Optimized Aggregate Gradations for Concrete Mixture Designs

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16. Abstract

Tennessee does not currently have procedures or specification requirements that fully support the use of optimized gradations in concrete mixtures. This research project focused on optimizing aggregate gradation for concrete mixtures used by the Tennessee Department of Transportation (TDOT), aiming to improve concrete durability, economy, and sustainability. Beginning with a comprehensive literature review and industry survey, the project explored various Optimized Aggregate Gradation (OAG) methods and current practices. The study then investigated concrete mixtures using materials representative of Tennessee's geological diversity, employing Portland-limestone cement, Class F fly ash, and various aggregate types. Optimization techniques included the Tarantula Curve method and the Coarseness Factor Chart method. The research designed concrete mixtures for TDOT Class A and Class D/DS, incorporating systematic cementitious material reductions and various aggregate combinations. Results showed that optimized mixtures generally exhibited improved performance characteristics, including higher compressive strengths, better freeze-thaw durability, and enhanced resistance to chloride ion penetration. Even with a 20% reduction in cementitious material, optimized mixtures maintained acceptable performance levels. Key recommendations include updating TDOT specifications to incorporate OAG techniques, adjusting minimum cementitious material content requirements, and introducing new quality control measures. The study also suggested considering SAM number and surface resistivity as specification requirements for freeze-thaw durability and chloride penetration resistance, respectively. This research provides valuable insights for improving concrete quality and sustainability in Tennessee's construction industry, demonstrating the potential benefits of using optimized concrete mixtures while highlighting the importance of considering various factors when designing concrete mixtures for specific applications.

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Executive Summary

This research project focuses on optimizing aggregate gradation for concrete mixtures used by TDOT, with the goal of improving concrete durability, economy, and sustainability of concrete mixtures. The study aligns with the Federal Highway Administration's Performance Engineered Mixtures (PEM) initiative. This initiative aims to improve the durability, economy, and sustainability of concrete infrastructure by shifting focus from prescriptive specifications to performance-based requirements. The project addresses limitations in Tennessee's current prescriptive specifications for concrete mixtures, which may hinder the adoption of more efficient designs. By optimizing aggregate gradation, the research aims to reduce the amount of cementitious material required, leading to cost savings and a reduced carbon footprint. This approach is expected to enhance both fresh and hardened concrete properties.

The project began with a comprehensive literature review, exploring various OAG methods and their latest developments. This review provides the foundation for the research and contextualizes the study within the broader field of concrete mixture optimization. This study then presents the results of a survey conducted among Departments of Transportation (DOTs), ready-mix plants, and precast plants, offering valuable insights into current practices for optimized gradation in concrete mixtures and perspectives across the industry.

This study explored the optimization of concrete mixtures using a wide range of materials representative of Tennessee's geological diversity and the four regions of the state of Tennessee. To thoroughly investigate the influence of aggregates collected from different regions, comprehensive sieve analyses and shape analyses were conducted on all the aggregates used in the study. The research employed Portland-limestone cement (PLC) Type IL and Class F fly ash as cementitious materials. For coarse aggregates, the study incorporated three types of limestone, two types of granite, and gravel samples for Class A mixtures (i.e. concrete for general use), while Class D/Ds mixtures (i.e. concrete for bridges and bridge deck applications) used one sample of limestone, granite, and gravel. The fine aggregates used in the study included both natural and manufactured sands and intermediate aggregates of #7 and #89 sizes which were incorporated in Class A and Class D/Ds mixtures to develop combined and optimized aggregate gradations. To enhance concrete properties, chemical admixtures such as air-entraining and water-reducing agents were utilized. The optimization process employed both the Tarantula Curve method and the Coarseness Factor Chart method, facilitated by a custom-developed Excel spreadsheet. This tool allowed for incorporating sieve analysis data, calculating combined aggregate gradation, and determining optimal aggregate volumes within Tarantula Curve limits, while also checking sieve limit constraints for workable mixtures. It was observed 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. The study designed concrete mixtures for various TDOT Classes, including Class A and Class D/DS, incorporating systematic cementitious material reductions (0%, 10%, and 20%), various combinations of coarse, intermediate, and fine aggregates, and targeted water-to-cementitious material ratios. This comprehensive approach enabled a thorough evaluation of how optimized gradations affected concrete performance across different mix designs and material combinations, providing valuable insights for improving concrete quality and sustainability in Tennessee's construction industry.

For Class A mixtures, fresh properties testing included slump, unit weight, air content, and SAM number. The findings indicated that optimized mixtures generally exhibited slightly higher unit weights, ranging from 1% to 4% more than non-optimized control mixtures. This increase in unit weight can be attributed to improved particle packing in optimized mixtures. Slump values were maintained within the TDOT Class A mixtures'

specified range of 3±1 inches, with water-reducing admixture (WRA) dosages adjusted as needed. Interestingly, optimized mixtures often required additional WRA to achieve the same slump as non-optimized control mixtures, indicating improved packing density that initially reduced workability. Almost all non-optimized control mixtures surpassed the 0.30 SAM number threshold, indicating potential issues with freeze-thaw durability. In contrast, the optimized mixtures generally recorded lower SAM numbers, most of them staying within the 0.30 limit, which suggests enhanced freeze-thaw durability.

Hardened properties and durability testing for Class A mixtures included compressive strength, modulus of elasticity (MOE), drying shrinkage, and surface resistivity. Optimized concrete mixtures generally demonstrated slightly higher (average 2-3%) compressive strength compared to non-optimized ones when using the same cement content. Furthermore, even with a 20% reduction in cementitious material, the optimized mixtures maintained compressive strength, which exceeds the TDOT requirement of 3,000 psi at 28 days. This improvement can be attributed to better particle packing and enhanced microstructure in optimized mixtures. The modulus of elasticity decreased with reduced paste content, suggesting that decreasing the paste content leads to reduced stiffness. The paste forms the bond between aggregates, and its reduction can weaken the interfacial transition zone (ITZ), which results in increased microcracking and lower overall stiffness. Drying shrinkage results met the AASHTO R 101 requirement (i.e. maximum 420 microstrain at 28 days) for all the optimized mixtures, although non-optimized control mixtures exhibited lower shrinkage compared to optimized mixtures with the same cement content. This was attributed to the replacement of coarse aggregates with intermediate aggregates in optimized mixtures. Surface resistivity measurements indicated improved resistance to chloride ion penetration in optimized mixtures.

For Class D/Ds mixtures, fresh properties testing yielded similar trends to Class A mixtures. The target slump was 5±1 inch per TDOT requirements, and WRA dosages were adjusted accordingly. Air content was maintained at around 7% as per TDOT specifications. SAM numbers for optimized mixtures were generally lower than those of non-optimized control mixtures, indicating better freeze-thaw durability. The study found that mixtures using #7 intermediate aggregate generally achieved higher compressive strengths compared to those with #89 aggregate, likely due to the #7 aggregate providing a more favorable surface area for cement paste bonding and better interlocking within the concrete matrix.

The analysis of Class D/DS concrete mixtures revealed that optimized mixtures generally demonstrated slightly higher (average 3-4%) compressive strength compared to non-optimized ones with the same cement content. Limestone aggregates exhibited superior strength characteristics compared to granite and gravel, which can be attributed to limestone's physical and mechanical properties such as rougher surface texture, and angular shape. The modulus of elasticity showed a positive correlation with cementitious content, with optimized mixtures generally demonstrating higher (ranging 4-5%) MOE values compared to non-optimized control mixtures with similar cementitious content. Drying shrinkage results met the AASHTO R 101 criterion for all but two optimized mixtures, although non-optimized control mixtures exhibited lower shrinkage compared to their optimized counterparts due to partial replacement of coarse aggregate with intermediate aggregate size.

Overall, this study demonstrated that optimized mixtures generally performed better than non-optimized control mixtures in terms of both fresh and hardened properties. 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 and the need for higher WRA dosages to maintain workability in optimized mixtures. The optimized mixtures exhibited a 5-20% increase (with an average of 7%) in shrinkage compared to the non-optimized control mixtures. Nonetheless, all optimized mixtures from Class A, as well as all but two mixtures from Class D/Ds, remained within the shrinkage limit of 420 microstrains at 28 days. Reducing the amount of cement content in the optimized mixtures can reduce the shrinkage and overcome the effects of partial replacement of coarse aggregates with intermediate aggregate. These findings highlight the potential benefits of using optimized concrete mixtures in construction projects, while also emphasizing the importance of considering various factors when designing concrete mixtures for specific applications.

Key Findings

- Concrete mixtures designed using optimized aggregate gradation techniques, such as the Tarantula Curve method and the Coarseness Factor Chart method, generally exhibited enhanced performance characteristics. These optimized mixtures demonstrated higher compressive strengths and lower SAM numbers, indicating improved freeze-thaw durability.
- Reducing cementitious content in optimized mixtures led to decreased compressive strength and modulus of elasticity. However, even with a 20% reduction in cementitious content, many mixtures maintained acceptable performance levels. With the reduction of cement content across all mixtures, the use of water-reducing admixtures (WRA) was crucial in maintaining workability in these reduced cement mixtures, with higher dosages required as cement content decreased.
- Drying shrinkage was generally lower in non-optimized control mixtures and decreased with reduced cementitious content, highlighting the complex relationship between mix design and dimensional stability.
- Optimized mixtures demonstrated better resistance to chloride ion penetration, as evidenced by higher electrical resistivity values, particularly at later ages. This improvement in durability is a significant benefit of optimized aggregate gradation techniques.
- Natural sand showed superior performance compared to manufactured sand. This is attributed to its particle shape, gradation, and inherent characteristics, which contribute significantly to improved bond formation and interlocking within the concrete matrix.

Key Recommendations

- TDOT specifications should be updated to include a new section allowing for the use of OAG techniques. This section should provide acceptable limits for combined aggregate gradation using the Tarantula Curve method and define the optimal zone (Zone II) in the Coarseness Factor Chart for well-graded mixtures. It should also allow flexibility in aggregate proportioning to meet these gradation requirements, including the use of intermediate aggregates (#7 or #89 sizes). New quality control measures specific to OAG mixtures should be introduced. These should include regular aggregate gradation checks to ensure compliance with the optimized gradation and field-testing protocols to verify that reduced cementitious content mixtures are meeting performance requirements.
- Current minimum cementitious material content requirements should be adjusted to allow for reductions based on optimized gradations. For Class A mixtures, reductions of up to 10% from the current 564 lb/yd³ should be allowed, with a new minimum of 508 lb/yd³ with 25% fly ash and 75% cement. Similarly, for Class D/DS mixtures, reductions of up to 10% from the current 620 lb/yd³ should be permitted, with a new minimum of 559 lb/yd³ with 25% fly ash and 75% cement. These reductions should only be allowed when using approved OAG techniques and meeting all performance requirements.

- The SAM number should be considered as a specification requirement for freeze-thaw durability. Based on the study's findings and AASHTO T 395 guidelines, a maximum SAM number of 0.30 should be recommended, with a preferred value below 0.20.
- Given Tennessee's varied climate and potential exposure to deicing salts, assessing chloride penetration resistance is important for long-term durability of concrete structures. Implementing surface resistivity testing aligns with the broader goal of moving towards performance-based specifications, as outlined in the research objectives. TDOT could consider adopting surface resistivity requirements similar to AASHTO T 358.
- For future research, TDOT should prioritize a comprehensive investigation into the workability characteristics of OAG concrete mixtures. The proposed study should emphasize key areas such as rheological properties, time-dependent workability, pumping characteristics, and extensive field trials to validate laboratory findings. A critical aspect of the research should be the examination of admixture effectiveness and dosage requirements in OAG mixtures, as the current study revealed that these mixtures often require different admixture dosages compared to conventional concrete. That in-depth analysis would provide valuable insights into the practical implementation of OAG mixtures in various construction scenarios, potentially leading to improved guidelines for mixture design and placement. By understanding these workability aspects more thoroughly, TDOT can enhance the adoption and effectiveness of OAG mixtures, ultimately leading to more durable and sustainable concrete infrastructure.

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Chapter 1 Introduction

1.1 Background

This project focuses on enhancing concrete mixture design through optimized aggregate gradation, aligning with the Federal Highway Administration's PEM initiative. This effort aims to improve the durability, economy, and sustainability of concrete infrastructure in Tennessee.

Currently, Tennessee's prescriptive specifications may limit the adoption of more efficient concrete mixtures. By optimizing aggregate gradation, the study seeks to reduce the amount of cementitious material required, leading to cost savings and a reduced carbon footprint. This approach not only addresses economic and environmental concerns but also enhances fresh and hardened concrete properties such as workability, strength, and durability.

The research is particularly timely as it supports Tennessee's participation in the PEM initiative, which emphasizes performance-based requirements over traditional prescriptive methods. By developing procedures for optimized gradations, Tennessee can potentially achieve more durable and cost-effective infrastructure solutions. Through comprehensive testing and analysis, the study provides evidence-based strategies for improving concrete performance across various applications, ultimately contributing to longer-lasting infrastructure with reduced maintenance needs.

1.2 Problem Statement

Tennessee is part of the PEM initiative led by the Federal Highway Administration (FHWA) aiming to improve the durability, economy, and sustainability of the concrete infrastructure using both prescriptive and performance specification provisions and emerging technologies. The PEM addresses concrete durability and performance issues rather than designing and accepting concrete primarily on strength. Since aggregates typically account for 60% to 75% of the volume in a concrete mixture, aggregate properties such as aggregate grading and durability play a major role in concrete performance and are key elements for the development of PEM concrete. In particular, aggregate grading can have a significant effect on the amount of cementitious material needed to obtain the desired fresh and hardened properties of concrete. An optimum design for a concrete mixture will usually incorporate an 'optimized' aggregate gradation that minimizes the paste volume and increases the aggregate packing density through careful consideration of the aggregate particle size distribution. Optimized aggregate and reduced cementitious material content are economical and environment friendly compared to concrete currently used in practice. A lower material cost, reduced carbon footprint, improved fresh (workability, finishability), and hardened (strength and durability) properties can be achieved. Tennessee does not currently have procedures and/or specification requirements that fully support the use of optimized gradations in concrete mixtures (TDOT, 2021, Section 604.03). The current prescriptive specifications adapted by TDOT and many DOTs and agencies for setting minimum and maximum contents of various mixture components and rate of strength gain may preclude the acceptance of mixtures that have superior economy, durability, sustainability, and satisfactory mechanical performance. Thus, it is urgent to develop new procedures to allow producers designing more durable and equal and/or higher-strength concrete mixtures through optimizing aggregate gradation. With improvements to the aggregate structure of the concrete mixtures, future designs could have much lower paste contents. This improvement would lead to both a reduction in overall price of the mixtures and a reduction in the overall carbon footprint of each mixture. Implementation of this research will support the current economic and policy environment led by FHWA and supported by public agencies and industry to move towards performance-engineered construction materials as a means of reducing maintenance and replacement costs.

1.3 Significance of the Project

The significance of this research lies in its potential to revolutionize concrete mixture design and infrastructure development in Tennessee. By focusing on optimizing aggregate gradation, the study addresses a critical aspect of concrete performance that has been historically underutilized. The current prescriptive specifications in Tennessee, like many other states, may inadvertently limit the adoption of more efficient and effective concrete mixtures. This research aims to bridge that gap by developing procedures that allow for the creation of optimized gradations, which can lead to numerous benefits.

Optimized aggregate gradations can significantly reduce the amount of cementitious material required in concrete mixtures, resulting in lower material costs and a reduced carbon footprint. This aligns with the growing emphasis on sustainability in construction and supports efforts to mitigate climate change. Moreover, the improved aggregate structure can enhance both fresh and hardened concrete properties, including workability, finishability, strength, and durability.

Furthermore, the implementation of optimized gradations could result in significant long-term cost savings for the state. Improved concrete durability and performance can reduce maintenance and replacement costs over the lifespan of infrastructure projects. This economic benefit, coupled with the environmental advantages of reduced cement usage, makes the research highly relevant in the current economic and policy landscape.

In essence, this research has the potential to transform how concrete is designed and used in Tennessee's infrastructure projects. By addressing the limitations of current specifications and embracing performance-based approaches, it paves the way for more economical, sustainable, and durable concrete infrastructure, aligning with both state and national objectives for improved construction materials and practices.

1.4 Objectives of the Project

This research aims at developing new procedures to allow producers to design more durable and equal and/or higher strength concrete mixtures while reducing cost and environmental impacts through optimizing aggregate gradation. The technical objectives of the proposed research include the following:

1. Collect data regarding the available aggregates from Tennessee concrete producers.

2. Determine/Analyze the effects of adjusting the target mixture gradations in relation to the paste content and the overall strength of each mixture.

3. Observe the performance of TDOT concrete mixtures with and without an optimized gradation.

4. Determine necessary changes needed to the 2021 TDOT Standard specifications, supplemental specifications, and/or Standard Operating Procedure (SOP) 4-4.

1.5 Scope of the Project

The scope of this research encompasses a comprehensive investigation into optimizing aggregate gradations for concrete mixtures used in Tennessee's infrastructure projects. The research scope includes:

- Literature Review and Industry Survey

A thorough review of existing state DOT specifications for optimized aggregate gradations was conducted through a DOTs survey and another survey of ready-mix and precast plant capabilities within Tennessee, providing a baseline for current practices and potential for improvement.

- Material Acquisition and Characterization

The study includes collecting and characterizing a wide range of aggregates, cementitious materials, and supplementary cementitious materials (SCMs) from various regions of Tennessee. This diverse selection ensured the research outcomes applicable across the state.

- Mixture Design and Optimization

A substantial number of concrete mixtures (approximately 75) were designed and tested, focusing on structural concrete and bridge deck applications. These mixtures include various aggregate gradations, proportions, and cementitious material contents, utilizing different optimization techniques.

- Fresh and Hardened Concrete Testing

An extensive testing program was implemented to evaluate both fresh and hardened properties of the optimized mixtures. This includes assessments of workability, strength development, durability, and other performance indicators crucial for infrastructure applications.

- Data Analysis and Recommendations

The research team analyzed the test results to identify optimal gradations and mixture designs. Based on these findings, recommendations are provided for updating TDOT specifications and practices.

This comprehensive scope aims to provide TDOT with performance-based strategies for improving concrete performance through optimized aggregate gradations, potentially leading to more durable, economical, and sustainable infrastructure across Tennessee.

1.6 Research Approach

The research approach for this study is comprehensive and multi-faceted, focusing on both theoretical and experimental methods to improve concrete performance.

- Aggregate Gradation Optimization

This study employed multiple criteria to determine the best aggregate blends for TDOT concrete mixtures by using (1) Tarantula curve, and (2) Coarseness factor chart. These techniques were used to optimize aggregate gradations, with a focus on ternary aggregate blends to reduce void volume and paste content within the concrete mix.

- PEM Implementation

To align with the latest industry standards, the research incorporated methods adopted by AASHTO R 101 for evaluating concrete performance. This approach ensures that TDOT remains at the forefront of PEM implementation.

- Comprehensive Testing Program

A detailed testing program was conducted, encompassing both fresh and hardened concrete properties:

- Fresh Concrete Testing:
    - Slump Test (ASTM C143)
    - Unit Weight (ASTM C138)
    - Air Content (ASTM C231)
    - SAM number (AASHTO T 395)
- Hardened and Durability Concrete Testing:
    - Compressive Strength (ASTM C39)
    - Static Modulus of Elasticity (ASTM C469)
    - Drying shrinkage (ASTM C157)
    - Electrical Resistivity of a Concrete Cylinder (AASHTO T 358)

For Class A and Class D/DS mixtures, strength tests were conducted at 7 and 28 days and durability tests were conducted at 28, 56, and 90 days to assess the development of concrete properties over time. This comprehensive approach combines theoretical optimization techniques with extensive laboratory testing to develop concrete mixtures that are not only optimized for performance but also aligned with the latest industry standards and TDOT requirements.

1.7 Project Outcomes

This research yielded significant benefits for TDOT: (1) The study delivers comprehensive guidelines for implementing optimized gradations in concrete mixtures. These specifications will enable a reduction in paste volume, leading to cost savings, decreased environmental impact through reduced cement usage, and improved resistance to shrinkage cracking. Consequently, this may result in lower long-term maintenance and replacement costs. (2) The research provides recommendations for optimized gradation mixtures tailored to the existing stockpiles and capabilities of ready-mix producers in Tennessee. This approach facilitates a smooth and efficient transition to optimized gradations for TDOT concrete mixtures. (3) By supporting the implementation of PEM, this research positions TDOT at the forefront of efforts to enhance concrete durability, economy, and sustainability. In conjunction with other PEM-aligned initiatives, this research is expected to generate substantial cost savings for TDOT across various areas, including construction, quality assurance and control, maintenance, and extended infrastructure lifespan. (4) The study developed recommended specifications and mixing procedures for concrete mixtures with reduced cementitious content. This outcome aligns with broader efforts to minimize cement usage while maintaining or improving concrete performance. (5) In light of the high Alkali-Silica Reaction (ASR) risk identified in Tennessee's concrete structures and pavements, the implementation of optimized aggregate grading is anticipated to yield concrete with lower permeability and reduced cementitious content. These characteristics are expected to enhance resistance against ASR, addressing a critical durability concern.

