A-GR2-NS-20	3.50	140.8	8.1	0.13

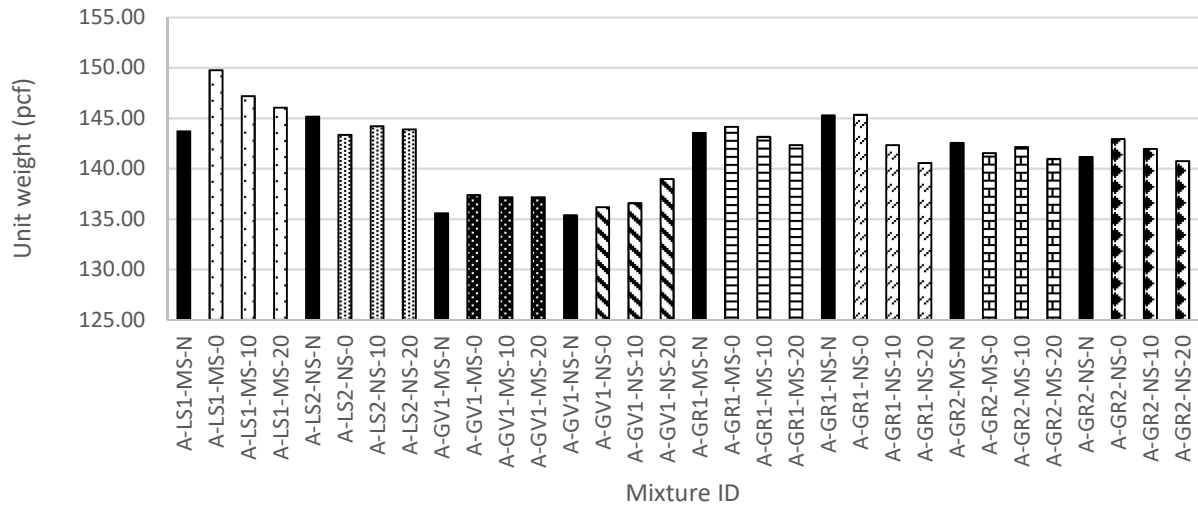


Figure 4-3 Unit weight of Class A mixture

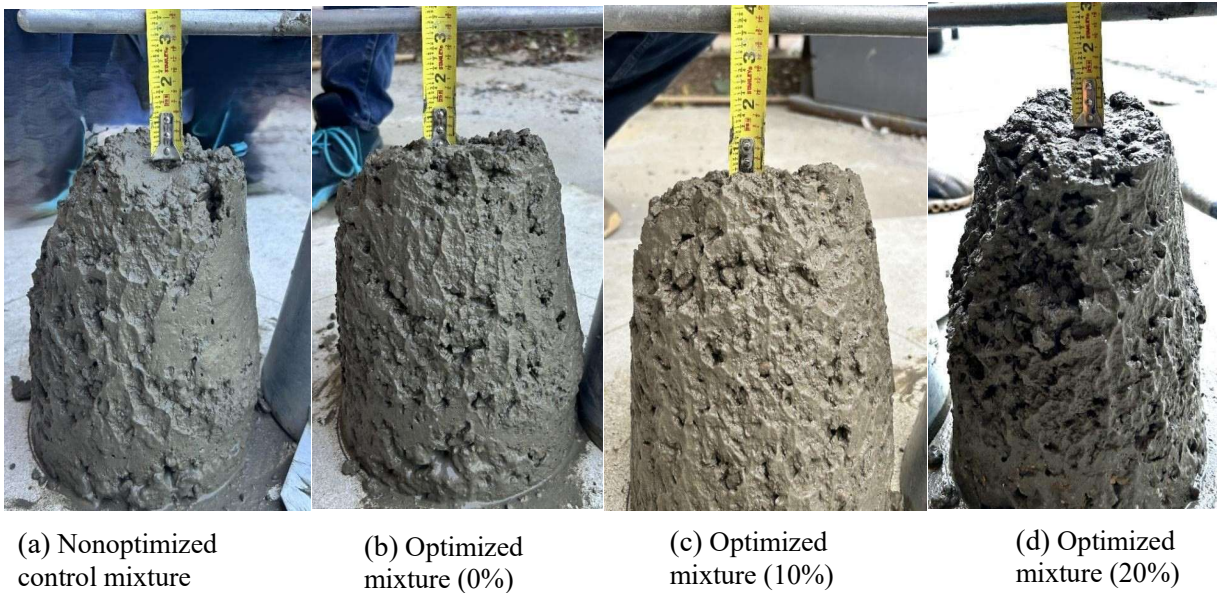


Figure 4-4 Slump test for nonoptimized and optimized mixtures

Figure 4-5 illustrates the slump variations observed in initial batches of optimized mixtures using different aggregates, all maintained within specified slump limits. Adjustments in WRA were crucial in achieving the desired slump consistency. It was seen that, as paste content decreased, there was a significant increase in the demand for WRA. When the paste content is reduced, the concrete mixture becomes stiffer and less workable. To maintain the desired level of workability and consistency, more WRA is required (Lamond and Pielert, 2006). To maintain the target slump, mixtures with a 20% reduction in cementitious content required remarkably higher WRA dosages compared to mixtures with no reduction. Mixtures with no cementitious content reduction maintained the required slump without additional admixtures to reduce water content. In other cases, WRAs were added at rates ranging from 0.80 to 20.25 oz/cwt. Some of the mixtures with 20% cementitious content reduction exceeded the manufacturer recommendation (3 to 15 oz/cwt). In the experimental design, a key priority was to ensure that all concrete mixtures exhibited a comparable slump range. By maintaining consistency in slump

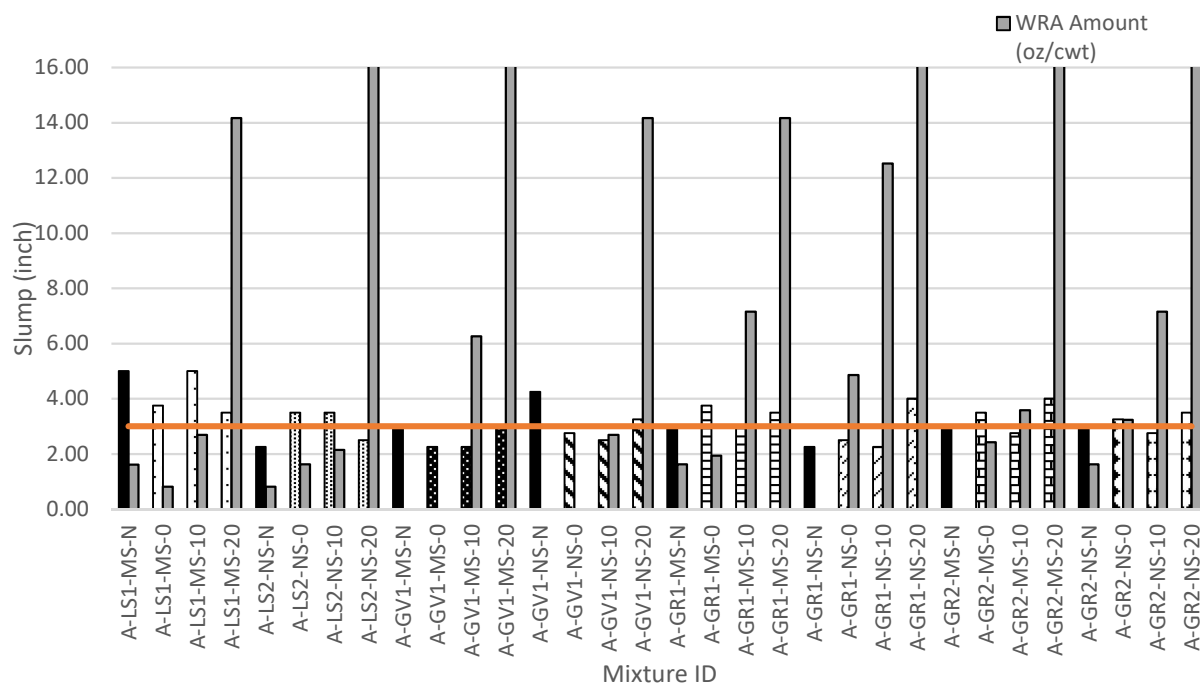


Figure 4-5 Slump of Class A mixtures

values across all mixtures, the researchers aimed to eliminate this variable as a potential confounding factor, thereby enhancing the reliability and significance of the comparative analysis. Comparing optimized mixtures with no reduction in cementitious content to nonoptimized mixtures, it was observed that optimized mixtures required additional WRA dosage to achieve the same slump as their non-optimized counterparts. This outcome was anticipated due to the improved packing of the optimized mixtures. It is noteworthy that mixtures with a slump below 3 inches were deemed acceptable only if proper consolidation into specimen molds could be effectively achieved.

4.2.1.3 Air Content

The mixtures subjected to batch testing for this research consistently exhibited an air content within the range of 6.0 ± 2.0 percent, aligning with the specifications mandated by TDOT. This adherence proved crucial in minimizing potential fluctuations in test results that could arise from significant variations in air content.

To maintain the desired air content within the concrete mixture, an AEA was introduced. The dosage of AEA ranged from 0.40 to 0.75 oz/cwt for both optimized and non-optimized aggregate gradation mixtures which is also within the manufacturer's recommendation (0.125 to 1.5 oz/cwt). The air content was observed to be higher in the optimized mixtures compared to the non-optimized control mixtures with no reduction in cementitious content when the same amount of AEA was used. While optimized mixtures generally reduce overall void space, they can create more uniformly distributed small voids that are ideal for air entrainment. These voids act as nucleation sites for air bubbles, potentially increasing the effectiveness of the AEA (Marczewska & Piasta, 2018). **Figure 4-6** illustrates the air content results for the small-scale optimized mixtures.

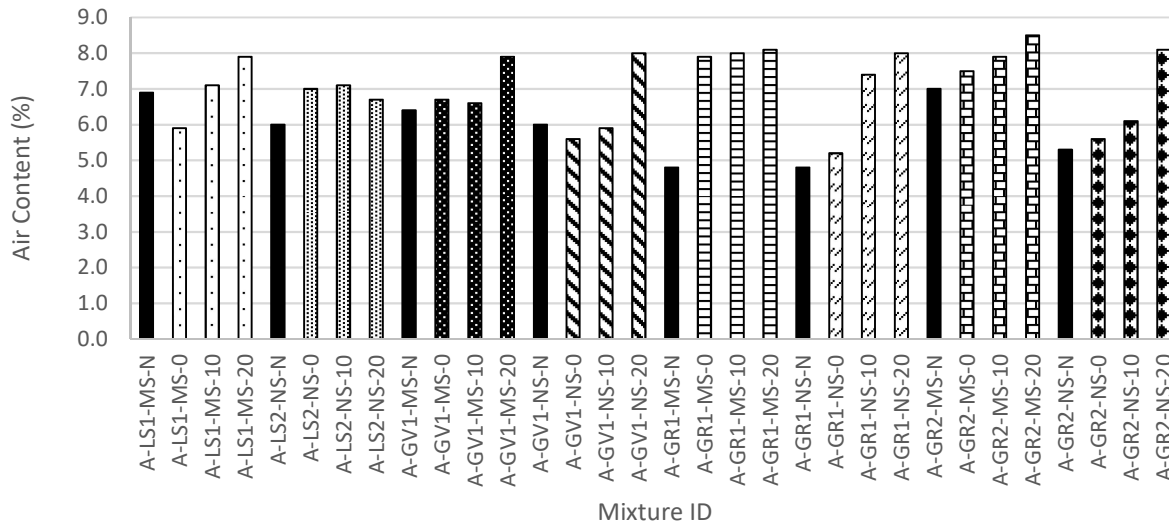


Figure 4-6 Air content of Class A mixtures

4.2.1.4 SAM Number

In accordance with the specifications outlined in AASHTO T 395 for gradation mixtures, SAM numbers have been calculated for all optimal aggregate mixtures. Guidelines state that the recommended SAM number should preferably be less than 0.20, but any mixture that is less than 0.30 is considered acceptable.

In **Figure 4-7**, the SAM number results for the Class A mixtures are presented. The non-optimized control mixtures exhibited higher SAM numbers compared to the optimized mixtures. It was observed that the majority of non-optimized control mixtures surpassed the acceptable limit of 0.30 SAM, indicating inferior workability and potential durability concerns. However, following optimization procedures, these mixtures demonstrated a significant decrease in SAM numbers, effectively falling within the 0.30 threshold. Optimized mixtures typically have better aggregate gradation and packing, which leads to a more uniform distribution of air voids throughout the concrete matrix. This improved packing can result in a more stable and effective air void system, leading to lower SAM numbers (Smith et al., 2024). The observed trend towards

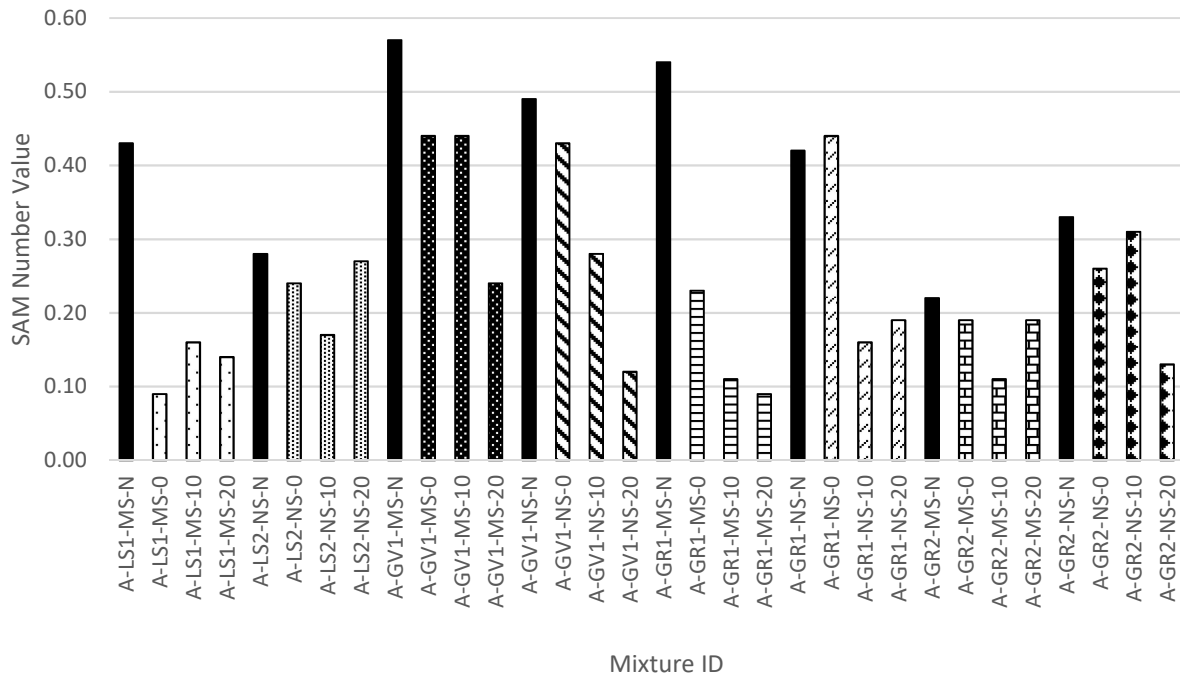


Figure 4-7 SAM number results for Class A mixtures

lower SAM numbers in optimized mixtures is indicative of enhanced freeze-thaw durability. By achieving more efficient particle packing through optimization, the mixtures demonstrate improved resistance to freeze-thaw cycles.

4.2.2 Effect of Fine Aggregates on Fresh Properties

Figure 4-8 displays the unit weight (in pcf) of Class A concrete mixtures using manufactured sand and natural sand across various mixture IDs. Based on the data extracted from the figure, the average unit weight for manufactured sand is approximately 140.6 pcf, while for natural sand, it is around 140.6 pcf. This highlights no significant difference between the two types of sand. However, nine out of twelve mixtures incorporating manufactured sand demonstrated slightly higher unit weights (about 0.15% to 1.28%) than those with natural sand, attributable to the higher specific gravity of manufactured sand. These variations in unit weight are typical when mixture proportions are varied.

