Final Report

Optimization of Cement Modified Recycled Base (CMRB) Mixture Design

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Principal Investigators:
Prasad Rangaraju, PhD, PE, FACI
Mohannad Naser, PhD, PE
Glenn Department of Civil Engineering
Clemson University

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16. Abstract:

SCDOT is focused on improving the design of Cement-Modified Recycled Base (CMRB) to enhance the long-term durability and performance of pavements. The current approach emphasizes using unconfined compressive strength (UCS) and other parameters such as optimum moisture content (OMC) and maximum dry density (MDD) along with treatment depth in designing CMRB treatment. However, the current design process does not address durability parameters such as resistance to wetting-drying cycles, freeze-thaw cycles, or shrinkage-induced cracking, as well as the impact of content and size of Recycled Asphalt Pavement (RAP) in the mix or the influence of soil type on CMRB design. The present study was conducted to evaluate the influence of a range of parameters on the performance of CMRB. Findings from this study show that the base soil type can have a significant influence on the cement content needed to achieve desired performance characteristics. Introduction of RAP particles larger than ¾ inch as well as RAP content up to 35% in the mix did not significantly influence UCS, allowing greater flexibility in RAP size and content in the mix. The study also recommended refining sampling practices, which included smaller intervals in sampling base material, and focusing on samples with the highest clay content as the reference material. The slurry method in preparing UCS samples was also recommended for enhancing the mixing and compaction process in the lab setting, although field construction issues need to be considered. Methods to evaluate the drying shrinkage of CMRB are also suggested, with a maximum allowable deviation of moisture content of no more than 1% to 2% from the Optimum Moisture Content (OMC), depending on the base soil type. The study recommends several modifications to the current Full-Depth Reclamation (FDR) mixture design to enhance the efficacy and performance of CMRB. These adjustments include sampling at smaller intervals, allowing RAP particles larger than ¾" without significantly impacting UCS, allowing testing at higher cement content levels for clay-rich base soils, exploring the slurry method in preparing UCS samples, incorporating drying shrinkage in mix design, ensuring in-situ moisture content not to deviate by more than 1% to 2% from the OMC, implementing stringent quality control procedures, modifying soaking duration for durability assessment under wet-dry cycling, and establishing shrinkage thresholds for each soil type.

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Executive Summary

The South Carolina Department of Transportation (SCDOT) faces the challenge of efficiently maintaining an extensive network of roadway that is rated mostly as in either fair or in poor condition. Cement-Modified Recycled Base (CMRB) has been a cornerstone of pavement rehabilitation efforts, but its design and specifications have seen minimal updates to capture the wide range of variables encountered in the field across the state. The current approach emphasizes unconfined compressive strength (UCS) in design and factors like treatment depth, moisture content, and compaction in the field. This study focused on scrutinizing existing practices and determining if significant enhancements in CMRB planning, design, and testing could be made to improve the long-term performance of CMRB. The goal of this study was to improve long-term durability and performance through a streamlined, performance-based design methodology.

In order to investigate the performance of CMRB prepared from materials across the state, base soils from four sites from across the state, i.e., Myrtle Beach, Walhalla, Clemson, and Lugoff, of varying composition were sourced for this project. In addition, a commercial source of clay was used in combination with Walhalla base material to determine the effects of clay content on the CMRB performance. A Recycled Asphalt Pavement (RAP) from a local project in the upstate area was sourced for use in this study. Extensive laboratory testing was conducted on CMRB samples to evaluate properties such as UCS, tensile strength, moisture susceptibility through wetting and drying (W/D) cycles and freezing and thawing (F/T) cycles, and drying shrinkage. In addition, the effect of factors, such as RAP content and gradation, Moisture content variation, and clay content on the UCS and durability of CMRB were explored. Synthetic FDR, where foreign materials are incorporated into the pavement materials, such as virgin aggregate, was investigated. Also, at the beginning of this research study, Type I/II Portland cement meeting ASTM C 150/AASHTO M 85 standards was the primary cement, and therefore Type I/II cement was used in the CMRB testing. However, toward the end of this research, the local cement industry had changed the cement to Type IL cement meeting ASTM C595/AASHTO M240 standard and only some preliminary testing was conducted with Type IL cement.

The study's key findings are summarized as follows: Soils classified as A-1-b required a 6% cement dosage to achieve a minimum UCS of 300 psi, while A-3 soil demanded closer to 9% cement content for the same strength target. Lower cement dosages demonstrated that RAP content had minimal influence on UCS, underlining the need for customized mix designs. Higher cement dosages allowed for RAP content exceeding 40% without compromising UCS. Moisture content deviations of more than 1% from the OMC level notably affected UCS, particularly with elevated clay and cement content. RAP gradation and maximum particle size moderately impacted UCS, affording flexibility in incorporating larger RAP sizes in mixtures. Durability tests highlighted that the presence of clay sustained CMRB's resistance to wetting/drying and freeze/thaw cycles. These results were generally supported by insights from the Tube Suction Test (TST), although additional testing and correlation with TST is recommended. Tensile strength testing unveiled complicated relationships between diverse base soils and clay content. Shrinkage studies underscored the influence of clay content on drying shrinkage behavior, with greater plasticity leading to accelerated shrinkage rates. An increase in RAP content correlated with decreased CMRB shrinkage, presenting a potential mitigation strategy for drying shrinkage. Additionally, the investigation of alternative binders like Portland limestone cement (PLC) exhibited promise in reducing cement consumption, while slurry application demonstrated superior performance with specific soil types, especially with coastal sandy soils for preparing UCS samples in a lab setting. However, potential field concerns, such as the formation of wet spots, have to be considered.

As a direct result of this study, several modifications to the current practice of the SCDOT in Full-Depth Reclamation (FDR) mixture design are recommended. These adjustments are anticipated to improve the design and performance of CMRB:

1. **Sampling:** Considering the variability of the soil composition, conduct sampling at multiple locations at smaller intervals to more accurately represent soil composition. Sieve the collected samples separately and perform the UCS tests on samples with the highest clay content.

2. **RAP Particle Size:** Allow RAP particles larger than ¾ inch (up to 1.5in.) without significantly impacting UCS.

3. **Cement Content Testing and OMC Determination:** Increase the minimum cement content used in UCS testing to a higher level, for instance, 5%, particularly for clay-rich soils.

4. **Mixing and Compaction:** Explore the slurry method in preparing UCS samples and if possible as a field construction practice.

5. **Drying Shrinkage:** Incorporate drying shrinkage in the mix design, especially with higher clay-content soil. Monitor drying shrinkage rates and adjust RAP content to mitigate shrinkage while maintaining acceptable UCS levels. The RAP content may be adjusted by considering the pavement thickness and the depth of FDR treatment. While accommodating shrinkage concerns in the production phase may present some difficulty, it is proposed that a careful study of this aspect be conducted in a future study to establish broad thresholds of clay content where specific shrinkage mitigation strategies may need to take into effect and develop potential guidelines to mitigate shrinkage.

6. **Moisture Content and Density Check:** Ensure in-situ moisture content does not deviate by more than 1%-2% from the OMC. Use the lower limit for clay-rich soils and the upper limit for granular soils.

7. **Quality Control and Assurance:** Implement stringent quality control procedures to ensure mixtures meet or exceed the minimum design requirement of 300 psi at 7 days for UCS. Recommend on-site molding of CMRB samples for enhanced quality assurance.

8. **Curing and Strength Testing:** Modify the soaking duration from "overnight soaking" to 24 hours or establish a minimum saturation level for each UCS test. If soaking over a 24-hour period presents an operational and scheduling difficulty, it is suggested that a comparative analysis be conducted by testing samples that are unsoaked and soaked overnight to evaluate the influence of moisture saturation on the properties of CMRB and establish threshold levels for acceptability.

9. **UCS Analysis and Cement Content Selection:** While cement content selection depends on specific soil type and the desired UCS, the impact of cement content on shrinkage should also be considered as a parameter in the mixture design process. As noted in item No. 5, broad threshold levels for shrinkage based on clay content of the soil should also be considered in the mix design process.

10. **Influence of Portland Limestone Cement on CMRB:** Preliminary studies on the use of Type IL cement (Portland Limestone Cement) on CMRB have indicated similar performance on the UCS of

CMRB as offered by OPC. However, the variability in the performance of PLC across the dosage range was found to be higher than OPC. It should be noted that the preliminary tests did not allow for a comprehensive investigation with PLCs to conduct a statistically valid analysis to draw definitive conclusions. Therefore, future study with Type IL cements will be critical and is recommended to ensure its comprehensive evaluation.

The findings from this study hold significant promise to improve the design and performance of CMRB. This study advocates for a new design/testing methodology that integrates mechanical performance of CMRB with adequate durability considerations to ensure long-term success of CMRB projects.

While recommendations from this study provide a firm basis for making significant improvements in the CMRB design process, additional work is needed to develop broad thresholds for considerations to account for certain durability issues, shrinkage mitigation in particular, in the CMRB mix design. In the present investigation, test methods to measure drying and restrained shrinkage of CMRB were successfully developed. In addition, additional testing is needed to better understand the impact of Type IL (PLC) cements on CMRB mix design process as a function of the base soil type and clay content, particularly on the early-age strength development and the potential impact on opening the stabilized base to traffic before final paving operations.

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1. Introduction

The success of any modern society largely depends on its transportation infrastructure. To this effect, routine pavement maintenance and rehabilitation measures are of paramount importance. In this context, the use of Cement Modified Recycled Base (CMRB) has emerged as a standard technique for pavement rehabilitation within many transportation agencies, including SCDOT. CMRB has proven to be a sustainable pavement rehabilitation solution that effectively extends the life of pavement with minimal need for additional resources. Nevertheless, despite the achievements of CMRB, there is a significant need to optimize the design practices of CMRB and develop suitable testing to evaluate its long-term performance. This research aims to address this gap in an attempt to optimize the CMRB mixture design and explore improved implementation strategies for SCDOT. Additionally, this research will enable SCDOT to identify areas of concern not currently addressed in the mix design and follow up with future field evaluations to determine if these issues are impacting performance.

Problem Statement

The SCDOT maintains a roadway network consisting of 41,315 centerline miles (90,676 lane-miles) of paved roads, categorized into five different systems: Interstate, NHS Primary, Non-NHS Primary, Federal Aid Eligible Secondary, and Non-Federal Aid Eligible Secondary. Of these, 31% (28,101 lane-miles) of the SCDOT system consists of primary routes that handle about 55% of the traffic (SCDOT 2019). The pavement condition of the primary roadway system is summarized in Figure 1, which shows that more than half of the overall network of the primary system (NHS and Non-NHS combined) is in poor condition (based on lane-miles). With such a large pavement network, the SCDOT is challenged to maximize available funds to maintain the network in the best condition possible for commuters and the traveling public.

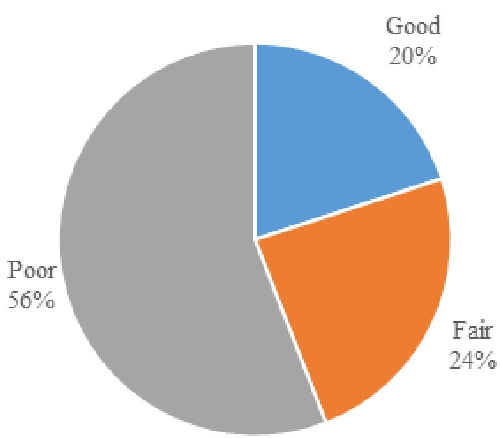

Figure 1 Pavement condition of the overall SCDOT pavement network (based on lane-miles) (SCDOT 2019a).

Over the last few decades, CMRB has been a successful reconstruction strategy for the SCDOT, however, minimal changes have been implemented to optimize the design and testing parameters and move towards performance specifications. The current design practices focus on unconfined compressive strength (UCS) and the current field practices focus on depth of treatment, moisture content, and degree of compaction. These practices may not be the most effective factors for the assessment of durability and long-term performance. The proposed research is focused on conducting a critical evaluation of existing strategies and practices and determining if significant improvements can be made in the planning, design, and testing of CMRB with an intent to achieve long-term durability and performance.