1.8 Report Outline

The report outline for this research project is structured to provide a comprehensive and logical presentation of the study's findings and recommendations.

The report begins with an introductory chapter that sets the stage for the research. This chapter includes background information, a clear problem statement, and a detailed description of the project's scope, objectives, and significance. It also outlines the research approach and expected project outcomes, providing readers with a clear understanding of the study's purpose and methodology. Following the introduction, a thorough literature review is presented in Chapter 2. This chapter offers an overview of existing knowledge in the field, focusing on various OAG methods and their latest developments. This review provides the theoretical foundation for the research and contextualizes the study within the broader field of concrete mixture optimization.

Chapter 3 presents the results of a survey conducted among Departments of Transportation (DOTs), ready-mix plants, and precast plants. This chapter offers valuable insights into current practices and perspectives across the industry, helping to identify gaps and opportunities for improvement in aggregate gradation optimization.

The methodology of the study is detailed in Chapter 4, which describes the materials used, the optimization process employed, mix design development, and the various testing procedures for both fresh and hardened concrete properties. This chapter provides a clear and replicable account of the research process, ensuring the study's scientific rigor.

Chapter 5 forms the core of the report, presenting the results and discussion of the experimental work. It is divided into sections focusing on Class A and Class D/Ds mix optimizations, with each section detailing the fresh and hardened property results for both small-scale and up-scaled mixtures. This comprehensive presentation of results allows for a thorough analysis of the optimized mixtures' performance.

The report concludes with Chapter 6, which summarizes the key findings and conclusions of the study. This chapter also provides recommendations for specification modifications, translating the research findings into practical guidelines for TDOT.

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.

Workability factor = $P + \frac{2.5*(M-564)}{94}$ Equation 2.1

Coarseness factor = $\frac{R}{S}*100$ Equation 2.2

Where,

P = Cumulative percent passing on the number 8 sieve

M = Cementitious material content (lb/yd^3)

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.

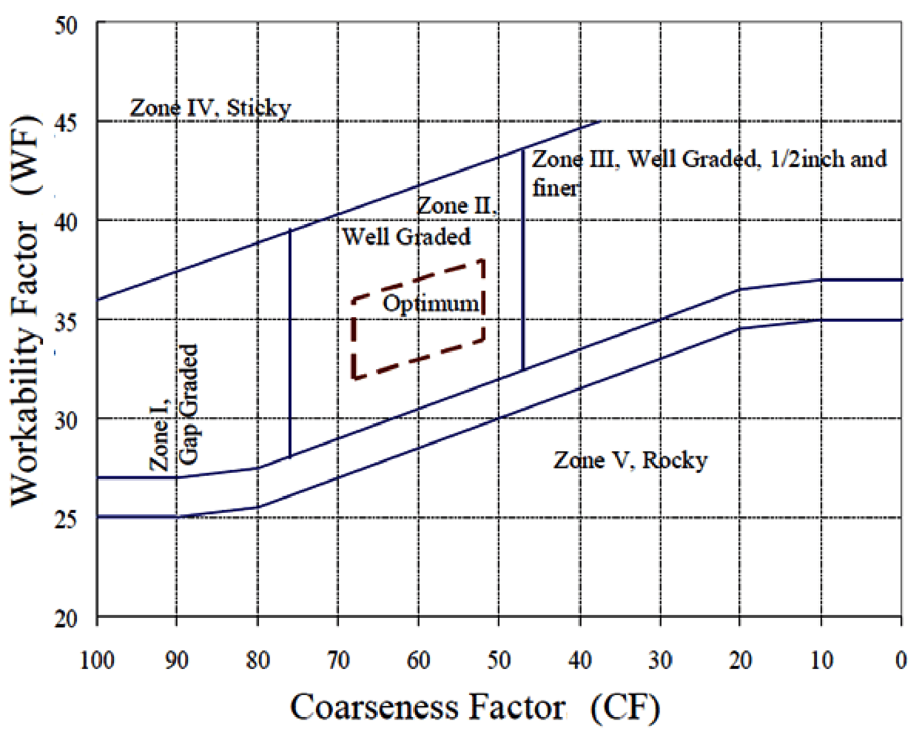


Figure 2-1 Coarseness factor chart

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.

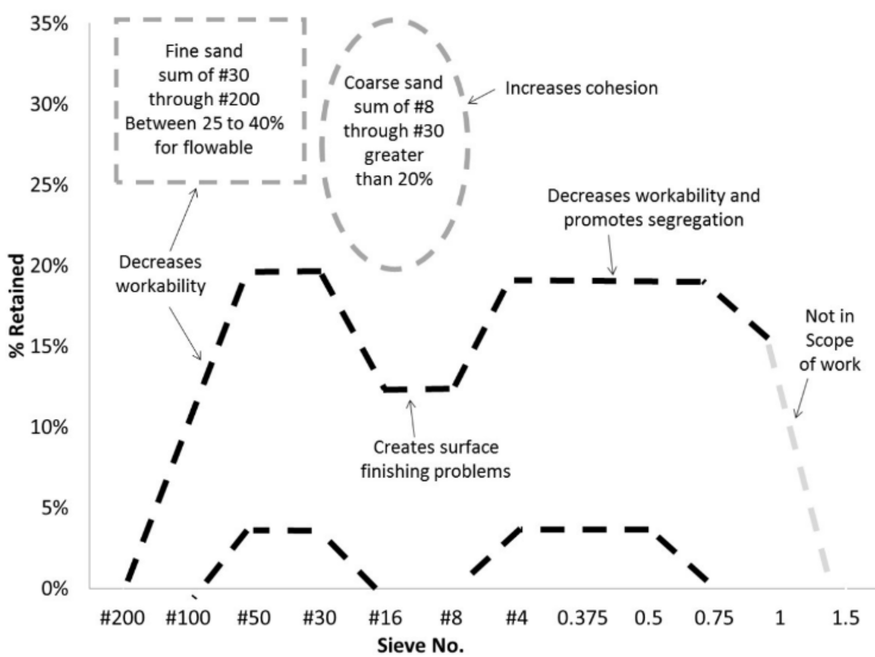


Figure 2-2 Tarantula curve limits

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.

A survey was conducted for Departments of Transportation (DOTs), ready-mix plants, and precast plants which provided valuable insights into current practices and perspectives regarding OAG in concrete mixtures. This comprehensive survey, detailed in Appendix C, covers various aspects of concrete mixture design, aggregate selection, and performance requirements.

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 project. 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 project.

Figure 3-1 Type IL cement used in the project

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 project. 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 project.

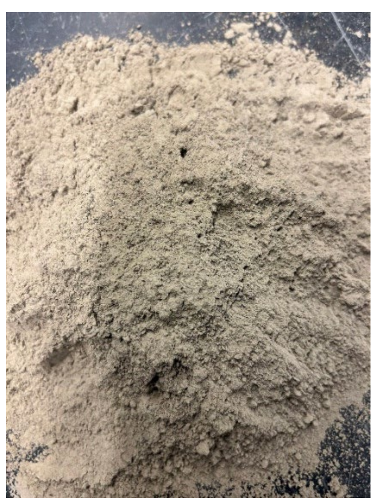


Figure 3-2 Class F fly ash used in the project

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, a diverse range of coarse aggregates was selected to represent the geological variety across Tennessee and to assess the optimization effects on different regional materials. 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.

a) LS1 b) LS2 c) LS3

a) GR1 b) GR2 c) GV1

Figure 3-3 Coarse aggregate samples from different sources

3.2.4 Fine Aggregate

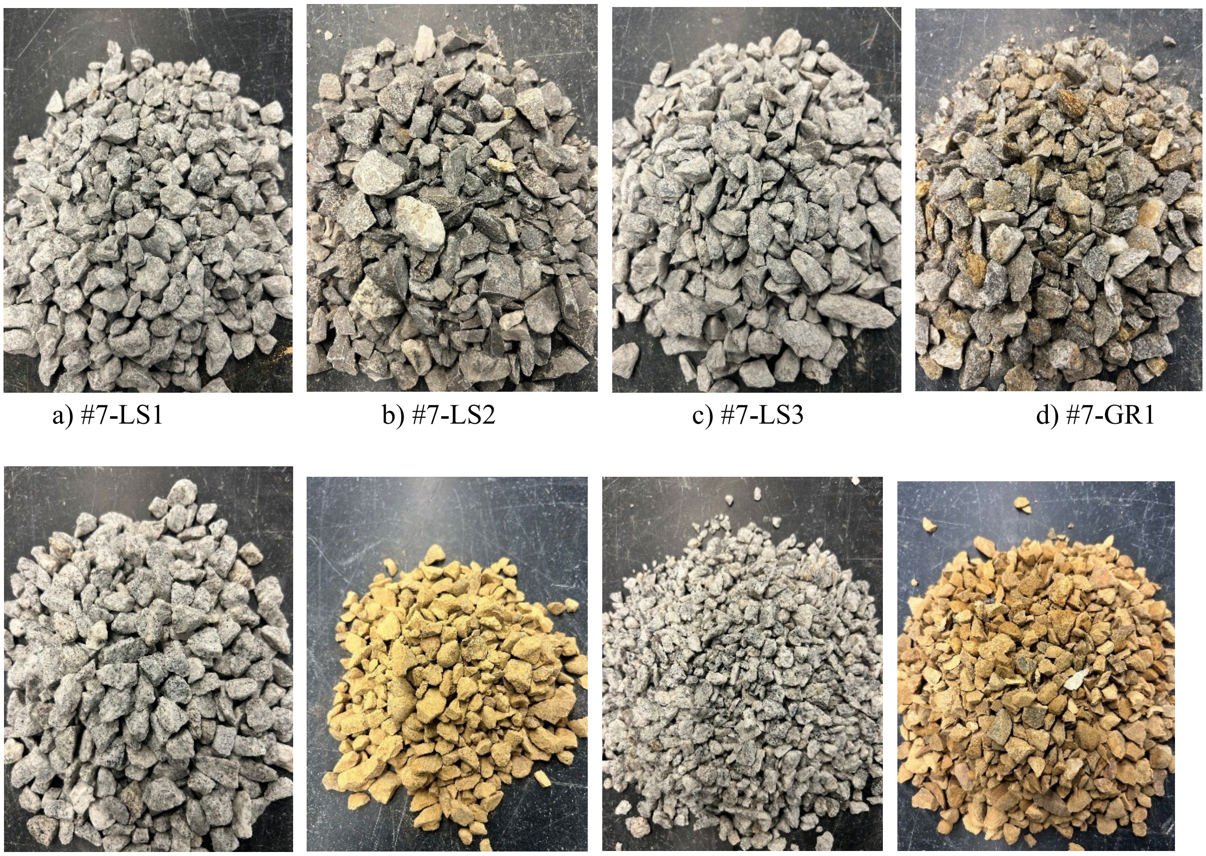
For Class A mixtures, the researchers employed a natural sand sample and a manufactured sand sample. These samples were sourced from different regions within the state, providing a representative cross-section of fine aggregates available in Tennessee. In the case of Class D/Ds mixtures, which are typically used for bridge deck applications, 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 incorporated intermediate aggregates into the concrete mixtures for optimization. For Class A mixtures, #7 sized intermediate aggregates were utilized, sourced from the same producers as the corresponding coarse aggregates. This approach ensured consistency in material properties within each aggregate type. 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.



a) #7-LS1 b) #7-LS2 c) #7-LS3 d) #7-GR1

e) #7-GR2 f) #7-GV1 g) #89-GR2 h) #89-GV1

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 these sections, aggregates from two sections were selected and mixed again to ensure homogeneity. A splitter was then used to obtain three representative samples from this mixture. Each sample underwent sieve analysis to determine particle size distribution.

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:

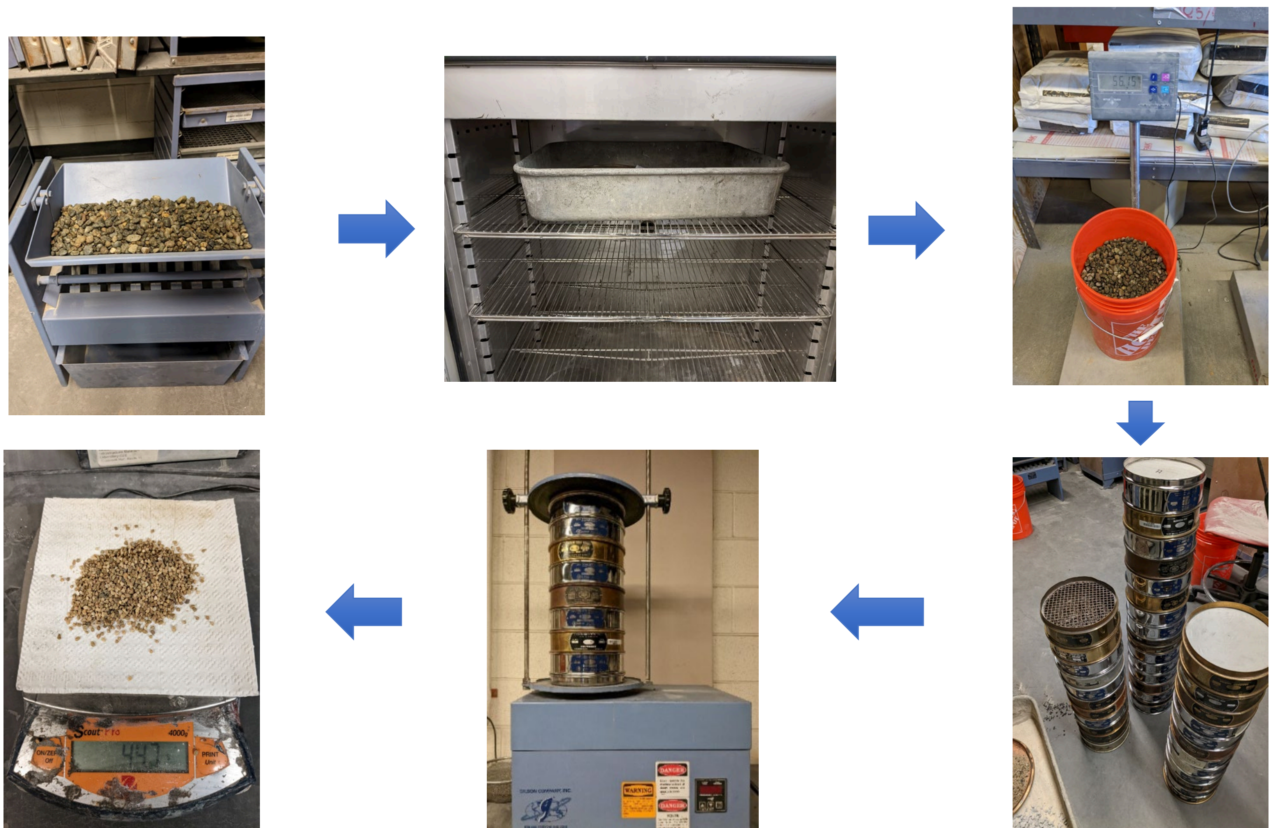


Figure 3-8 Sieve analysis procedure

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:

- **<u>Step -1: Input Sieve Analysis data</u>**

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 Ib/yd^3, and the estimated paste volume content ranges between 25.5-27.1 %. Estimated cementitious paste volume is computed by the minimum total cementitious materials content and maximum water to cementitious materials. The control mixtures (control mixtures) will be re-produced using Type IL cement.

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
# 67 stone	-	-	-
# 7 stone	-	-	-
Coarse Limestone	LR1-C2	LR2-C2	-
Coarse Gravel	-	-	-
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
H/MRWR (oz/cwt)	Per MFG	Per MFG	Per MFG
Accelerator	-	-	-
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 Ib/ yd^3

Using above control mixtures previously designed, batched, and tested by the TDOT as a preliminary data set, companion concrete mixtures were created using the Tarantula Curve and Shilstone workability-coarseness chart to optimize the aggregate gradation of concrete mixtures with a uniform paste reduction. Four parameters were identified as key variables for the evaluation: cementitious material content, fly ash replacement, type and shape of coarse aggregates (limestone, granite, and gravel), and type and shape of fine aggregates (natural sand and manufactured sand). These variables are selected and controlled to replicate mixtures typical for TDOT including Class A, Class D/DS.

- **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 IL and 25% Class F 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 two coarse aggregate types (#57 limestone and #57 uncrushed gravel), #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/yd^3); estimated paste volume = 26.4%
- 10% Cementitious Reduction (508 lb/yd^3); estimated paste volume = 23.7%
- 20% Cementitious Reduction (451 lb/yd^3); 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. Trial batch mixtures were performed to determine optimum admixtures dosages before every production mixture.

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 Ib/ yd^3

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 Ib/ yd^3

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 (Ib/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 Ib/ yd^3

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 Ib/ yd^3

- **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 IL 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/yd^3); estimated paste volume = 27.1%
- 10% Cementitious Reduction (559 lb/yd^3); estimated paste volume = 24.5%
- 20% Cementitious Reduction (496 lb/yd^3); 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.

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 Ib/ yd^3

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 (Ib/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 Ib/ yd^3

3.6 Mix Proportioning

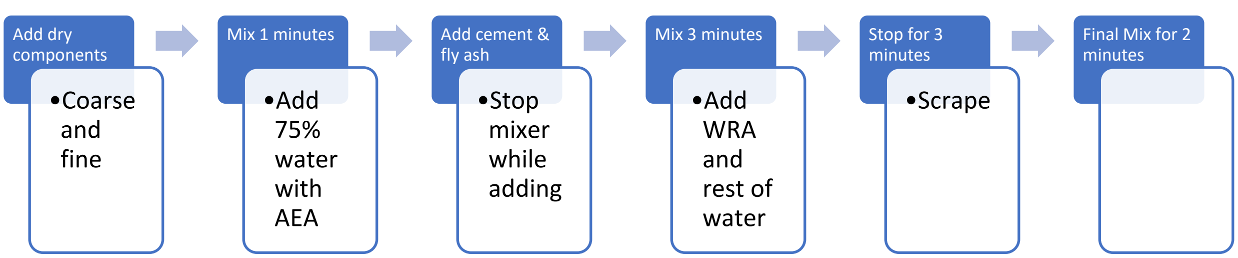
In a lab setting, concrete mixtures were performed in a three cubic feet concrete drum mixer. Based on the amount of material needed to make the test specimens required to finish the necessary tests and the anticipated waste, batch sizes were calculated. Figure 3-9 shows the drum mixer that was used to mix the concrete.

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.

The flow chart summarizes the mixing procedure:



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.

Figure 3-10 Slump test

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 3-11 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.

Figure 3-12 Air content testing using 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 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.

Figure 3-13 SAM number testing result for a mixture

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 tank that was used for curing.

Figure 3-14 Curing tank

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.

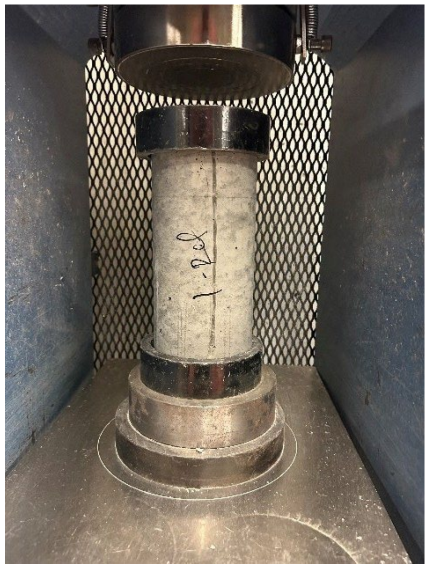


Figure 3-15 Compressive strength test setup

3.9.2 Modulus of Elasticity

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

Figure 3-16 Modulus of Elasticity test setup

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

Figure 3-17 Shrinkage beam placed into a 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 3-18 Surface resistivity testing using resipod concrete resistivity meter

Chapter 4 Results and Discussion

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.