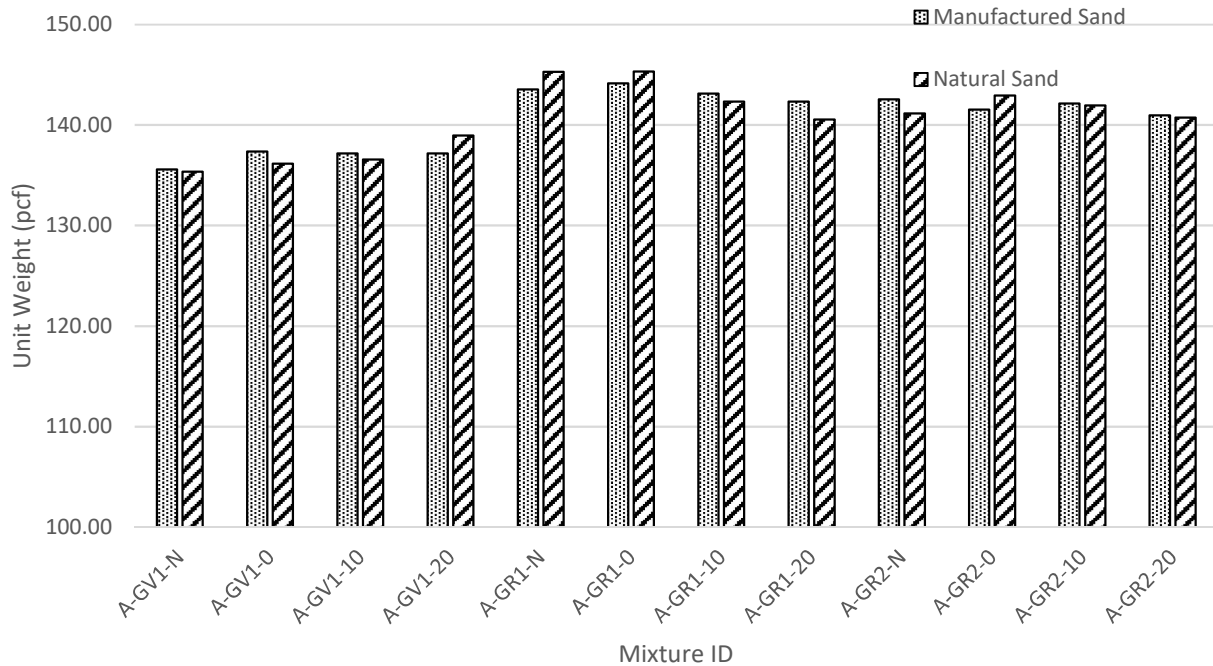


Figure 4-8 Effect of different fine aggregates on unit weight

Figure 4-9 presents a comprehensive analysis of SAM Number results comparing manufactured sand and natural sand in Class A concrete mixtures across various optimized and non-optimized mixture designs. The relationship between manufactured and natural sand demonstrates significant variability across different mixture designs. While manufactured sand performs better with gravel aggregates, natural sand shows superior performance with granite aggregates. This variation suggests that the interaction between sand type and coarse aggregate plays a crucial role in determining the air void characteristics of the concrete mixture. The results indicate that the choice between manufactured and natural sand should be carefully considered based on the specific mixture design and aggregate type being used, rather than assuming one type's superiority over the other. This understanding is crucial for optimizing concrete mixtures for specific applications and achieving desired air void characteristic

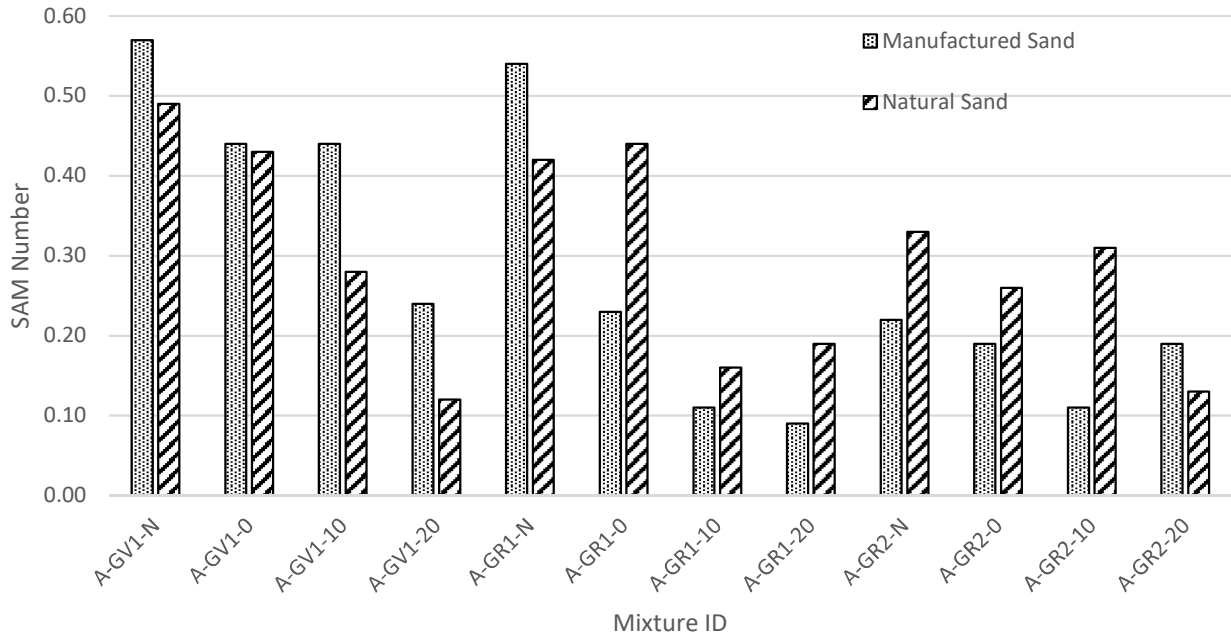


Figure 4-9 Effect of different fine aggregates on SAM number

4.2.3 Hardened Property Testing

This section presents the findings from hardened property tests conducted on both optimized and nonoptimized aggregate gradation mixtures. The assessment of hardened properties encompasses evaluations of 7 and 28-day compressive strength, modulus of elasticity, drying shrinkage, and electrical resistivity for the optimized mixture following scaling up.

4.2.3.1 Compressive Strength

As per TDOT specifications, Class A concrete is mandated to possess a minimum compressive strength of 3000 psi at the end of 28 days. To assess the early-age strength development, compressive strength testing was conducted on three cylindrical specimens from each mixture at the 7-day mark.

Figure 4-10 illustrates the 28-day compressive strength results obtained from upscaled Class A concrete mixtures. Notably, all the mixtures but one mixture exhibited strengths exceeding the

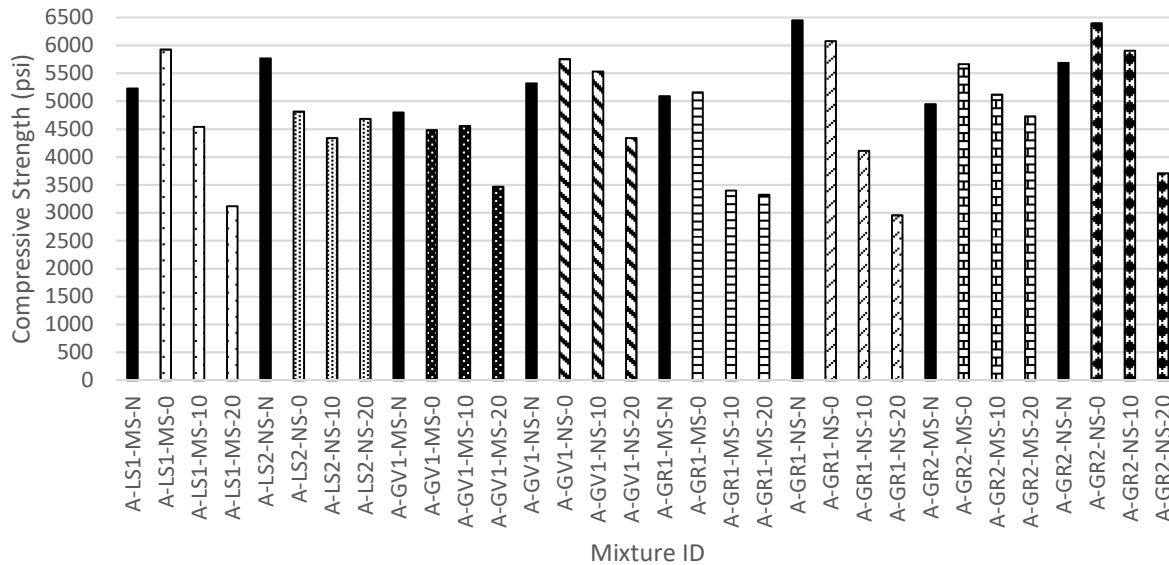


Figure 4-10 28 days compressive strength of Class A mixtures

critical threshold of 3000 psi, with an average strength of 4855.1 psi observed for the optimized mixtures. Comparatively, when considering both optimized and non-optimized control mixtures with the same cement content, the optimized mixtures generally demonstrated slightly superior strength characteristics. The Federal Highway Administration's technical brief supports this concept, stating that "Well-graded aggregates are thought to be packed more densely in a mixture, leaving less void space that must be filled by paste" (Taylor & Sadati, 2021). This denser packing may contribute to improved strength characteristics. As anticipated, reducing cementitious content correlated with decreased compressive strength. Cement paste is the primary source of strength in concrete. When cementitious content is reduced, there are fewer hydration products formed, which can lead to lower strength. Also as paste content decreases, the relative proportion of aggregates increases. This can lead to more interfacial transition zones (ITZs) between paste and aggregates, which are typically weaker than the bulk paste (Kolias & Georgiou, 2005).

Figure 4-11 illustrates the compressive strength results obtained at both 7 days and 28 days for

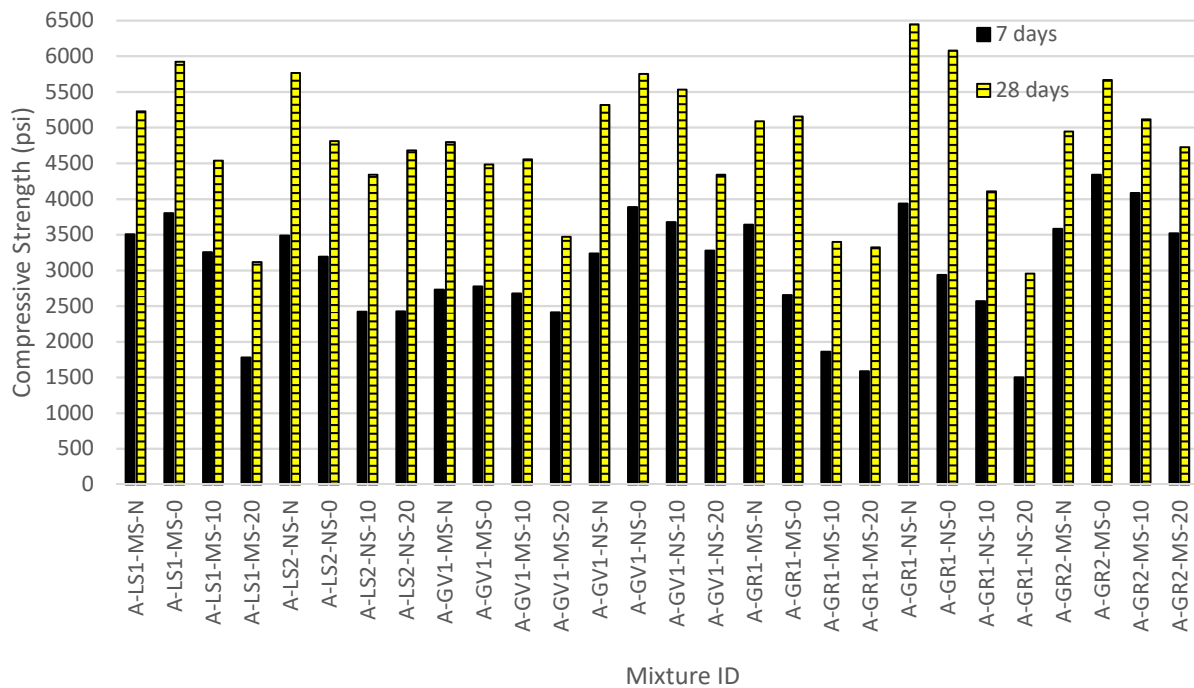


Figure 4-11 7 days and 28 days compressive strength results

the optimized and nonoptimized concrete mixtures following scale-up. The compressive strength results obtained at both 7 days and 28 days for the optimized and non-optimized concrete mixtures following scale-up showed a substantial enhancement in compressive strength, ranging between 30% to 45% from the initial 7-day assessment to the subsequent 28-day evaluation. This significant strength gain is expected in concrete due to continuous curing and ongoing hydration. However, it's important to address the influence of fly ash on strength development, particularly when using Class F fly ash. Class F fly ash typically leads to lower early strength due to its pozzolanic reactivity nature (Lebow, 2018). This is because Class F fly ash is not self-cementing and requires calcium hydroxide from cement hydration to form strength-contributing compounds (Van Dam, 2019). As a result, concrete mixtures containing Class F fly ash often exhibit slower strength gain in the early stages compared to mixtures without fly ash. It's worth noting that while early strength (7-day) might have been lower in fly ash mixtures compared to non-fly ash

mixtures, the substantial strength gain by 28 days suggests that the pozzolanic reaction of fly ash contributed significantly to later-age strength development. This aligns with literature findings that fly ash concrete often achieves comparable or higher ultimate strengths compared to conventional concrete, despite potentially lower early-age strengths.

4.2.3.1.1 Effect of Different Fine Aggregates on Compressive Strength

The influence of fine aggregates on the properties of optimized mixtures, particularly in terms of 28-day compressive strength for upscaled batches, is illustrated in **Figure 4-12**. In this study, both manufactured sand and natural sand were employed as fine aggregates in conjunction with different coarse aggregates to assess their impact on the properties of the optimized mixtures. The results underscore a notable disparity in strength characteristics between natural sand and manufactured sand, with natural sand demonstrating superior performance.

The findings emphasize the critical role of fine aggregate selection in shaping the properties of mixtures containing limestone. Moreover, natural sand exhibited finer characteristics compared to manufactured sand, which facilitated better particle packing within the mixtures. This finer particle size distribution is known to enhance the overall mechanical properties of concrete mixtures. The enhanced performance of natural sand can be primarily attributed to its particle shape, gradation, and inherent characteristics, all of which contribute significantly to improved bond formation and interlocking within the concrete matrix.