Summary of the current SCT-26: Standard Specification for CMRB Standard Method of Test for Sampling, Preparing and Testing of Cement Modified Recycled Base Compression Specimens in the Laboratory, SCDOT Designation: SCT-26 (08/2017)

The SCDOT's current CMRB standard, SCT-26 [1], involves the following steps that are also shown in Figure 2, with Type I Portland cement as the primary binder:

1. **Materials Preparation:** The sampled pavement materials are dried at 140 °F, and then sieved through a ¾" sieve. The reclaimed asphalt pavement (RAP) retained on the sieve is heated to (257±9) °F for 25 minutes and broken up to pass the ¾" sieve. Materials retained on the ¾" sieve after this process are discarded.
2. **Cement Content Testing and OMC Determination:** Three cement contents (3%, 6%, and 9% by mass of the blended pavement materials) are tested unless determined otherwise by the reclamation engineer. The Optimum Moisture Content (OMC) for achieving Maximum Dry Density (MDD) is established using a blend stabilized with 6% cement. Two cylindrical specimens (4-inch diameter by 4.58-inch length, the standard proctor mold dimensions) per cement content are molded.
3. **Mixing and Compaction:** Cement, RAP, and base soil are mixed dry and then water is added, at the OMC level, to create a homogeneous blend. After 5 to 10 minutes of dispersion and moisture absorption, the blend is remixed. Specimens are compacted in three equal layers into the standard proctor mold. Each layer is compacted 25 times, then the surface is scratched by a straightedge to create a good bond between layers.
4. **Moisture Content and Density Check:** Moisture samples are taken before and after molding to verify moisture content and dry density. Deviations from the design MDD are limited to within 2 pcf, while the deviations from the OMC are limited to within ±1%.
5. **Curing and Strength Testing:** Specimens are cured in a standard room at (73±4) °F and 100% humidity for seven days. After soaking overnight, UCS testing is conducted the following day. Loading rates for the UCS test follow the SCT-26 specifications: 500 lbs/min for the first 100 lb., increasing to 1000 lb./min up to 6000 lb., and returning to 500 lb./min until failure.
6. **UCS Analysis and Cement Content Selection:** UCS values are plotted against cement content. The appropriate cement content is chosen based on the required UCS.

In conclusion, the SCT-26 [1] procedure outlines a comprehensive process for CMRB testing, encompassing cement content determination, mixing, compaction, moisture and density checks, curing, strength testing, and final cement content selection for optimal performance.

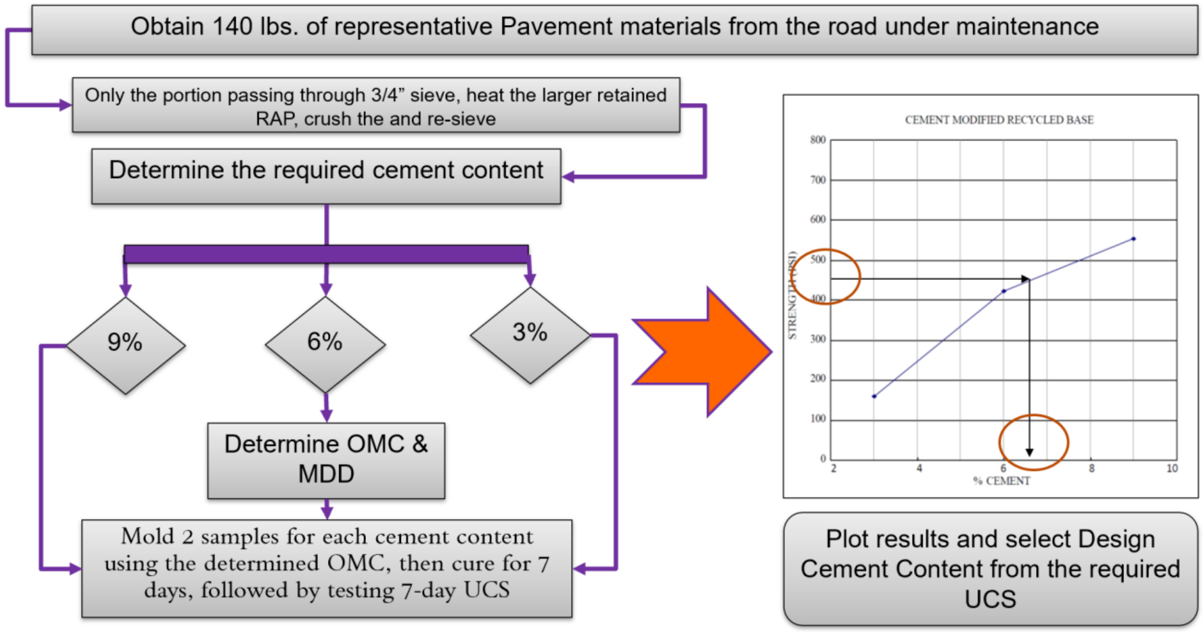

Figure 2 SCT-26 Procedures for the CMRB mixture design.

Examining the current practice of FDR in SCDOT

Cement has long served as the primary chemical stabilizer for Full-Depth Reclamation (FDR). However, alternative chemical stabilizers such as Lime and Lime Kiln Dust (LKD) need to be explored to assess the potential benefits, particularly considering the increasing concerns with carbon footprint of Portland cement.

Additionally, the Optimum Moisture Content (OMC) determined from a 6% Cement mixture and its proximity to the OMC values required for cement contents of 3% and 9% needs to be examined. To comprehensively address this concern, an evaluation across various soil types found in South Carolina is necessary.

The prevalent practice of determining cement content for CMRB based solely on the required UCS prompts several considerations. The effect of underlying soil type, especially with varying clay content, as well as the influence of Recycled Asphalt Pavement (RAP) content and gradation on the UCS, must be scrutinized. Additionally, the responsiveness of UCS to varying moisture content raises questions about its reliability as a standalone indicator of durability.

An exploration into the correlation between CMRB's resistance to Wet/Dry (W/D) and Freeze/Thaw (F/T) cycles and the UCS is vital. The prospect of the Tube Suction Test (TST) potentially replacing the lengthy W/D and F/T tests introduces a practical angle that requires thorough examination.

Addressing the influence of drying shrinkage on mix design encompasses various facets. Factors like clay content, cement content, and the diversity of base soil types across South Carolina necessitate comprehensive analysis. The search for an effective and easily applicable method to assess CMRB's shrinkage becomes crucial in establishing a well-rounded understanding.

Furthermore, the question of whether introducing external materials into the FDR mix could lower the required cement content without compromising performance necessitates investigation. The concept of

Synthetic FDR, involving the introduction of outside materials, challenges conventional practices and requires careful evaluation of its potential benefits and drawbacks.

Collectively, these inquiries point to the necessity for improved optimization in FDR mix design and the reevaluation of existing standards. This study underscores the need to critically examine existing practices of CMRB design and testing, and for a comprehensive revision of current practices to enhance the efficiency and effectiveness of CMRB employed by the SCDOT.

POTENTIAL BENEFITS FOR SCDOT

In 2018, the SCDOT completed its first Transportation Asset Management Plan (TAMP), which outlines how the SCDOT will operate, maintain, and improve the network of pavements and bridges maintained by the Department. The plan focuses on undertaking engineering and economic analysis to make data-informed decisions to identify a planned sequence of maintenance, preservation, repair, rehabilitation, and reconstruction activities to realize a state of good repair over the life-cycle of infrastructure assets as cost-effectively as possible (SCDOT 2019b).

The historical trend of the condition of the primary system is shown in Figure 3. This figure shows that the percentage of the system that is in good condition has steadily increased since 2012. Interestingly, this figure also shows that the percentage of the system in Poor condition has remained fairly consistent at more than 50% since 2014 after seeing substantial increase in deterioration from 2008 through 2014 (SCDOT 2019a).

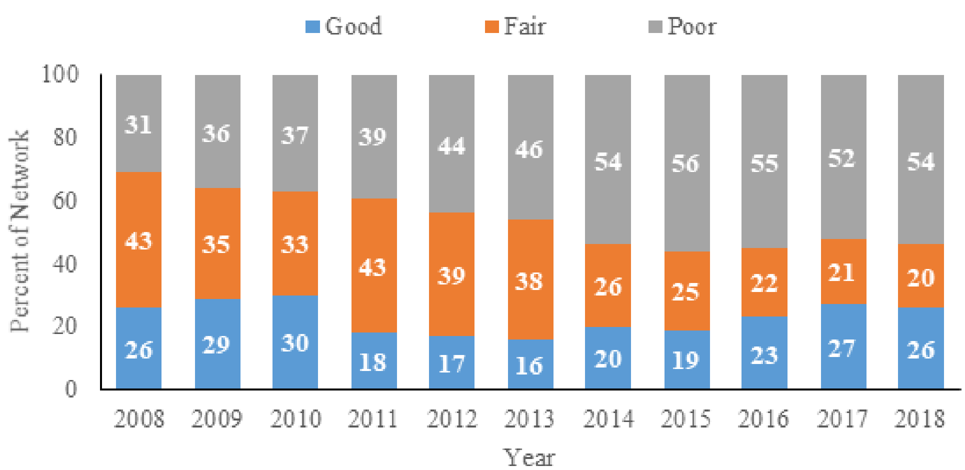

Figure 3 Pavement condition of the SCDOT primary system from 2008 to 2018 (SCDOT 2019a).

One purpose of the TAMP is to support the SCDOT Strategic Plan, which outlines five goals with supporting strategies and objectives. Goal 2 is to “maintain and preserve our existing transportation infrastructure” (SCDOT 2018a). Concerning pavements specifically, the plan calls for the use of a performance-based approach to drive the recovery of South Carolina’s pavements through a blend of preservation, rehabilitation, and reconstruction projects” (SCDOT 2018b). The 10-year goal is to improve the quality of the pavement network to the targets outlined in Table 1.

Table 1 SCDOT's 10-year pavement condition performance targets based on the PQI scale.

System	2016 Actual		2026 Target	
	% Good	% Poor	% Good	% Poor
Interstate	65	11	92	3
Non-Interstate NHS	28	45	72	16
Non-NHS Primaries	20	61	28	37
Federal Aid Secondary	19	52	40	35
Non-Federal Aid Secondary	15	55	25	45

Table 1 highlights the pressing need for road network improvement due to shrinking construction budgets and escalating costs, making full pavement replacement increasingly impractical. Sustainable practices are gaining momentum, favoring cost-effective on-site material reuse. Experience shows promise in using CMRB-based FDR as a forward path. CMRB's success in South Carolina stems from its simple approach, enabling high construction volume. Yet, this simplicity can lead to unforeseen failures if CMRB design and testing lack performance-based measures. Agency specifications, particularly in cement-based FDR, often lack well-defined stabilizing agent dosage rates. Our team investigated and established a connection between compressive strength values, and FDR blend properties, while also exploring the correlation between FDR strength and durability to enhance performance-oriented acceptance criteria.

Many state agency specifications simply state a percentage of the dry pulverized material that should be used for all projects regardless of the parent material. Some agency specifications are starting to coalesce around a 7-day compressive strength value of between 250 and 600 psi. Our research team intends to study this problem further and attempt to develop a relationship between compressive strength values for various FDR blends and anticipated deterioration modes of rutting and cracking of the FDR material. Further, we intend to investigate the correlation between the strength and durability of FDR and will develop more appropriate acceptance criteria that are performance-focused.

This research aligns with SCDOT's strategic plan, enhancing candidate selection and CMRB design/testing for prolonged pavement life cycles. New methods will retain user-friendliness while anchoring in performance metrics. The study anticipates improved candidate selection, enhanced design with different stabilizers, and performance-based specifications. These changes offer contractor flexibility and incentivize performance, amplifying SCDOT's effectiveness in a constrained funding environment.

Study Objectives

The primary objective of this research is to critically examine the current practices used by SCDOT in reclamation treatments, particularly Cement-Modified Recycled Base (CMRB), and conduct a comprehensive investigation to update the planning phase, design methodology, and testing procedures for CMRB. The anticipated outcome from this investigation is a performance-based approach to designing CMRB that will ensure long-term durability while ensuring that the process is simplistic so that it is readily implementable.

The specific sub-objectives that will ensure the successful accomplishment of the primary objective will include:

1. A comprehensive review of the existing database of information from past FDR projects across South Carolina to identify any trends and correlations amongst various parameters.
2. Based on the review, develop a process of identifying candidate pavements that are suitable for CMRB, which may include parameters such as soil type, traffic volumes, any test data such as FWD, etc.

3. Review existing sampling procedures employed in assessing the pavement condition and collection of materials for developing CMRB mix designs and rectify any deficiencies or develop new procedures to reflect the field conditions more accurately.
4. Review existing design procedures and test methods employed in determining the optimum dosage of chemical stabilizing agent and address the deficiencies by either modifying the existing procedures or developing alternative procedures that focus not only on mechanical properties but also the durability performance of CMRB. This process will be developed through a comprehensive experimental program that will involve not only Portland cement but also lime and lime kiln dust. Also, a range of base materials that reflect the diversity of material types in South Carolina will be considered in this study. The precise number of base materials and their location in the state will be determined after consultations with the steering committee.
5. Evaluate existing procedures and test methods employed in quality control and quality assurance and streamline the process with more efficient and reliable methods that are user-friendly to contractors and SCDOT personnel. In achieving this objective, the research team will ensure that a good correlation exists between the results from field verification test methods and procedures to those obtained from lab-based evaluations.
6. If possible, within the scope and timeframe of this project, conduct field verification of the developed protocols on two projects selected by SCDOT.

All aspects of the proposed research will address FDR from not only a traditional reclamation process (i.e. using in-place materials) but also from a synthetic reclamation (i.e. foreign granular materials are blended in to improve the native materials) or used entirely by themselves in situations where additional lanes are to be added.

Work Plan

The project team executed the tasks outlined in Figure 4 and listed below to accomplish the study's main deliverables. These tasks were open to adjustments upon SCDOT's request. Historical data from previous FDR projects was utilized for this project.