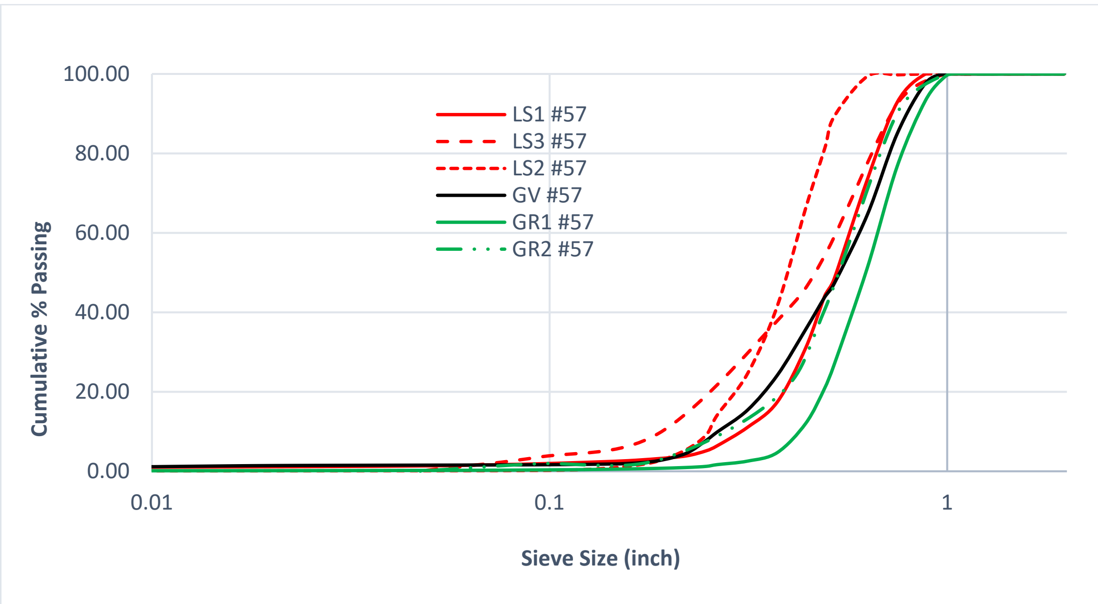


Figure 4-1 Gradation curve of coarse aggregates

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.

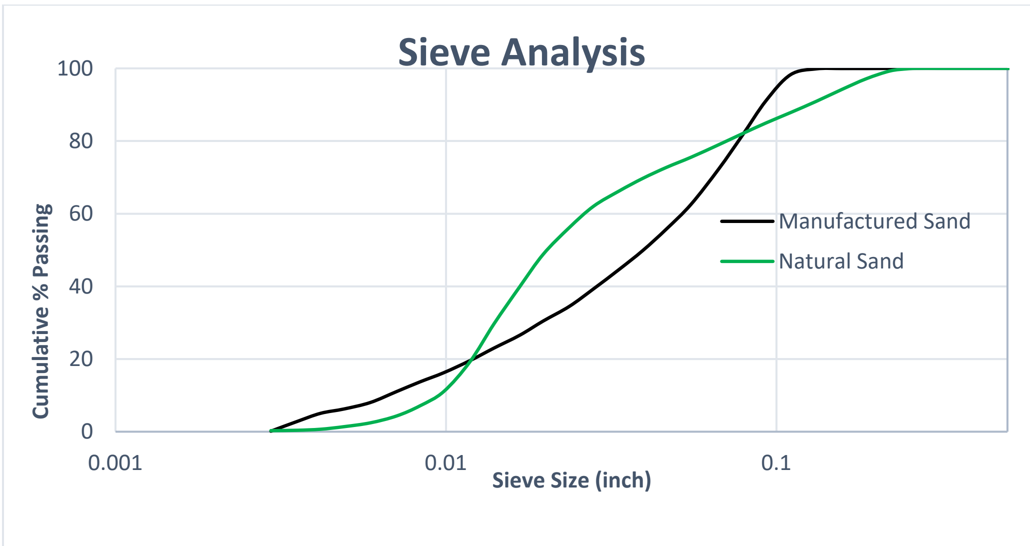


Figure 4-2 Gradation curve of fine aggregates

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.

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

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.

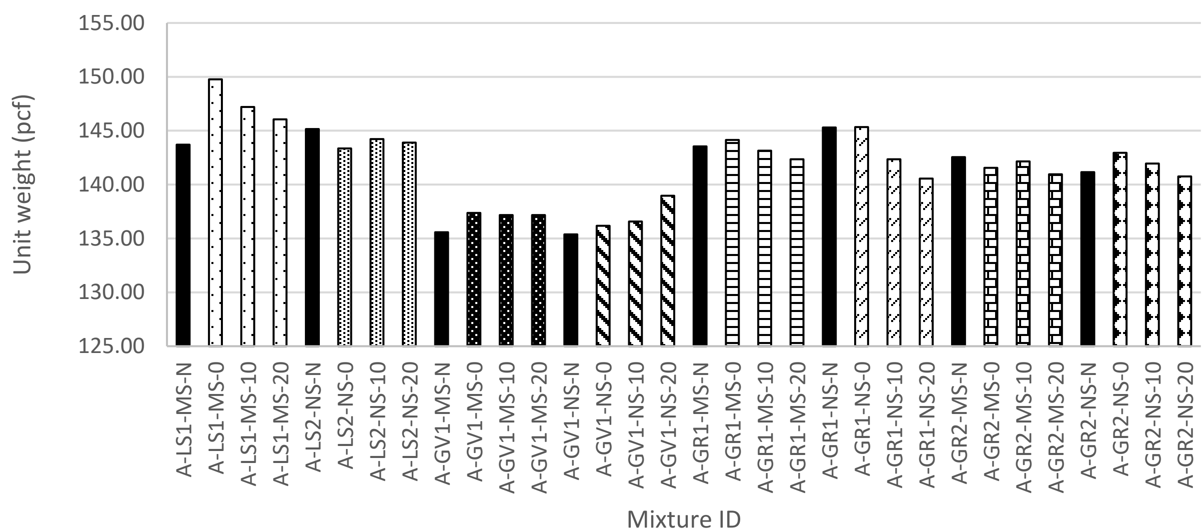


Figure 4-3 Unit weight of Class A mixture

4.2.1.2 Slump

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

(a) Nonoptimized control mixture | (b) Optimized mixture (0%) | (c) Optimized mixture (10%) | (d) Optimized mixture (20%)

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. Remarkably, 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 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.

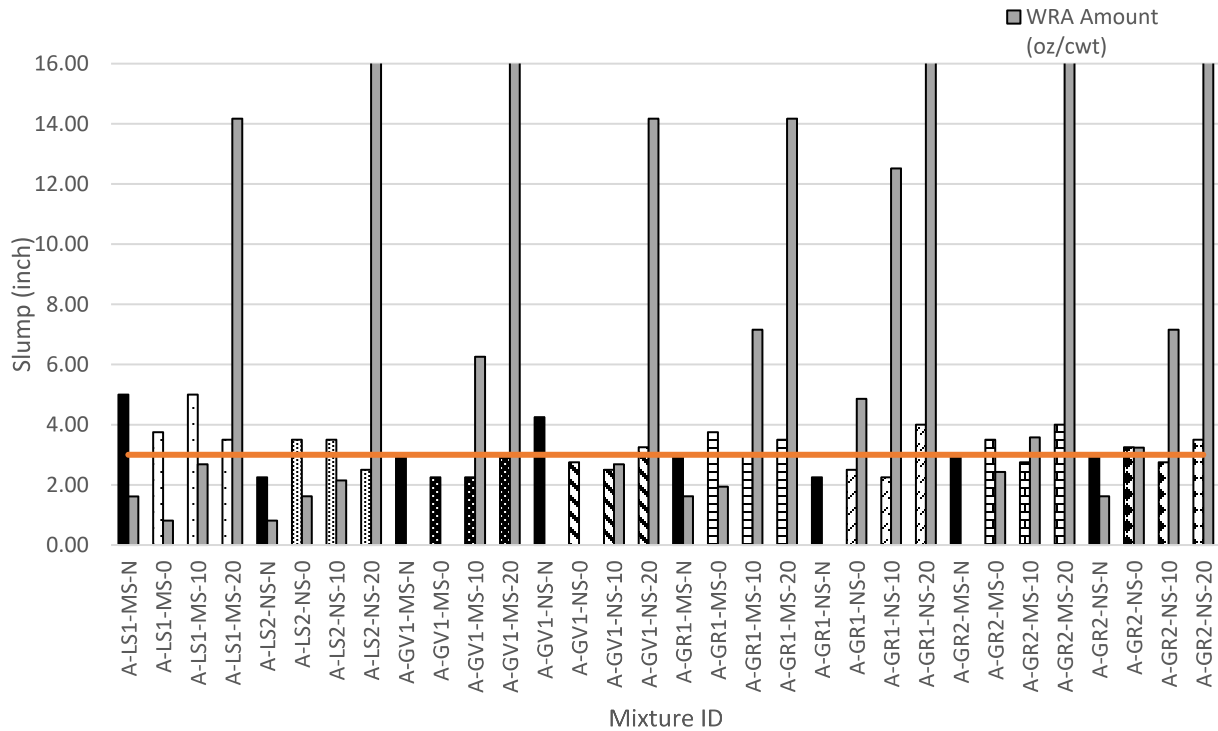


Figure 4-5 Slump of Class A mixtures

4.2.1.3 Air Content

The mixtures subjected to batch testing for this project 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.

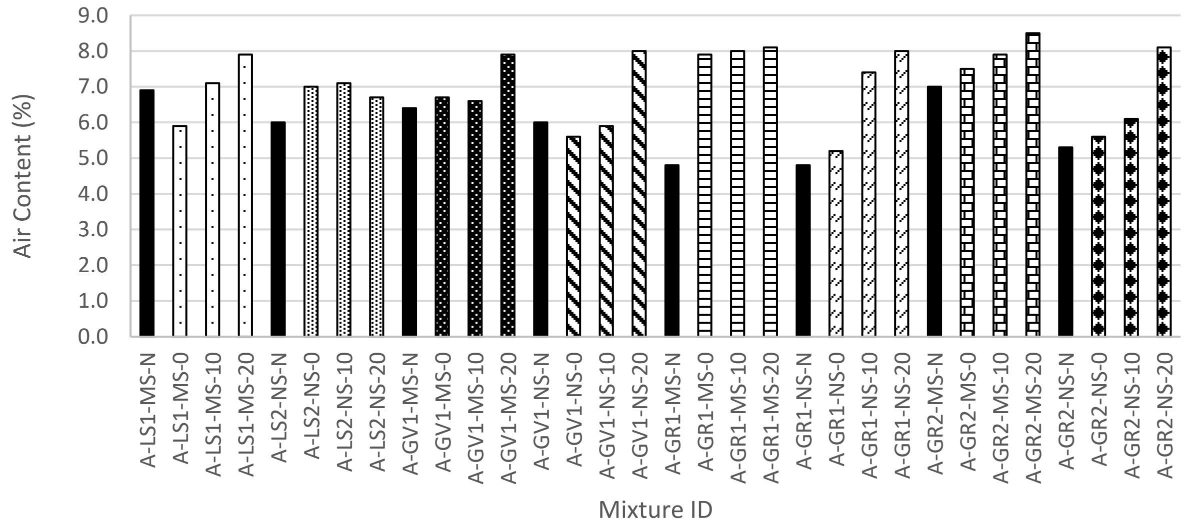


Figure 4-6 Air content of Class A mixtures

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 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.

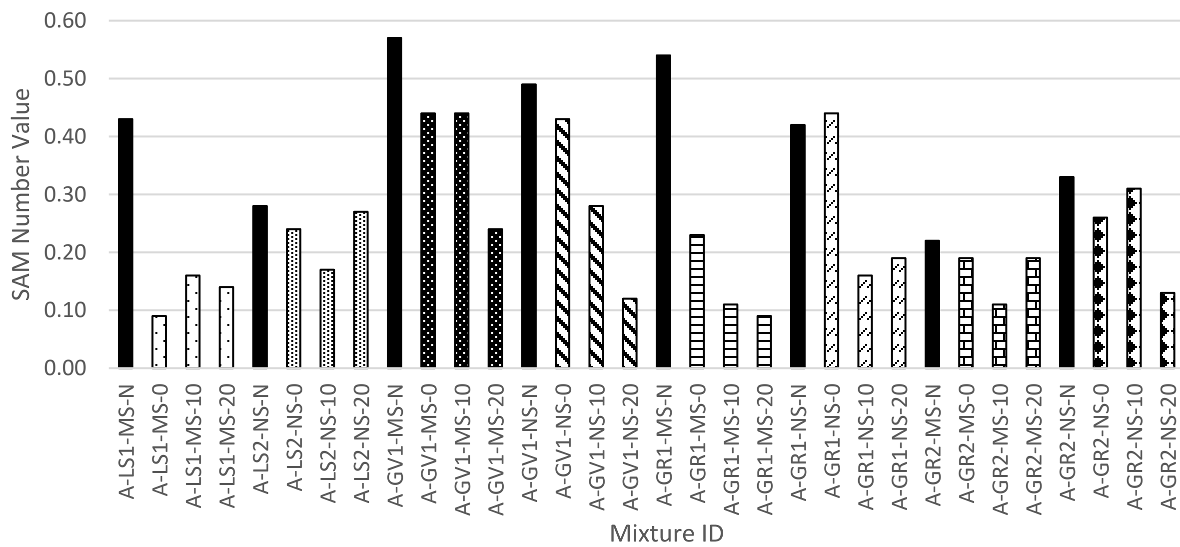


Figure 4-7 SAM number results for Class A mixtures

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.

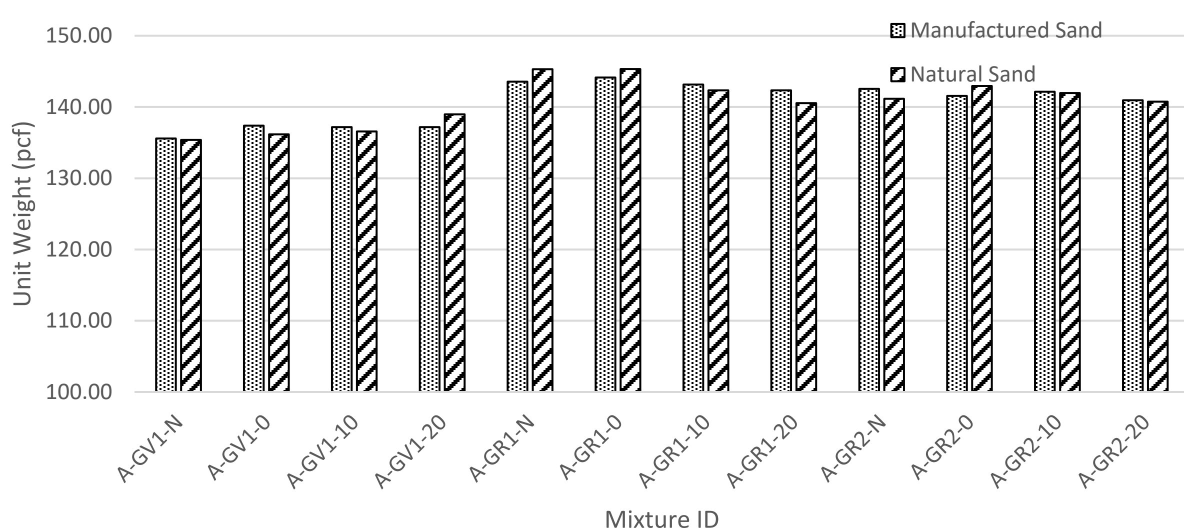


Figure 4-8 Effect of different fine aggregates on unit weight

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 characteristics.

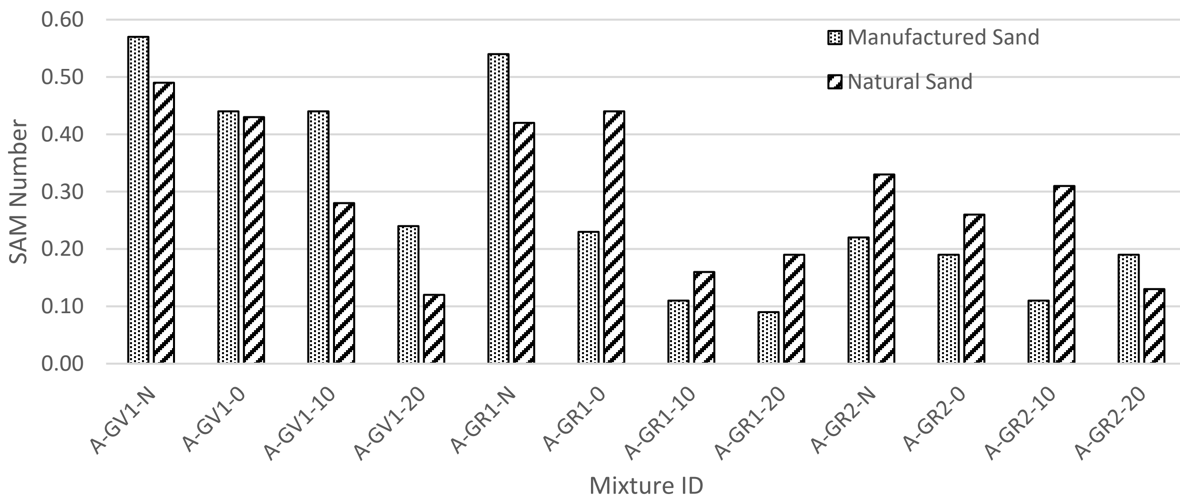


Figure 4-9 Effect of different fine aggregates on SAM number

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 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).

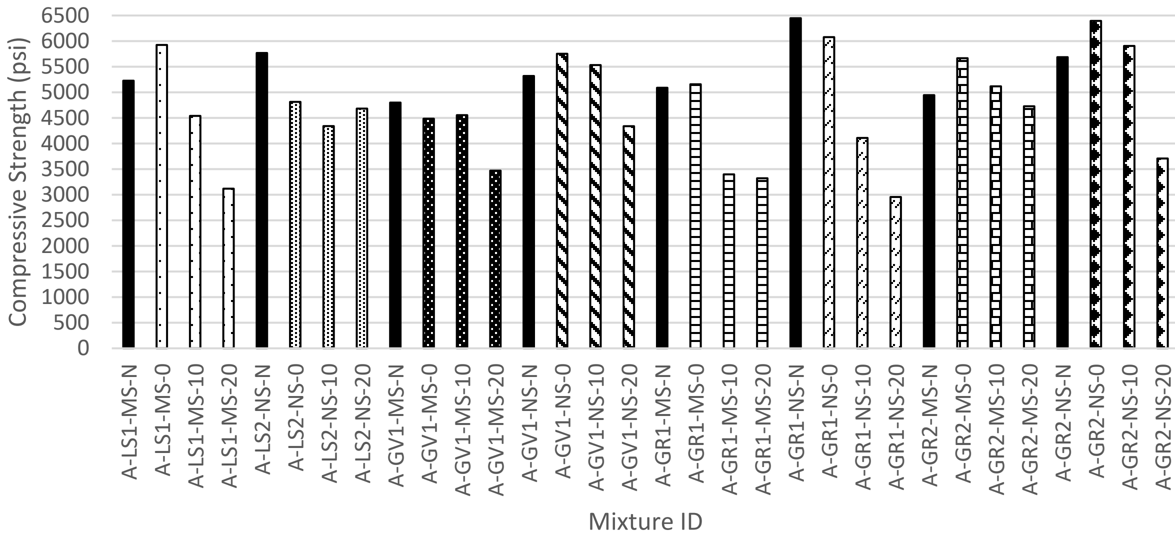


Figure 4-10 28 days compressive strength of Class A mixtures

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

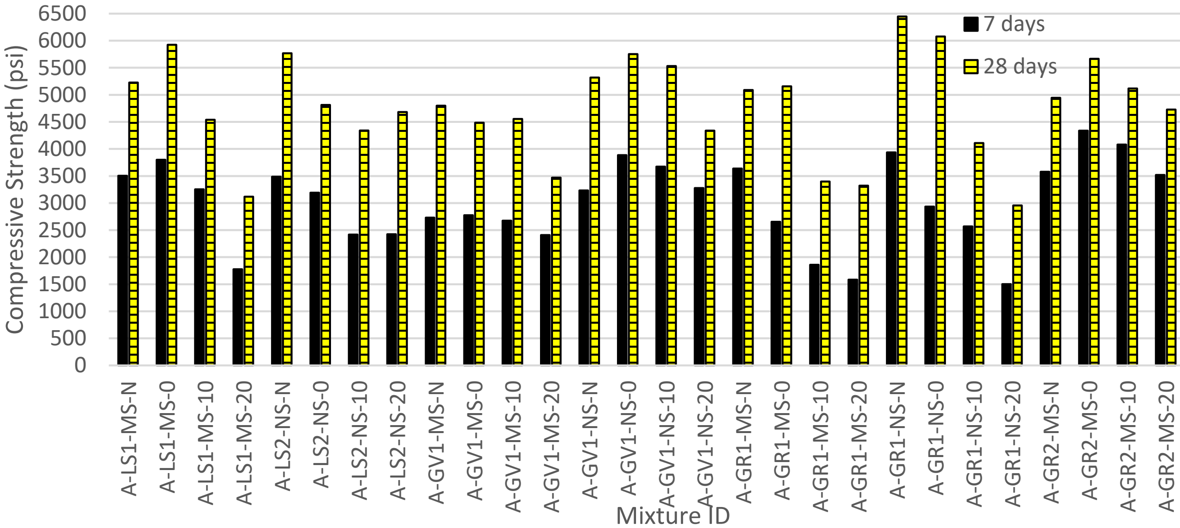


Figure 4-11 7 days and 28 days compressive strength results

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.