4.2.3.1.2 Effect of Different Coarse Aggregates on Compressive Strength

Three limestone, two granite, and one Gravel samples were collected from different regions. The evaluation of compressive strength followed ASTM standards at a 28-day curing period. **Figure 4-13** presents a comparative analysis of the influence of various coarse aggregates on the compressive strength of both optimized and nonoptimized mixtures. The shape of coarse

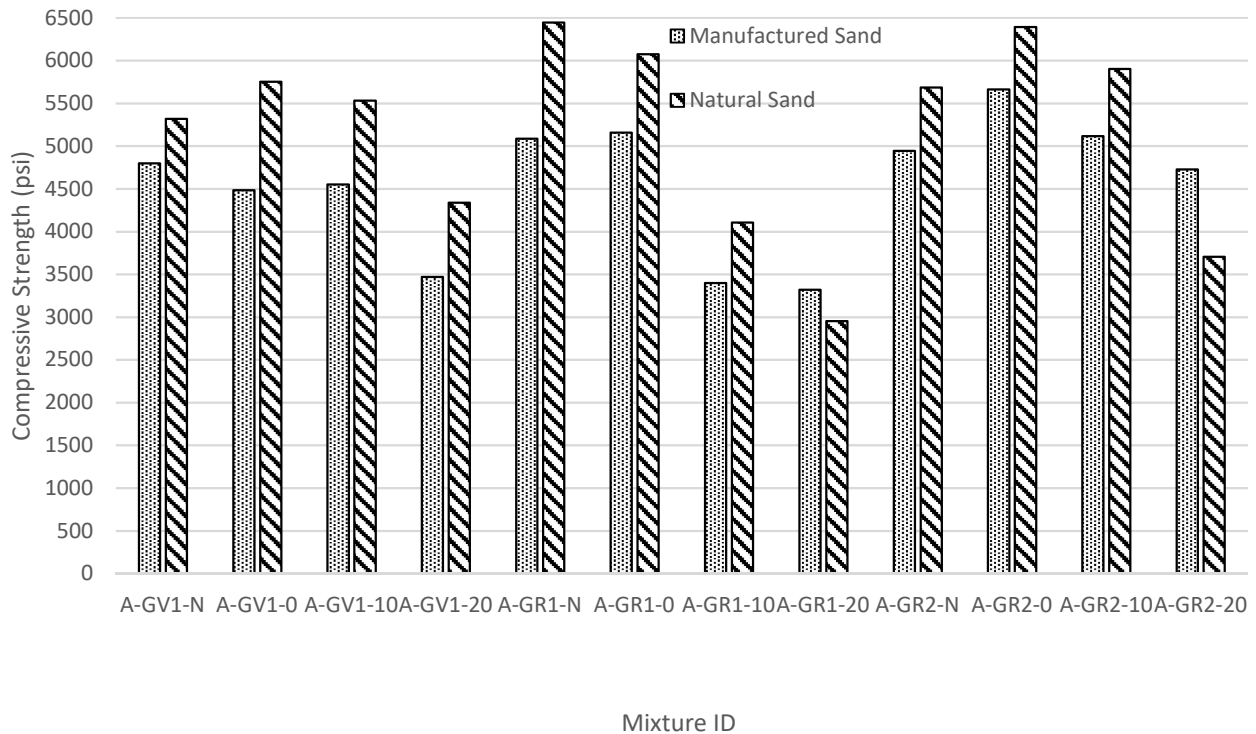


Figure 4-12 Effect of different fine aggregates on compressive strength

aggregates plays a crucial role in determining the mechanical properties of concrete. Flat and elongated particles are considered less desirable for concrete strength. Flaky, elongated, angular, and rough particles create more voids and require more sand to fill voids and provide workable concrete, thus increasing the water demand. In this study, Gravel 1 and Granite 2 exhibited the most favorable shape characteristics among all tested aggregates, with the lowest number of flat and elongated particles. This optimal shape contributes to improved packing density, reduced void content, and enhanced interlocking between aggregate particles, resulting in superior strength performance. Conversely, Granite 1 displayed the lowest compressive strength among all tested aggregates at 10% and 20% paste reduction. This suboptimal performance can be primarily attributed to the higher proportion of flat and elongated particles present in Granite 1 compared to the other aggregates. The presence of such particles can negatively impact the

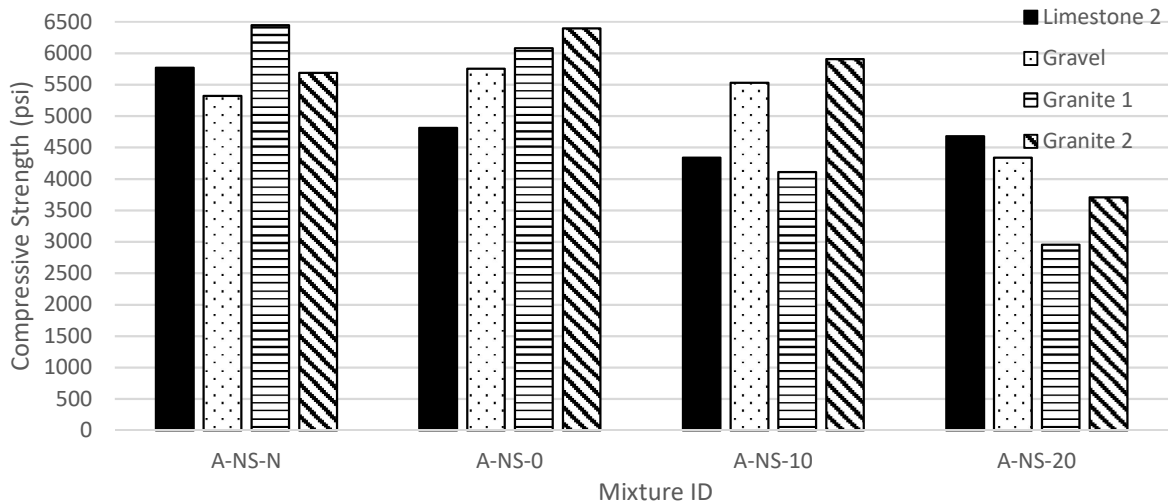


Figure 4-13 Effect of different coarse aggregates on compressive strength

concrete's workability, compaction, and overall strength development. Flat and elongated particles tend to create weak zones within the concrete matrix, leading to stress concentrations and potential failure points under load (Polat et al., 2013).

4.2.3.2 Modulus of Elasticity

Figure 4-14 shows the results of the Modulus of Elasticity (MOE) for different Class A concrete mixtures at 28 days, conducted according to ASTM C469 standard.

In evaluating the stiffness and deformation resistance of concrete mixtures, MOE is a critical parameter. Our comprehensive analysis indicates a significant correlation between the cementitious content and MOE of the concrete mixtures. Specifically, a reduction in the cement paste content is associated with a corresponding decrease in the MOE. Cement paste is a key component in determining concrete's elastic properties. Reducing cementitious content typically results in less paste volume, which can lead to a lower MOE (Alves & Otani, 2022). The paste forms the bond between aggregates, and its reduction can weaken the ITZ, which is the weakest link in concrete. This results in increased microcracking and lower overall stiffness (Mehta & Monteiro, 2014). Additionally, most of the non-optimized control mixtures exhibited lower MOE

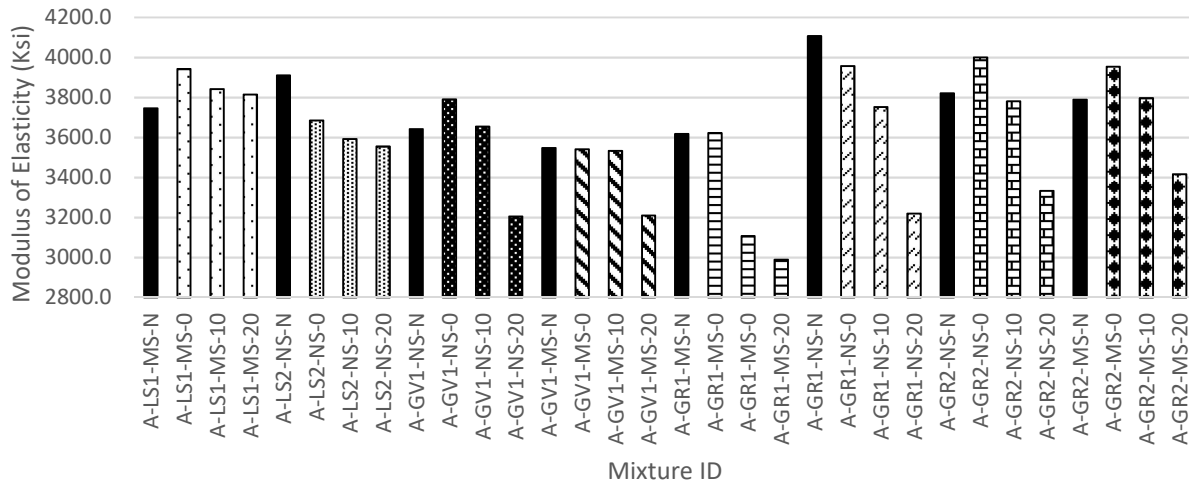


Figure 4-14 MOE results for Class A mixtures

values compared to the optimized mixtures that had similar cementitious content. The optimized mixtures are designed to achieve a more homogeneous and densely packed microstructure, which contributes to higher MOE values(Alves & Otani, 2022).

4.2.3.3 Drying Shrinkage

The Drying Shrinkage testing was carried out in compliance with ASTM C157 guidelines.

Specimens were moist cured for 7 days in a curing tank and then put in controlled temperature storage for drying and later tested at 28 days and 56 days. **Figure 4-15** presents the drying shrinkage results observed at 28 days for both optimized and non-optimized control mixtures of aggregate gradation. Remarkably, all optimized aggregate gradation mixtures met the stringent AASHTO R 101 requirement of 420 microstrains during the 28-day test phase.

These results offer important insights into the drying shrinkage properties of the materials under test across various time intervals. Non-optimized control mixtures exhibited lower shrinkage compared to the optimized mixtures despite containing the same cement content. This can be due to the replacement of coarse aggregate with intermediate aggregates as coarser aggregates give more restraint, thus less shrinkage. Aggregates provide restraint because they do not undergo

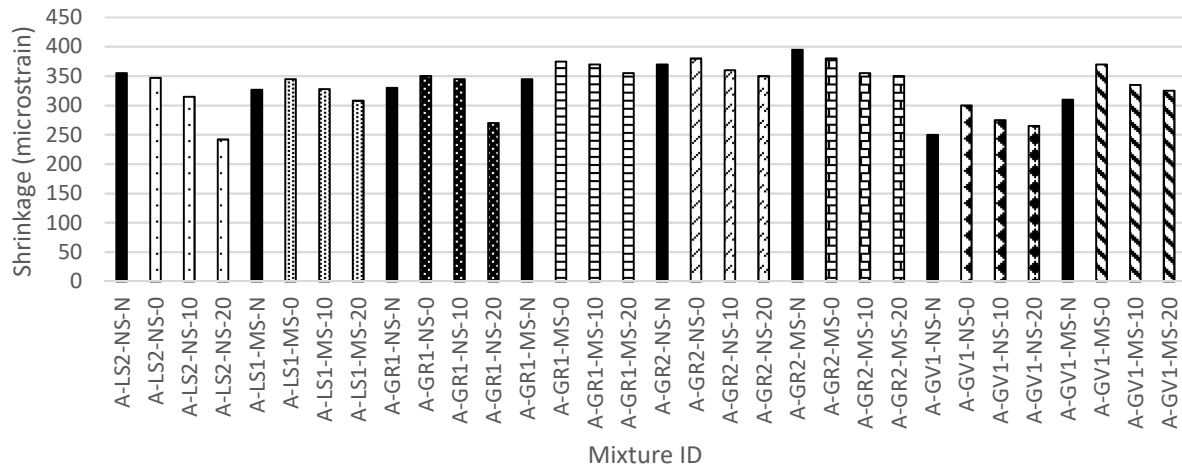


Figure 4-15 Drying shrinkage results at 28 days

volume changes due to changing moisture conditions. In general, shrinkage is reduced when concrete contains a coarse aggregate volume as high as is practical (Simonton & Shearer, 2021). Furthermore, both optimized and non-optimized control mixtures demonstrated reduced shrinkage tendencies with decreasing cementitious material content. This trend aligns with expectations, as cement content predominantly influences shrinkage characteristics in concrete (Nmai et al., 2018). These findings provide significant insights into the drying shrinkage behavior of the tested materials over varying timeframes. **Figure 4-16** presents the drying shrinkage results observed at 28 days and 56 days for both optimized and non-optimized control mixtures.

4.2.3.4 Electrical Resistivity

Electrical resistivity measures a material's ability to resist electric current. In concrete, its purpose is to provide precise data regarding the specimen's permeability. This provides information about the concrete's ability to resist chloride penetration. Lack of penetration resistance could lead to severe damage from natural occurrences, such as weathering and freeze-thaw. The electrical resistivity of the concrete was measured by using a Wenner probe, or

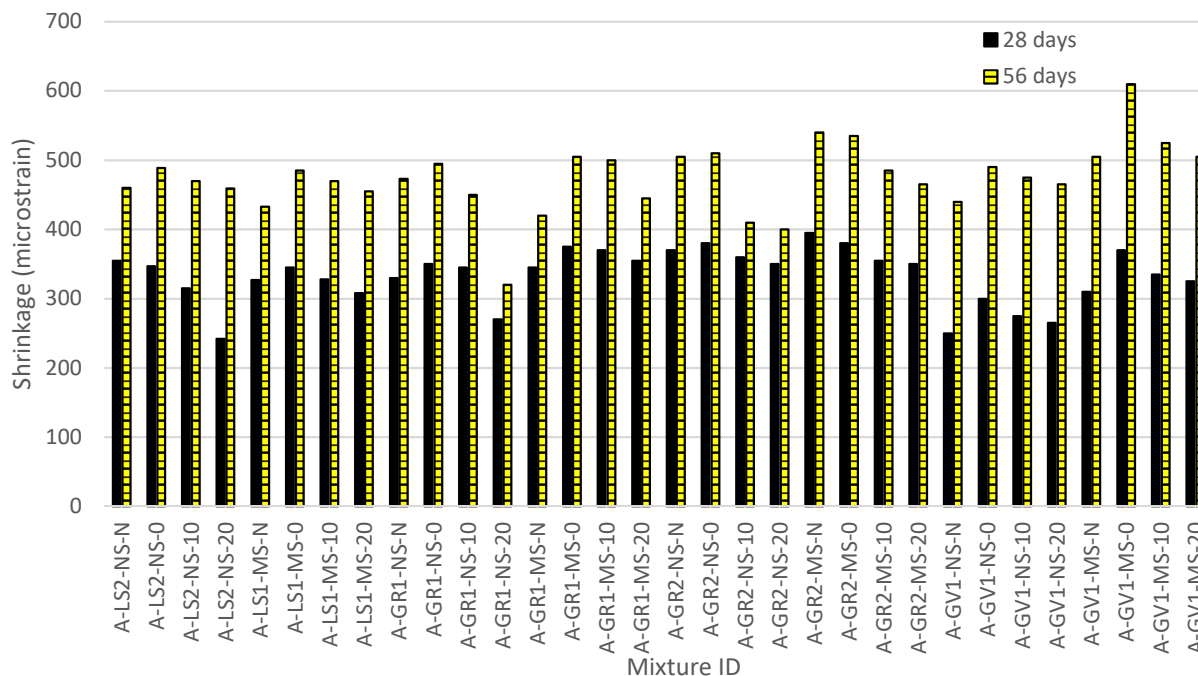


Figure 4-16 Drying shrinkage results at 28 days, and 56 days

probing instrument operating under a similar principle. A current is applied by the outer probes, and the inner probes measures the ions flowing through the liquid in the pores. For this reason, it is recommended to test the specimens while moist.

The probes uses the ions to measure the resistance ($K\Omega$) with respect to probe spacing (cm.). The surface resistivity was determined following AASHTO T 358. As the surface resistivity increased, the chloride ion penetration decreased. Resistance values below 12 $K\Omega$ -cm were considered high in terms of ion penetration. Values between 12 and 21 were considered moderate, values between 21 and 37 were classified as low, and values between 37 and 254 were classified as very low.

While initial measured value was important for data interpretation, it was also important to correct this data in regard to cylindrical specimen geometry. This was because surface resistivity was a function of probe spacing and specimen size, which became less reliable for smaller specimens. This correction was especially important for estimating service life. The average

resistivity values for data interpretation, and for service life estimations for Class A mixtures were displayed in **Table 4-4**. Note that all data had been given the recommended 10% increase according to AASHTO for samples cured in lime water.

At 28 days, all specimens had high, moderate, or low average resistance values. The high penetration tier was only averaged by the A-LS2-NS-10 and A-GR1-NS-20 specimens. At 56 days, all specimens had a low or very low penetration except for A-GR1-NS-20, which had moderate penetration. At 90 days, all specimens, except for A-GR1-NS-20, had low or very low average values, with most reaching very low values. This pattern of high/moderate to low to very low was expected; as the concrete gets more time to cure, it continues to harden and achieves greater strength and durability. The surface resistivity nearly doubled on average from day 28 to day 56, whereas compressive strength typically doesn't change that drastically in that timeframe.

Fly ash presence is a significant contributor to surface resistivity (Ghosh & Tran, 2015). Fly ash does consist of chloride ions, but its significance is more so attributed to its ability to decrease the porosity of a mixture. With its fineness, it is able to fill pores and reduce the ability of substances to penetrate the hardened composite. This does not correlate with the overall compressive strength, however, the general correlation seemed stronger in comparison to air content: the lower the air content, the higher the resistivity. This is due to air content and its relation to overall voids in the concrete.