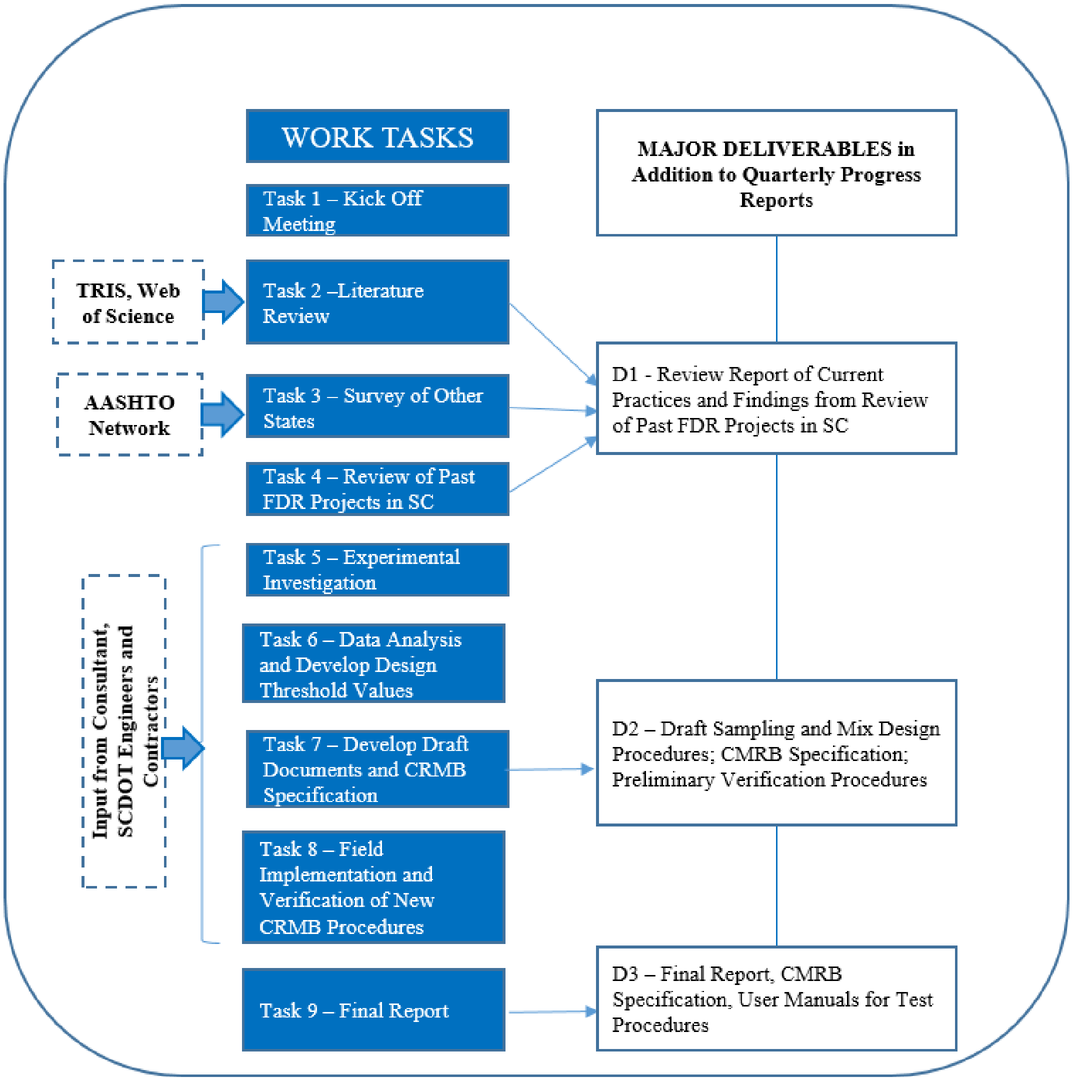

Figure 4 Work tasks and anticipated deliverables.

Details of the scope of each task are included in the appendix.

2. Literature Review

The design and construction of Full-Depth Reclamation (FDR), with an emphasis on CMRB, are the major themes of the detailed literature study in this chapter. The literature evaluation, which will lay a solid groundwork for the subsequent study, has three main objectives:

Objective 1: The state of practice of FDR
This review of the literature's primary objective is to look at the most recent developments in FDR design and construction, focusing on the use of CMRB. This section reviewed several studies, research papers, and technical reports to understand the factors influencing the performance of CMRB. The evaluation will also emphasize the significance of selecting and maximizing the CMRB mix design and center on significant CMRB utilization-related issues. Additionally, this section reviews the existing state of practice to identify best practices, challenges, and potential areas for improvement in the design and construction of FDR with CMRB.

Objective 2: SCDOT evaluation of earlier FDR data
The second objective of this literature research is to examine and assess previous Full-Depth Reclamation (FDR) data obtained from the SCDOT. The information in these precious files pertains to FDR projects, and each project's precise location is provided, along with the street name and mileposts. Additionally included are statistics about the strength of the trial batches of CMRB, including the choice of the design cement composition, the depth of FDR, the average daily traffic (ADT), and other relevant data. This part will investigate the current data to identify trends, patterns, and correlations between design parameters and performance results to generate data-driven insights and recommendations.

Objective 3: Survey of States; evaluation of FDR design and construction
The final objective of this literature review is to survey different states and regions on their FDR design and construction methods. Crucial information about the experiences, insights learned, and innovations in FDR with CMRB from transportation organizations and industry professionals in various locations is sought to be collected. To compare these techniques to those employed by SCDOT and identify potential areas for improvement, the survey's major objective is to understand the variations in design methodology, mix design methodologies, and construction processes.

Overall, the subsequent chapters of this study will be built around the findings of this literature review. The necessary knowledge to choose long-term, cost-effective pavement solutions can be gathered by merging and analyzing the most recent research and information.

Cold Recycling of Asphalt Pavements

This section provides a comparison of the three methods of Cold Recycling of Asphalt pavement: Cold in-place recycling (CIR), Cold central plant recycling (CCPR), and Full-depth reclamation (FDR). Each method is evaluated based on its process location, methodology, reclaimed material usage, applicability, depth of processing, advantages, and challenges/limitations. This comparison offers insights into the distinctive features and potential drawbacks of each method, aiding in a comprehensive understanding of their respective suitability for various pavement rehabilitation scenarios. Table 2 provides the comparison, which is summarized from the work of Xiao et al. [2].

Table 2 Comparison between the three different types of cold recycling of asphalt pavement.

Method	Cold in-place recycling (CIR)	Cold central plant recycling (CCPR)	Full-depth reclamation (FDR)
Process Location	In situ	Central or mobile plant	In situ
Methodology	Milling and paving at ambient temperature, partial-depth recycling	Milling, crushing, mixing at a plant, conventional wearing course paving	Milling and mixing asphalt and base layers in situ
Reclaimed Material Usage	In-place bituminous material and <25% underlying granular material	Crushed recycled materials, new materials, additives, water	Recycled asphalt and base materials mixed for a new base layer
Applicability	Base courses, some surface courses on low-medium traffic highways	Varies based on overall pavement design, improved CR mix quality	Base courses with improved crack resistance, homogenous base
Depth of Processing	65 to 125 mm	--	100 to 300 mm
Advantages	Repair of various distresses, extended pavement life, cost and energy savings	Cost reduction, environmental benefits, extended design life	Crack resistance, raw material and cost savings, superior structural properties
Challenges and Limitations	Limited knowledge impacts mechanistic-based designs, material selection challenges	Need for material compatibility, limitations on in-place additives use	Lack of practical experience, mix design challenges, overlay requirement, climate sensitivity

Full Depth Reclamation (FDR)

The recycling procedure for FDR is executed entirely in situ. The distinguishing aspect, compared with other rehabilitation methods, lies in the inclusion of milled asphalt layers combined with a portion of the base layer within the FDR technology. Consequently, the recycled materials include both reclaimed asphalt pavement (RAP) and base soil components. These combined materials are then stabilized by a chemical stabilizer and laid as a fresh base layer [3]. By integrating base layers milled alongside overlaid asphalt, this approach effectively limits the propagation of cracking into the base layer, offering enhanced crack resistance to the base course, especially regarding top-down cracking [4]. This methodology carries several advantages, including resource and cost savings, as well as improved structural properties of the new base layer, resulting in upfront cost reductions of 30% to 50% [2]. The FDR process is facilitated through specialized reclaiming machinery and multi-functional recycling trains, employing milling depths spanning from 100 to 300 mm [2], [3].

Nevertheless, despite its promise, certain limitations hinder the widespread adoption of FDR. A significant obstacle is the scarcity of practical experience and suitable mix design methodology. This design approach dictates the type and quantity of additives, subsequently influencing construction costs. Moreover, a protective overlay of specified thickness becomes necessary to enhance the water stability of rehabilitated pavements. Additionally, the feasibility of FDR is notably influenced by climate and environmental conditions [32–38].

Overview of CMRB

Basic Operations in the Construction of a Full-Depth Reclaimed CMRB

CMRB used with FDR is a process wherein a deteriorated asphalt pavement and the underlying base materials are stabilized by a chemical agent such as Portland cement. Figure 5 shows a schematic of the operations in a typical FDR process.

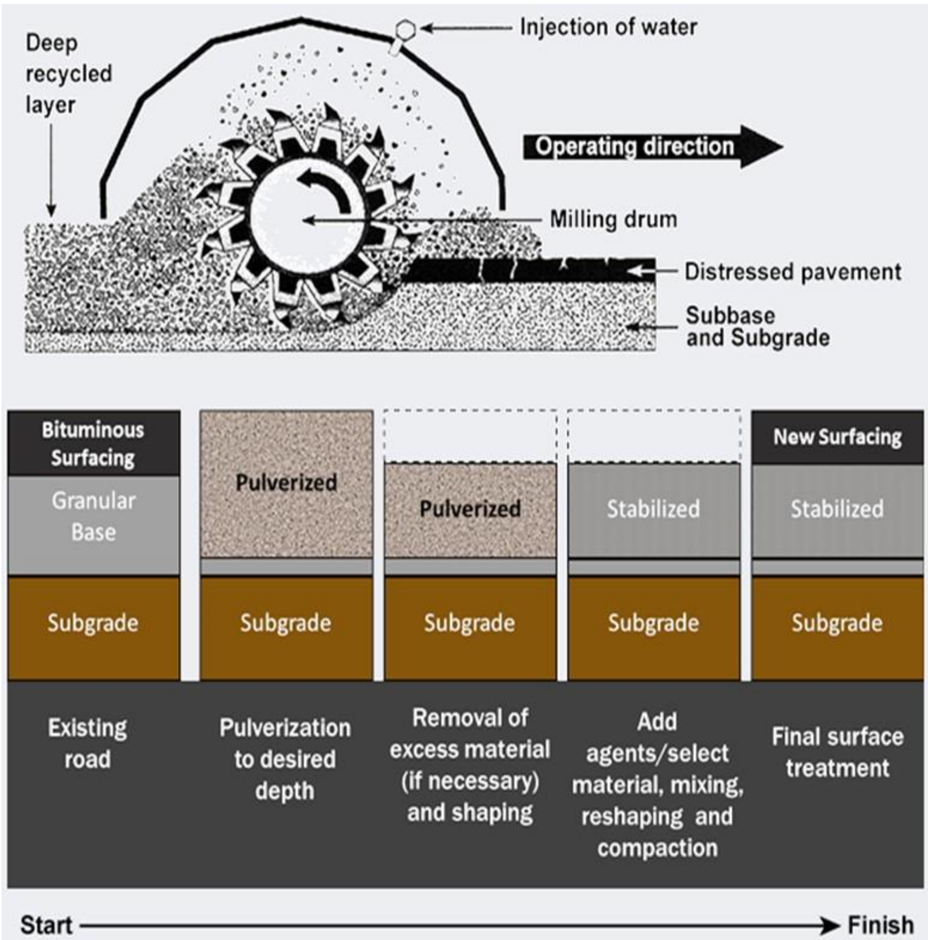

Figure 5 Schematic of Full-Depth Reclamation of Existing Asphalt Pavement (Courtesy: Ruston Pav. Co. Inc.)

In this type of rehabilitation, the distressed asphalt pavement and a portion of the base are pulverized usually to a depth of 6 in. to 10 in. After pulverization, the material is shaped to the desired cross-section and graded, at which stage the chemical stabilizing agent such as Portland cement or lime is applied. The stabilizing agent is typically applied by spreading in a dry form or pumped as a slurry form, although the dry form is used more commonly due to simplicity in application as shown in Figure 6 [3].

Figure 6 Spreading of Chemical Stabilizing Agent (Portland Cement and Lime) on the Recycled Base Layer for Blending [3]

However, wind-blown dust that arises during the dry form application can be of some concern, particularly in urban environments. After spreading, the base material and the cement powder are mixed while adding sufficient water to achieve an optimum moisture content in the mix. The blended material is reshaped to the desired profile before compaction. The addition of water during the mixing process also facilitates compaction operations. The mixture is compacted to achieve the required density, usually with vibratory rollers followed by pneumatic-tire rollers to finish the surface as shown in Figure 7 [3].