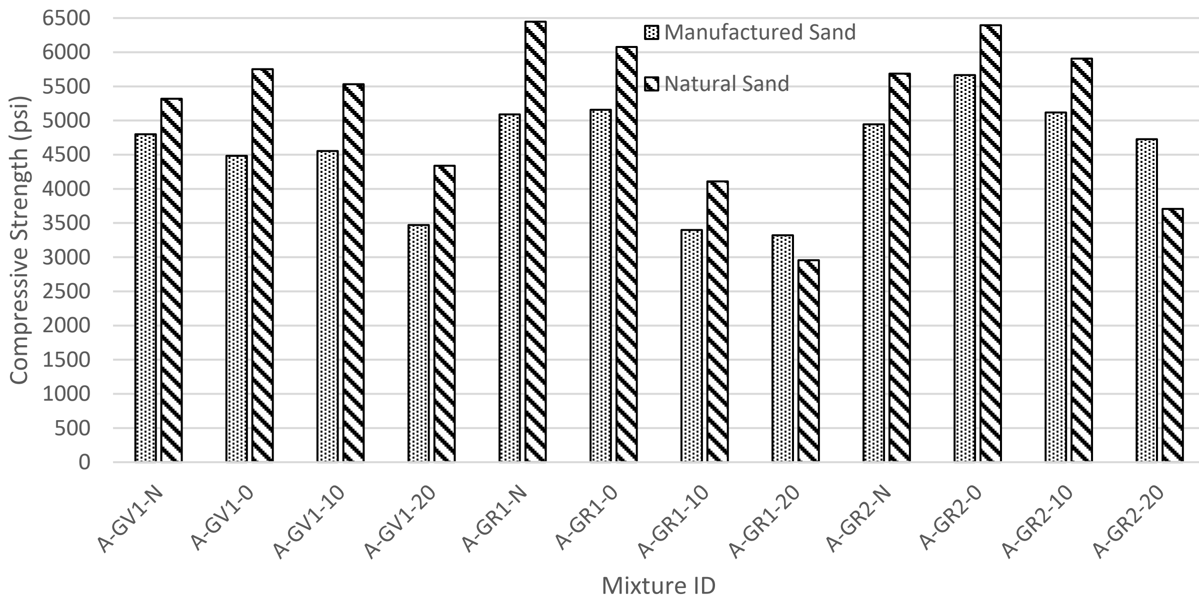


Figure 4-12 Effect of different fine aggregates on compressive strength

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 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 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).

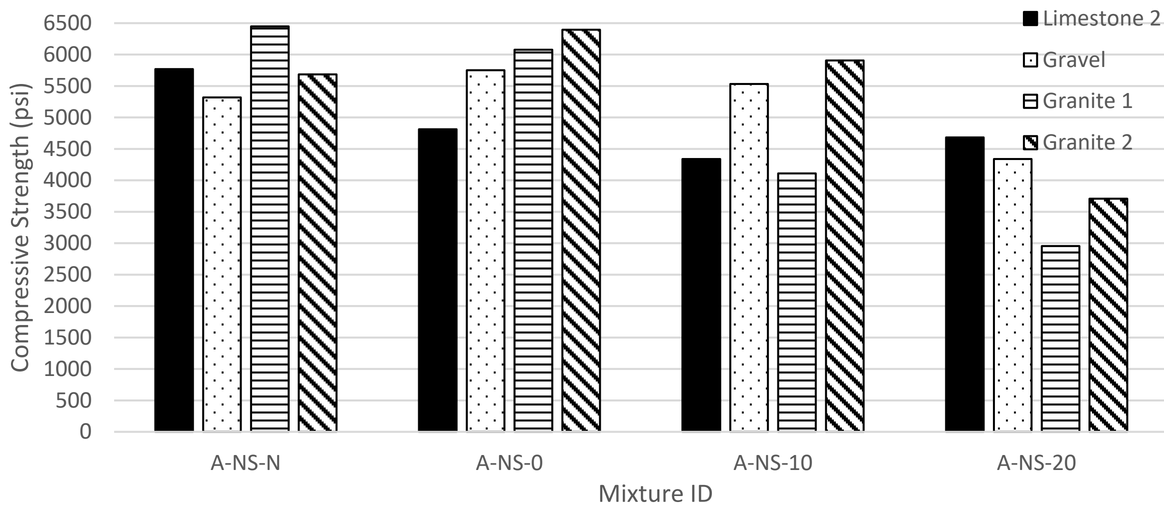


Figure 4-13 Effect of different coarse aggregates on compressive strength

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.

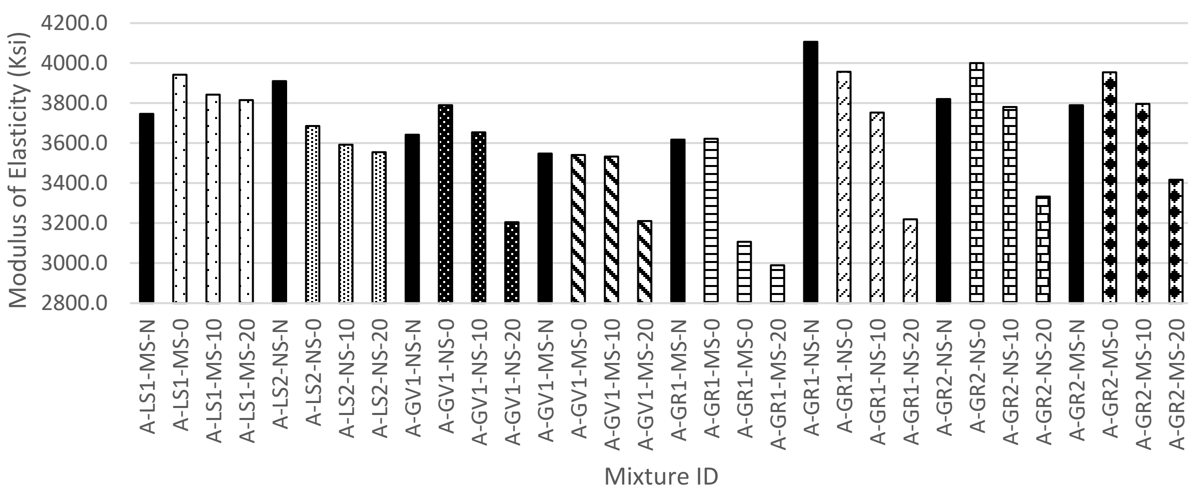


Figure 4-14 MOE results for Class A mixtures

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 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.

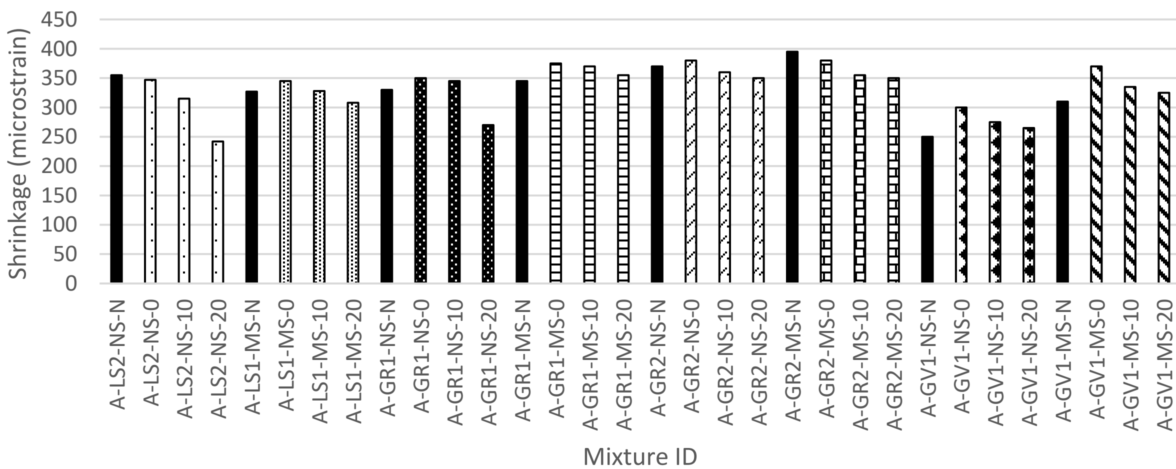


Figure 4-15 Drying shrinkage results at 28 days

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 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.

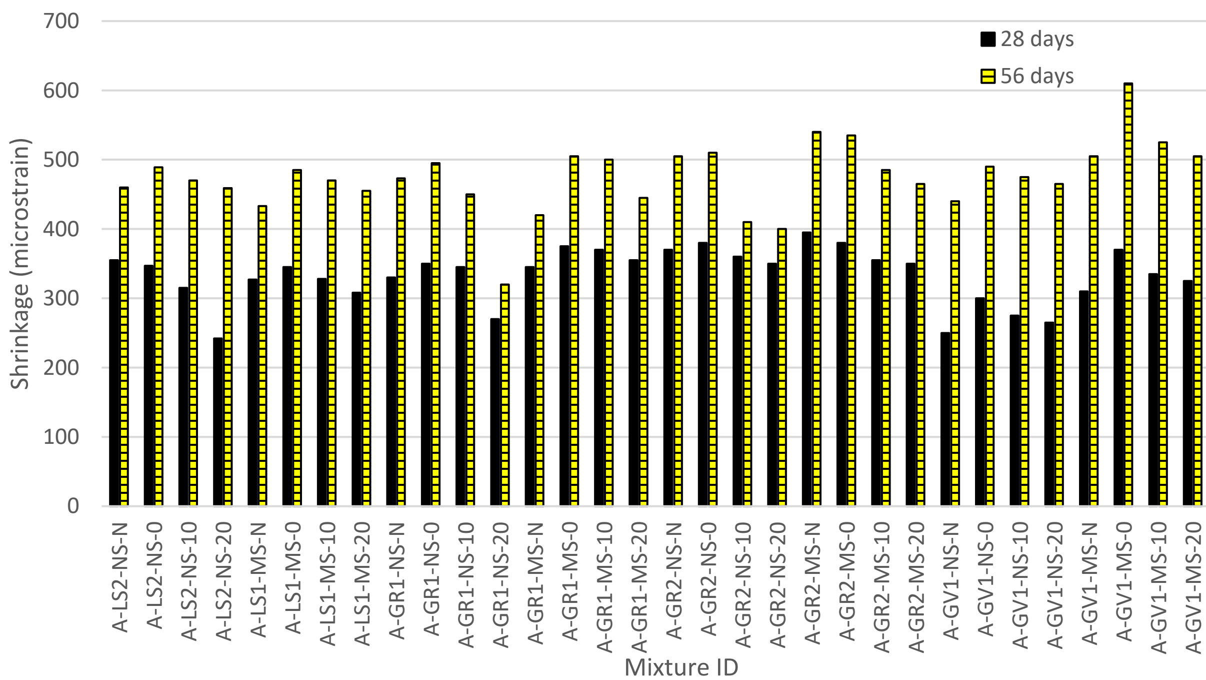


Figure 4-16 Drying shrinkage results at 28 days, and 56 days

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 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 (KΩ) 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 KΩ-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.

Table 4-4 Class A surface resistivity results

	Corrected Apparent Surface Resistivity (KΩ-cm)			Service Life Surface Resistivity (KΩ-cm)		
Mix ID	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

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 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.

Table 4-5 Class A surface resistivity results of comparable mixtures with a) Control Mixtures, b) 0% Reduction, c) 10% Reduction, and d) 20% Reduction

a	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	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	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	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

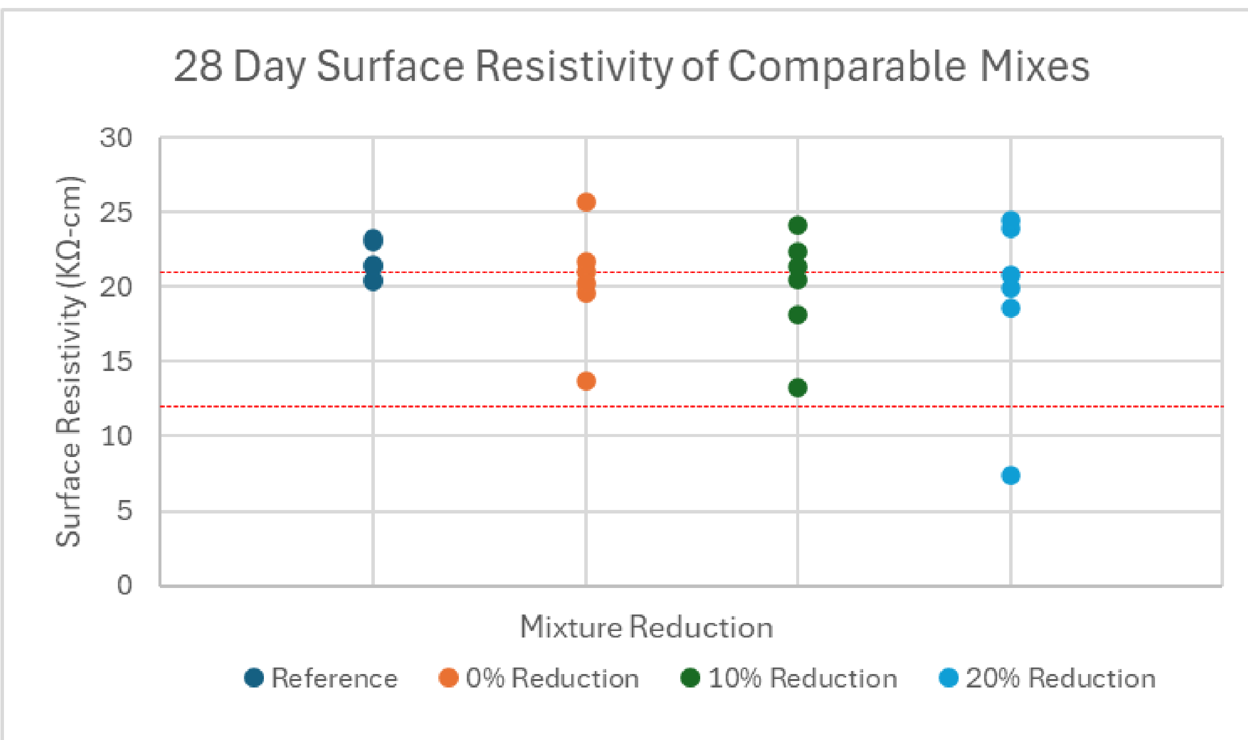


Figure 4-17 Surface resistivity of comparable Class A mixtures

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 crucial information for predicting potential cracking and long-term performance. Additionally, surface resistivity measurements were taken at 28, 56, and 90 days as a non-destructive indicator of permeability and potential 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.

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

Mixture ID	Slump (inch)	Unit Weight (pcf)	Air Content (%)	SAM Number
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

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, 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).

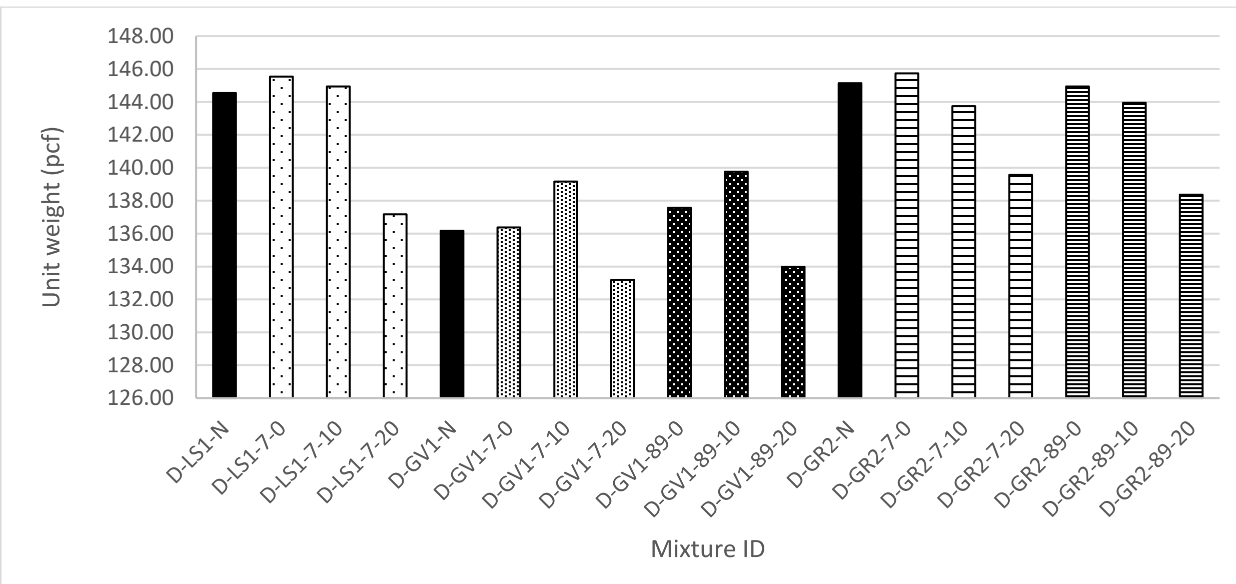


Figure 4-18 Unit weight of Class D/Ds mixtures

4.3.1.2 Slump

TDOT specifications for Class D/Ds concrete require a slump of less than 8 inches. To ensure a consistent basis for comparison across different mixtures, this project 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 aggregate packing in optimized mixtures.

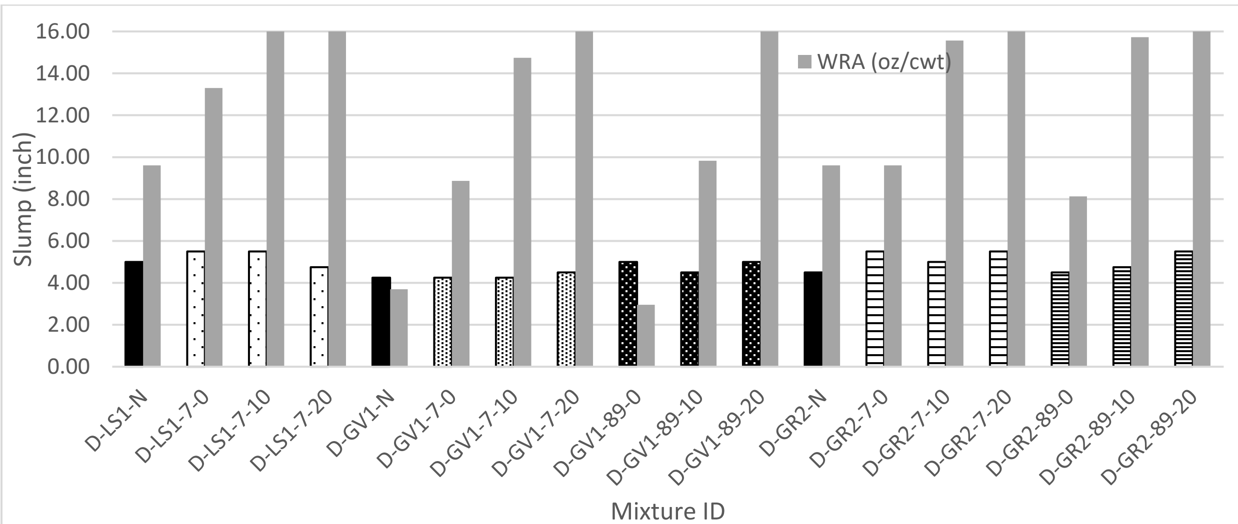


Figure 4-19 Slump of Class D/Ds mixtures

4.3.1.3 Air Content

In this project, 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. This range is within the manufacturer's recommended guidelines of 0.125 to 1.5 oz/cwt.

Interestingly, 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.