Regarding the effect of the cement reduction on resistivity, it did not seem to strongly affect the resistivity outcomes. While some mixtures had better performance at certain stages, the general trend seemed to be moderate/low to low to very low regardless of the cement reduction. The collected values of the mixtures with comparable materials are displayed in **Table 4-5**, as well as the 28-day comparable mixtures in **Figure 4-17**. The values of mixtures

Table 4-4 Class A surface resistivity results

Mix ID	Corrected Apparent Surface Resistivity (K Ω -cm)			Service Life Surface Resistivity (K Ω -cm)		
	28 Day	56 Day	90 Day	28 Day	56 Day	90 Day
A-LS1-MS-N	14.43	26.09	36.00	7.52	13.59	18.75
A-LS1-MS-0	18.65	45.03	61.27	9.72	23.45	31.91
A-LS1-MS-10	18.49	36.81	53.00	9.63	19.17	27.60
A-LS1-MS-20	12.23	21.63	29.05	6.37	11.26	15.13
A-LS2-NS-N	14.28	27.18	40.95	7.44	14.16	21.33
A-LS2-NS-0	14.28	32.32	51.05	7.44	16.83	26.59
A-LS2-NS-10	11.90	31.99	30.95	6.20	16.66	16.12
A-LS2-NS-20	19.30	37.86	45.54	10.05	19.72	23.72
A-GR1-NS-N	21.44	43.13	55.47	11.16	22.47	28.89
A-GR1-NS-0	13.68	28.98	44.39	7.13	15.09	23.12
A-GR1-NS-10	13.25	30.88	49.06	6.90	16.08	25.55
A-GR1-NS-20	7.38	19.26	23.42	3.84	10.03	12.20
A-GR1-MS-N	23.29	39.72	64.95	12.13	20.69	33.83
A-GR1-MS-0	25.65	34.98	53.18	13.36	18.22	27.70
A-GR1-MS-10	22.34	39.52	51.02	11.64	20.58	26.57
A-GR1-MS-20	23.97	34.32	54.13	12.48	17.88	28.19
A-GV1-NS-N	20.47	36.39	52.80	10.66	18.95	27.50
A-GV1-NS-0	19.63	35.32	46.98	10.22	18.40	24.47
A-GV1-NS-10	24.11	33.76	47.27	12.56	17.58	24.62
A-GV1-NS-20	24.51	36.21	47.64	12.76	18.86	24.81
A-GV1-MS-N	20.32	30.55	35.86	10.58	15.91	18.68
A-GV1-MS-0	21.02	28.70	33.28	10.95	14.95	17.34
A-GV1-MS-10	21.35	32.64	37.91	11.12	17.00	19.75
A-GV1-MS-20	19.97	29.13	36.33	10.40	15.17	18.92
A-GR2-NS-N	23.05	42.13	53.79	12.01	21.94	28.01
A-GR2-NS-0	20.24	39.50	54.84	10.54	20.57	28.56
A-GR2-NS-10	20.45	47.92	52.07	10.65	24.96	27.12
A-GR2-NS-20	18.55	49.06	41.62	9.66	25.55	21.68
A-GR2-MS-N	21.33	43.14	52.14	11.11	22.47	27.16
A-GR2-MS-0	21.65	42.71	47.19	11.28	22.24	24.58
A-GR2-MS-10	18.18	39.72	46.28	9.47	20.69	24.11
A-GR2-MS-20	20.82	41.40	49.19	10.84	21.56	25.62

Table 4-5 Class A surface resistivity results of comparable mixtures

A (Control Mixtures)	Corrected Apparent Surface Resistivity (KΩ- cm)		
Mix ID	28 Day	56 Day	90 Day
A-GR1- NS-N	21.44	43.13	55.47
A-GR1- MS-N	23.29	39.72	64.95
A-GV1- NS-N	20.47	36.39	52.8
A-GV1- MS-N	20.32	30.55	35.86
A-GR2- NS-N	23.05	42.13	53.79
A-GR2- MS-N	21.33	43.14	52.14

B (0% Reduction)	Corrected Apparent Surface Resistivity (KΩ- cm)		
Mix ID	28 Day	56 Day	90 Day
A-GR1- NS-0	13.68	28.98	40.36
A-GR1- MS-0	25.65	34.98	53.18
A-GV1- NS-0	19.63	35.32	46.98
A-GV1- MS-0	21.02	28.7	33.28
A-GR2- NS-0	20.24	39.5	54.84
A-GR2- MS-0	21.65	42.71	47.19

C (10 % Reduction)	Corrected Apparent Surface Resistivity (KΩ- cm)		
Mix ID	28 Day	56 Day	90 Day
A-GR1- NS-10	13.25	30.88	49.06
A-GV1- NS-10	24.11	33.76	47.27
A-GV1- MS-10	21.35	32.64	37.91
A-GR1- MS-10	22.34	39.52	51.02
A-GR2- NS-10	20.45	47.92	52.07
A-GR2- MS-10	18.18	39.72	46.28

D (20% Reduction)	Corrected Apparent Surface Resistivity (KΩ- cm)		
Mix ID	28 Day	56 Day	90 Day
A-GR1- NS-20	7.38	19.26	23.42
A-GR1- MS-20	23.97	34.32	54.13
A-GV1- NS-20	24.51	36.21	47.64
A-GV1- MS-20	19.97	29.13	36.33
A-GR2- NS-20	18.55	49.06	41.62
A-GR2- MS-20	20.82	41.4	49.19

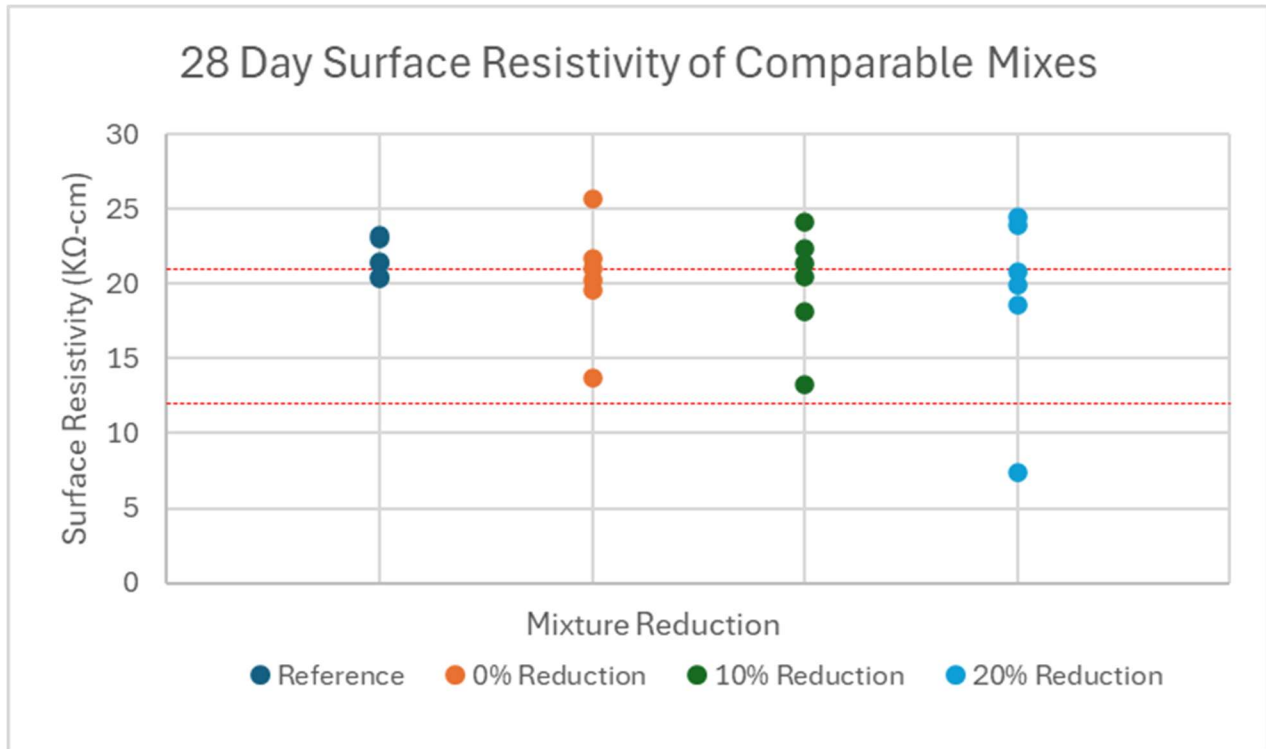


Figure 4-17 Surface resistivity of comparable Class A mixtures

with comparable materials are even closer at 56-days, with average resistivity values of 40.75, 40.75, 40.67, and 38.81 KΩ-cm for reference mixtures, 0% reduction, 10% reduction, and 20% reduction respectively. Despite the reduction of cement, this did not seem to drastically affect the presence of voids. The mixtures were designed to have nearly the same air content, which contributes to the standardization of the voids. Intermediate aggregate usage may have played a factor, as well, by providing an extra layer of gradation. Any variations of resistivity values within specimens of the same materials could be attributed to the air content variations or the quality of mixing/consolidating. There can also be significant changes on day 90, due to the long-term effects of the fly ash (Ghosh & Tran, 2015). However, the changes from 28 to 56 were larger on average in this testing procedure. The average increase from 28 to 56 days was 16.49 KΩ-cm while being a lower 10.65 KΩ-cm in the longer timeframe.

4.3 Class D/Ds Optimized and Non-optimized Control Mixtures

A comprehensive evaluation of various Class D/Ds concrete mixtures was conducted to assess their fresh, hardened and durability properties. The assessment of fresh properties encompassed slump, unit weight, air content, and SAM number, offering insights into workability, density, freeze-thaw resistance, and potential durability. Hardened property tests were performed at multiple time intervals to track the concrete's performance over time. Early strength development was evaluated through 7-day compressive strength tests, while long-term strength and elasticity were assessed via 28-day compressive strength tests and modulus of elasticity measurements. Dimensional stability was examined through drying shrinkage tests at 28 and 56 days, providing information for predicting potential cracking and long-term performance. Additionally, surface resistivity measurements were taken at 28, 56, and 90 days as an indicator of permeability and resistance to chloride ion penetration, offering insights into long-term durability.

4.3.1 Fresh Property Results

The experimental results for fresh concrete properties of Class D/Ds mixtures are presented in this section. The evaluation focused on critical parameters that influence the workability and consistency of the concrete. These parameters include the SAM number, unit weight, slump, and air content. **Table 4-6** provides a comprehensive summary of these results, offering a comparative analysis of the performance of optimized and non-optimized control mixtures.

4.3.1.1 Unit Weight

The optimization of aggregate gradation in Class D/Ds concrete mixtures resulted in notable changes to the unit weight characteristics. The average unit weight of non-optimized control mixtures was 142.0 pcf, while optimized mixtures showed a slight decrease to 140.3 pcf. This reduction can be attributed to the inclusion of mixtures with 20% reduced cementitious content,

Table 4-6 Fresh concrete properties of optimized and nonoptimized Class D/Ds mixtures

Mixture ID	Slump (inch)	Unit Weight (pcf)	Air Content (%)	SAM Numbe r
D-LS1-N	5.00	144.5	7.2	0.36
D-LS1-7-0	5.50	145.5	6.8	0.30
D-LS1-7-10	5.50	144.9	7.5	0.12
D-LS1-7-20	4.75	137.2	9.2	0.13
D-GV1-N	4.25	136.2	7.4	0.41
D-GV1-7-0	4.25	136.4	7.4	0.31
D-GV1-7-10	4.25	139.2	5.7	0.29
D-GV1-7-20	4.50	133.2	8.7	0.31
D-GV1-89-0	5.00	137.6	5.8	0.32
D-GV1-89-10	4.50	139.8	5.3	0.30
D-GV1-89-20	5.00	134.0	8.4	0.31
D-GR2-N	4.50	145.1	5.7	0.38
D-GR2-7-0	5.50	145.7	6.3	0.26
D-GR2-7-10	5.00	143.8	7.2	0.05
D-GR2-7-20	5.50	139.6	8.7	0.20
D-GR2-89-0	4.50	144.9	7.1	0.29
D-GR2-89-10	4.75	143.9	7.6	0.22
D-GR2-89-20	5.50	138.4	9.0	0.14

which exhibited higher air content values.

Individual optimized mixture values demonstrated significant variability, ranging from 133.2 to 145.7 pcf. This wide range reflects the diverse mixture proportions and their impact on unit weight. **Figure 4-18** visually represents these variations among the different mixtures. Contrary to initial expectations, not all optimized mixtures showed increased unit weights compared to their nonoptimized counterparts. While optimization of aggregate packing density typically leads to higher unit weights, this trend was not universally observed. The anomaly is primarily due to the higher air content in some optimized mixtures, which counteracted the anticipated increase in unit weight. Mixtures with 0% and 10% cementitious replacement generally exhibited higher unit weights compared to non-optimized control mixtures when the air content was constant. Mixtures containing gravel samples showed lower unit weights, attributed to the significantly lower specific gravity of gravel aggregates (2.57) compared to limestone (2.76) and granite (2.62).

4.3.1.2 Slump

TDOT specifications for Class D/Ds concrete require a slump of less than 8 inches. To ensure a

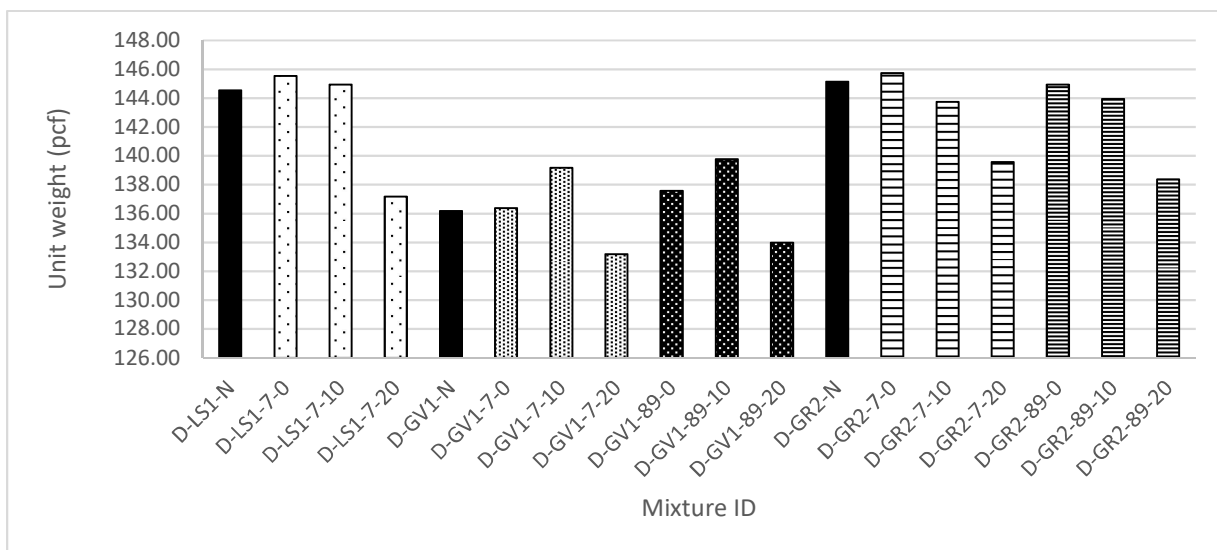


Figure 4-18 Unit weight of Class D/Ds mixtures

consistent basis for comparison across different mixtures, this research maintained a target slump of 5 ± 1 inches for all mixtures. By ensuring all concrete mixtures exhibited a comparable slump range, researchers aimed to eliminate slump as a confounding variable, thereby enhancing the reliability and significance of the comparative analysis.