Figure 7 Compaction of the FDR with Tamping Roller, Smooth-Wheeled Vibrating Roller and Pneumatic Tire Roller [3]

Final compaction is usually conducted no more than 2 hours after the initial mixing of water with the cement. The curing of the mixture is achieved by the application of a sealant or water spray, as shown in Figure 8, to keep the cement-treated base moist to allow for the hydration of cement and to achieve the desired level of strength and durability [3]. The final step in the CMRB treatment is the surfacing, which consists of a thin bituminous chip seal, hot-mix asphalt, or concrete. Some state agencies also saw joints in the base before the final application of a paving surface to minimize the random occurrence of reflective cracking resulting from the uncontrolled shrinkage of the CMRB [3].

Figure 8 Curing of FDR by Spraying Water [3]

History of CMRB

The history of CMRB traces back to the early 1930s when soil-cement mixtures were first explored in joint research by the South Carolina State Highway Department and the Portland Cement Association (PCA) [5]. Subsequently, the PCA made significant efforts to develop scientific control methods for producing uniform and durable mixtures of Portland cement and various soils [5]. Performance tests, such as the wet-dry test and freeze-thaw test, were developed based on density to determine optimum moisture content and cement content for soil-cement mixtures. Over time, the UCS test emerged as a simpler alternative to the cumbersome durability tests and became the primary criterion for selecting the optimal cement content [5]. However, this evolution led to variations in strength requirements across different agencies, ranging from 200 psi in Louisiana to 800 psi in Arizona [5].

Today, the UCS test remains the predominant criterion for selecting cement content, especially in full-depth reclamation (FDR) applications in South Carolina. While Portland cement is the most frequently used stabilizer in FDR, other agents like hydrated lime, Class C fly ash, asphalt emulsion, and foamed asphalt have been employed elsewhere [3], [6]. Although lime and asphalt-based stabilizers offer lower initial strength and increased moisture susceptibility compared to cement-based stabilization, cement remains suitable for a wider range of soil types, making it a preferred choice in many cases [3]. However, the scarcity of Class C fly ash in South Carolina has limited its usage, while some lime-based treatments have been employed in the past.

Overall, the historical methods and metrics used for soil-cement mixtures have become standard practices for modern-day stabilized bases, particularly when employing chemical stabilizers like Portland cement or lime. Understanding this historical context and the factors affecting CMRB and FDR performance is crucial for making informed decisions and enhancing the effectiveness of pavement rehabilitation techniques.

Experience with Cement-Modified Bases in South Carolina

Over the last decade, the SCDOT has successfully used Ordinary Portland Cement (OPC) in pavement rehabilitation projects using FDR. As a result of this on-going success, SCDOT has progressively ramped up the use of FDR in its pavement rehabilitation operations, considering over 50% of the roadways in South Carolina are rated as in “poor” condition [7]. Compared to the cement volume consumed in the year 2013 for FDR applications, the total OPC used in FDR projects has steadily grown from 2014 through 2016 and since has remained significantly high as shown in Figure 9 [personal communication, Kimberly Lyons, Reclamation Engineer at SCDOT, July 2023]. This trend indicates the continued commitment of SCDOT towards the use of CMRB as a successful strategy in improving pavement conditions in South Carolina.

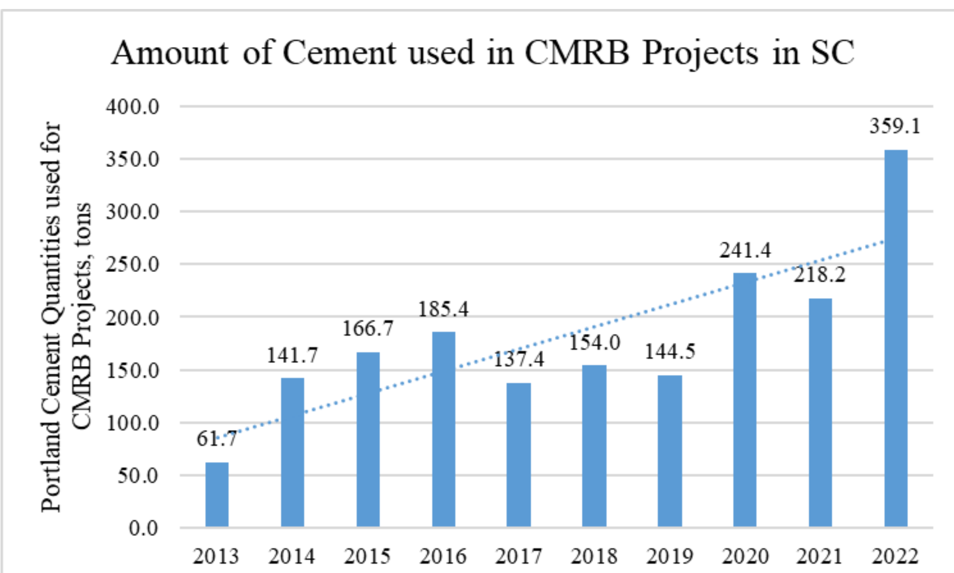

Figure 9 OPC Consumption in FDR projects in SC

SCDOT also employs Cement Stabilized Aggregate Base (CSAB) in new construction. A recent investigation into the performance of these bases indicated several failures within the last few years [8]. These failures prompted SCDOT to conduct a review of its current construction and design practices for CSAB to determine if improvements can be made to reduce the risk of future failures [8]. This evaluation consisted of a field performance review of in-place materials, a lab study examining current design testing procedures, a review of construction specifications for increased quality control procedures, and a look at the current pavement design practices. Findings from this study showed that several improvements could be made in improving the quality of CSAB, including ensuring mix uniformity, verifying that adequate cement content is present in the mixture, establishing that optimal moisture content was being used, ensuring adequate material passed #4 sieve, checking for gradation after blending of the material to ensure lack of segregation in aggregates, achieving and verification of adequate compaction and lift thickness and ensuring use of effective curing practices [8].

Factors affecting the performance of FDR

Cement Content

Past studies have consistently suggested that Portland cement stabilized materials tend to exhibit better performance compared to alternative chemical stabilizers, as observed in prior research conducted by Parsons and Milburn [9] and Henry et al. [10].

Increasing the cement content increases the UCS of the CMRB in the FDR layers [11], [12]. However, high UCS values can make the FDR layer more rigid, which may result in reduced flexibility and increased susceptibility to cracking under traffic loads. Additionally, it has been proven that higher cement content makes the CMRB more susceptible to drying shrinkage [13]–[16]. The drying shrinkage leads to the creation of all types of pavement cracking including transverse cracking [11], [17], [18], block cracking [11], [19], alligator cracks (Bottom-Up cracks) [16], and top-down cracking in the asphalt layer especially within the wheel path [17], [20], [21].

Base Soil Properties

Base soil classification

The classification of base soil has a major effect on the performance of FDR layers. The presence of sand particles or plastic clay fines may result in performance deficiency in the field [22]. The soil class also should be taken into consideration when selecting the chemical stabilizing agent (CSA) type [20], [23]. For silty clay base soil, the recommended CSA is either fly ash or lime, or a combination of both. Whereas cement is recommended more for low-plasticity granular soil. Asphalt emulsion is recommended for base soils with non-plastic fines [20]. However, cement is widely accepted for use with all types of base soils due to its availability, versatility, and relatively low cost.

Subgrade soils classified as A-4 to A-7-6 can exhibit low bearing strength, high volumetric instability, and freeze-thaw susceptibility [24], [25]. These soil characteristics are frequently cited as major contributors to the accelerated deterioration of pavement systems. Widespread use of cement stabilization has improved these soil conditions. In their study, Yang et al. evaluated a total of 28 cohesive and granular soils from nine construction locations with 4–12% Portland cement type I/II content. Specimens of 2-inch diameter by 2-inch length were prepared and tested for 28-day UCS with and without vacuum saturation. They proved that there are statistically significant relationships between soil index properties, UCS, cement content, and sand and fines content. In addition, their study suggested some general procedures for mixture design and selection based on the laboratory test results. These procedures are similar to the procedures listed in SCT-26 but with the use of predicting models.

Pulverization Level

Using extensive laboratory tests, Bozbey et al. [26] studied the effects of soil pulverization level on the resilient modulus of soils stabilized by lime. The researchers carried out resilient modulus tests on samples that were subject to both freeze and thaw and non-freeze and thaw cycles. The high plasticity soil used for the experiment was tested using California Bearing Ratio (CBR) and P-wave measurements. Bozbey et al. [26] displayed the significance of using extended curing and higher lime content as well as fine soil pulverization to enhance resistance to freeze and thaw cycles. From the research data, it was evidenced that if severe freeze and thaw cycles are expected in a region, planning of construction in that area should be done in a way to allow for at least two months of curing if lime is used for soil stabilization. Bozbey et al. demonstrated that soil pulverization level in soils stabilized by lime is as significant as the content of lime itself. It is, therefore, important to consider both pulverization and content of lime in field construction. If not considered, it may not be possible to achieve the targeted base soil properties in the field [26].

Content of Fines in Base Soil

Higher fines content in the base soil (passing #200 standard sieve) potentially increases the drying shrinkage. The cement treatment of base soils rich in clay raises the plastic limit and marginally lowers the liquid limit, thereby decreasing the plasticity index. In addition, the voids ratio decreases as cement content rises [27]. The compressibility of clayey soil is not substantially altered by a lower cement content, and a higher cement concentration is required to reduce it [27], [28].

Reclaimed Asphalt Pavement (RAP) content

Reclaimed asphalt pavement (RAP) also plays a vital role in the performance of CMRB. It has been demonstrated that increasing the RAP content has a positive impact on the resilient modulus of unbonded pavement materials compacted at the OMC level, but a negative impact on their persistent deformation [29]. However, a positive impact on resilience was not observed when the moisture level increased above the OMC [29].

Moisture Content

Another factor that affects the strength and shrinkage behavior of CMRB is the moisture content. Exceeding the level of OMC in moisture content negatively affects the performance of the CMRB as it decreases the resilient modulus and causes permanent deformations [29]. Extra shrinkage cracking occurs when the moisture level is over the OMC, as reported by George [30] [17]. Shrinkage can be minimized by controlling the relative humidity during the molding process, improving compaction density, minimizing montmorillonite clay, and limiting saturation to 70% [30] [17].

Method of cement application

Among other strategies used in FDR applications, Dixon et al. [31], studied the factors affecting the strength of the FDR-treated road base in which the cement was added as a slurry and compared it to the traditional dry cement FDR. Cement ratios tested were 2% and 6 % applied in both dry and slurry conditions. Several parameters were investigated among their test programs including mixing time, different set retarding and water-reducing admixtures, and water temperature for slurry. The use of cement slurry, according to the authors, would promote the use of FDR in urban areas where the cement dust creates a problem. All the investigated parameters had insignificant effects on the strength of cement-treated bases. However, the use of cement slurry resulted in a little lower strength than the use of dry cement [31].

Other chemical stabilizing agents used in FDR

The work done by Berthelot and Gerbrandt [32] investigated cost-effective alternatives for the thin membrane surface (TMS) method that used to be the standard rehabilitation method in the province of Saskatchewan, Canada. They tested both Partial Depth Rehabilitation (PDR) and Full Depth Rehabilitation (FDR) using different stabilizers including blended cement, class C fly ash, geogrids, geotextiles, and flax straw. Several test sections were constructed and monitored for deflection for a period ranging between 1 and 3 years. The study concluded that FDR using cementitious stabilization was the most effective alternative.

Jones et al. [33] examined four different stabilizing agents used in FDR for low-volume pavements: foamed asphalt with cement, cement only, engineered asphalt emulsion, and stabilizing without an additive. Laboratory tests and accelerated load tests were performed for each FDR strategy. The assessments were carried out under wet and dry conditions. Results from this study showed that in dry conditions, unstabilized recycled materials followed by a thin layer of asphalt concrete were the most cost-effective and environment-friendly methods for low-volume pavements. In their comparison between FDR using cement and FDR without any additive, Jones et al. [6] performed an accelerated load test on a manufactured test path. They monitored the permanent deflection at the pavement surface, the stabilized base layer under it, and the tensile strain under the asphalt pavement. They concluded that FDR with cement outperformed FDR without stabilizing in all aspects.

Asphalt emulsion and lime

According to the observations made by Ayar [34], employing a recycled mixture with Bitumen Emulsion (RMBE) as an alternative to cement in road rehabilitation projects is a sustainable alternative. RMBE technique provides construction engineers with the capacity to reuse considerable amounts of pavement material without the use of heat. Ayar observed that 1-3% lime could be used to improve the cohesiveness of RMBE and accelerate the setting of bitumen emulsion. This study also noted that a more homogenous coverage of slurry lime would improve the durability of RMBE better than lime powder. In employing other additives to RMBE such as cement, lime, and pozzolans, this study also showed that cement as an additive in a road rehabilitation process can improve both the long-term and short-term performance of RMBE as it favorably interacted with bitumen emulsions. In addition to accelerating the setting of the emulsion, cement stiffens bitumen by generating hydrating products.

Regional Experience with CMRB

A summary of some of the regional experiences and research studies related to the design, planning, and construction of FDR is presented below. See the Appendixes for more details about these studies.

Virginia:

A study by the Virginia Center for Transportation Innovation and Research assessed the conditions of trial road sections rehabilitated by FDR using different stabilizers. It found improved structural capacity and significant cost savings with FDR compared to traditional methods. Moreover, recent research has shown that FDR can be suitable for higher-volume roads [35] [36].