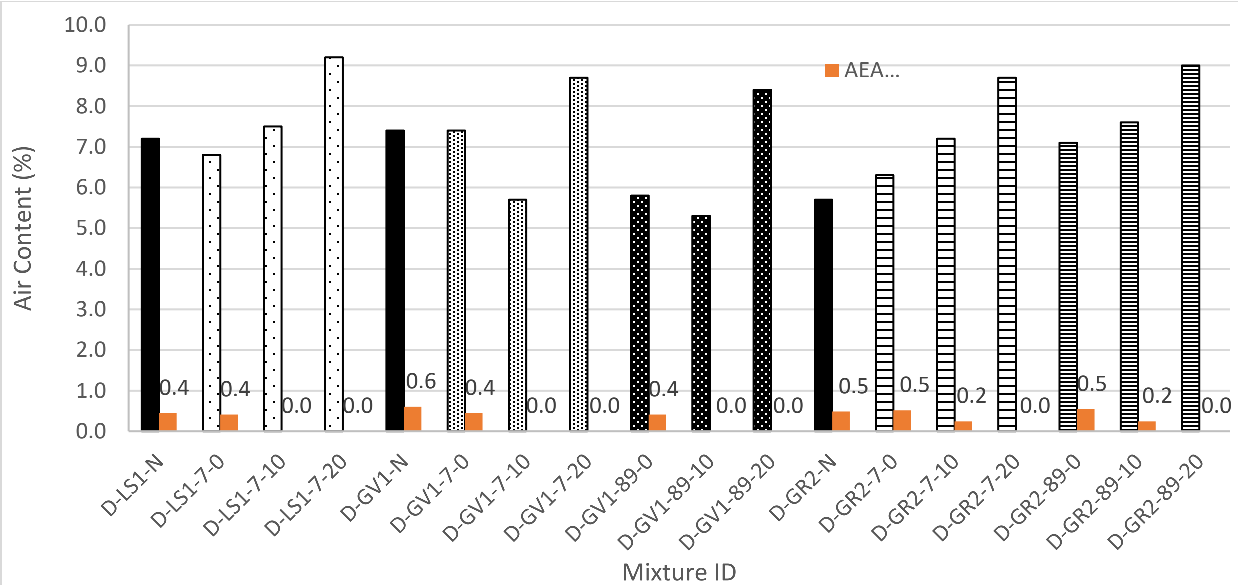


Figure 4-20 Air content of Class D/Ds mixtures

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 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.

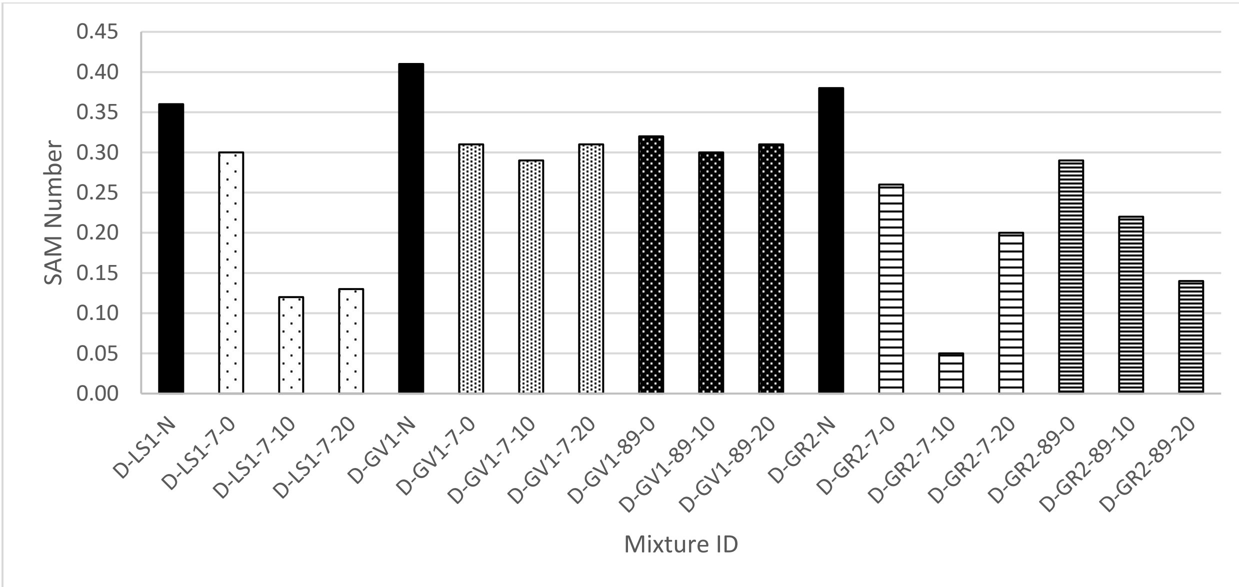


Figure 4-21 SAM number results for Class D/Ds mixtures

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

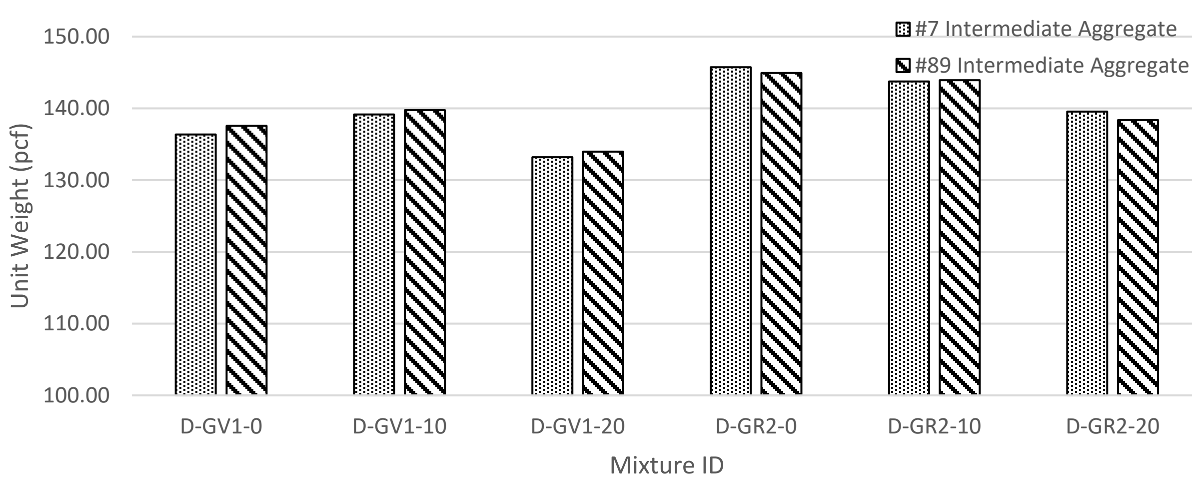


Figure 4-22 Effect of intermediate aggregates on unit weight

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.

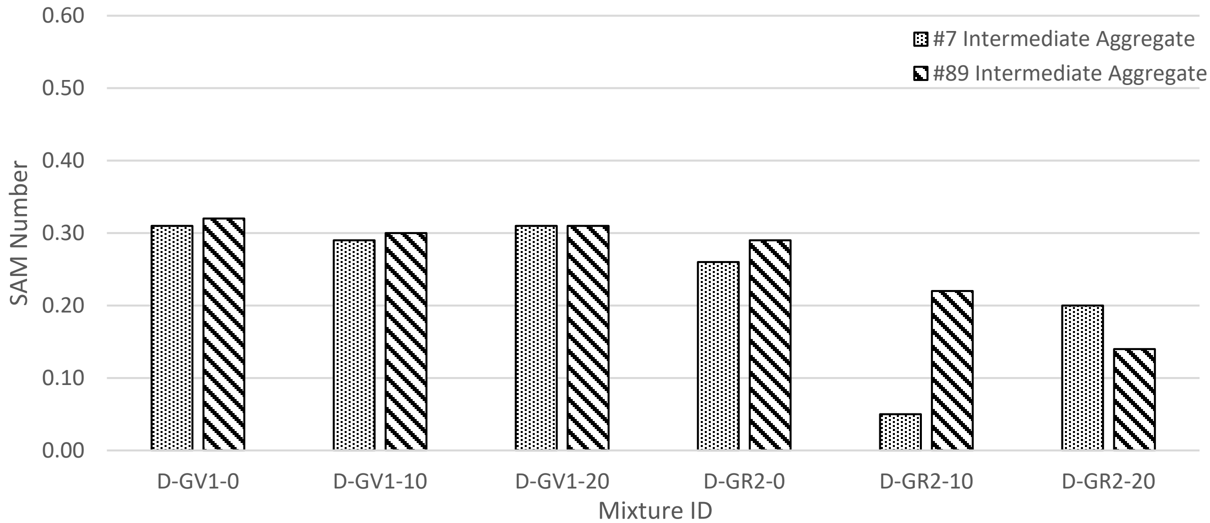


Figure 4-23 Effect of intermediate aggregates on SAM number

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 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 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 projects.

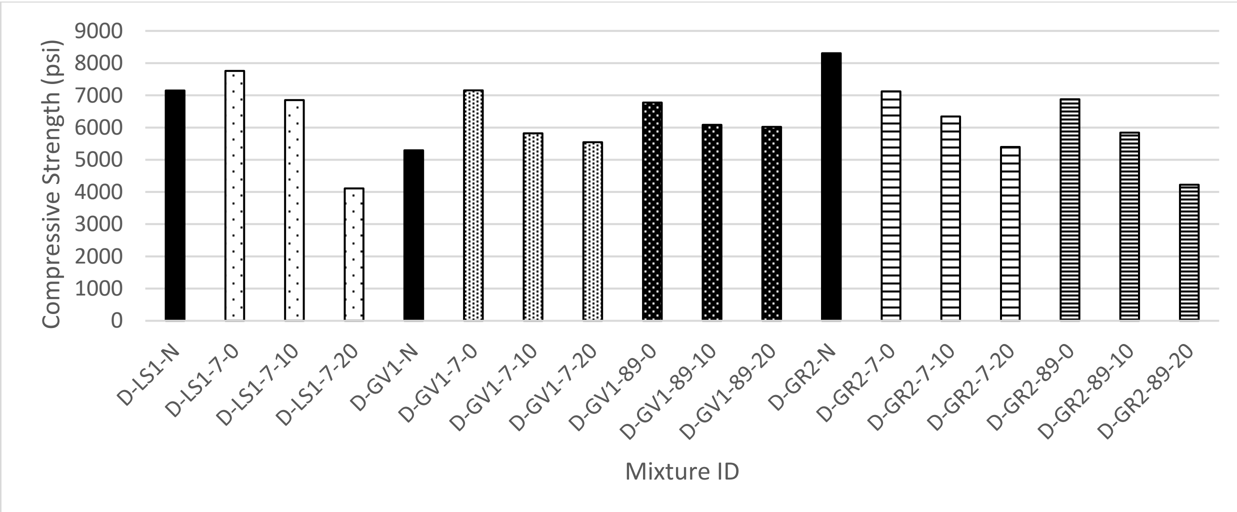


Figure 4-24 28 days compressive strength of Class D/Ds mixtures

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

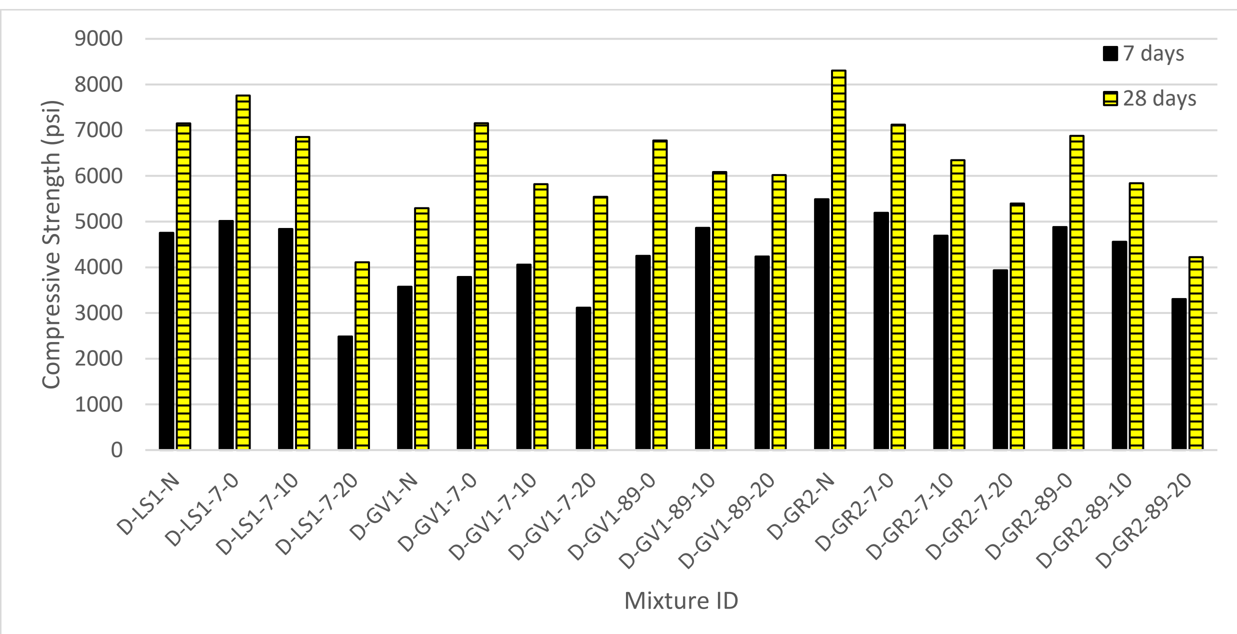


Figure 4-25 7 days and 28 days compressive strength results for Class D/Ds mixtures

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.

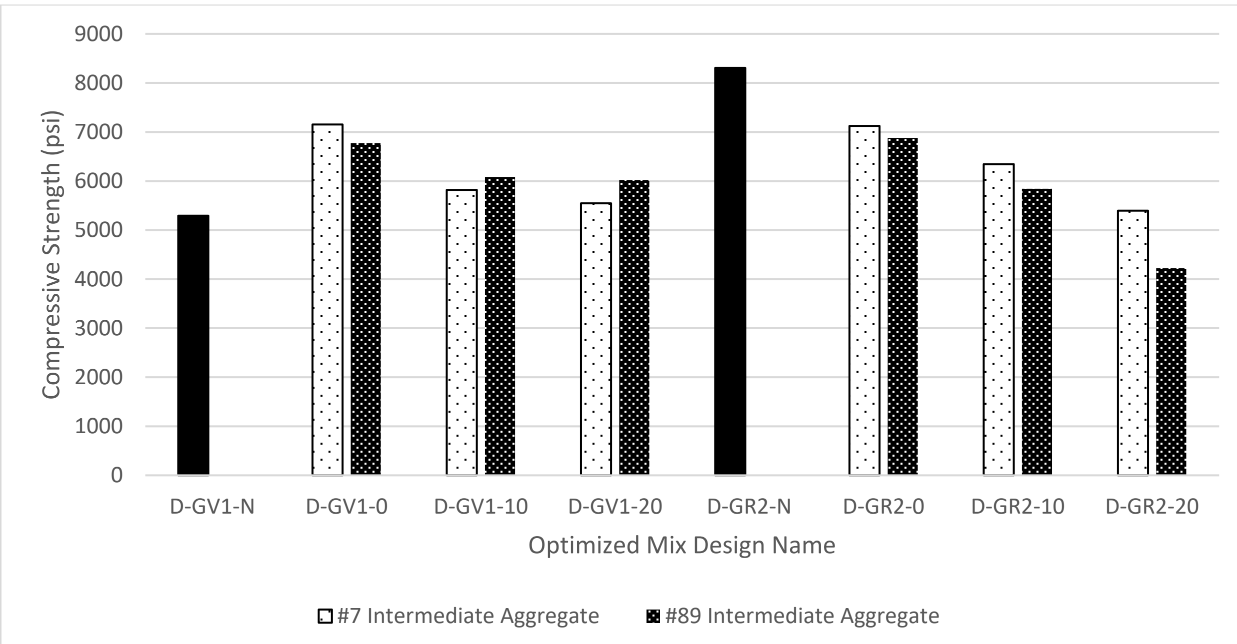


Figure 4-26 Effect of intermediate aggregates on compressive strength

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

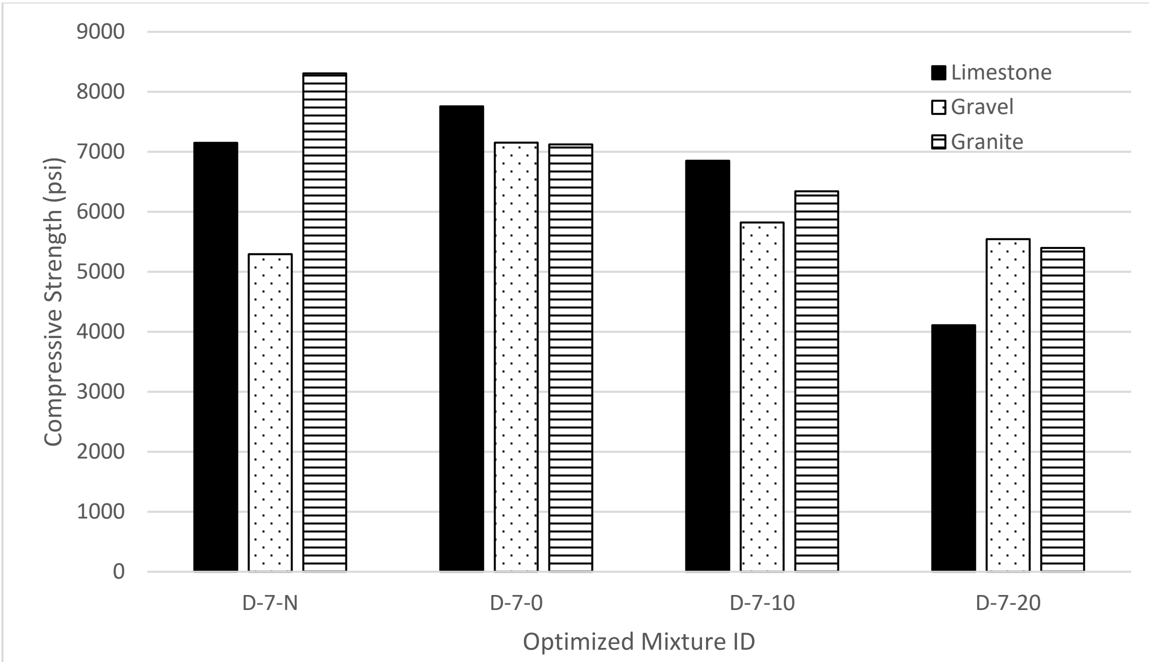


Figure 4-27 Effect of different coarse aggregates on compressive strength

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 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

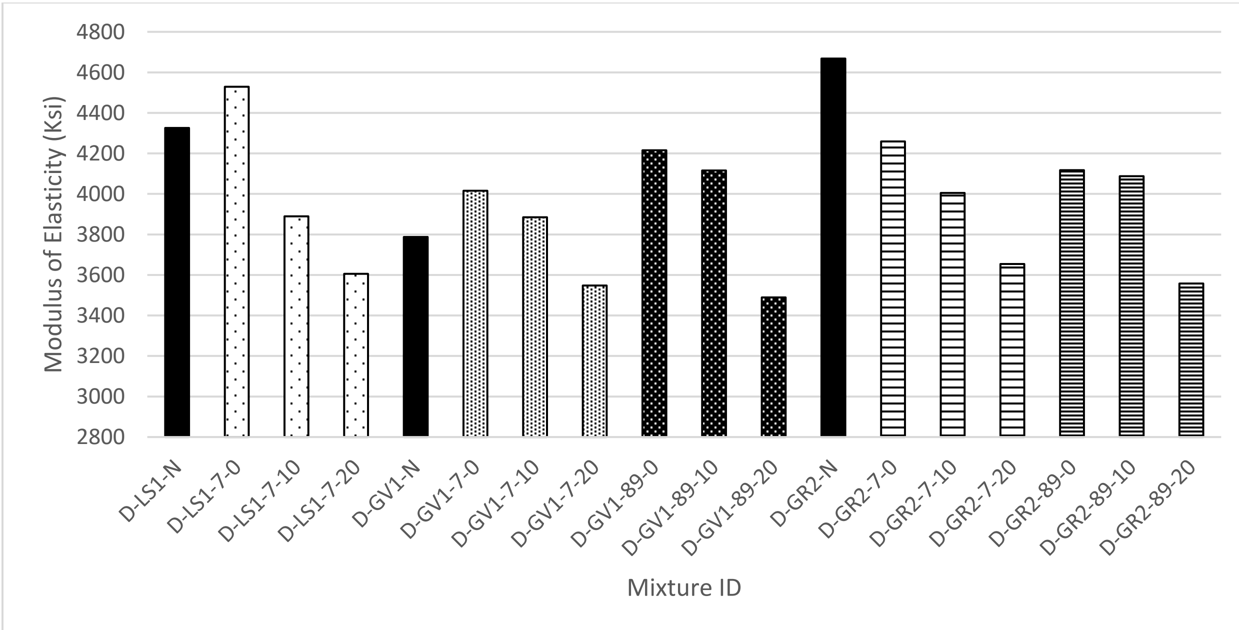


Figure 4-28 MOE results for Class D/Ds mixtures

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 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.