Figure 4-19 illustrates the slump variations in initial batches of optimized mixtures using different aggregates, all kept within specified limits. Achieving this consistency necessitated careful adjustments in water-reducing admixture (WRA) dosages. As cementitious content decreased, there was a notable increase in WRA demand, with mixtures having a 20% reduction in cementitious content requiring significantly higher WRA dosages compared to those with no reduction. The WRA dosages ranged from 2.95 to 42.48 oz/cwt, with the 20% reduction mixtures exceeding the manufacturer's recommended range of 3 to 15 oz/cwt. Since the paste content and water amount were constant, increasing WRA dosage was the only viable method to achieve the target slump, particularly in mixtures with reduced cementitious content. The study found that optimized mixtures with no reduction in cementitious content needed extra WRA to achieve the same slump as non-optimized counterparts, a result anticipated due to improved

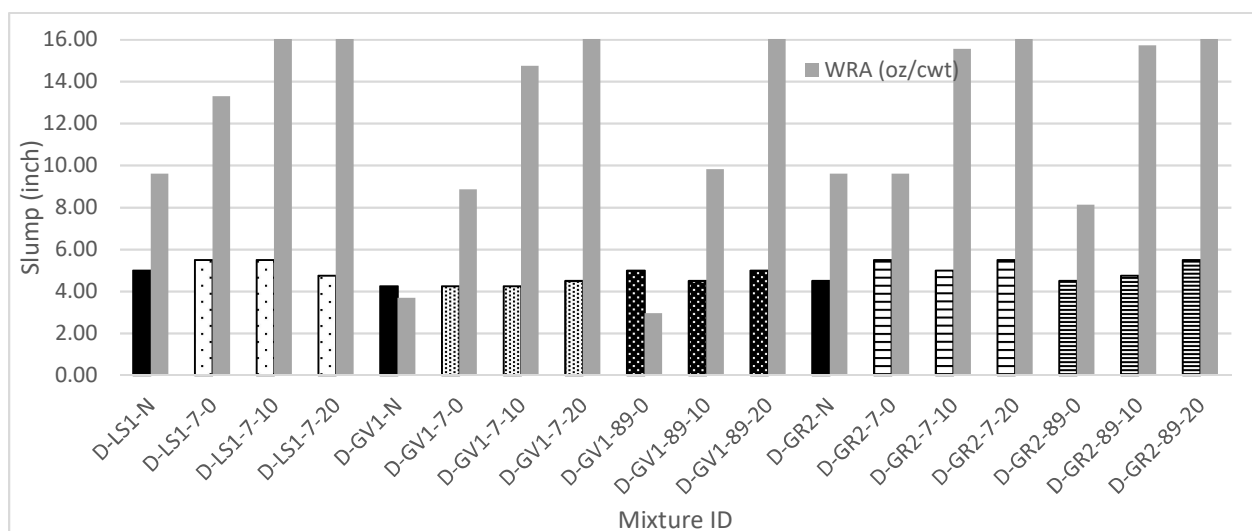


Figure 4-19 Slump of Class D/Ds mixtures

aggregate packing in optimized mixtures.

4.3.1.3 Air Content

In this research, maintaining an air content of approximately 7% in Class D/Ds concrete mixtures was crucial to align with TDOT specifications and minimize potential fluctuations in test outcomes due to air content variations. To achieve the desired air content, an Air Entraining Admixture (AEA) was used, with dosages ranging from 0.20 to 0.60 oz/cwt for both optimized and non-optimized aggregate gradation mixtures.

Mixtures with 10% and 20% cementitious content reduction did not require additional AEA to achieve the target air content yet exhibited higher air content values which attributed to the high dosages of WRA used in these mixtures (Van Dam et al., 2005). WRAs work by dispersing cement particles, which can indirectly affect air entrainment. The improved dispersion can create more space for air bubbles to form and stabilize within the mixture. The optimized mixtures generally showed higher air content compared to non-optimized control mixtures with no reduction in cementitious content when the same amount of AEA was applied. **Figure 4-20** presents the air content results for Class D/Ds optimized and non-optimized control mixtures.

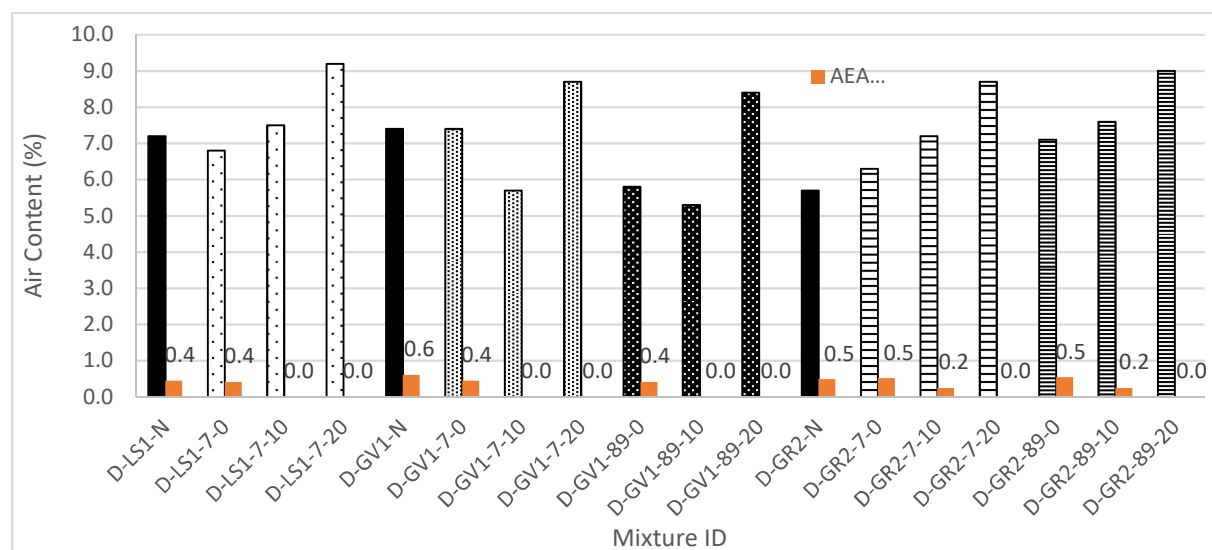


Figure 4-20 Air content of Class D/Ds mixtures

4.3.1.4 SAM Number

In accordance with AASHTO T 395 specifications for gradation mixtures, SAM numbers were calculated for all optimal aggregate mixtures. The correlation between lower SAM numbers and improved durability is well documented; a SAM number below 0.2 is generally associated with satisfactory freeze-thaw durability. The guidelines recommend a SAM number preferably below 0.20, with any value under 0.30 considered acceptable.

Figure 4-21 presents the SAM number results for Class D/Ds mixtures, showing that non-optimized control mixtures generally exhibited higher SAM numbers compared to optimized ones. Notably, most non-optimized control mixtures exceeded the acceptable limit of 0.30, indicating potential issues with workability and durability. Following optimization procedures, the SAM numbers for these mixtures significantly decreased, falling within the acceptable threshold of 0.30. This reduction in SAM numbers is indicative of enhanced freeze-thaw durability, as improved particle packing through optimization leads to better resistance against

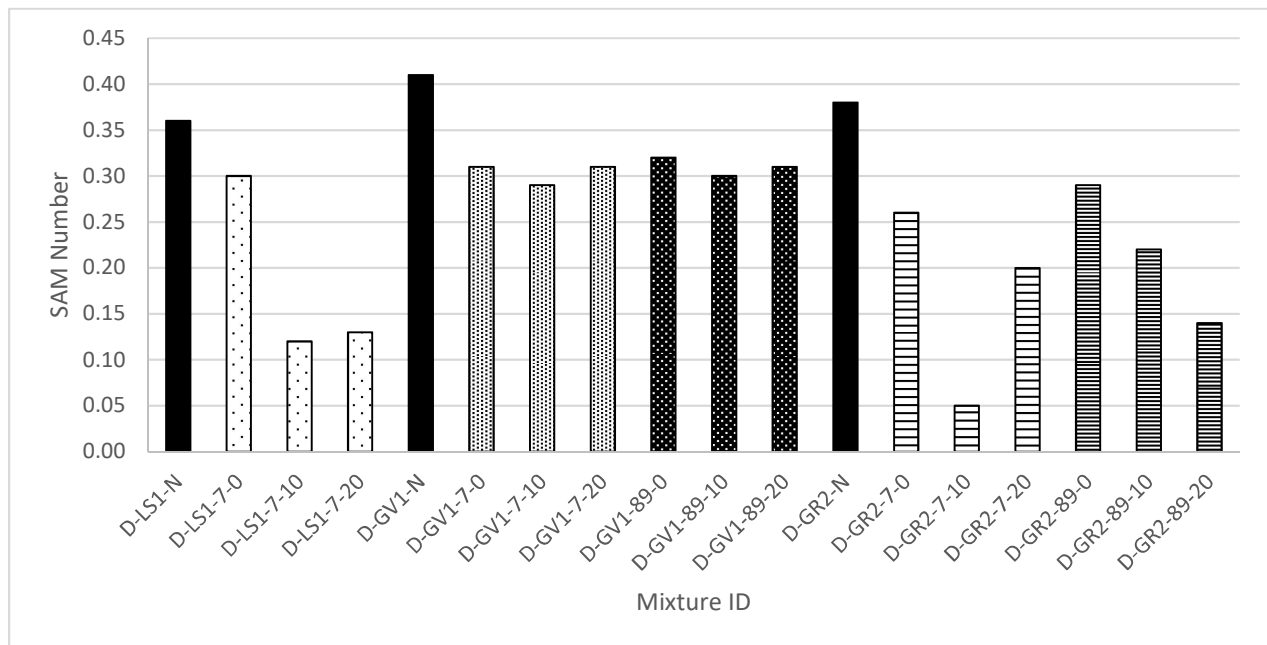


Figure 4-21 SAM number results for Class D/Ds mixtures

freeze-thaw cycles. Additionally, a decrease in cementitious content was observed to correlate with a decrease in SAM numbers. For Class D/Ds mixtures, air content was higher for the 10% and 20% cementitious content reduced mixtures. The correlation between air content in fresh concrete and SAM number, where increasing air content reduces the SAM number and achieves lower spacing of air voids, is a significant observation in concrete technology. As air content increases, the number of air voids per unit volume of concrete also increases. This naturally leads to a reduction in the average distance between voids (Wang et al., 2022). The observed improvements in optimized mixtures underscore the importance of aggregate optimization in achieving durable concrete mixtures that meet performance specifications.

4.3.2 Effect of Intermediate Aggregates on Fresh Properties

Figure 4-22 presents a detailed comparison of unit weights between concrete mixtures using #7 and #89 intermediate aggregates across different Class D/Ds mixture designs. The comparison between #7 and #89 intermediate aggregates shows remarkably similar performance across all mixture designs. The average unit weights of 139.6 pcf for #7 aggregate and 139.8 pcf for #89 aggregate demonstrate that the aggregate size has minimal impact on the concrete's unit weight.

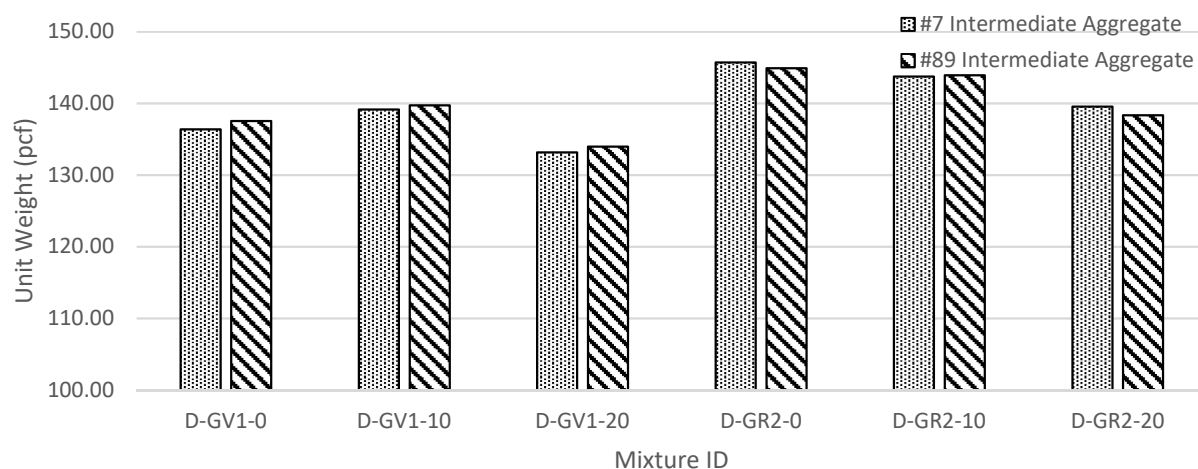


Figure 4-22 Effect of intermediate aggregates on unit weight

This negligible difference of just 0.13 pcf suggests that both aggregate sizes can effectively achieve similar density in concrete mixtures.

Figure 4-23 illustrates SAM Number results comparing #7 and #89 intermediate aggregates across different Class D concrete mixture designs. The result shows slight variation between the two aggregate types, with #89 aggregate generally performing marginally better. However, these differences are minimal and don't suggest a significant advantage of one aggregate size over the other. The consistent performance across mixture designs indicates that the specific mixture proportions and other design parameters have a more substantial impact on air void characteristics than the choice between #7 and #89 intermediate aggregates. This suggests that both aggregate sizes can effectively achieve desired air void characteristics in concrete mixtures, allowing flexibility in aggregate selection based on other performance criteria or practical considerations.

4.3.3 Hardened Property Testing

This section details the results from hardened property tests performed on mixtures with both optimized and non-optimized aggregate gradations. The evaluation of hardened properties

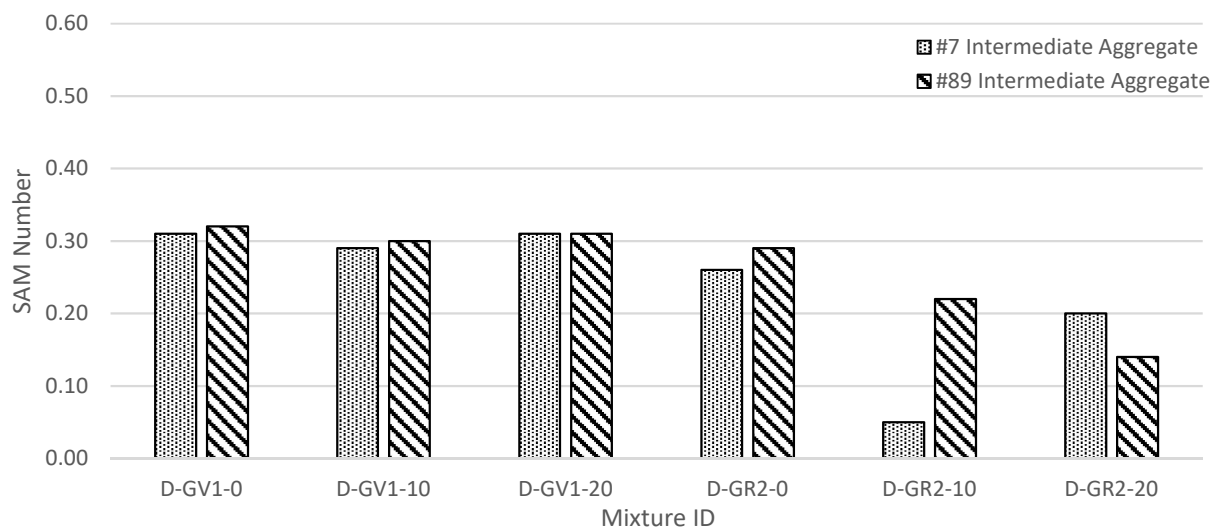


Figure 4-23 Effect of intermediate aggregates on SAM number

includes comprehensive assessments of compressive strength at both 7 and 28 days, providing insights into early and long-term strength development. Additionally, the study examines the modulus of elasticity, drying shrinkage and electrical resistivity. These evaluations collectively provide a thorough understanding of the mechanical and durability performance of the concrete mixtures under study.