Nevada:

Bemanian et al.'s work in Nevada DOT reviewed the state's practice regarding cold-in-place recycling (CIR) and FDR. The study revealed that both techniques resulted in substantial cost savings over reconstruction. The selection of CIR and FDR was based on the nature of pavement distress. It also outlined steps for effective project selection, design, and execution of both CIR and FDR projects [37].

Georgia:

Georgia DOT conducted a study favoring FDR with Portland cement over other stabilization methods. The results indicated more than a 40% reduction in cost and improved pavement performance with FDR. A 1.8-km road section was reconstructed using FDR, showcasing its effectiveness [38].

Texas:

A recent TxDOT report investigated the possibility of designing FDR mixtures using small samples tested by the indirect tensile strength (ITS). The study concluded that stabilizing with cement or other stabilizers showed acceptable results with both sample sizes. Further review is needed to enhance repeatability and reproducibility [39].

Mississippi:

The University of Mississippi and the Mississippi DOT conducted a comprehensive study from 2001 to 2005, involving six 1000 ft test sections with varying chemical stabilizers to investigate shrinkage crack performance. The study assessed different techniques of shrinkage cracking mitigation, including precracking and grooving. The precracked CMRB outperformed all other sections. The study provided valuable insights into material behavior over time [40]–[42].

Illinois:

Garg and Thompson's assessment of an Illinois Department of Transportation project demonstrated comparable performance between a RAP base and a crushed stone base. The study found that the RAP base provided adequate structural support and subgrade protection, with minor rutting as the only observed distress after two years of monitoring [43].

Massachusetts:

Highter et al.'s research for the Massachusetts Highway Department focused on exploring the utilization of RAP/aggregate blends. The study assessed the hydraulic conductivity and resilient modulus of nine distinct RAP/aggregate compositions. The findings provided key insights into material behavior, including effects on density, specific gravity, hydraulic conductivity, and resilient modulus with varying RAP content [44], [45].

Shrinkage of CMRB

Introduction to Shrinkage of CMRB

Shrinkage is a change in volume that can be caused by various reasons, such as temperature gradients, drying, and cement hydration. The shrinkage in CMRB can be broadly divided into two categories: autogenous shrinkage and drying shrinkage. The autogenous shrinkage is caused by the cement hydration (the volume of the products is less than the volume of the reactants) and is relatively negligible compared to the drying shrinkage of CMRB because of the small cement levels used in CMRB. Drying shrinkage is the major contributing factor in the development of cracks through the CMRB and the pavement surface triggering serious durability problems [4], [14]. Several factors may contribute to the drying shrinkage of CMRB, such as high cement content, poor compaction, high moisture content, and high clay content [4]. Water ingress through the reflected cracks in the pavement surface has major deteriorating effects that could cause complete failure of the road. Some of the techniques that have been in use for mitigating drying shrinkage cracks are lowering cement content, increasing pavement thickness, and decreasing the minimum 7-day UCS [4]. However, CMRB bases with low strength would be subject to other durability problems such as wetting/ drying or freezing/thawing. Therefore, it is important to optimize the mix design to accommodate both strength and shrinkage design criteria.

Some studies concluded that there is an optimum cement content around which the shrinkage could be minimized [42]. Considering other factors that affect the shrinkage performance, such as the moisture content, clay content, and RAP gradation and content, the importance of the proper selection and design of the CMRB is emphasized.

Mitigation Techniques for Shrinkage Cracks

There have been a few methods of mitigating shrinkage cracks such as pre-cutting and pre-cracking [46], [47]. The precutting is simply creating a weak section by transversely cutting the CMRB layer at equal intervals to force the cracks to occur at these sections. Controlling the crack pattern facilitates the ability to transfer the load safely across the cracked layers [46]. Although it has been investigated in a few studies, the precutting method has not been as popular as the pre-cracking method.

The pre-cracking can be employed by passing a vibratory roller over the CMRB at an early age (24 hours to 72 hours) a few times. This technique creates a huge number of uniformly spaced micro-cracks in the CMRB layer while it is still gaining strength at an early age. This method was first introduced in the 1960s by a study conducted in Japan and the results were promising [48]. The name microcracking has gained popularity for this method and it has been further investigated by several more laboratory and field studies [15], [49]–[54]. Most of the studies have expressed the superiority of this technique to mitigate shrinkage cracks development, while others showed no significant benefits when compared with un-microcracked systems having the same mix design [53].

Some DOTs, such as Louisiana DOT, use a chip seal interlayer between the CMRB and the asphalt pavement as a mitigation technique to reduce the susceptibility of reflective cracks on the pavement surface [54].

Pavement Issues linked to the shrinkage of CMRB

The shrinkage of CMRB leads to various types of cracks and crack patterns. The following section reviews the different types of cracks encountered in the pavement surface and caused by the shrinkage of CMRB.

Block Cracking in HMA

The block cracking of pavement is usually caused by the drying shrinkage of CMRB. It has been reported that this issue is associated with thin asphalt pavements laid over a stiff base such as CMRB [11], [19]. High UCS mixtures that have higher cement content are thought to have a higher rate of drying shrinkage and as such potentially prone to block cracking in pavement [55].

Transverse Cracking

Another type of cracking that is caused by the drying shrinkage of the CMRB is the transverse cracking of pavement [56]. These cracks are reflected from the base through the surface layer until eventually burst into the surface. The cracks in the CMRB affect the stress distribution in the pavement surface causing stress concentration at the section of cracked CMRB leading to pavement cracking [57]. The high UCS results in a high modulus and more drying shrinkage, thus leading to the creation of transverse cracking [11], [17], [18].

A limit of 300 psi for 7-day UCS was established by a study conducted by George [17], below which the potential to develop shrinkage cracks in the CMRB is low. This study also reported that the intensity of cracking is increased with the content of fine materials in the base soil, and the width of the developed cracks is directly linked to drying shrinkage. As for the crack spacing, the higher the friction between the CMRB and the pavement layer, the lower the spacing between cracks. This study also established a limit for shrinkage strain based on soil type: 525 με for fine soils and 310 με for granular soil.

Longitudinal Cracking

It has been reported that the CMRB helps prevent or mitigate alligator cracks (Bottom-Up cracks) [17]. However, the strong base leads (high stiffness and high modulus value) to the development of top-down cracking in the asphalt layer especially within the wheel path [17], [20], [21].

There is another type of longitudinal cracks called dry-land cracks that develop outside the wheel path and are also caused by drying shrinkage. These cracks propagate from the base through the pavement surface, especially with bases consisting of untreated expansive soils [58]. It was also reported in a study performed by the TXDOT that the moisture fluctuation between the center of the base and the shoulders caused longitudinal cracks as a result of the shrinkage and swelling of expansive soils [21], [59].

Bottom-Up Cracking (Alligator Cracking)

One of the problems associated with CMRB is that the surface of the CMRB layer tends to ravel [60]. This could create a layer of very fine materials separating the CMRB from the pavement layer and causing debonding [56]. The presence of this layer leads to the creation of alligator cracks and is usually seen in stabilized fine-grained base soils [60], [61]. Concerning raveling, the chip seal interlayer between the treated base and the asphalt pavement employed by some DOTs, such as LDOT [54], should mitigate this problem.

Fatigue cracking is another form of crack that CMRB and pavement surfaces can be subject to. The repeated traffic load causes the base and subbase to crack which then can reflect on the pavement surface [60], [62], [63]. The resistance of CMRB to fatigue-related cracks is lower when it is subject to deteriorating problems such as W/D and F/T [64]. The cracks that propagate from the bottom to the top are most likely due to the tension cracks developed at the bottom of the CMRB as a result of repeated traffic loads [64]. Fatigue cracking is also a potential problem that has been associated with thin asphalt layers on top of strong bases [18]. A minimum thickness of 8in. was recommended by the study conducted by Little et al. [18].

De Beer [61] stated that the loose materials between either the CMRB and the asphalt pavement or between the lifts of CMRB increase fatigue crack potential. Additionally, according to [63], the combination of transverse shrinkage cracking and longitudinal fatigue cracks develop ladder-shaped like cracks, especially under the wheel path.

However, the fatigue resistance is potentially improved with the higher flexural strength and the indirect tensile strength (ITS) of the CMRB [65], [66].

Importing Foreign Materials into the FDR Layers

Geocells

In a field study, Khan et al. [67] investigated the effectiveness of using geocells to reinforce the FDR layers containing RAP to enhance the stiffness and control the expansive nature of the subgrade in the study area. They used high-density polyethylene geocells to offer lateral restraint for the subgrade which would improve the overall stiffness. The structured test sections were monitored for deformation and compared with control sections in which no geocells were used. They concluded that the use of geocells had improved the overall performance of the subgrade as negligible deformations were observed [67]. A few other studies have investigated the use of geocells to reinforce the base soil layer with similar outcomes [68]– [70].

Virgin Aggregate

Taha et al. created RAP-virgin aggregate blends with 0%, 3%, 5%, and 7% Type I Portland cement by dry weight of the aggregate and RAP-to-virgin aggregate ratios of 100/0, 90/10, 80/20, 70/30, and 0/100 [11]. The resilient modulus was correlated with the UCS tests on treated and untreated aggregates. The UCS test findings from samples cured for 3, 7, and 28 days showed that blend strength and modulus increased with virgin aggregate and cement concentration [71].

CMRB Mixture Design

In this section, a summary and main findings of studies that have investigated procedures for CMRB mixture design will be provided. The first study was done by Guthrie et al. [73] for designing two different types of aggregate base: limestone aggregate and recycled concrete aggregate. The study emphasizes the importance of considering various factors beyond compressive strength when designing cement-stabilized aggregates. The findings support the use of specific cement contents depending on the type of stabilized aggregates, backed by laboratory testing. Additionally, the adoption of pre-cracking techniques in the field was recommended to improve the performance of cement-treated base layers and mitigate reflection cracking.

The study showed the importance of the physical and chemical characterization of the base materials. The mineralogical investigations revealed the presence of smectite compositions (expansive nature when absorbing water) in both limestone and recycled concrete aggregates, contributing to poor performance in untreated conditions. Stabilization was identified as necessary based on this finding. Laboratory testing indicated significant improvement in performance with minimal cement additions. The properties tested included strength, shrinkage, durability, and moisture susceptibility. Based on the laboratory testing results, it was recommended to use 3.0 percent cement for stabilizing the limestone aggregate and 1.5 percent cement for the recycled concrete aggregate. These percentages fulfill requirements for UCS, durability, and moisture susceptibility.

The recommendations made by this study include the following:

Laboratory Procedures:

- For future testing of aggregate base materials, the joint utilization of the Soil Cement Compressive Strength Test and the Tube Suction Test is recommended.
- Samples should be treated with enough cement to achieve a minimum seven-day UCS of 300 psi and a maximum average surface dielectric value of 10.
- Linear shrinkage test and the South African Wheel Tracker Erosion Test used in this project are not recommended for use in determining optimum cement contents.

Field Procedure:

- Pre-cracking is recommended as a method to reduce reflection cracking in surface layers over cement-treated bases.
- Pre-cracking should be performed within one to three days after placement using heavy traffic or vibratory rollers.
- A provisional pre-cracking specification, presented in the appendix of the report, is suggested for further evaluation and potential adjustments based on different construction scenarios and conditions.

The following is a summary of another study that investigated the strength assessment of soil cement by Wilson [73]. The study addresses concerns about the strength assessment of fully cured soil-cement base roadbeds. It aims to answer whether strength testing of soil-cement can be approached similarly to conventional concrete, and if field-molded samples can be used to assess the strength of soil-cement base. The research develops a testing program to evaluate curing methods, capping techniques, and the impact of length-to-diameter ratios on the compressive strength of soil-cement cylinders.

The study found that moist curing and bag curing yielded similar compressive strength results, with fan and air curing showing higher strengths. Neoprene pads were found to be not suitable for capping soil-cement cylinders, and gypsum capping was recommended if necessary for specific tolerances. The study recommended using field-molded cylinders for strength assessment of soil-cement base and suggested that ASTM C39 length-to-diameter correction factors were not applicable for soil-cement cylinders with length-to-diameter ratios between 1.0 and 2.0.

The conclusions of the study emphasized the importance of proper curing, capping, and testing procedures to accurately assess soil-cement base strength. Recommendations for future work included further testing to validate the proposed field-molding procedure and investigating the variability in core results to identify potential sources of strength data discrepancies in field projects.

Quality Control Measures

A research study by Bittar Marin et al. [74] focused on assessing the quality control measures for cement-stabilized soil pavement layers used in bases and sub-bases. The study investigated the suitability of the porosity/cement (η/C_{iv}) index for field pavement projects and compares the wet-dry accumulated loss of mass (ALM) and unconfined compression tests on soil-cement cores that were mixed, compacted, and cured in field layers. The field layers consisted of sand-Portland cement blends with varying dry unit weights and cement contents. The results were compared with laboratory samples of similar characteristics.