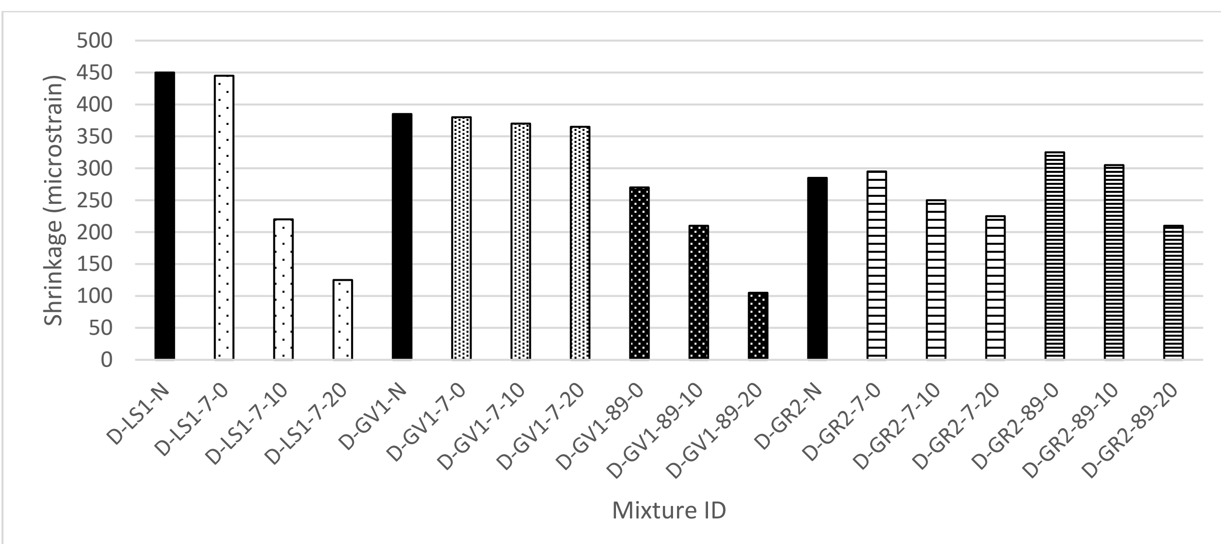


Figure 4-29 Drying shrinkage results at 28 days

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.

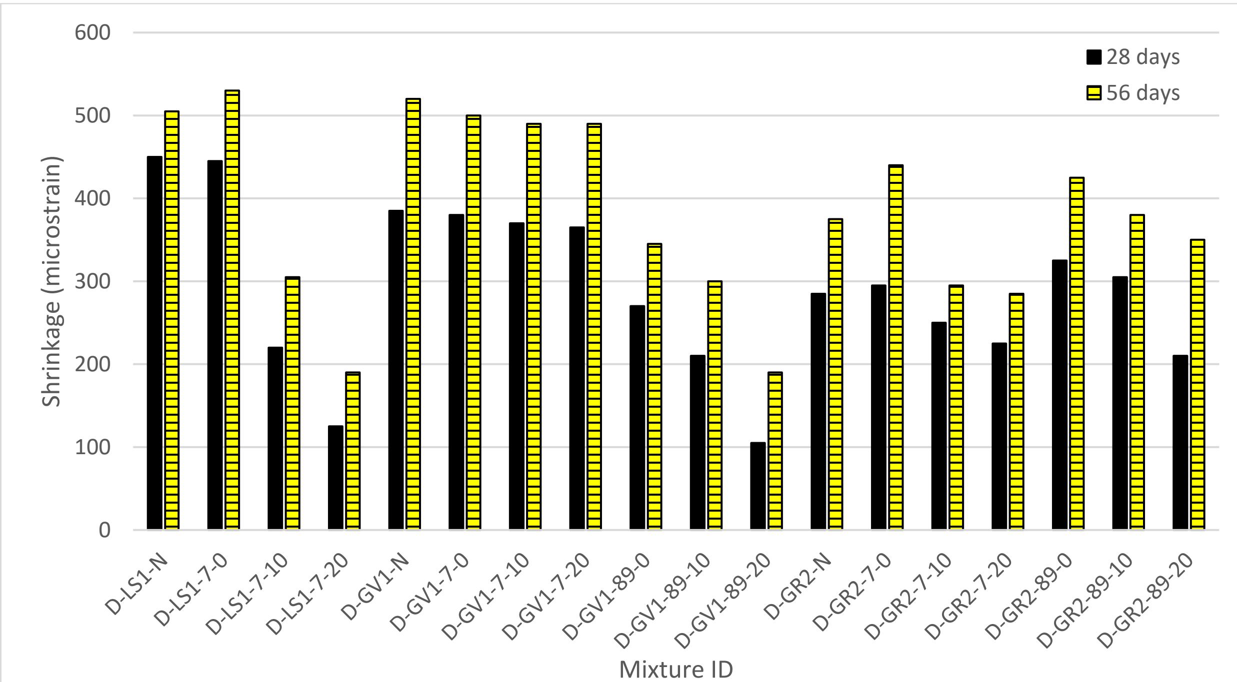


Figure 4-30 Drying shrinkage results at 28 days and 56 days

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.

Table 4-7 Class D/Ds surface resistivity results

	Corrected Apparent Surface Resistivity (KΩ-cm)			Service Life Surface Resistivity (KΩ-cm)		
Mix ID	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

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.

Table 4-8 Class D/Ds surface resistivity results of comparable mixtures with a) Control Mixtures, b) 0% Reduction, c) 10% Reduction, and d) 20% Reduction

a	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	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	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	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

At 90 days, there was actually a larger change in average resistivity (19.16 KΩ-cm) than at 56 days (18.61 KΩ-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 KΩ-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 KΩ-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.

Chapter 5 Conclusions

5.1 Findings and 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.

5.2 Specification Modification Recommendations

Based on the research findings presented in the document, here are some recommendations for TDOT Specification modifications to incorporate OAG techniques:

- Introduce a new section in the TDOT specifications that allows for the use of optimized aggregate gradation techniques, specifically mentioning the Tarantula Curve method and the Coarseness Factor Chart method. This section should:

  a) Provide the acceptable limits for combined aggregate gradation using the Tarantula Curve method according to Cook et al. (2013).

  b) Define the optimal zone (Zone II) in the Coarseness Factor Chart for well-graded mixtures.

  c) Allow flexibility in aggregate proportioning to meet these gradation requirements, including the use of intermediate aggregates (#7 and #89 sizes).

- An additional bin for intermediate aggregates would be highly beneficial for implementing OAG procedures. For coarse aggregates, a minimum of two bins is recommended. The survey shows that most plants already use multiple coarse aggregate sizes, predominantly #57 and #67. Having at least two bins for coarse aggregates makes it easier to combine different sizes while choosing coarse aggregate for optimized mixtures. This will be beneficial for achieving the desired gradation curves in OAG methods such as the Tarantula curve or Shilstone chart. For fine aggregates, at least one bin is necessary, but two would be ideal. While most surveyed plants currently use only one bin for fine aggregates, having an additional bin would allow for the combination of natural and manufactured sands. By implementing these minimum bin requirements, TDOT can ensure that concrete plants across Tennessee have the basic capabilities needed to adopt OAG procedures.
- Modify the current minimum cementitious material content requirements to allow for reductions based on optimized gradations:

  a) For Class A mixtures: Allow reductions of up to 10% from the current 564 lb/yd^3, with a new minimum of 508 lb/yd^3.

  b) For Class D/DS mixtures: Allow reductions of up to 10% from the current 620 lb/yd^3, with a new minimum of 559 lb/yd^3.

  c) Include a clause stating that these reductions are permissible only when using approved OAG techniques and meeting all performance requirements.

- Introduce new quality control measures specific to OAG mixtures:

  a) Require regular aggregate gradation checks to ensure compliance with the optimized gradation.

  b) Implement field testing protocols to verify that reduced cementitious content mixtures are meeting performance requirements.

- Consider adopting the SAM number as a specification requirement for freeze-thaw durability. Recommend a maximum SAM number of 0.30, with a preferred value below 0.20, based on the study's findings and AASHTO T 395 guidelines.

- Given Tennessee's varied climate and potential exposure to deicing salts, assessing chloride penetration resistance is important for long-term durability of concrete structures. Implementing surface resistivity testing aligns with the broader goal of moving towards performance-based specifications, as outlined inthe research objectives. TDOT could consider adopting surface resistivity requirements similar to AASHTO T 358.

- For future research efforts, TDOT should prioritize a comprehensive investigation into the workability characteristics of OAG concrete mixtures. That future study should focus on key areas including rheological properties, time-dependent workability, pumping characteristics, and extensive field trials to validate laboratory findings. A critical aspect of this research should be the examination of admixture effectiveness and dosage requirements in OAG mixtures, as the current study revealed that these mixtures often require different admixture dosages compared to conventional concrete. That analysis would provide valuable insights into the practical implementation of OAG mixtures in various construction scenarios, potentially leading to improved guidelines for mixture design and placement. By understanding these workability aspects more thoroughly, TDOT can enhance the adoption and effectiveness of OAG mixtures, ultimately leading to more durable and sustainable concrete infrastructure.

These recommendations aim to incorporate the benefits of optimized aggregate gradation into TDOT specifications while ensuring that concrete performance and durability are maintained or improved. The modifications should be implemented gradually, with proper training and guidance provided to TDOT personnel, contractors, and producers to ensure successful adoption of these new practices.

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Appendix A: Material Properties

- Chemical composition of the cement (type IL)

Chemical	ASTM C-114
SiO_2 (%)	19.2
Al_2O_3 (%)	4.2
Fe_2O_3 (%)	3.16
CaO (%)	63.6
MgO (%)	3.5
SO_3 (%)	2.33
Total Alkali ($Na_2O + 0.658K_2O$)	0.52
Ignition Loss	5.0
Insoluble Residue	0.58
C_3S (%)	73.5
C_2S (%)	-0.3
C_3A (%)	5.8
C_4AF (%)	9.6
$C_3S + 4.75C_3A$	101.1
CO_2 (%)	4.3
Limestone (%)	10.4
$CaCO_3$ in Limestone (%)	88.5

Physical	ASTM C-150	
Time of Set (Vicat)		
Initial Set (min.)	134	
Final Set (min.)	242	
Compressive Strength	PSI	MPa
1 Day	1982	13.7
3 Day	3502	24.1
7 Day	4723	32.6
28 Day	6477	44.7
Cube Flow	119	
Fineness, Blaine	3894	
325 Mesh (%)	92.2	
Air Content (%)	5.7	
Normal Consistency (%)	24.3	
False Set (%)	66.4	
Autoclave Expansion (%)	0.04	
Specific Gravity	3.14	

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

- Specific gravity of the 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

- Chemical composition of the fly ash (Class F)

Chemical Analysis	Results (wt%)	Specification (Class F) ASTM C618-22	Specification (Class F) AASHTO M295-19
Silicon Dioxide (SiO_2)	**43.5**	----	----
Aluminum Oxide (Al_2O_3)	**19.5**	---	----
Iron Oxide (Fe_2O_3)	**13.32**	----	----
Sum of Silicon Dioxide, Iron Oxide & Aluminum Oxide (SiO_2+Al_2O_3+Fe_2O_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_2O)	**1.16**	----	----
Potassium Oxide (K_2O)	**1.53**	---	----
"Sodium Oxide Equivalent (Na_2O+0.658K_2O)"	**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_2O) as Available Alkalies	**0.26**	----	----
Potassium Oxide (K_2O) as Available Alkalies	**0.29**	----	----
Available Alkalies as "Sodium Oxide Equivalent (Na_2O+0.658K_2O)"	**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: Control Average, psi: 4960; Test Average, psi: 4420	**89%**	75 % min.† (of control)	75 % min.† (of control)
At 28 Days: Control Average, psi: 6010; Test Average, psi: 5970	**99%**	75 % min.† (of control)	75 % min.† (of control)
Water Requirements (Test H_2O/Control H_2O) Control, mls: 242; Test, mls: 230	**95%**	105% max.† (of control)	105% max.† (of control)
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.

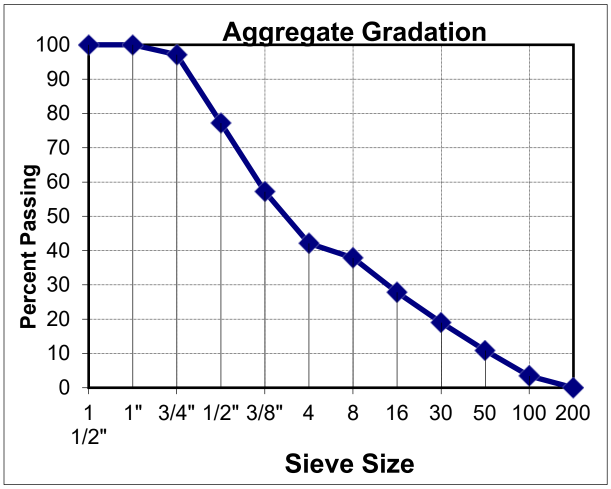
Appendix B: Optimization Process

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

	Percent Passing Sieve					Combined (by Volume)
	VCV SAND	Sand 2	A	B	C	(%)
Sieve Size	40.8%	0.0%	35.9%	23.3%	0.0%	100.0
1.5"	100	100	100	100	100	**100.0**
1"	100	100	100	100	100	**100.0**
3/4"	100	100	92.01	99.95	99.6	**97.1**
1/2"	100	100	40.79	93.33	57.2	**77.2**
3/8"	100	100	16.63	44.77	30.3	**57.2**
4	99.75	98.9	2.31	2.54	1	**42.1**
8	90.98	82.7	1.47	0.92	0	**37.9**
16	66.89	55.9	1.15	0.59	0	**27.8**
30	45.35	37.3	1	0.48	0	**19.0**
50	25.51	17.2	0.88	0.42	0	**10.8**
100	7.57	6.1	0.71	0.34	0	**3.4**
200	1.23	2.2	0.13	0.07	0	**0.6**

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

Sieve Number	Combined % Passing	Combined % Retained
1.5"	100.00%	0.00%
1"	100.00%	0.00%
3/4"	97.23%	2.77%
1/2"	77.37%	19.86%
3/8"	58.14%	19.23%
#4	42.37%	15.77%
#8	38.43%	3.94%
#16	29.21%	9.21%
#30	19.92%	9.29%
#50	10.96%	8.96%
#100	3.57%	7.39%
#200	1.66%	1.90%



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

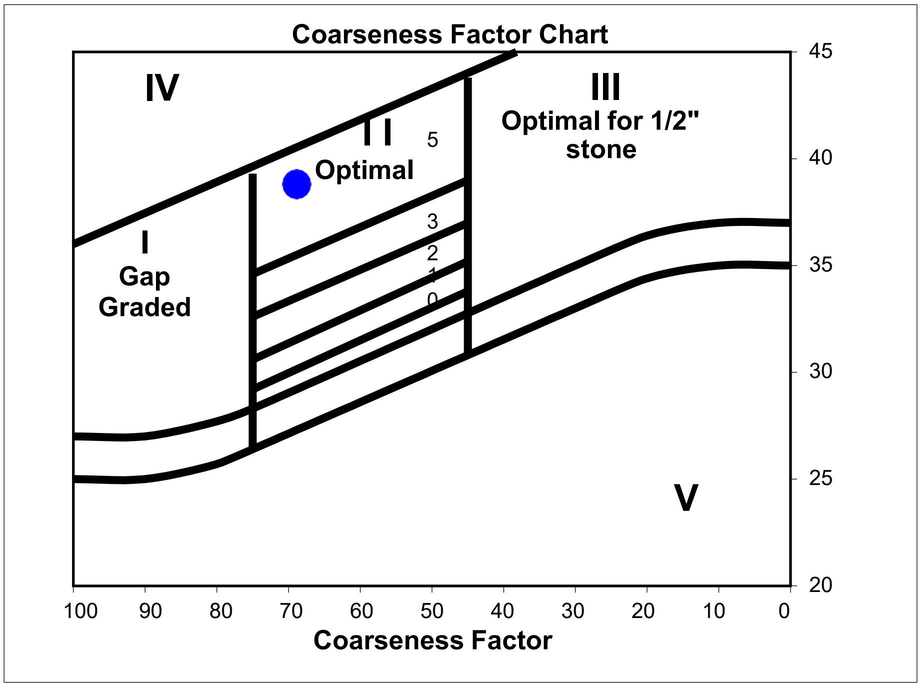
Mix Constituent		Sp. Grav.	Qty (SSD)	Vol (cu.ft.)	Comments	
Type IL		3.15	423	2.152		75%
Fly Ash Type F		2.54	141	0.890		25%
		2.89	0	0.000		0%
Sand	VCV SAND	2.69	1251	7.453		
Sand2	# 8 CA	2.74	0	0.000		
A	#57 BW	2.78	1138	6.560		
B	#7 BW	2.75	730	4.254		
C	3/8"	2.74	0	0.000		
Water (gallons)		1	30.50	4.072		
Admix 1 (air)	2.00	oz/CY	6.00%	1.620	Entrapped Air	
Admix 2	7.00	oz/cwt	0.0	0.000	ADVA 140	
Admix 3	0.00	oz/cwt	0.0	0.000		
Total cementitious content:		564	Total	27.00		
Unit Weight (pcf): 145.82		Water/Cement Ratio:		0.450		

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

Combined (by Volume)	Retained on Sieve	Retained Requirement
(%)	(%)	(%)
100.0		
100.0	0.0	0-0
100.0	0.0	0-16
97.1	2.9	0-20
77.2	19.9	4-20
57.2	20.0	4-20
42.1	15.1	4-20
37.9	4.3	0-12
27.8	10.0	0-12
19.0	8.9	4-20
10.8	8.2	4-20
3.4	7.4	0-10
0.6	**56.5**	**0-2**

Coarse Sand % (#8-30) =	**22.45%**	**YES**
Should be greater than 20%		
Fine Sand % (#30-200) =	**27.55%**	
This allowable range for **slipforming** is between 24-34%		**YES**
This allowable range for **pumping** is between 25-40%		**YES**

- **<u>Step -5: Check the value with Coarseness Factor Chart</u>**



Appendix C: Survey Summary

- ***Survey Questions for DOTs, Ready Mix Plants, and Precast Plants***

The survey conducted for DOTs, ready-mix plants, and precast plants provides valuable insights into current practices and perspectives regarding OAG in concrete mixtures. This comprehensive survey covers various aspects of concrete mixture design, aggregate selection, and performance requirements. For DOTs, the survey focused on three main areas: mixture parameters, fresh performance, and hardened performance. The questions aimed to understand the specific methods and limits used for aggregate gradation optimization, such as the Tarantula curve, Power 45 curve, Shilstone chart, or Haystack limits. It also inquired about gradation limits for individual sieves, minimum cementitious content, paste volume limits, and fine-to-total aggregate ratio limits. These questions help gauge the level of adoption of OAG techniques across different state DOTs and the specific parameters they prioritize. The fresh and hardened performance sections of the DOT survey sought information on slump limits, air content requirements, strength specifications, and durability measures such as shrinkage and electrical resistivity. This comprehensive approach allows for a holistic understanding of how OAG is integrated into concrete specifications and performance expectations. For ready-mix plants, the survey delved into the practical aspects of implementing OAG. It inquired about the use of combined aggregate gradation in mix designs and the specific techniques employed. The detailed questions about aggregate types, sizes, and bin configurations provide insight into the logistical considerations and capabilities of ready-mix plants in adopting OAG methods. This information is crucial for understanding the feasibility of implementing new gradation techniques in real- world production settings. The survey for precast plants followed a similar structure to that of ready-mix plants but was tailored to the specific applications common in precast production. This differentiation allows for a nuanced understanding of how OAG might be applied differently in precast versus ready-mix environments. Both the ready-mix and precast plant surveys included questions about aggregate types and sizes used for various concrete applications, such as paving mixtures, bridge decks, and self-compacting concrete. This information helps in understanding the current practices and potential areas for optimization in different concrete applications. The final question in both plant surveys, regarding specific aggregate or concrete characteristics maintained for better pumping and finishability, provides valuable practical insights into the challenges and considerations in concrete production beyond just gradation optimization. Overall, this comprehensive survey approach allows for a multi-faceted understanding of OAG implementation across different sectors of the concrete industry. It provides a basis for identifying gaps between current practices and potential improvements, as well as understanding the practical constraints and considerations in implementing OAG techniques.

A.1 DOT Survey Questions

I:Mixture Parameters

a) Do you specify an optimization method for combined aggregate gradation (i.e. Tarantula curve, Power 45 curve, Shilstone chart, or Haystack limits (8-18%)?

b) What are the gradation limits for individual sieves (coarse and fine aggregates) and gradation tolerance, if specified?

c) What is the minimum specified cementitious content (lbs./yd^3 or kg/m^3)?

d) Do you specify a limit for the paste volume/content in concrete? Please provide the limit if specified.

e) What is the fine-to-total aggregate ratio limits, if specified?

II:Fresh Performance

a) What is the slump limit for OAG mixtures?

b) What is the air content and SAM number requirement?

III:Hardened Performance

a) What is the compressive, flexural, and tensile strength requirements for OAG mixtures?

b) What is the shrinkage requirement, if specified?

c) What is Electrical Resistivity and Permeability requirements and testing methods adapted?

A.2 Ready Mix Plants Survey Questions

1. Do you use a combined aggregate gradation in your mix design?

☐ Yes
☐ No

If yes, which technique do you use for developing/optimizing combined aggregate gradation?