4.3.3.1 Compressive Strength

According to the TDOT specifications, Class D/Ds concrete must achieve a minimum compressive strength of 4000 psi at 28 days. **Figure 4-24** displays the 28-day compressive strength results for Class D/Ds concrete mixtures. Remarkably, all the tested mixtures exceeded the critical threshold of 4000 psi, with mixtures averaging a compressive strength of 6259.6 psi. When comparing mixtures with the same cement content, optimized mixtures generally exhibited slightly superior strength characteristics compared to non-optimized ones. The observed trend aligns with existing literature, which indicates that optimizing aggregate packing and mixture

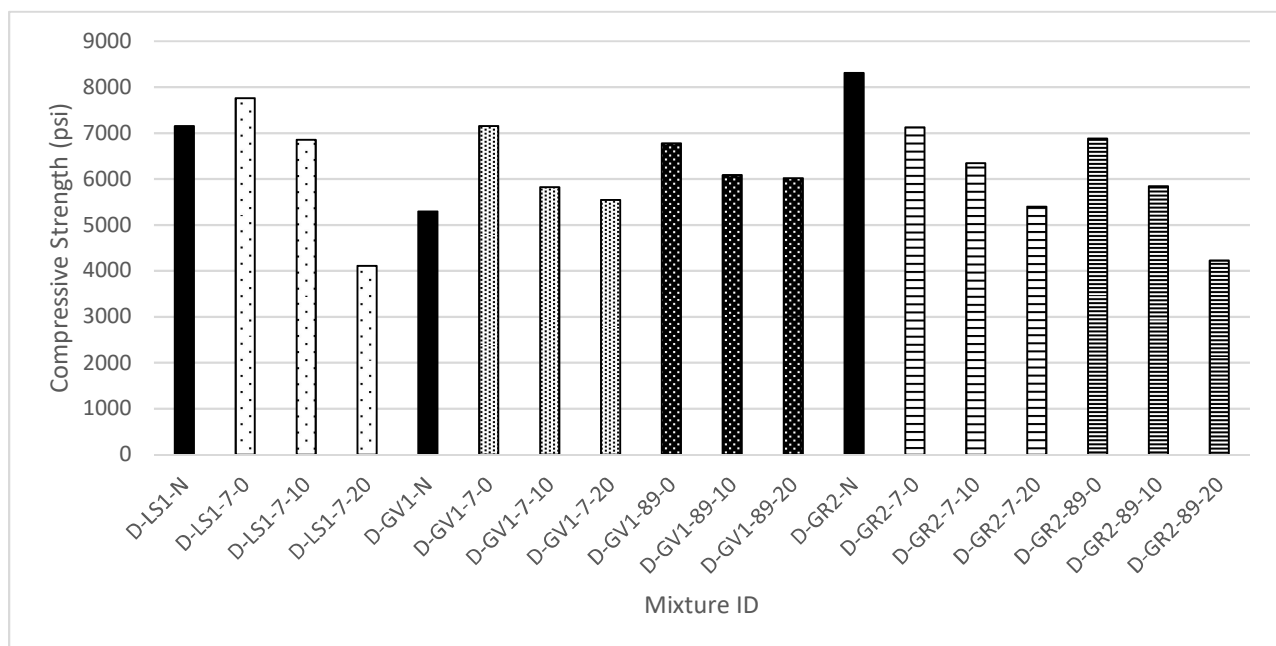


Figure 4-24 28 days compressive strength of Class D/Ds mixtures

design can enhance concrete's mechanical properties (Antunes & Tia, 2018). Additionally, as anticipated, reducing cementitious content correlated with decreased compressive strength. The early-age strength at 7 days of the optimized mixtures indicates their potential to not only meet but potentially exceed the specified 28-day compressive strength requirement of 4000 psi set by TDOT standards.

This high compressive strength underscores the effectiveness of mixture optimization strategies in improving concrete performance. By focusing on efficient particle packing and appropriate use of admixtures, these optimized formulations demonstrate enhanced durability and mechanical properties, offering significant advantages for construction researches.

Figure 4-25 presents the compressive strength results for both optimized and non-optimized concrete mixtures at 7- and 28-days following scale-up. The data highlights that all mixtures surpassed the specified 4000 psi threshold at 28 days, with most achieving well over 5000 psi, underscoring their robust performance. At the 7-day mark, optimized mixtures achieved between

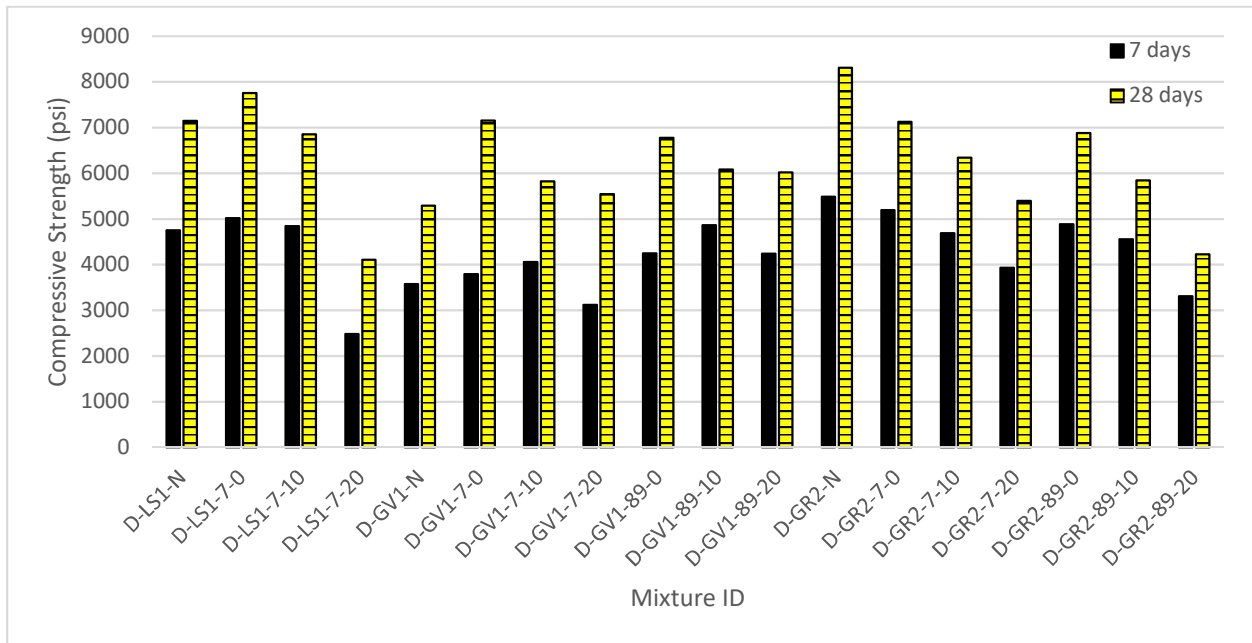


Figure 4-25 7 days and 28 days compressive strength results for Class D/Ds mixtures

52% to 78% of their 28-day compressive strength, demonstrating significant early-age strength development.

4.3.3.1 Effect of Different Intermediate Aggregates on Compressive Strength

Figure 4-26 illustrates the compressive strength results for optimized concrete mixtures using two different intermediate aggregate sizes: #7 and #89. Although the differences in strength are not substantial, mixtures incorporating the #7 aggregate generally achieved higher compressive strengths compared to those with the #89 aggregate. This suggests that the #7 aggregate may offer advantages in enhancing the mechanical properties of concrete. The likely reason for the superior performance of the #7 aggregate is its ability to provide a more favorable surface area for cement paste bonding, which strengthens the interfacial zones within the concrete (Konitufe et al., 2023). Additionally, the gradation and shape of the #7 aggregate might facilitate better interlocking within the concrete matrix, further contributing to its enhanced strength characteristics.

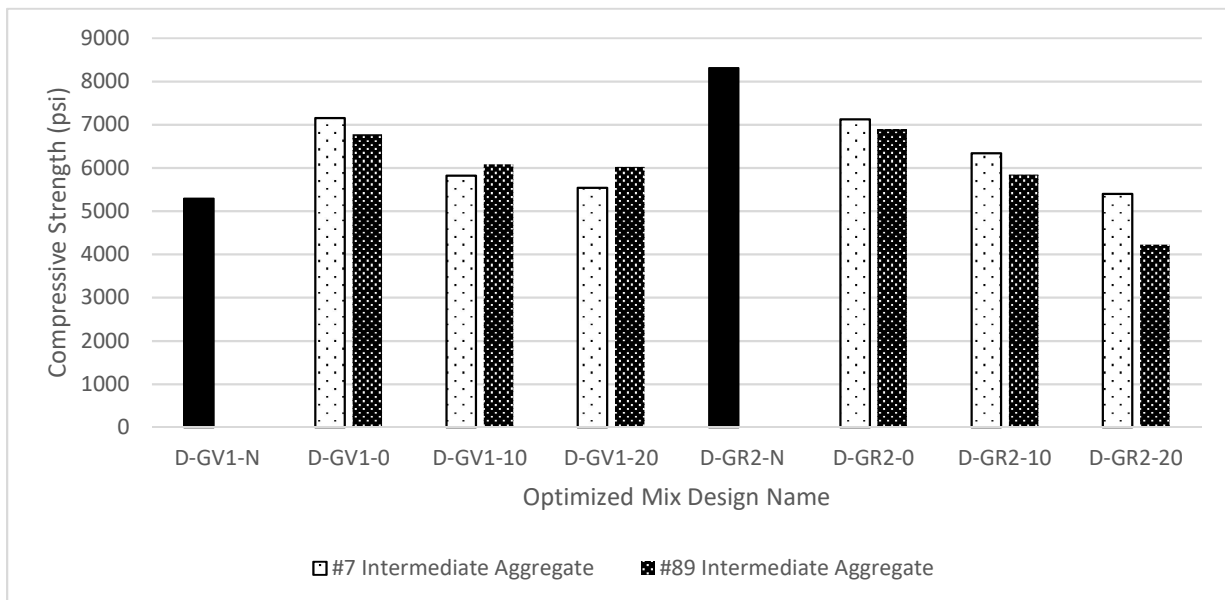


Figure 4-26 Effect of intermediate aggregates on compressive strength

4.3.3.1 Effect of Different Coarse Aggregates on Compressive Strength

Figure 4-27 presents a comparative analysis of the effect of different coarse aggregates on the compressive strength of concrete mixtures. The study evaluated three types of coarse aggregates: limestone, granite, and gravel, likely collected from different regions. The compressive strength tests were presumably conducted following ASTM standards after a 7-day curing period. Limestone samples exhibited superior strength characteristics compared to the other aggregates, achieving the highest compressive strength. This superior performance can be attributed to several factors. Limestone typically has a rougher surface texture and angular shape, which promotes better bonding with the cement paste. Additionally, limestone can react chemically with cement compounds, potentially leading to the formation of carboaluminate phases that contribute to strength development (Goguen, 2014). Surprisingly, gravel samples yielded the lowest compressive strength, despite potentially having the least number of flat and elongated particles. The mineralogical composition of gravel can vary significantly depending on its

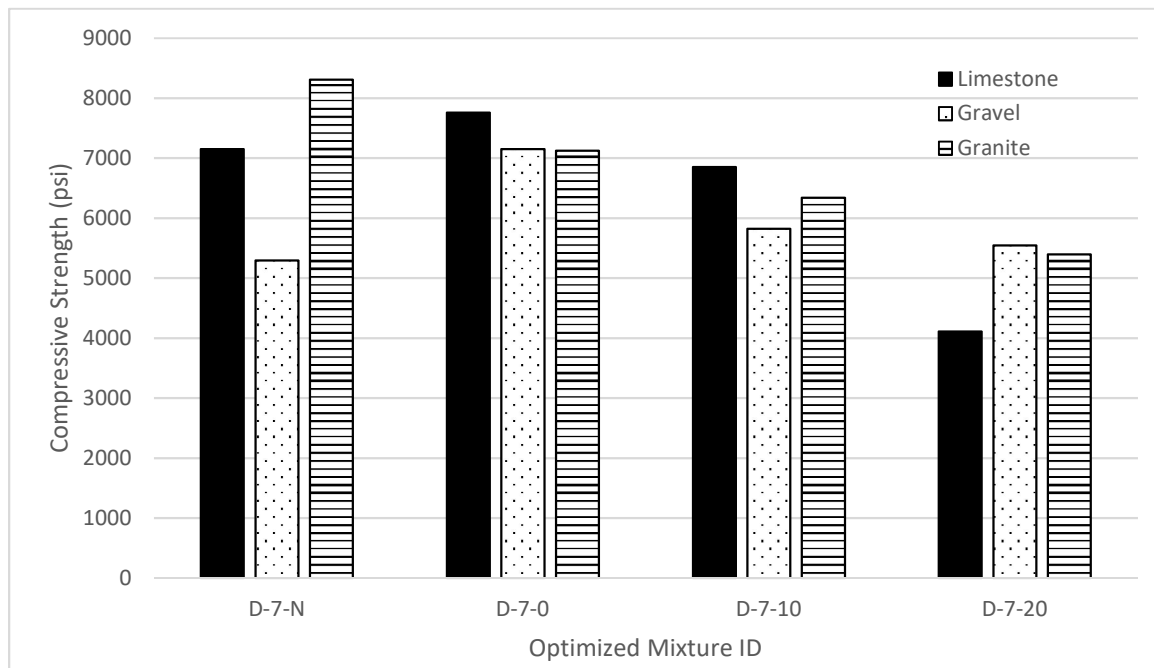


Figure 4-27 Effect of different coarse aggregates on compressive strength

source, potentially including weaker rock types that could compromise overall strength (Chen et al.,2023).

4.3.3.2 Modulus of Elasticity

Figure 4-28 shows the results of the Modulus of Elasticity (MOE) for different Class D/Ds concrete mixtures at 28 days. This data provides valuable insights into the mechanical properties of concrete and how they are influenced by mixture design. Upon analysis of the graph, a clear positive correlation between cementitious content and MOE is evident. As the cementitious content decreases, there is a corresponding drop in the Modulus of Elasticity. This trend suggests that decreasing the paste content in concrete mixtures leads to reduced stiffness and lower resistance to deformation. Usually, lower cementitious content leads to increased porosity in the concrete. Higher porosity is associated with lower elastic modulus. Even with optimized

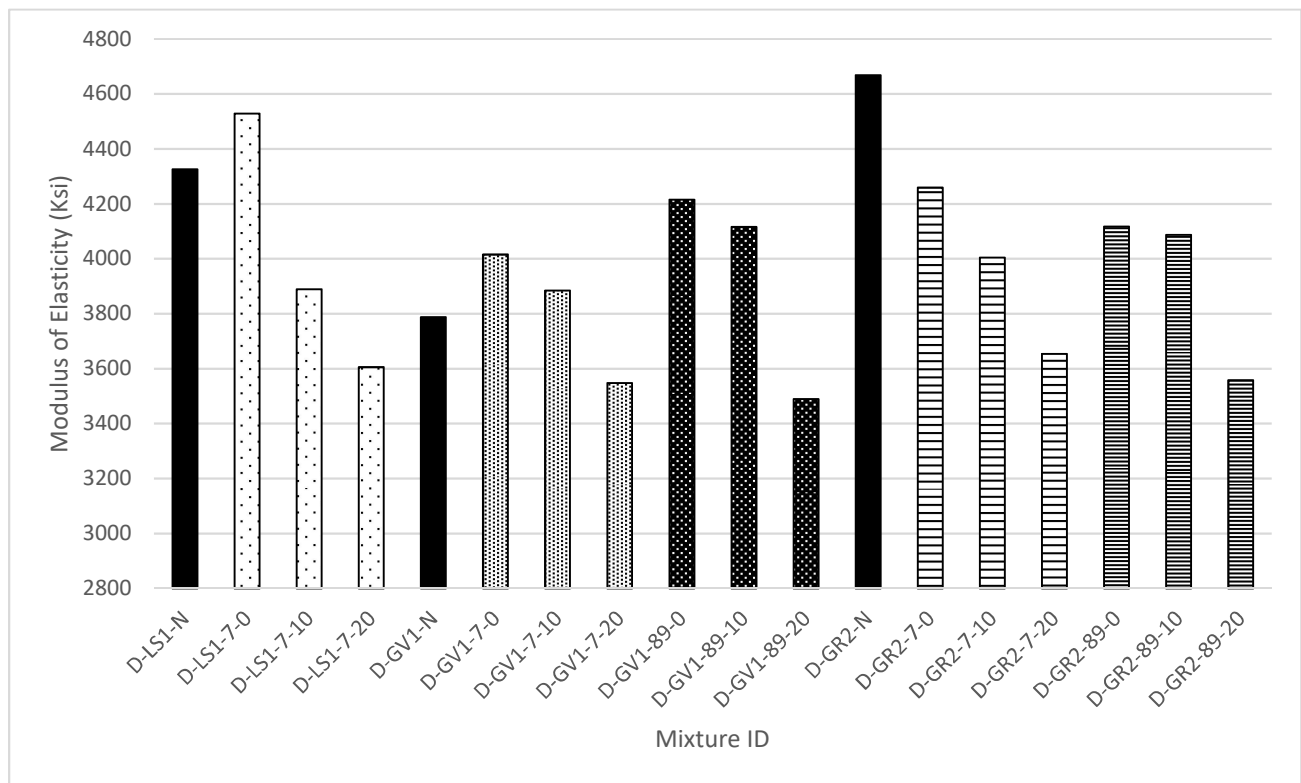


Figure 4-28 MOE results for Class D/Ds mixtures

aggregates, the interfacial transition zone between paste and aggregates remains critical. A reduction in cementitious content can weaken this zone (Korolev et al., 2021). Secondly, the additional cementitious material may contribute to a more complete hydration process, resulting in a more refined pore structure and consequently, a stiffer concrete. A key observation is that non-optimized control mixtures tend to have lower MOE values compared to optimized mixtures with similar cementitious content. Optimized mixtures are specifically engineered to achieve a denser and more homogeneous microstructure. As a result, optimized mixtures exhibit higher stiffness and deformation resistance, leading to increased MOE values .