The study drew the following conclusions:

- Light falling-weight deflectometer (LWD) tests were effective in assessing the uniformity of compacted cement-stabilized bases or sub-bases. These tests also captured the increase in material stiffness due to cement reactions.
- Increasing cement content, dry unit weight, and curing time led to higher values of unconfined compression strength (UCS) and accumulated loss of mass (ALM) in both field and laboratory tests.
- The adjusted porosity/cement index ($\eta/Civ^{0.28}$) was found to be a suitable method for designing sand-Portland cement mixtures for pavement bases and sub-bases. It correlated well with UCS and ALM results, indicating its effectiveness in dosage determination.
- Unconfined compression tests on soil-cement cores were more susceptible to damage during extraction compared to wet-dry durability tests. This sensitivity difference could be due to the relatively small diameter of the core samples used. The recommendation is to use core samples with diameters no less than 76 mm to minimize extraction-related influences.
- While durability tests require more effort and time compared to unconfined compression tests, they provide valuable insights when combined with the latter. Durability tests appear to be less affected by coring processes, enhancing the reliability of the results.

In conclusion, the research demonstrated the applicability of the porosity/cement index for assessing the durability and strength of compacted sand-Portland cement layers in field pavement projects. It highlighted the importance of considering both wet-dry durability tests and unconfined compression tests, especially in quality control assessments using extracted core samples. The study suggested that LWD tests can be useful for assessing uniformity and that the porosity/cement index is a valuable tool for designing pavement mixtures [74].

Summary of the literature review

CMRB has its roots in the 1930s when soil-cement mixtures were explored by the South Carolina State Highway Department and the Portland Cement Association. Performance tests, such as the wet-dry and freeze-thaw tests, were developed to determine the optimal moisture content and cement content for soil-cement mixtures. The UCS test became the primary criterion for selecting cement content, especially in full-depth reclamation (FDR) applications in South Carolina. The SCDOT has successfully used Ordinary Portland Cement (OPC) in pavement rehabilitation projects using FDR. Factors affecting FDR performance include cement content, base soil properties, and the use of chemical stabilizers like Portland cement or lime. Soil pulverization level is crucial for enhancing resistance to freeze and thaw cycles. Chemical stabilizing agents have been explored in FDR, with cementitious stabilization being the most effective alternative for Partial Depth Rehabilitation.

Research on FDR has shown its potential for higher volume facilities and stabilizing imported materials. It has been found to be cost-effective and efficient in pavement rehabilitation projects, with a life cycle cost analysis comparing CIR, FDR, and traditional methods. A study by the Georgia DOT favored FDR with Portland cement over other stabilization methods, resulting in a 40% reduction in cost and lower falling weight deflectometer readings.

A comprehensive study by the University of Mississippi and the Mississippi DOT investigated shrinkage cracks performance in six 1000 ft test sections. Techniques for mitigating shrinkage cracks include pre-cutting and pre-cracking, with some DOTs using a chip seal interlayer between the CMRB and asphalt pavement as a mitigation technique. From these studies, pre-cracking was found to be the most effective treatment to mitigate reflective cracking from shrinkage-induced cracking in the CMRB. Other strategies to deal with shrinkage issues included incorporating foreign materials into FDR layers, such as geocells, lowering cement content, increasing pavement thickness, and decreasing the minimum 7-day UCS.

Soil cement strength assessment has been conducted using field-molded samples, with moist curing and bag curing yielding similar compressive strength results. The porosity/cement index was found to be effective in assessing the uniformity of compacted cement-stabilized bases or sub-bases, with increasing cement content, dry unit weight, and curing time leading to higher values of unconfined compression strength and reducing the accumulated loss of mass in both field and laboratory tests.

Studying and analyzing previous FDR data obtained from SCDOT

The FDR data were provided by SCDOT in the form of a spreadsheet (See the appendix for the data). The data included FDR projects spanning from 2012 to July 2020 with a total number of 1182 projects distributed throughout the state of SC. The data, as received, contained information about the date of the project (for some projects only the year was provided, while for other projects, both the month and the year were provided); the location, identified by the county, the road name, and the milepost (shown in Figure 10), the road type, average daily traffic (ADT) and the percent truck traffic. In addition, the data included the laboratory results of the maximum dry density (MDD), the optimum moisture content (OMC), and the UCS at cement content of 3%, 6%, and 9% of the total mix weight. Finally, the design cement content, the spread rate of cement (in psy), and the depth of CMRB were also provided.

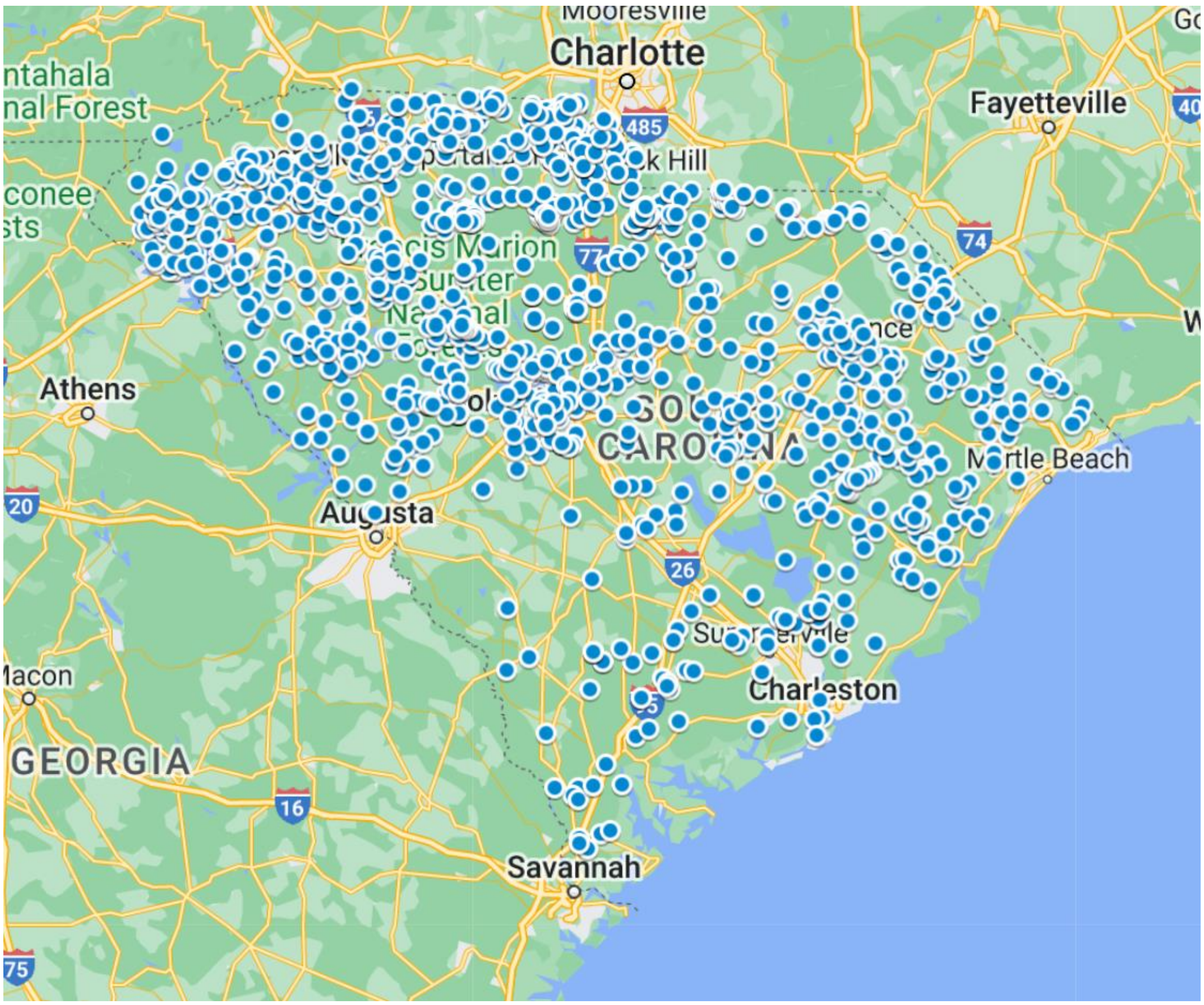

Figure 10 Locations of the projects whose data were obtained from SCDOT from 2012 to June 2023

To analyze such a large amount of data, the state of SC was divided into 7 different districts based on the SCDOT Engineering District Map shown in Figure 11. In addition, the state of SC was divided into five groups in terms of the dominant soil type in each county. The seven different districts in SC are shown in Figure 11 and the soil profile of the state of SC is shown in Figure 12 and is used as a tool in the analysis of the data to investigate any correlations or patterns. The FDR data covered most counties in the state except the following counties: Allendale, Bamberg, Barnwell, Beaufort, Calhoun, Clarendon, Hampton, and Orangeburg. Most of these counties are in District 7 and color code 3 (purple).

Table 3 shows the number of FDR projects for each year and the length of the FDR-treated roads based on the start and the end mileposts that were given in the provided data. Although the collected data ended in June of 2023, there were no details of what month in 2012 the data started to be collected. Hence, it is assumed that the full year-round FDR data were available for the years 2013 to 2022. During these years, the number of FDR projects peaked in 2018 with 223 projects, while the length of the FDR-treated roads peaked in 2017 at 470.15 miles. It should be noted that to obtain a better indication of the number of FDR-treated pavements, the length should be expressed by lane miles, but there was no way to extract this number from the provided data.

Table 3 FDR projects and the length of FDR-treated miles for each year.

Year	No. of Projects	FDR-treated roads, miles
2012	60	97.82
2013	36	75.4
2014	72	113.222
2015	166	320.08
2016	135	280.388
2017	182	470.15
2018	223	279.31
2019	153	264.982
2020	196	432.06
2021	203	333.484
2022	183	350.846
2023	134	264.43
TOTALS	**1743**	**3282.172**

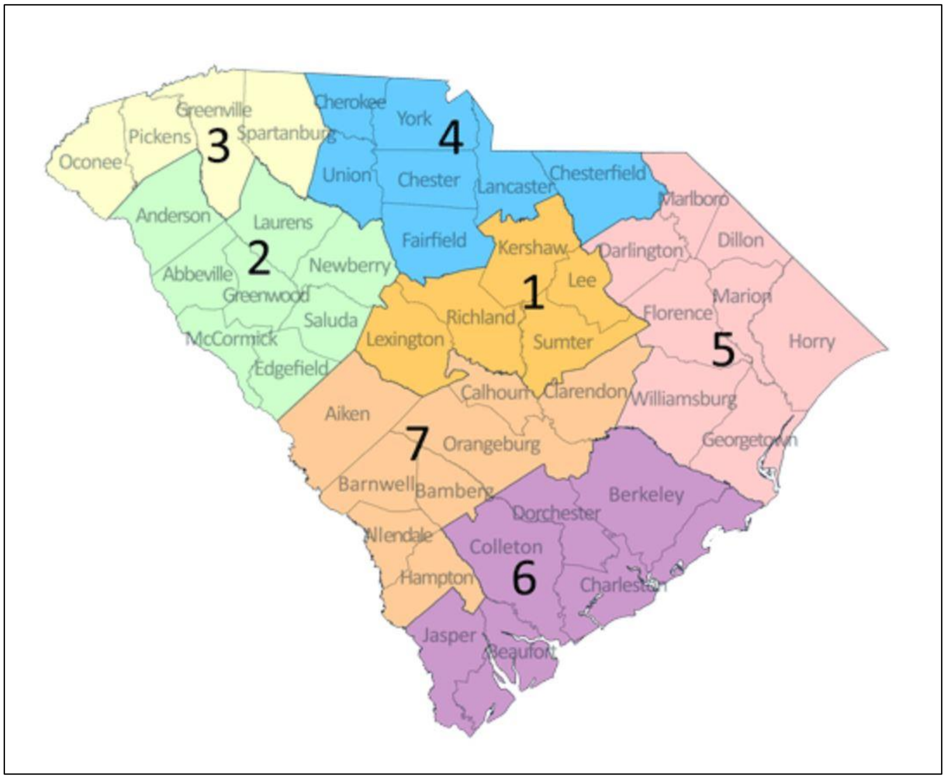

Figure 11 The state of SC counties and seven districts (Courtesy: SCDOT)

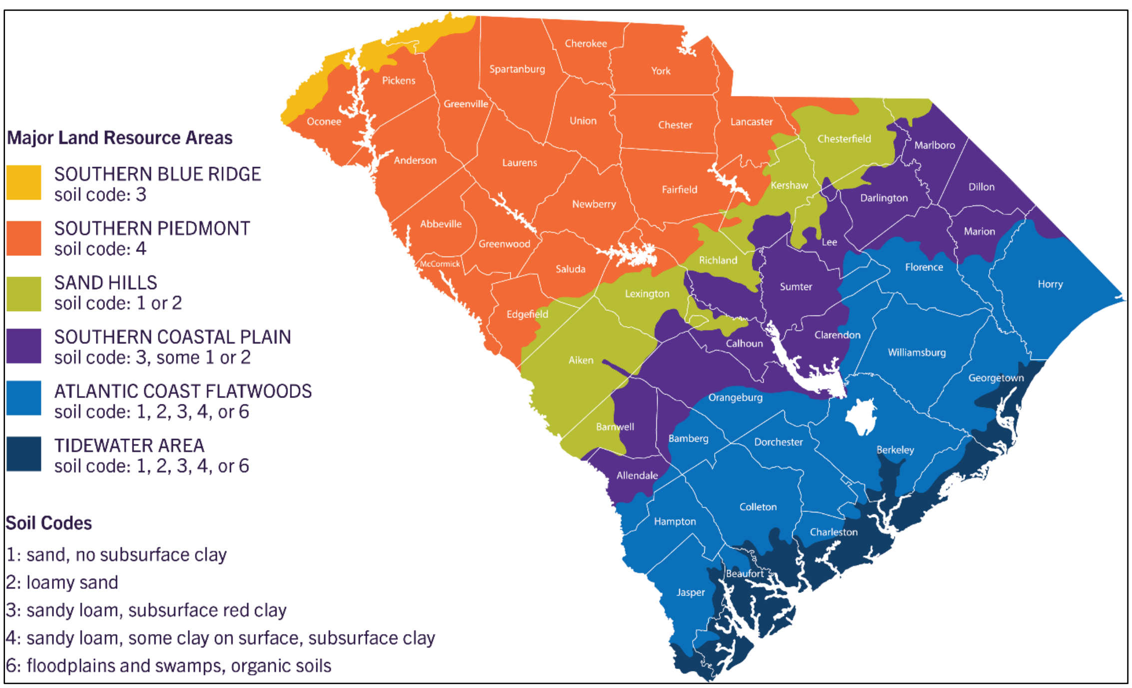

Figure 12 Soil Codes of the state of SC (https://www.clemson.edu/public/regulatory/ag-srvc-lab/soil-testing/soil-codes.html)

Table 21 (in the appendix) shows all the counties with available data and the associated predominant soil code. Provided in the same table are the average OMC, the average MDD, and the average design cement content for each county. In addition, the average UCS is also provided for each county at three different levels of cement content: 3%, 6%, and 9% of the total weight of the pavement materials.