☐ Tarantula curve (indicate limits you adapt……………………………………………………………………..)
☐ Power 45 curve
☐ Shilstone Workability-Coarseness Chart
☐ Haystack limits (8-18%)
☐ Other …………………………….

2. How many bins do you carry in your plant for coarse and fine aggregate? (Check all that apply)

Aggregates	**Type of Aggregates in the plant**	**Size of Aggregates in the plant**	**Number of bins per aggregate**
Coarse Aggregates	☐ Crushed Limestone ☐ Granite ☐ Crushed Gravel ☐ Gravel ☐ Other …………………..	☐ #57 ☐ #67 ☐ #7 ☐ #4 ☐ Combined ☐Other…………………..	☐ 1 bin ☐ 2 bins ☐ 3 bins ☐Other…………………..
Fine Aggregates	☐ Natural Sand ☐ Manufactured Sand ☐ Other……………….		☐ 1 bin ☐ 2 bins ☐ 3 bins ☐Other…………………..

Intermediate Aggregate	☐ Crushed Limestone ☐ Granite ☐ Crushed Gravel ☐ Gravel ☐ Other …………………..	☐ 1/2 inch ☐ 3/8 inch ☐ #4 ☐ Other………………..	☐ 1 bin ☐ 2 bins ☐ 3 bins ☐ Other……………..

3. **What is the type and size of coarse and fine aggregate you use for the following applications? (Check all that apply)**

Concrete Application	Type of Coarse Aggregates	Size of Coarse Aggregates	Type of Fine Aggregates
Paving Mixtures (TDOT Class CP, Class A)	☐ Crushed Limestone ☐ Granite ☐ Crushed Gravel ☐ Gravel ☐ Other …………………..	☐ #57 ☐ #67 ☐ #7 ☐ #4 ☐ Combined ☐Other…………………..	☐ Natural Sand ☐ Other………………
Bridge Deck (TDOT Class D)	☐ Crushed Limestone ☐ Granite ☐ Crushed Gravel ☐ Gravel ☐ Other …………………..	☐ #57 ☐ #67 ☐ #7 ☐ #4 ☐ Combined ☐Other…………………..	☐ Natural Sand ☐ Manufactured Sand ☐ Other………………
Bridge Deck – Surface (Polished Resistance) (TDOT Class DS)	☐ Crushed Limestone ☐ Granite ☐ Crushed Gravel ☐ Gravel ☐ Other …………………..	☐ #57 ☐ #67 ☐ #7 ☐ #4 ☐ Combined ☐Other…………………..	☐ Natural Sand ☐ Other………………
General Structural Applications	☐ Crushed Limestone ☐ Granite ☐ Crushed Gravel ☐ Gravel ☐ Other …………………..	☐ #57 ☐ #67 ☐ #7 ☐ Combined ☐Other…………………..	☐ Natural Sand ☐ Manufactured Sand ☐ Other………………
Drill shaft and Self Compacting mixtures (TDOT Class SCC)	☐ Crushed Limestone ☐ Granite ☐ Crushed Gravel	☐ #67 ☐ #7 ☐ Combined	☐ Natural Sand ☐ Manufactured Sand ☐ Other………………

	☐ Gravel ☐ Other …………………..	☐Other…………………..	
High Early Strength Mixtures	☐ Crushed Limestone ☐ Granite ☐ Crushed Gravel ☐ Gravel ☐ Other …………………..	☐ #57 ☐ #67 ☐ #7 ☐ #4 ☐ Combined ☐Other…………………..	☐ Natural Sand ☐ Manufactured Sand ☐ Other……………….

Please specify any aggregate/concrete characteristics you maintain for better concrete pumping and finishability? (e.g. paste content, % volume of fine/coarse aggregate, limits for the flat or elongated coarse aggregate, etc)

A.3 Precast Plants Survey Questions

1. Do you use a combined aggregate gradation in your mix design?

☐ Yes
☐ No

If yes, which technique do you use for developing/optimizing combined aggregate gradation?

☐ Tarantula curve (indicate limits you adapt……………………………………………………………………..)
☐ Power 45 curve
☐ Shilstone Workability-Coarseness Chart
☐ Haystack limits (8-18%)
☐ Other …………………………….

2. How many bins do you carry in the plant for coarse and fine aggregate? (Check all that apply)

Aggregates	**Type of Aggregates in the plant**	**Size of Aggregates in the plant**	**Number of bins per aggregate**
Coarse Aggregates	☐ Crushed Limestone ☐ Granite ☐ Crushed Gravel ☐ Gravel ☐ Other …………………..	☐ #57 ☐ #67 ☐ #7 ☐ #4 ☐ Combined ☐Other…………………..	☐ 1 bin ☐ 2 bins ☐ 3 bins ☐Other…………………..
Fine Aggregates	☐ Natural Sand ☐ Manufactured Sand ☐ Other……………….		☐ 1 bin ☐ 2 bins ☐ 3 bins ☐Other…………………..

Intermediate Aggregate	☐ Crushed Limestone ☐ Granite ☐ Crushed Gravel ☐ Gravel ☐ Other …………………..	☐ 1/2 inch ☐ 3/8 inch ☐ #4 ☐ Other ………………..	☐ 1 bin ☐ 2 bins ☐ 3 bins ☐ Other………………..

3.What is the type and size of coarse and fine aggregate you use for the following applications? (Check all that apply)

Concrete Application	Type of Coarse Aggregates	Size of Coarse Aggregates	Type of Fine Aggregates
General Structural Applications (Bridge Deck Panels , Beam girders, Culverts, Pipes, Walls, etc) (TDOT Class P, D A)	☐ Crushed Limestone ☐ Granite ☐ Crushed Gravel ☐ Gravel ☐ Other …………………..	☐ #57 ☐ #67 ☐ #7 ☐ #4 ☐ Combined ☐Other…………………..	☐ Natural Sand ☐ Manufactured Sand ☐ Other……………….
Bridge Deck Panels – Surface (Polished Resistance) (TDOT Class DS, P, A)	☐ Crushed Limestone ☐ Granite ☐ Crushed Gravel ☐ Gravel ☐ Other …………………..	☐ #57 ☐ #67 ☐ #7 ☐ #4 ☐ Combined ☐Other…………………..	☐ Natural Sand ☐ Other……………….
Self-Compacting mixtures (TDOT Class P- SCC)	☐ Crushed Limestone ☐ Granite ☐ Crushed Gravel ☐ Gravel ☐ Other …………………..	☐ #67 ☐ #7 ☐ Combined ☐Other…………………..	☐ Natural Sand ☐ Manufactured Sand ☐ Other……………….

Please specify any aggregate/concrete characteristics you maintain for better concrete pumping and finishability? (e.g. paste content, % volume of fine/coarse aggregate, limits for the flat or elongated coarse aggregate, etc)

- ***DOTs Survey Summary***

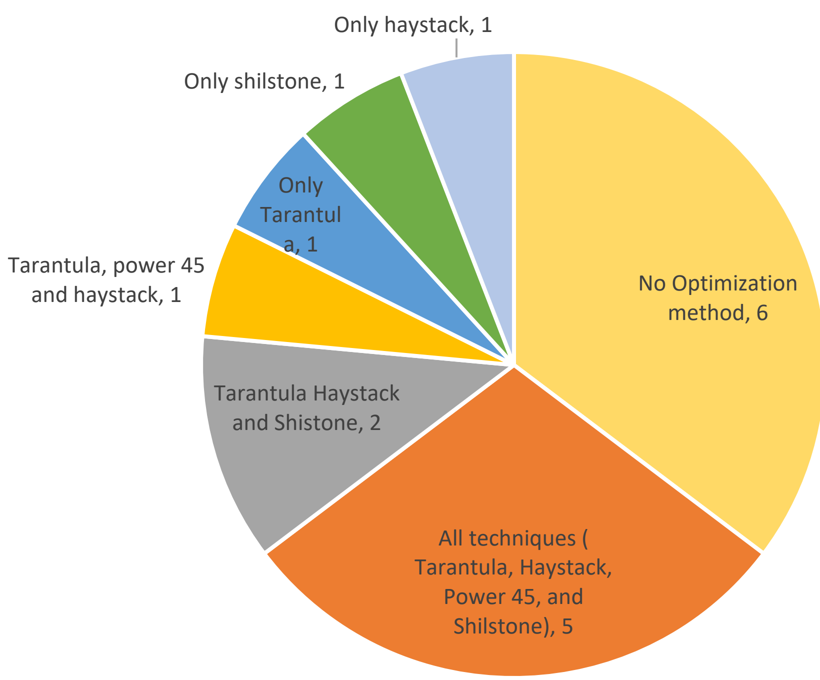
➢ **Questionnaire Recipients**

A survey of state DOTs was conducted to gather specifications related to OAG in other states. Survey questionnaires were sent to several DOTs to learn more about the state of the practice of optimized aggregate gradations for structural applications. The survey questions address the mixture parameters, fresh performance, and hardened performance requirements. Among the fifty-one DOTs, questionaries responses were returned by seventeen DOTs.

The summary of responses received are summarized below:

- **Q I(a) - Previous use of optimization method**

The Optimized Aggregate Gradation technique has never been used, according to six respondents. Of the seventeen respondents, eleven DOTs reported they have used the optimal gradation method in the past. Of these eleven DOTs, five DOTs permit any of the optimization techniques (namely Tarantula curve, Power 45 curve, Shilstone Curve, and Haystack limits). The Tarantula, Shilstone, and Haystack methods are used by Michigan DOT and New York State DOT, and the Illinois DOT permits the use of the Tarantula, Power 45, and Haystack methods for gradation optimization. The remaining three DOTs (Indiana DOT, Florida DOT, and Louisiana DOT) use the Tarantula Curve, Modified Coarseness Factor Chart, and Haystack 5-20, respectively. Figure below shows a pie chart that illustrates DOT responses regarding the optimized aggregate gradation techniques allowed.

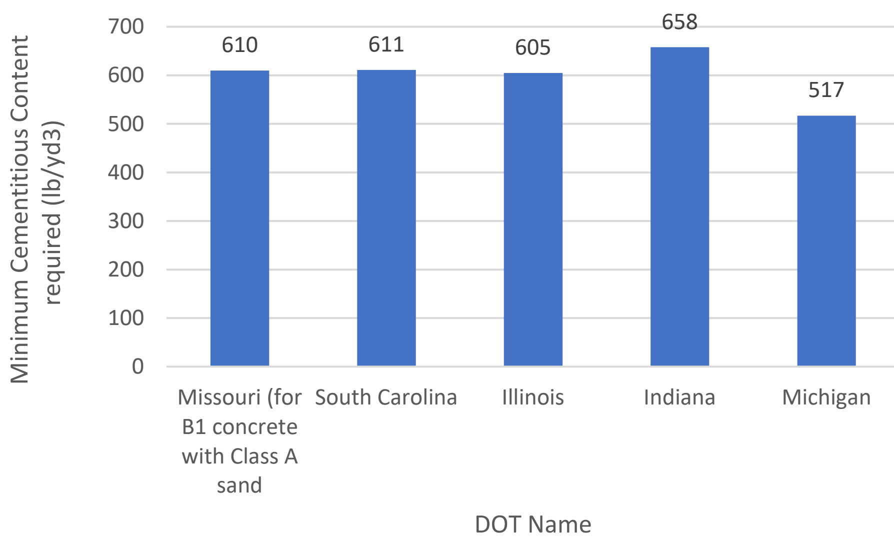


- **Q I(b) - Gradation limit for individual sieve**

Questionnaire recipients were requested to provide information on the gradation limit for individual sieves and gradation tolerance. Among seventeen respondents, eight of them do not have any requirements in this regard. Florida DOT respondents reported that the gradation limit can be any combination of coarse aggregates but ASTM C33 #57 and #89 are typically used. Illinois DOT requires a minimum of 45% passing the ½-in. sieve if pumping bridge superstructure concrete. And for what it's worth, the allowable coarse aggregate (CA) gradations for bridge superstructure concrete are CA 7 (100% passing through 37.5 mm sieve) or CA 11 (100% passing through 25mm sieve) and a blend of CA 13 (100% passing through 19mm sieve), CA 14 (90 ± 10 passing through 12.5mm sieve), and/or CA 16 (100% passing through 12.5mm sieve) with a CA 7 or CA 11. Haystack 5-20 optimization method is used in Louisiana DOT where no individual sieve outside of the 5-20 limit is allowed. When ACI 211 is used AASHTO M 43 and M 6 grading are required in Alaska DOT. According to the survey, there is a limitation of the maximum size of the aggregate to 1" and a limitation of the amount passing the #200 sieve as well in Missouri.

- **Q I(c) - Cementitious Content**

There is no minimum cementitious content requirement in ten of the seventeen responder DOTs. The Class of concrete determines Florida DOT's minimum cementitious contents, which is unaffected by aggregate gradation. According to Missouri DOT's response, for B-1 concrete (intermediate bents, such as footings, collision walls, tie beams, web beams, caps, and columns) with Class A sand the minimal cementitious material quantity is 610 pounds per cubic yard. However, the contractor may lower the amount to no less than 560 pounds per cubic yard with optimization. For a standard mix, South Carolina DOT mandates a minimum cement content of 611 lb/yd3, and 480 lb/yd^3 if fly ash replacement is maximized. For cementitious materials, Illinois and Indiana DOT have minimum requirements of 605 lb/yd3 and 658 lb/yd3 respectively. The highest cementitious content requirement, according to Maine DOT respondents, is 660 lb/yd3. The range for cementitious material composition for Michigan DOT is 517 lb/yd3 to 658 lb/yd3. Figure below shows the required cementitious content required by different DOTs.



- **Q I(d) - Paste volume**

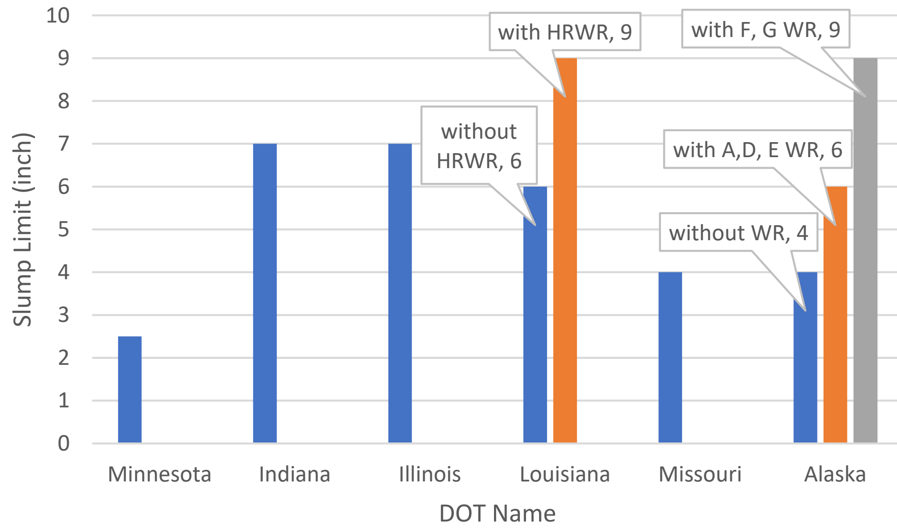
The questionnaire requested information regarding the limit of the volume of paste in concrete. The paste volume of a concrete mixture is the sum of the volumes of cement, water, mineral addition, and chemical admixtures. Among the seventeen DOTs that responded to our survey, sixteen DOTs do not have any specific paste volume limit. Only New York State DOT has the paste volume limit which is 25% for concrete paving and 27% for structural concrete. However, Florida DOT officials responded that though they do not have any limit for the volume of paste in concrete, they suggest starting with 26% by volume. Illinois DOT has a maximum cementitious content requirement of 705 lb/yd3 and a maximum water-cement ratio limit of 0.44, despite having no paste volume limit. Respondent of Minnesota DOT replied that they have a maximum supplementary cementitious material limit for fly ash at 30%, slag at 35%, Silica fume at 5%, and ternary at 40%.

- **Q I(e) - Fine to total aggregate ratio**

Indiana DOT has a limit of 40-45% fine to total aggregate ratio if the Tarantula method is not used. Illinois DOT officials responded that the proportions of fine and coarse aggregate are controlled by their Mortar Factor ranges which generally keep the maximum fine aggregate content to around 40%. Though they do specify a maximum of 50% when using self-consolidating concrete. While answering regarding the limit of fine to total aggregate volume, Michigan DOT respondent replied that they have a minimum requirement of 65% for the coarse to total aggregate volume and for optimized mixtures, this volume also includes the intermediate aggregates. Despite having no limitation, Missouri DOT's guidance gives typical values for the fine aggregate percentage as 35-46% but does not give a separate value between optimized or non-optimized mixtures. Besides these DOTs, thirteen other DOTs do not specify any fine to total aggregate limit.

- **Q II(a) - Slump limit**

Out of seventeen respondent DOTs, eight DOTs do not have any slump limit. For optimized mixtures, Minnesota DOT and Indiana DOT have slump limits of 2.5 inches and 6 inches respectively, and Michigan DOT has a limit from 0 to 7 inches depending on admixture usage. Vermont DOT respondents stated that for their DOT, slump limit for conventional mixtures, only that no segregation is observed. For SCC mixtures, J Ring testing for upper and lower limits should be conducted and show no more than inches difference between J ring and spread tests for each limit and visual stability index (VSI) of 1 or less for each limit. Florida DOT determines slump limit by the Class of concrete and is not affected by aggregate gradation. Illinois DOT officials provided information regarding slump limit that their DOT has nothing specific to OAG, but they allow up to 7 inches if a superplasticizer (HRWR) is used. Louisiana DOT officials stated that the slump limit for their DOT varies but is generally less than 6 inches unless an HRWR is used. If HRWR is used, then the slump limit can go to 9 inches. Alaska DOT has a maximum slump limit of 4 inches if there is no WR used, for types A, D, and E water reducer's maximum slump should be 6 inches and for types, F and G water reducer it has to be 9-inch maximum. The slump limit for Missouri DOT depends on the mix type and maximum slump specification remains same if a mix is optimized, for a B-1 mix (intermediate bents, such as footings, collision walls, tie beams, web beams, caps, and columns) the maximum slump would be 4 inches even if the mix was optimized. The required slump limit for different DOTs is shown in Figure below.

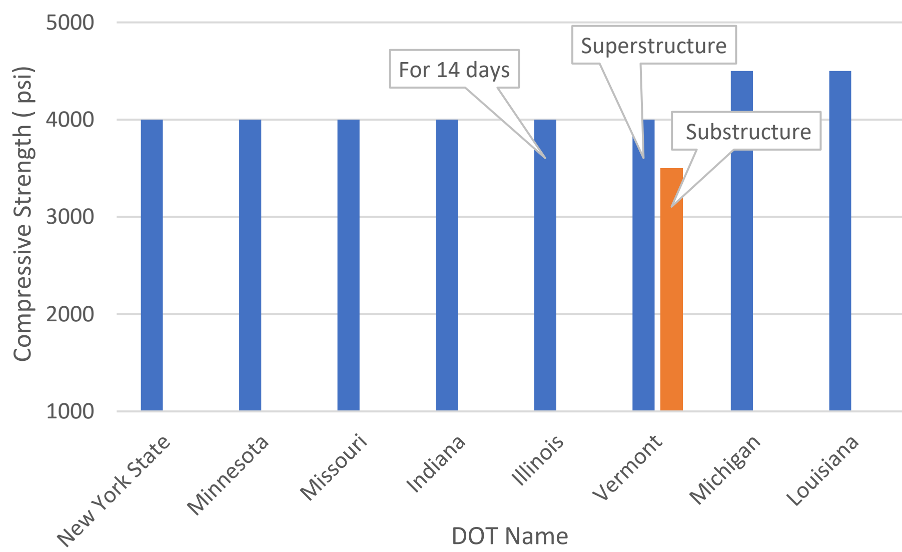


- **Q II(b) - Air Content and SAM number**

Questionnaire recipients were requested to provide information on the requirement of air content and SAM number for optimized aggregate concrete. Ten DOTs do not have any required air content limit. Louisiana DOT, Indiana DOT, and New York State DOT have a limit of 2-7%, 5-8%, and 5-9% air content requirement for OAG mixtures respectively. Illinois DOT officials responded that they do not have any specific air content requirement for OAG but air contents are generally 5.0 – 8.0%. The air content target for Minnesota DOT is 6.5% (+2.0%/-1.5%). Alaska DOT respondent provides information that their DOT has different air content requirements for different mixtures. For Class A, AA mix design air content should be 6.0±0.5%, and for Class P (Bridge Girders) air content limit is 3.5%. Air content requirements for Missouri DOTs don't change if a mix is optimized. Air content is required to be within 4.5 to 9.0%, though at the contractor's risk, the air content is allowed to be between 7.5 to 9.0 percent. Fifteen out of Seventeen respondent DOTs do not have any SAM number requirements. Even one of the respondents stated that producers are very much against the SAM number. The SAM number must be 0.20 or less for New York State and Alaska DOT.