4.3.3.3 Drying Shrinkage

The drying shrinkage analysis was conducted following ASTM C15 standards. Samples underwent a 7-day curing period before being transferred to a temperature-controlled environment for drying. Subsequent testing occurred at 28- and 56-days post-mixing. **Figure 4-29** illustrates the drying shrinkage outcomes at 7 days, as observed at the 28-day mark for both

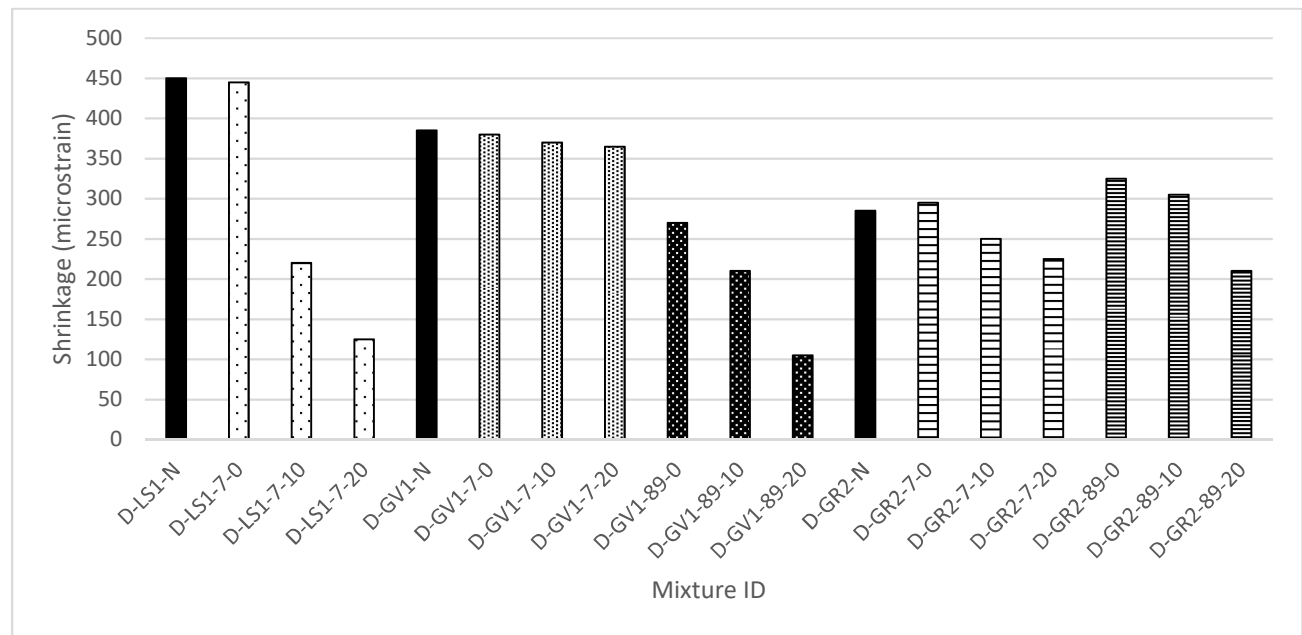


Figure 4-29 Drying shrinkage results at 28 days

optimized and non-optimized Class D/Ds aggregate gradation mixtures. Notably, all optimized aggregate gradation mixtures, except for D-LS1-R and D-LS1-7-0, successfully met the rigorous AASHTO R 101 criterion of 420 microstrains during the 28-day testing phase.

Interestingly, non-optimized control mixtures exhibited lower shrinkage compared to their optimized counterparts, despite containing identical cement content. This phenomenon can be attributed to the substitution of coarse aggregates with intermediate aggregates in the optimized mixtures. Coarser aggregates typically offer greater restraint, resulting in reduced shrinkage (Simonton & Shearer, 2021). Additionally, both optimized and non-optimized control mixtures demonstrated a trend of decreasing shrinkage as the paste material content was reduced. This observation aligns with expectations, as paste content is a primary factor influencing shrinkage behavior in concrete (Nmai et al., 2018). **Figure 4-30** shows the results of 28 days and 56 days shrinkage for optimized and non-optimized control mixtures. At 56 days, shrinkage increased an average of 35% of the shrinkage results at the 28 days.

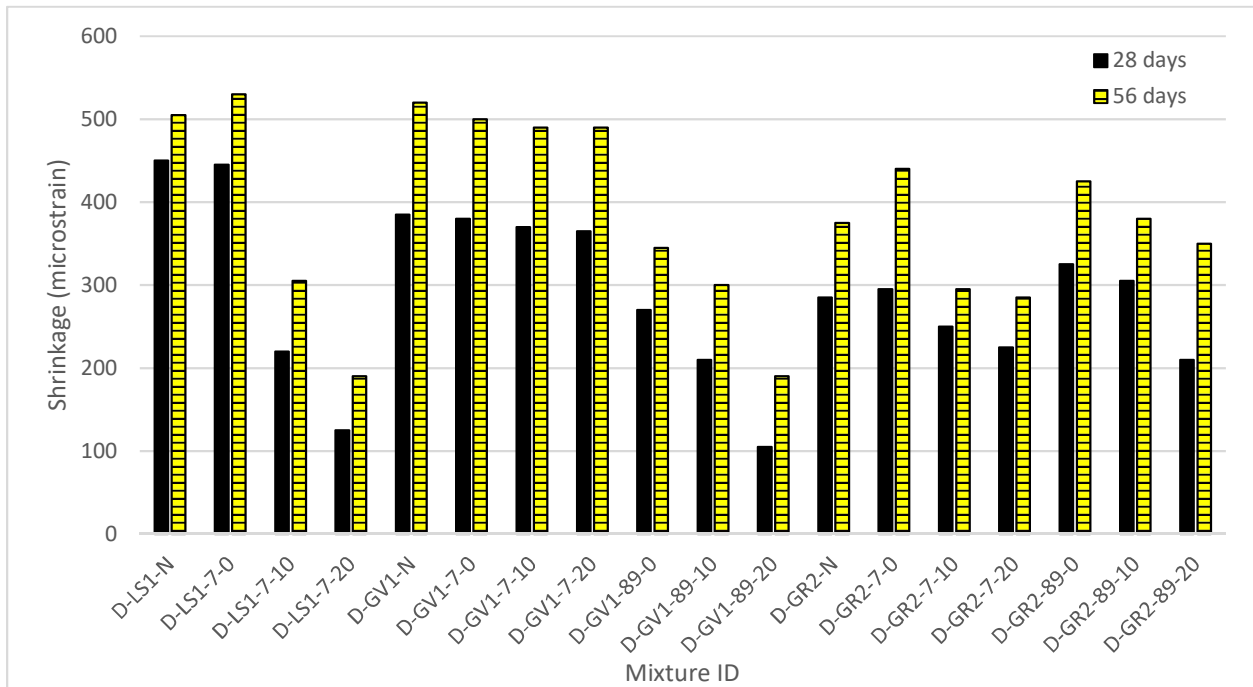


Figure 4-30 Drying shrinkage results at 28 days and 56 days

4.3.3.4 Electrical Resistivity

The average resistivity values for data interpretation, and for service life estimations for Class D mixtures are displayed in **Table 4-7**. While the penetration level trend remained the same (moderate/low to very low), the Class D mixtures had a slightly higher average value at every stage. This makes sense due to the change in mixture composition, utilizing higher cementitious content, being able to reduce the concrete's porosity (Ghosh & Tran, 2015). The change from #7 to #89 intermediate aggregate did not create a clear trend in resistivity results, but there was an average increase in values. However, no conclusions about the intermediate aggregate can be made from those results, as the increase was too minor for the data set. The values for comparable mixtures are displayed in **Table 4-8**. Most of the specimens had a low value at 28 days, with a very low value at 56 days. However, some values at 28 days were moderate in terms of penetration, while some at 56 were low in terms of penetration. All but D-GV1-7-R had a very low penetration at 90 days.

At 90 days, there was actually a larger change in average resistivity (19.16 K Ω -cm) than at 56 days (18.61 K Ω -cm). This is also different than the Class A mixtures. Not only that, but the increases also themselves were larger for Class D/Ds mixtures. This led to some significantly higher peak resistivity values. The highest Class A average, 64.95 K Ω -cm, was surpassed by 10 of the 18 specimens. The highest average of all of the specimens belonged to D-GR2-7-R, which had a value of 83.52 K Ω -cm. While the tier remains in the very low tier, this data trend does seem significant enough to conclude Class D/Ds mixtures will often result in more surface resistance, likely due to the cementitious content.

Table 4-7 Class D/Ds surface resistivity results

Mix ID	Corrected Apparent Surface Resistivity (K Ω -cm)			Service Life Surface Resistivity (K Ω -cm)		
	28 Day	56 Day	90 Day	28 Day	56 Day	90 Day
D-LS1-7-N	27.17	45.81	69.96	14.15	23.86	36.44
D-LS1-7-0	27.67	48.19	78.88	14.41	25.10	41.09
D-LS1-7-10	23.63	48.04	71.13	12.31	25.02	37.05
D-LS1-7-20	13.15	28.85	45.91	6.85	15.03	23.91
D-GV1-7-N	18.07	28.90	36.22	9.41	15.05	18.87
D-GV1-7-0	28.23	55.11	78.96	14.70	28.70	41.13
D-GV1-7-10	19.89	34.60	45.52	10.36	18.02	23.71
D-GV1-7-20	25.80	44.65	62.46	13.43	23.25	32.53
D-GV1-89-0	27.03	41.33	52.53	14.08	21.53	27.36
D-GV1-89-10	27.71	42.85	56.33	14.43	22.32	29.34
D-GV1-89-20	31.11	49.47	63.71	16.20	25.77	33.18
D-GR2-7-N	33.38	56.97	83.52	17.39	29.67	43.50
D-GR2-7-0	32.02	53.26	79.64	16.68	27.74	41.48
D-GR2-7-10	35.77	58.95	76.02	18.63	30.70	39.60
D-GR2-7-20	36.13	56.38	82.17	18.82	29.37	42.79
D-GR2-89-0	36.87	61.55	81.59	19.20	32.06	42.49
D-GR2-89-10	33.93	49.05	70.77	17.67	25.55	36.86
D-GR2-89-20	21.73	30.37	43.86	11.32	15.82	22.85

Table 4-8 Class D/Ds surface resistivity results of comparable mixtures

A (Control Mixtures)	Corrected Apparent Surface Resistivity (KΩ-cm)		
Mix ID	28 Day	56 Day	90 Day
D-GV1-7-N	18.07	28.9	36.22
D-LS1-7-N	27.17	45.81	69.96
D-GR2-7-N	33.38	56.97	83.52

B (0% Reduction)	Corrected Apparent Surface Resistivity (KΩ-cm)		
Mix ID	28 Day	56 Day	90 Day
D-GV1-7-0	28.23	55.11	78.96
D-LS1-7-0	27.67	48.19	78.88
D-GR2-7-0	32.02	53.26	79.64

C (10% Reduction)	Corrected Apparent Surface Resistivity (KΩ-cm)		
Mix ID	28 Day	56 Day	90 Day
D-GV1-7-10	19.89	34.6	45.52
D-LS1-7-10	23.63	48.04	71.13
D-GR2-7-10	35.77	58.95	76.02

D (20% Reduction)	Corrected Apparent Surface Resistivity (KΩ-cm)		
Mix ID	28 Day	56 Day	90 Day
D-GV1-7-20	25.8	44.65	62.46
D-LS1-7-20	13.15	28.85	45.91
D-GR2-7-20	36.13	56.38	82.17

CHAPTER 5

CONCLUSIONS

This study conducted a comprehensive investigation into the fresh, hardened, and durability properties of optimized and non-optimized Class A and Class D/Ds concrete mixtures. The study employed two main optimization techniques: the Tarantula Curve method and the Coarseness Factor Chart method. These methods were used to design concrete mixtures with optimized aggregate gradations, aiming to reduce paste volume while maintaining or improving performance. The research used a variety of aggregates from different regions of Tennessee, including limestone, granite, and gravel for coarse aggregates. For Class A mixtures, 36 optimized designs were developed, exploring different combinations of coarse and fine aggregates. For Class D/DS mixtures, 18 designs were created, focusing on bridge deck applications. The study explored cementitious material reductions of 0%, 10%, and 20% compared to standard TDOT mixtures. Finding from the study is that all the non-optimized control mixtures (i.e. typical TDOT mixtures) for Class A and Class D/Ds exceeded the limits set by the Tarantula Curve, indicating potential for optimizing the aggregate gradation in these mixtures. Although Tarantula Curve was originally developed for pavement concrete, it can still be applied to TDOT structural mixtures after optimization as the result shows that optimized mixtures generally led to improved concrete performance, including higher compressive strengths and lower SAM numbers, indicating enhanced freeze-thaw durability. Other key findings from the study include:

- For Class A:
- Non-optimized mixtures exhibited lower unit weights compared to optimized mixtures. The average unit weight of non-optimized Class A concrete mixtures was determined to be 141.6

pcf. Following the optimization of aggregate gradation, the unit weight experienced a slight increase, averaging 141.8 pcf.

- The use of water-reducing admixtures (WRA) was crucial in maintaining slump consistency in mixtures with reduced cementitious content, with higher dosages required as cement content decreased.
- The air content was observed to be higher in the optimized mixtures compared to the non-optimized mixtures with no reduction in cementitious content when the same amount of AEA was used.
- The majority of non-optimized control mixtures surpassed the acceptable limit for SAM number value of 0.30. However, after optimization, most of the mixture's SAM number values were within 0.30, indicating enhanced freeze-thaw durability.
- Nine out of twelve mixtures incorporating manufactured sand demonstrated slightly higher unit weights (about 0.15% to 1.28%) than those with natural sand.
- Reducing cementitious content in optimized mixtures led to decreased compressive strength. 0% optimized mixtures gave an average 2.5% increased strength than nonoptimized mixtures. However, strength reduces about 13.5% for 10% replacement and 30% for 20% cementitious content replacement.
- Natural sand demonstrates superior performance (10-20% higher strength) than manufactured sand due to its particle shape, gradation, and inherent characteristics, all of which contribute significantly to improved bond formation and interlocking within the concrete matrix.
- Gravel 1 and Granite 2 exhibited the most favorable shape characteristics among all tested aggregates, with the lowest number of flat and elongated particles. Granite 1 displayed the

lowest compressive strength among all tested aggregates while having the greatest number of flat and elongated particles in compare to other aggregates.

- Reducing paste content in optimized mixtures also resulted in decreased modulus of elasticity. Though optimized mixtures at 0% replacement showed a little higher stiffness (about 1%), MOE decreased by an average of 4% at 10 % replacement and 11.5% at 20% replacement.
- Despite having the same cement content, non-optimized mixtures showed less shrinkage, which is attributed to the presence of coarse aggregates that provide greater restraint. The optimized mixtures, which replaced some coarse aggregates with intermediate ones, exhibited higher shrinkage. Both types of mixtures demonstrated a consistent pattern of reduced shrinkage as the paste material content decreased, confirming the significant role of paste content in concrete shrinkage behavior.
- Optimized mixtures showed good resistance to chloride ion penetration, as indicated by higher electrical resistivity values, particularly at later ages. The surface resistivity nearly doubled on average from day 28 to day 56. Reducing cementitious content in optimized mixtures did not result in a significant reduction in penetration resistance, even at 20% reduction.

➤ For Class D/Ds:

- Non-optimized mixtures exhibited lower unit weights compared to optimized mixtures. Mixtures with 20% cementitious content reduction showed low unit weight due to high air content. The average unit weights of 139.6 pcf for #7 aggregate and 139.8 pcf for #89 aggregate demonstrate that the intermediate aggregate size has minimal impact on the concrete's unit weight.

- To achieved the desired slump, the WRA dosage required at 20% cementitious content replacement was more than the manufacturers' recommended maximum dosage.
- Air content was greater at 20% cementitious content replacement mixtures without the use of air entraining admixtures.
- All the non-optimized control mixtures surpassed the acceptable limit for SAM number value of 0.30. Also, with the decrease in cementitious content, SAM number also decreased.
- The average unit weights of 139.6 pcf for #7 aggregate and 139.8 pcf for #89 aggregate demonstrate that fine aggregate has minimal impact on the concrete's unit weight.
- All tested mixtures exceeded the critical threshold of 4000 psi, with mixtures averaging a compressive strength of 6259.6 psi. When comparing mixtures with the same cement content, optimized mixtures generally exhibited slightly superior strength characteristics compared to non-optimized ones. The #7 intermediate aggregate generally yielded higher compressive strengths compared to the #89 aggregate in Class D/Ds mixtures.
- Non-optimized control mixtures tend to have lower MOE values compared to optimized mixtures with similar cementitious content. A higher air content in the 20% cementitious content reduced mixtures resulted in a decrease in their modulus of elasticity.
- Similar to Class A, despite having the same cement content, non-optimized mixtures showed less shrinkage also shrinkage decreased when paste material content decrease.
- The Class D/Ds mixtures had a notably higher average surface resistivity than the Class A mixtures. The results indicate that Class D/Ds mixtures exhibit more surface resistance than class A mixtures, which is likely attributed to their higher cementitious content.