UCS has been the main parameter based on which the CMRB mixtures are designed. Based on the available UCS data, a location-based correlation was investigated. One of the factors that affects the UCS is the base soil properties (such as grain size distribution, clay content, and plasticity indices). Therefore, UCS data was studied for each district.

The heat map shown in Figure 13 represents the average UCS at the median cement content of 6% for all counties in SC. Compared with the soil distribution map shown in Figure 12, the UCS distribution is compatible. Figure 14 shows the average UCS distribution for each district. From Figure 14, It can be seen that districts one and five had approximately the same and highest average UCS, followed by district six and then finally district two and three. The maximum and minimum UCS for 3%, 6% and 9% cement levels were (145 psi, 360 psi), (319 psi, 657 psi), and (443 psi, and 982 psi), respectively.

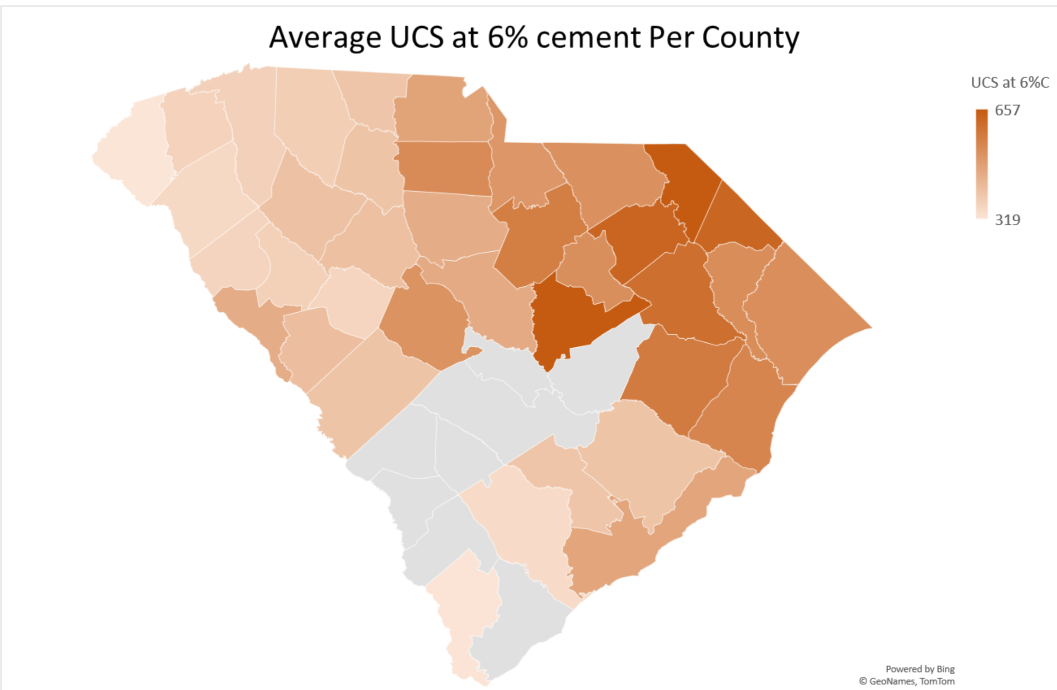

Figure 13 The average UCS at 6% cement for SC counties with available data.

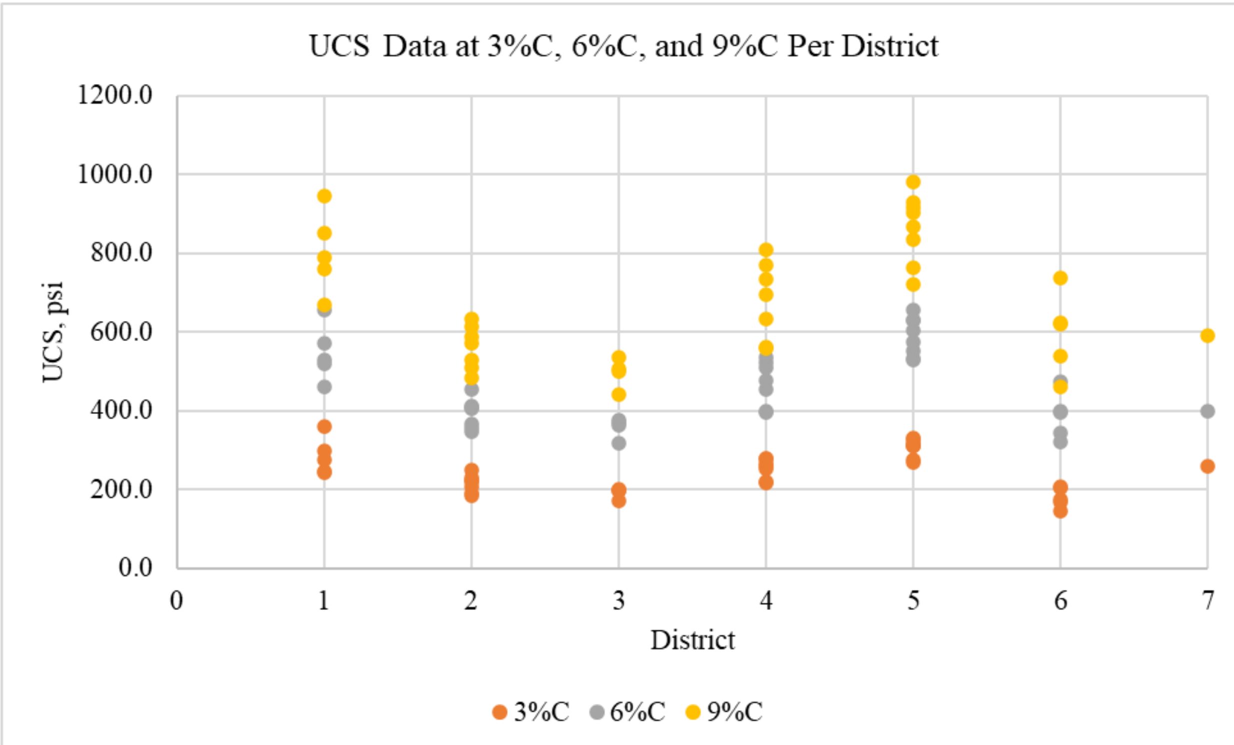

Figure 14 UCS data per district

The average data per district for the average design cement content (DCC), and the maximum dry density (MDD) are shown in Figure & Figure 156, respectively.

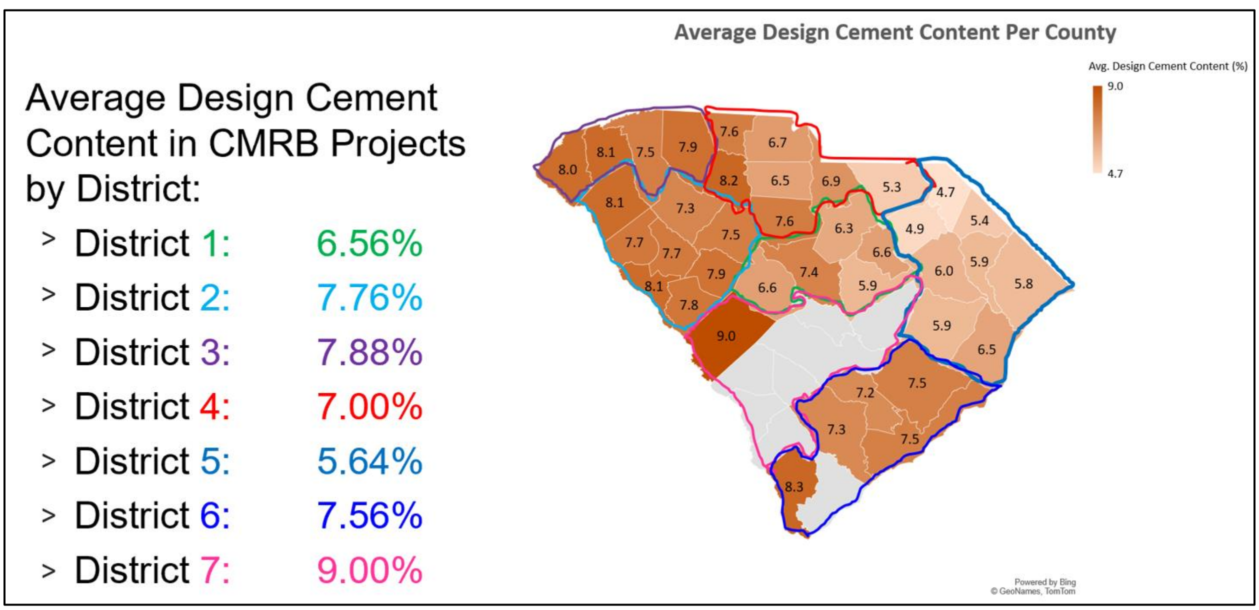

Figure 15 Average Design Cement Content per County and District.

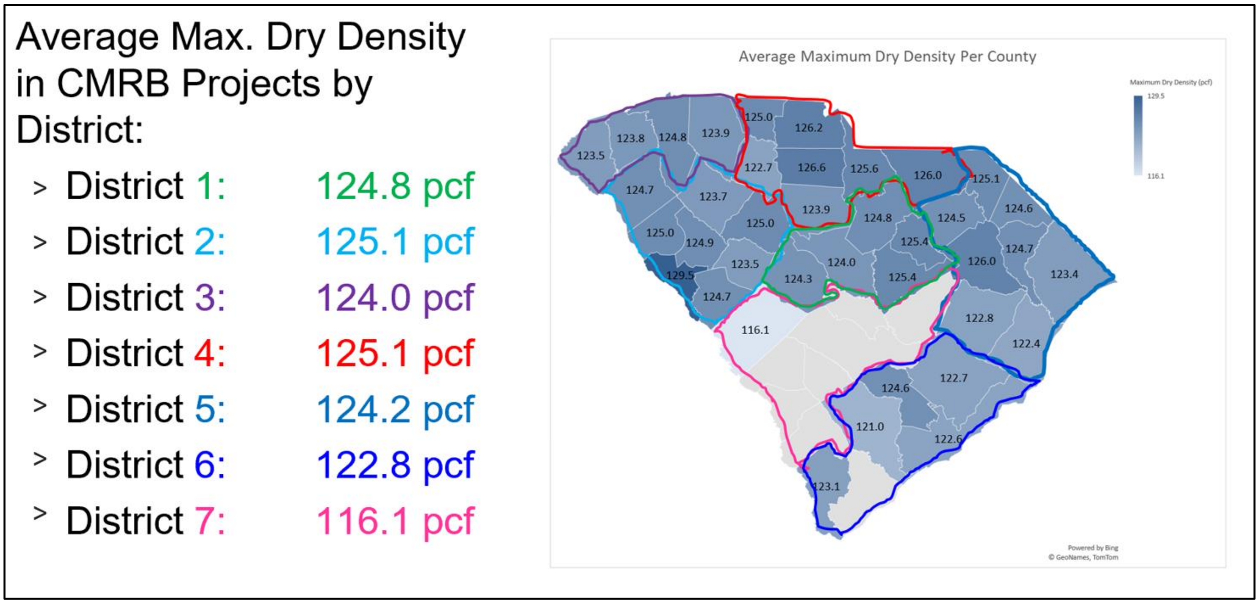

Figure 156 Average Maximum Dry Density in CMRB Projects per District

Survey of States

Introduction:

The objective of this section is to present the survey questionnaire that was designed to gather information from various Departments of Transportation (DOT) and State Highway Agency (SHA) officials regarding the general usage and mix design procedures associated with Cement-Modified Recycled Base (CMRB). The questionnaire aimed to provide insights into the current practices and perspectives related to CMRB utilization, enabling a better understanding of the state of CMRB implementation across different jurisdictions. See the appendix for the survey questions and main findings.