- **Q III(a) - Strength Requirement**

The questionnaire asked for information on the requirements of tensile, flexural, and compressive strength. Four out of the seventeen responding DOTs (New York State, Minnesota, Missouri, and Indiana) require a minimum compressive strength of 4000 psi at 28 days, and Illinois DOT requires 4000 psi at 14 days. Alaska DOT mandates a minimum compressive strength of 5000 psi. According to the Florida DOT representative, aggregate gradation has no bearing on compressive strength, which is determined by the Class of concrete. For Vermont DOT, the required compressive strength for the superstructure is 4000 psi and 3500 psi for the substructure. Michigan DOT has a requirement of 4500 psi for superstructure at 28 days and lowers for other applications. Louisiana DOT officials stated that it depends upon Classes but ranges from 4500 psi to 10000 psi at 28 days. The remaining seven DOTs do not have compressive strength requirements. Only three out of seventeen DOTs have flexural strength requirements for optimized mixtures. Alaska DOT has a requirement of 650 psi flexural strength at 28 days. Illinois DOT has a requirement of 675 psi at 14 days. Indiana DOT respondent replied that flexural strength requirements for their DOT depend on the application, however, typically 550 psi strength is needed. There is no requirement for tensile strength in any responded DOTs. Figure below illustrates the required compressive strength for different DOTs.



- **Q III(b) - Shrinkage requirement**

Column 'Shrinkage requirement' of table 3-3 contains the replies from the respondents on shrinkage requirements. Out of seventeen DOTs, only three have shrinkage requirements and fourteen DOTs do not have any shrinkage requirements. Minnesota DOT has shrinkage requirements of no greater than 0.040% at 28 days. Vermont DOT has different shrinkage requirements for superstructure mixtures and substructure mixtures. For mixtures used in the superstructure, the qualification mix needed to be 0.032% or less, in the substructure, it has to be 0.042%.

- **Q III(c) - Electrical resistivity and permeability requirement**

Out of the seventeen responding DOTs, twelve do not have any requirements for electrical resistivity and permeability. Two of the DOTs (Vermont and New York State) follow ASTM T358 for surface resistivity. Between these two DOTs, New York State DOT has a resistivity requirement of greater than 30 k ohm-cm for superstructures and substructures and greater than 18 k ohm-cm for footings, piles, and shafts. Louisiana DOT officials responded that their DOT requires a minimum of 22 kOhm-cm at 28 days unless it is considered mass concrete, then 22 KOhm-cm at 56 days is the minimum. Alaska DOTs is developing a performance test matrix that would set minimum resistivity values for some Classes of concrete, possibly 15 or 20 ohm-m for Bridge Girder mixtures. ASTM C1202 is followed by Minnesota DOT where less than 1500 coulombs are required at 56 days. The sixth column of Table 3-3 shows the responses from DOT officials regarding electrical resistivity and permeability requirements.

- **Other requirements**

The questionnaire asked if there are any other requirements for optimized concrete mixtures. Vermont DOT officials responded that they did develop an allowable change table. Usually, pozzolans and admixtures may suddenly dry up and require replacing. Typically, a change in material/proportions would force the producer to do all new testing which results in 3+ months of testing and thousands of dollars. So, Vermont DOT came up with a table that tried to address most of the common substitutions and tried to determine which concrete properties would be affected. Then they decide if testing would be required, if yes, which tests and if no, new testing is needed. New York State DOT has a limitation to substitute cement by mass with 20%-25% Class F Fly Ash or 20%-25% GGBFS in combination with 6% micro silica for bridge decks and approach slabs when the mix has ASR potential. The contactor/producer may also submit an alternate mix design if they wish to use a different percentage of SCM as called out in their specifications to control ASR. If an alternate amount of SCM is chosen by the contractor then the mix has to be designed per AASHTO R 80. They also use a saturated lightweight fine (30% of the sand) for an internal cure in bridge decks and approaches.

- ***Ready Mix and Precast Plants Survey Summary***

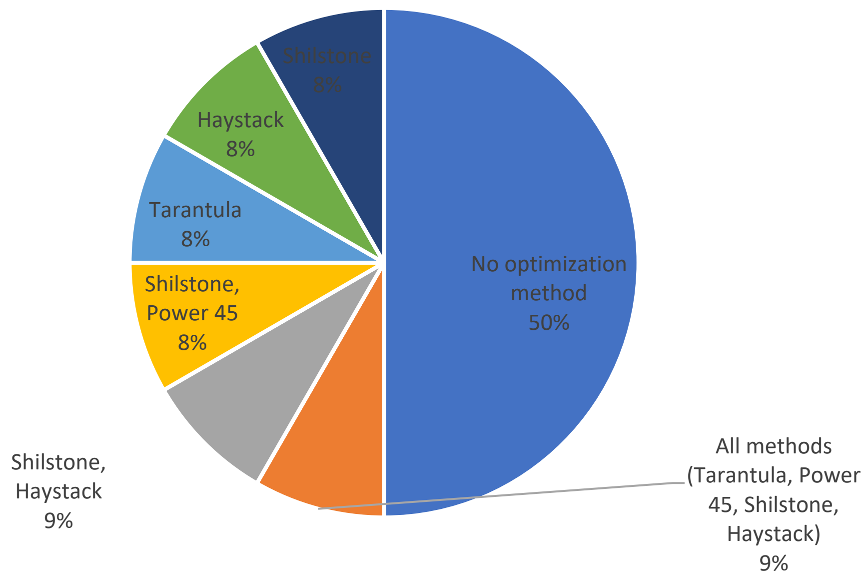
  - **Questionnaire Recipients**

Precast plant and Ready-Mix Concrete (RMC) plant officials were handed a questionnaire to better understand current procedures and plant capabilities. There was a total of 4 questions in the survey, some of them had subquestions. Out of the seventy plant officials, twelve officials responded to the questions. Among these twelve plants, three were precast plant officials and nine were RMC plant officials. The summary of responses received so far are summarized below:

  - **Q1 - Previous use of Combined aggregate gradation**

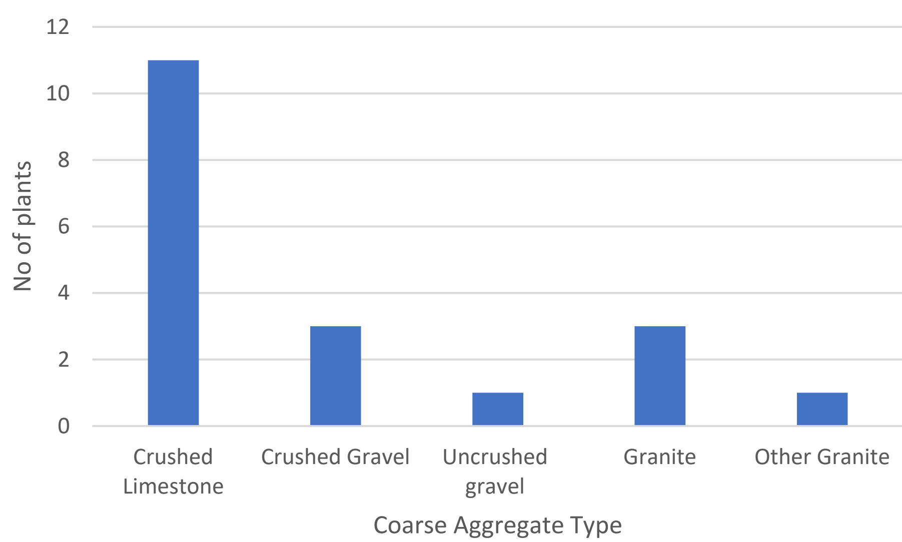
The questionnaire asked for information on whether RMC plants and precast plants use the combined aggregate gradation technique or not and if yes which technique they follow. Three precast plant officials responded that they do not use any combined aggregate gradation methods. Among Nine RMC plants, six of them use combined aggregate gradation. One of the plants uses all four optimization methods (Tarantula, power 45, shilstone, and haystack 8-18). One of the RMC officials stated that they use both shilstone and haystack methods, and another plant officials responded that they use both power 45 and shilstone methods.

Tarantula curve is used in one plant, similarly, shilstone and haystack methods are used in one plant each. The figure below displays a pie chart which shows the aggregate optimization methods used by the number of precast and RMC plants.

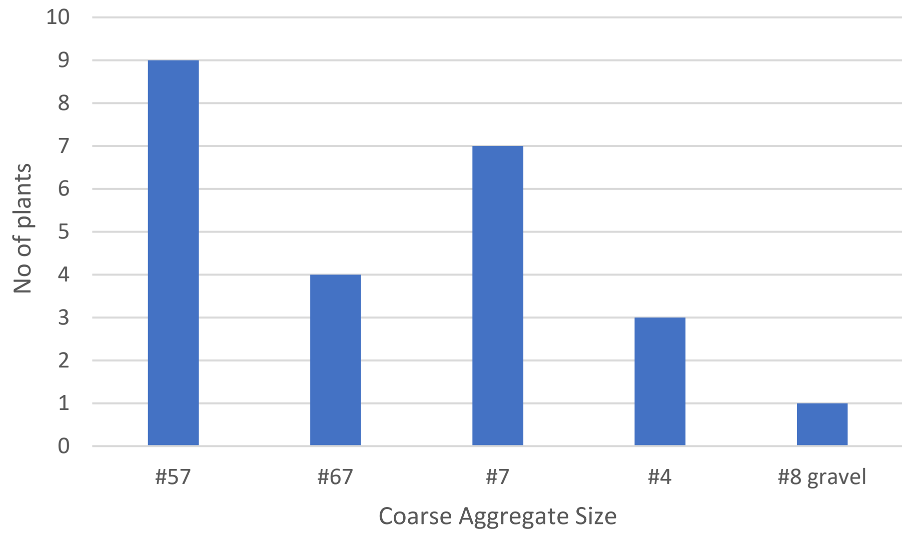


- **Q2 - Type and size of aggregates used for optimized gradation**

Most plants use crushed limestone as a coarse aggregate. One of the plants utilizes uncrushed gravel, while three of the twelve use crushed gravel and granite. Figure below shows different coarse aggregates used by the number of RMC and precast plants.

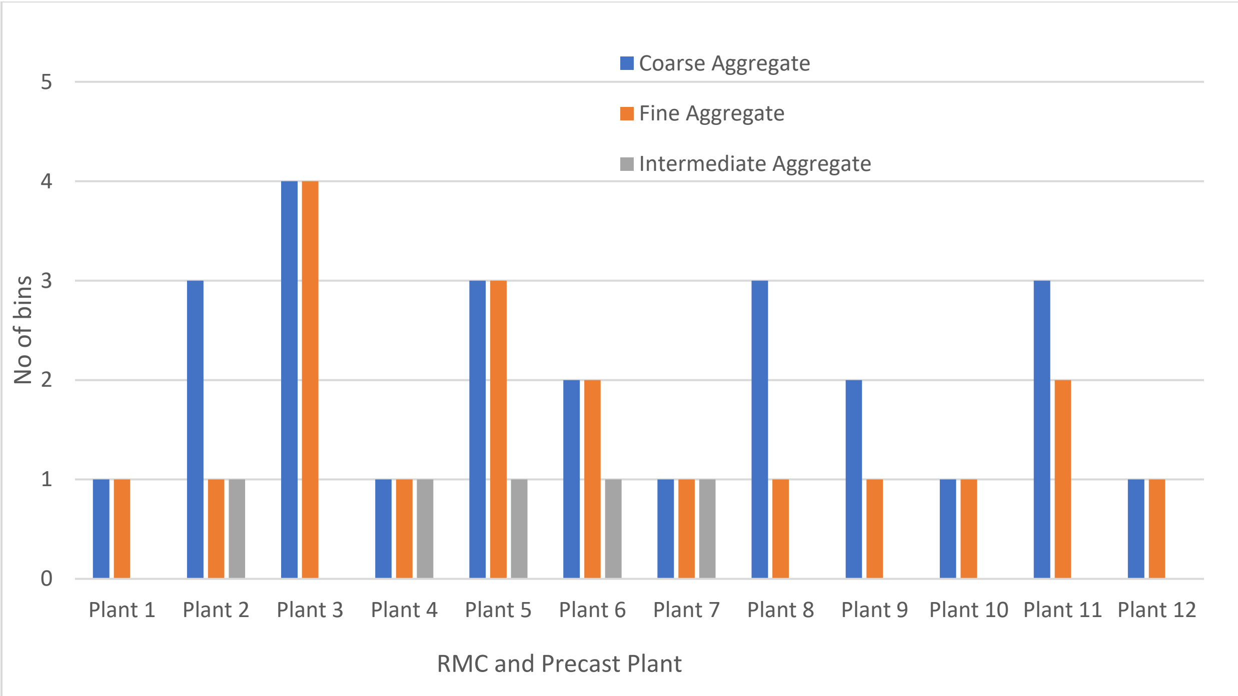


Since #57 is the size used by every RMC plant, it is the most popular coarse aggregate size for RMC plants. Only one of the three precast plants, though, uses #57 size CA. Two of the three plants reported utilizing CA size #67, indicating that they prefer this size more. Two plant officials also stated that they use #67-sized CA as well. Seven of the total twelve plants use #7 CA size as well and three of them use #4 sized CA. Another plant official reported that they use #8-sized gravel as CA. Figure below displays different coarse aggregate sizes used by the number of plants.



Five plants carry only one bin for coarse aggregate, two plants carry two bins, four plants carry three bins and only one plant out of twelve plants carries four bins to carry coarse aggregates.

Officials from nine out of the twelve plants indicated they utilize natural sand as fine aggregate, while six officials said they use manufactured sand. According to the survey, eight plants carry one bin of fine aggregate, two plants carry two bins, and two other plants carry three and four bins. There are no intermediate aggregates used in any of the three precast plants or the three RMC plants. Crushed limestone is used in five RMC plants, whereas only one plant uses pea gravel, uncrushed gravel, crushed gravel, and granite as intermediate aggregates. Officials from four of the six RMC plants say they utilize 1/2" aggregate, while only two use 3/8" aggregate. #8 gravel is used in one plant and #4 size aggregate is also used in another plant as intermediate aggregate. All plants where intermediate aggregate is used carry only one bin. The figure below illustrates the number of bins used by different plants for aggregates.



- **Q3 - Type and size of aggregates for different applications**

The questionnaire asked the respondents about the type and size of aggregates used in their plants for different applications.

- General structural applications (TDOT Class P, D, A): All the precast and RMC plants use only crushed limestones for general structural applications. Eight of the twelve plants use only #57 CA size, and two precast plants use only #67 size. One plant uses both #57 and #7 coarse aggregate and another uses #57, #67, and #7 coarse aggregate sizes. Only natural sand is used by six plants for general structural works, whereas five plants use only manufactured sand. One of the plant officials stated that they use both natural and manufactured sand for general structural applications.

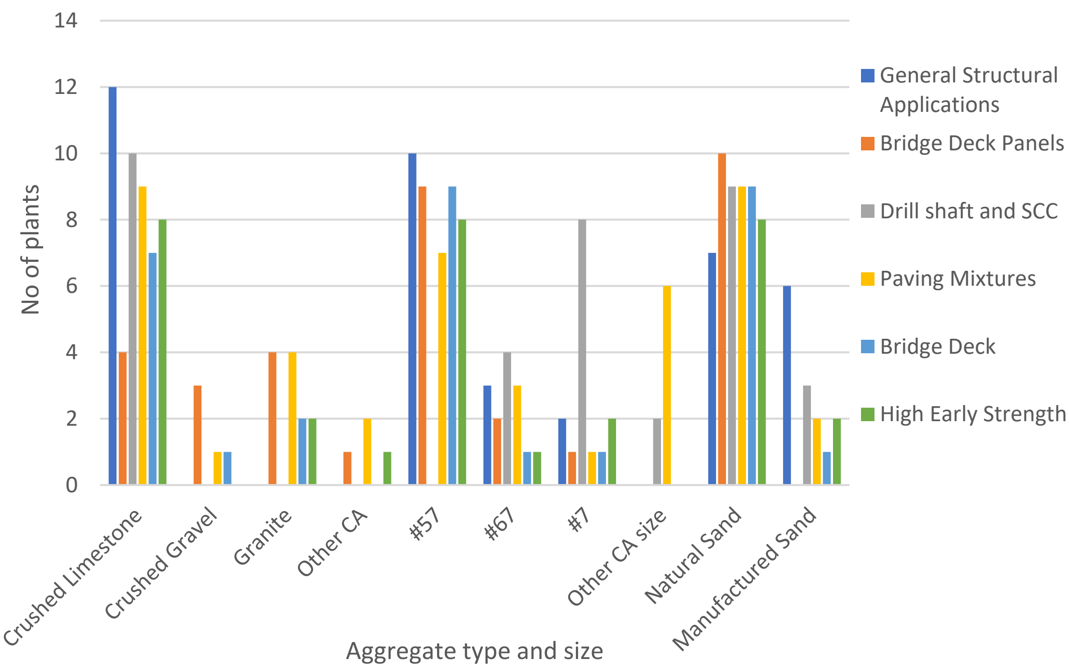
- Bridge Deck Panels- Surface Resistance (TDOT Class DS, P, A): For uses such as bridge deck panels, three out of twelve plants utilize crushed limestone, three use crushed granite, and three use crushed gravel. Crushed limestone, granite, and other quartzites are used as coarse aggregate in one of the plants. Eight of the twelve plants that answered the questionnaire use only aggregate in the #57 size. One RMC facility uses #57, #67, and #7 size coarse aggregate, while only one precast plant (Ross Prestress) uses #67 size. The only fine aggregate used in the construction of bridge deck panels is natural sand.

- Drill shaft and Self-compacting Mixtures (TDOT Class SCC): Out of twelve respondent plants, ten plants only use crushed limestone as coarse aggregate for drill shaft work and self-compacting concrete (SCC) mixtures. Two of the precast plants did not answer the questions related to the application questions. #7 size coarse aggregate is the most common type of aggregate as five plants use only this size for SCC mixtures. Three plants use both #67 and #7 coarse aggregate whereas one plant uses only #67 and another plant uses combined coarse aggregate. Seven plant officials said that they use only natural sand as fine aggregate. Two plants use both natural and manufactured sand, and only one plant uses manufactured sand as fine aggregate.

- Paving Mixtures (TDOT Class CP and A): For paving mixtures, all RMC plants employ crushed limestone. In four of the nine RMC plants, the coarse aggregate is granite mixed with crushed limestones. One of the plants also mixtures crushed limestone with crushed gravel and pea gravel 3/8. Because seven out of nine RMC plants utilize this size, #57, it is the most used coarse aggregate size for paving mixtures. According two plant officials, their facilities use both #4 and #67. During paving projects, four facilities mix #4 coarse aggregate with #57 aggregates, and two of them employ combined coarse aggregates. According to another plant's official, they use #57, #67, and #7-sized coarse aggregate in their plant. All nine RMC plants use natural sand as fine aggregate and two of them use manufactured sand as well.

- Bridge Deck (TDOT Class D): Six of the nine RMC responders that responded do all of their bridge deck work with crushed limestones in their plant. Granite is used as coarse aggregate in two of them. A plant representative responded that crushed limestone and crushed gravel are used in their facility. All of the plants that replied to the survey utilize coarse aggregate of size #57 in their plants, and one of them also uses #67 and #7 together with #57 coarse aggregate. Manufactured sand is the only fine aggregate used in one plant's bridge deck mixtures. According to the survey, every plant uses natural sand.

- High Early Strength: Crushed limestone is once more the most common coarse aggregate used in high early strength combinations because it is used in every RMC facility. Nine out of nine plants also use granite. All plants employ coarse aggregate in the #57 size for early strength, making it the ideal coarse aggregate size. One plant uses coarse aggregate #7, while another combines #67 and #7 aggregate with #57. As for fine aggregate, two respondents from different plants responded that they utilize both natural and manufactured sand. The remaining plants exclusively employ natural sand during works of high early strength. Figure below shows the type and size of aggregates used in RMC and precast plants for different applications.



- **Q4 - Other aggregates/concrete characteristics**

In the questionnaire, we asked plant officials to specify any aggregate/concrete characteristics they maintain for better concrete pumping and finishability. One plant respondent replied that they use OAG in many of their flatwork mix designs. They try to combine at least 2 coarse aggregates and 2 types of sands in their OAG mixtures. They mainly use OAG on interior & exterior slabs/flatwork and concrete paving. They use a minimum paste volume of 520 lbs/yard and 44% to 48% fine to coarse aggregate. Another official from a different plant stated that they try to maintain a 58 to 42% ratio of coarse to fine aggregate and they recommend a minimum cementitious content of 500 lbs/pcy as well as a minimum of 3cf/pcy of natural sand in their pumpable mix designs. According to one of the plants officials, TDOT mixtures typically pumps very well because of the cementitious volume. Flow fill and lightweight can be tricky at times. Another plant evaluates the paste and fine content if there is a significant amount of hose line being pumped.