A focused recommendation for implementing a 10% reduction in cementitious content in OAG concrete mixtures is supported by the findings of this study. The research demonstrates that,

when OAG techniques such as the Tarantula Curve and Coarseness Factor Chart are employed, a 10% reduction in cementitious material can be achieved without compromising essential performance criteria for both Class A and Class D/DS structural concretes. Specifically, optimized mixtures with a 10% reduction still maintained satisfactory workability, freeze-thaw durability (as indicated by SAM numbers below 0.30), and resistance to chloride ion penetration, while also showing only a moderate decrease in compressive strength and modulus of elasticity compared to control mixtures.

REFERENCES

- Ahmad, S., & Alghamdi, S. A. (2014). A statistical approach to optimizing concrete mixture design. *The Scientific World Journal*, 2014(1), 561539.
- Agrawal, A., Tamsen, E., Unger, J. F., & Koutsourelakis, P.-S. (2024). From concrete mixture to structural design—a holistic optimization procedure in the presence of uncertainties. *Data-Centric Engineering*, 5, e20. doi:10.1017/dce.2024.18
- Alves, H., & Otani, L. B. (2022). Determination of elastic moduli of concrete by Impulse Excitation Technique (Revision 1.5). ATCP Physical Engineering, Sonelastic Division.
- American Association of State Highway and Transportation Officials. (2022). R 101-22: Standard practice for developing performance engineered concrete pavement mixtures. Washington, D.C.: AASHTO.
- American Association of State Highway and Transportation Officials. (2022). T 358-22: Standard method of test for surface resistivity indication of concrete's ability to resist chloride ion penetration. Washington, D.C.: AASHTO.
- American Association of State Highway and Transportation Officials. (2022). T 395-22: Standard method of test for characterization of the air-void system of freshly mixed concrete by the sequential pressure method. Washington, D.C.: AASHTO.
- American Concrete Institute. (2002). ACI 211.1-91: Standard practice for selecting proportions for normal, heavyweight, and mass concrete (Reapproved 2002). American Concrete Institute.
- Antunes, R., & Tia, M. (2018). Effects of aggregate packing on concrete strength and consistency. *Advances in Civil Engineering Materials*, 7(1), 479-495.

- Chen, Z. L., Shi, H. Z., Xiong, C., He, W. H., Wang, H. Z., Wang, B., Dubinya, N., & Ge, K. Q. (2023). Effects of mineralogical composition on uniaxial compressive strengths of sedimentary rocks. *Petroleum Science*, 20(5), 3062-3073.
- Chung, H. W., Jeong, H., Park, S., & Kim, Y. J. (2021). The effects of reduced paste volume in Portland limestone cement concrete. *Magazine of Concrete Research*, 73(18), 958-972.
- Cook, D., Ghaeezadeh, A., & Ley, T. (2013). Investigation of optimized graded concrete for Oklahoma. Oklahoma Transportation Center, Midwest City, OK.
- Cook, M. D., Seader, J. N., Ley, M. T., & Russell, B. W. (2015). Investigation of Optimized Graded Concrete for Oklahoma - Phase 2. Oklahoma Department of Transportation
- Cross, W., Duke, E., Kellar, J., & Johnston, D. (2000). Investigation of low compressive strengths of concrete paving, precast and structural concrete. South Dakota Department of Transportation, Pierre, SD.
- Fuller, W. B., & Thompson, S. E. (1907). The laws of proportioning concrete. *ASCE Journal of Transportation Engineering*, 59.
- Goguen, C. (2014). Portland-Limestone Cement. NPCA. <https://precast.org/blog/portland-limestone-cement/>
- Goltermann, P., Johansen, V., & Palbol, L. (1997). Packing of aggregates: an alternative tool to determine the optimal aggregate mix. *ACI Materials Journal*, 94(5), 435-443.
- Handojo, T. (2009). Use of Water Reducers, Retarders, and Superplasticizers.
- Kennedy, T., Huber, G., Harrigan, E., Cominsky, R., Hughes, C., Quintus, H., & Moulthrop, J. (1994). Superior performing asphalt pavements (Superpave): The Product of SHRP Asphalt Research Program.

- Kolias, S., & Georgiou, C. (2005). The effect of paste volume and of water content on the strength and water absorption of concrete. *Cement and Concrete Composites*, 27(2), 211-216. <https://doi.org/10.1016/j.cemconcomp.2004.02.009>
- Konitufe, C., Abubakar, A., & Baba, A. S. (2023). Influence of aggregate size and shape on the compressive strength of concrete. *Construction*, 3(1), 15-22.
- Korolev, A. S., Kopp, A., Odnoburcev, D., Loskov, V., Shimanovsky, P., Koroleva, Y., & Vatin, N. I. (2021). Compressive and tensile elastic properties of concrete: Empirical factors in span reinforced structures design. *Materials*, 14(24), 7578.
- Kozul, R., & Darwin, D. (1997). Effects of aggregate type, size, and content on concrete strength and fracture energy (Master's thesis, University of Kansas, Civil and Environmental Engineering).
- Lamond, J. F., & Pielert, J. H. (2006). Significance of tests and properties of concrete and concrete-making materials (Vol. 169). ASTM International.
- Ley, T., Cook, D., & Fick, G. (2012). Concrete pavement mixture design and analysis (MDA): Effect of aggregate systems on concrete mixture properties. National Concrete Pavement Technology Center.
- Ley, T., & Cook, D. (2014). Aggregate gradations for concrete pavement mixtures. CP Road Map. Moving Advancements into Practice (MAP) Brief October 2014. FHWA TPF-5-(286).
- Marczewska, J., & Piasta, W. (2018). The impact of air content on the durability of concrete under combined sulphate and freeze-thaw attack. In *MATEC Web of Conferences* (Vol. 163, p. 05002). EDP Sciences.

- Mehta, P. K., & Monteiro, P. J. M. (2014). Concrete: Microstructure, properties, and materials (4th ed.). McGraw-Hill Education.
- Minnesota Department of Transportation. (2023). Establishing fresh properties of fiber reinforced concrete for performance evaluation.
https://mdl.mndot.gov/_flysystem/fedora/2023-02/202223.pdf
- Polat, R., Yadollahi, M. M., Sagsoz, A. E., & Arasan, S. (2013). The correlation between aggregate shape and compressive strength of concrete: Digital image processing approach. *International Journal of Structural and Civil Engineering Research*, 2(3), 63-80.
- Lebow, C. (2018). Effect of Cement Content on Concrete Performance [Master's thesis, University of Arkansas].
- Liu, Z., Milla, J., & Saunders, W. (2024). Optimizing Aggregate Gradation to Reduce Concrete's Permeability (No. FHWA/LA. 24/701).
- Saykat, S., Napper, C., Abd-Elssamd, A., & Ma, Z. J. (2025). Optimized Aggregate Gradations for Concrete Mixture Designs.
- Sebaaly, H., Varma, S., & Maina, J. W. (2018). Optimizing asphalt mix design process using artificial neural network and genetic algorithm. *Construction and Building Materials*, 168, 660-670.
- Shilstone, J. M., Sr. (1990). Concrete mixture optimization. *Concrete International*, 12(6), 33-39.
- Simonton, E., & Shearer, C. R. (2021). Low shrinkage mix designs to reduce early cracking of concrete bridge decks (No. SD2018-04-F). South Dakota Department of Transportation, Office of Research.

- Smit, M., & Kearsley, E. (2015). Effect of paste content on the properties of high-strength concrete pavements. *Journal of the South African Institution of Civil Engineering*, 57(4), 20–29.
- Smith, G., Wathne, L., Hanson, T., Masten, M., Reichelt, S., Bahmer, E., ... & Hunter, B. J. (2024). Using performance engineered mixtures to improve pavement performance and sustainability: State Experiences. *Transportation Research Circular*, (E-C287).
- Sobolev, K., & Amirjanov, A. (2010). Application of genetic algorithm for modeling of dense packing of concrete aggregates. *Construction and Building Materials*, 24(8), 1449-1455.
- Sobolev, K., Moini, M., Muzenski, S., Pradoto, R., Kozhukhova, M., Flores-Vivian, I., Cramer, S., Pham, L., & Faheem, A. (2015). Laboratory study of optimized concrete pavement mixtures (No. WHRP 0092-13-04). Wisconsin Highway Research Program.
- Taylor, P., Bektas, F., Yurdakul, E., & Ceylan, H. (2012). Optimizing cementitious content in concrete mixtures for required performance.
- Taylor, P., & Sadati, S. (2021). Reduced cementitious material in optimized concrete mixtures (No. NRRA202102). Minnesota Department of Transportation.
- Taylor, P. C., & Voigt, G. F. (2007). Integrated materials and construction practices for concrete pavement: A state-of-the-practice manual (No. FHWA HIF-07-004). United States. Federal Highway Administration. Office of Pavement Technology.
- Taylor, P. (2015). Blended aggregates for concrete mixture optimization: Best practices for jointed concrete pavements (No. FHWA-HIF-15-019). Federal Highway Administration.
- Tennessee Department of Transportation. (2021a). Standard operating procedure (SOP) 4-4: Procedures for submittal and approval of concrete mixture designs.

https://www.tn.gov/content/dam/tn/tdot/hq-materials-tests/standard-operating-procedures/SOP_4-4.pdf

Tennessee Department of Transportation. (2021b). Standard specifications for road and bridge construction. https://www.tn.gov/content/dam/tn/tdot/construction/2021-standard-specifications/January_1_2021_Standard_Specifications.pdf

Theilgard, P. (2022). Optimized aggregate gradation concrete mixtures with cementitious material reduction [Doctoral dissertation, The University of North Carolina at Charlotte].

Tia, M., Chung, H. W., & Subgranon, T. (2021). Phase II-Reducing portland cement content and improving concrete durability (No. P1024150). Florida Department of Transportation.

Van Dam, T., Sutter, L., & Peterson, K. (2005). Challenges in air entrainment with polycarboxylate admixtures. *Journal of Concrete Technology*, 18(3), 45-52.

Van Dam, T. J. (2019). Specifying, designing, and proportioning paving concrete (No. FHWA-HIF-18-012). Federal Highway Administration.

Wang, Y., Lu, H., Xiao, R., Hu, W., & Huang, B. (2022). Experimental study on the stability and distribution of air voids in fresh fly ash concrete. *Materials*, 15(23), 833

APPENDIX

Chemical	ASTM C-114	Physical	ASTM C-150	
SiO ₂ (%)	<u>19.2</u>	Time of Set (Vicat)		
Al ₂ O ₃ (%)	<u>4.2</u>	Initial Set (min.)	<u>134</u>	
Fe ₂ O ₃ (%)	<u>3.16</u>	Final Set (min.)	<u>242</u>	
CaO (%)	<u>63.6</u>	Compressive Strength	PSI	MPa
MgO (%)	<u>3.5</u>	1 Day	<u>1982</u>	<u>13.7</u>
SO ₃ (%)	<u>2.33</u>	3 Day	<u>3502</u>	<u>24.1</u>
Total Alkali (Na ₂ O + 0.658K ₂ O)	<u>0.52</u>	7 Day	<u>4723</u>	<u>32.6</u>
Ignition Loss	<u>5.0</u>	28 Day	<u>6477</u>	<u>44.7</u>
Insoluble Residue	<u>0.58</u>	Cube Flow	<u>119</u>	
C ₃ S (%)	<u>73.5</u>	Fineness, Blaine	<u>3894</u>	
C ₂ S (%)	<u>-0.3</u>	325 Mesh (%)	<u>92.2</u>	
C ₃ A (%)	<u>5.8</u>	Air Content (%)	<u>5.7</u>	
C ₄ AF (%)	<u>9.6</u>	Normal Consistency (%)	<u>24.3</u>	
C ₃ S + 4.75C ₃ A	<u>101.1</u>	False Set (%)	<u>66.4</u>	
CO ₂ (%)	<u>4.3</u>	Autoclave Expansion (%)	<u>0.04</u>	
Limestone (%)	<u>10.4</u>			
CaCO ₃ in Limestone (%)	<u>88.5</u>	Specific Gravity	<u>3.14</u>	

This Portland-Limestone T-IL cement complies with ASTM C595 specifications.

Figure A-1 Chemical composition of cement

Chemical Analysis		Results (wt%)	Specification (Class F)	
			ASTM C618-22	AASHTO M295-19
Silicon Dioxide (SiO ₂)		43.5	----	----
Aluminum Oxide (Al ₂ O ₃)		19.5	---	----
Iron Oxide (Fe ₂ O ₃)		13.32	----	----
Sum of Silicon Dioxide, Iron Oxide & Aluminum Oxide (SiO ₂ +Al ₂ O ₃ +Fe ₂ O ₃)		76.3	50.0 % min.	50.0 % min.
Calcium Oxide (CaO)		11.7	18.0 % max.	18.0 % max.
Magnesium Oxide (MgO)		3.0	----	----
Sodium Oxide (Na ₂ O)		1.16	----	----
Potassium Oxide (K ₂ O)		1.53	---	----
“Sodium Oxide Equivalent (Na ₂ O+0.658K ₂ O)”		2.17	----	----
Sulfur Trioxide (SO ₃)		2.25	5.0 % max.	5.0 % max.
Loss on Ignition		2.5	6.0 % max.	5.0 % max.
Moisture Content		0.4	3.0 % max.	3.0 % max.
Total Chlorides		0.001	---	----
Available Alkalies				
Sodium Oxide (Na ₂ O) as Available Alkalies		0.26	----	----
Potassium Oxide (K ₂ O) as Available Alkalies		0.29	----	----
Available Alkalies as “Sodium Oxide Equivalent (Na ₂ O+0.658K ₂ O)”		0.45	----	1.5 % max.*
Physical Analysis				
Fineness (Amount Retained on #325 Sieve)		10.4%	34 % max.	34 % max.
Strength Activity Index (Using Lehigh Leeds Alabama Portland Cement)				
At 7 Days:		89%	75 % min. [†] (of control)	75 % min. [†] (of control)
Control Average, psi: 4960	Test Average, psi: 4420			
At 28 Days:		99%	75 % min. [†] (of control)	75 % min. [†] (of control)
Control Average, psi: 6010	Test Average, psi: 5970			
Water Requirements (Test H ₂ O/Control H ₂ O)		95%	105% max. [†] (of control)	105% max. [†] (of control)
Control, mls: 242	Test, mls: 230			
Autoclave Expansion:		-0.03%	---	± 0.8 % max.
Uniformity Requirements		Variation		
Specific Gravity: 2.54	Average: 2.53	0.5%	5 % max. from average	5 % max. from average
% Retained #325 Sieve: 10.4	Average: 10.5	-0.1%	5 % max. from average	5 % max. from average

[†] Meeting the 7 day or 28 day strength activity index will indicate specification compliance

* Optional

The results of our testing indicate that this sample complies with ASTM C618-22 and AASHTO M295-19 specifications for Class F pozzolans.

Figure A-2 Chemical composition of fly ash

Table A-1 Specific gravity of coarse aggregates

Aggregate	Specific Gravity
LS1	2.75
LS2	2.77
LS3	2.77
GR1	2.74
GR2	2.62
GV1	2.59
Natural Sand	2.61
Manufactured Sand	2.75

VITA

Sazzadul Shahriar Saykat is currently a PhD student and Graduate Research Assistant at the Tickle College of Engineering, University of Tennessee, Knoxville, where he is engaged in advanced research at the Center for Transportation Research. He began his academic journey in Bangladesh, earning his Bachelor of Science in Building Engineering and Construction Management from Khulna University of Engineering and Technology. His research focuses on sustainable building materials, high-strength cementitious materials, and reinforced concrete structures. Saykat has contributed to several high-impact projects funded by the Tennessee Department of Transportation and the U.S. Department of Energy, including work on optimized aggregate gradations, low-carbon concrete technologies etc. He hopes to continue his research and contribute to the advancement of sustainable construction practices in the future.