Respondent Profile:

A total of 22 DOTs (20 responded online and two by email) participated in the survey, representing a wide geographical distribution shown in Figure 16. The diverse range of participants ensures that the survey results reflect the practices and perspectives of professionals involved in CMRB implementation across different regions.

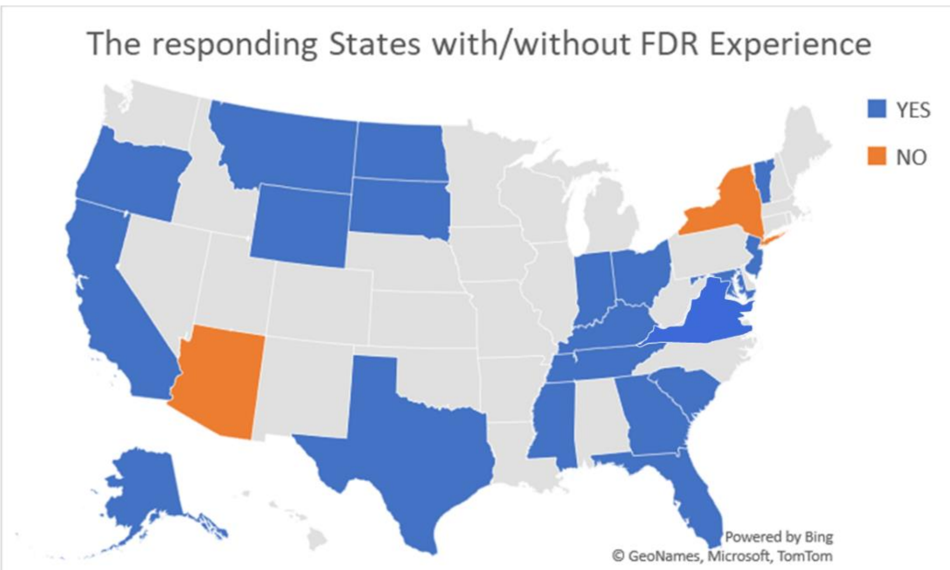

Figure 16 The responding States to the survey with or without FDR experience.

Survey Results and Analysis:

The survey results provided valuable insights into the current practices and trends related to CMRB. The data collected was analyzed to identify common patterns and variations in the usage and mix design procedures. The findings shed light on the level of CMRB adoption, the preferred types and sources of recycled materials, the selection criteria used for mix designs, and the testing methods employed to ensure quality control. Furthermore, the survey highlighted any challenges or limitations faced by DOTs in implementing CMRB, providing opportunities for knowledge sharing and improvement.

Key Findings:

The following key findings emerged from the analysis of the survey data:

The FDR adoption rate and frequency of CMRB utilization among respondents was 20 out of the 22 responding states (Based on Q5). Among the 20 states that have used FDR (Based on Q6), 15 states (75% of respondents) reported selecting cement as their primary stabilizing agent on FDR projects. Cement is a widely recognized and commonly used stabilizing agent known for its strength and durability-enhancing properties. The high percentage of states choosing cement suggests its popularity and widespread acceptance as a preferred stabilizing agent for FDR applications.

Three states; Wyoming, Florida, and Alaska (15% of respondents) indicated the use of an alternative stabilizing agent categorized as "Other." Unfortunately, the survey did not specify the nature of these alternative agents, but based on a post-survey communication, asphalt emulsion, and fly ash are the most used stabilizing agents following cement. The remaining two states did not specify what chemical stabilizing agent is used in their FDR mix design process.

In terms of the amount of FDR-treated square yards of pavements (Based on Q7), Texas (TX) and South Carolina (SC) do more FDR than the other responding states. The FDR-treated area of pavements per year ranged from less than 70,000 yd^2/year to more than 210,000 yd^2/year.

Based on Q8, the average daily traffic (ADT) for the FDR-treated roads ranged from less than 5000 (most of the responding states) to more than 50,000 (SC and TX). With these numbers of ADT, the percentage of trucks (Based on Q9) varied from less than 5% in Maryland to 40% in Oregon.

More than half of the responding DOTs (total of 11) indicated that they use the UCS for the selection of the chemical stabilizing agent (CSA) content. Five DOTs indicated that they use other stabilizing agents, and the rest did not specify the type of CSA they use. The design UCS, as shown in Figure 18, ranged from 150-250 psi in TX to 500-1500 psi in Montana. The average range that most of the responding DOTs utilize for their SCA content selection is between 300 psi and 450 psi.

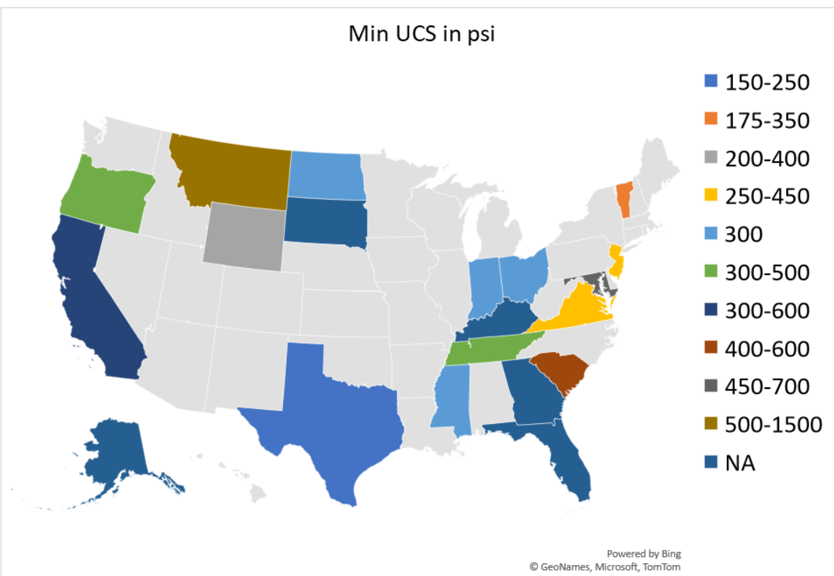

Figure 18 Range of UCS for the FDR-treated pavements.

Summary of the results of the survey of States

Table 4 Summary of the results of the survey of States.

Question	Summary
Q5	FDR Adoption Rate: 20 out of 22 responding states
Q6	Primary Stabilizing Agent: 75% chose Cement (15 states); 15% chose "Other" (Wyoming, Florida, Alaska); 10% didn't specify
Q12	CSA Selection Criteria: 11 DOTs use UCS; 5 use other stabilizing agents; rest didn't specify
Q14	Design UCS Range: TX (150-250 psi), Montana (500-1500 psi), Majority (300-450 psi)
Q13	Additional Criteria for CSA Design: Marshall Stability, Resistance to Moisture Damage, Historical Performance/Experience
Q15	Durability Assessment: Montana performs AASHTO T135 (W/D) and T136 (F/T)
Q16	Most Common Deterioration Mode: Shrinkage Cracking (Most DOTs), F/T Cycles (NDDOT), Tent Cracking due to High UCS (Vermont)
Q17	Pavement Design Standards: Majority use AASHTO 1993 or earlier; TX, CA, FL, and AK use locally developed specs
Q18	Structural Coefficient: Range from 0.16 to 0.26; Some DOTs use Resilient Modulus (20,000 psi to 150,000 psi)
Q22 & Q23	Additional Material Processing: Further crushing and sieving
Q24 & Q25	Moisture Content Testing: All DOTs measure OMC; Field testing methods include pan-dry and nuclear gauge
Q26	Allowable Moisture Content Window: Ranges from 4% below OMC to 4% above OMC
Q28	QC Plan: Includes tests for Thickness, AASHTO T27 (Gradation), T255 (Moisture Content), T310 (In-Place Density), ITS, Surface Irregularities

3. Methodology

This chapter is dedicated to listing all the materials and test methods followed in this study. A brief description of each material and test method is presented. Also, the experimental work plan and the research parameters are all shown in Figure 1719.

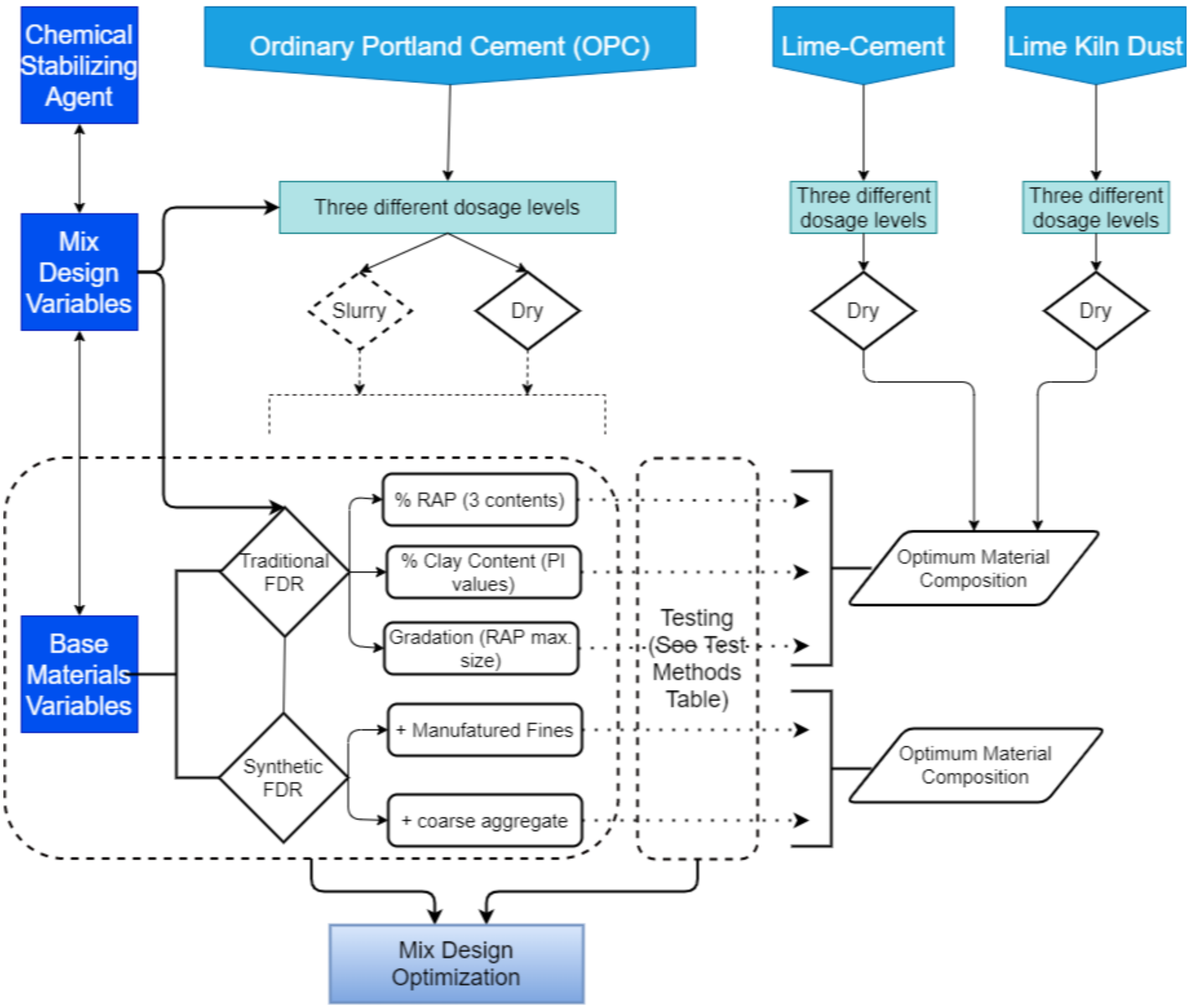

Figure 17 Material Variables Explored in this study.

Materials

Ordinary Portland Cement (ASTM C150, Type I/II)

Type I/II ordinary Portland cement (OPC) (Na_2O_{eq} = 0.38%) that was obtained from Argos cement company, Harleyville Plant, SC, was used in this study.

Quicklime

High calcium quicklime (QL), obtained from Carmeuse, was used in this study to evaluate the use of alternative chemical binders in CMRB. According to Carmeuse, this product contained 93-97% calcium oxide (CaO) by weight, less than 4% magnesium oxide (MgO), less than 2% silica-crystalline quartz (SiO_2), and trace amounts of other chemical compounds. High calcium quicklime is produced from quarried limestone which is processed through a series of crushers and calcined in a lime kiln. For this study, the quicklime was passed through a No. 10 sieve (2mm).

Hydrated Lime

High-calcium hydrated lime (HL), obtained from Carmeuse, was used in this study to evaluate the use of alternative chemical binders in CMRB. According to Carmeuse, this product contained 94-97% calcium hydroxide ($Ca(OH)_2$) by weight and less than 1% silica-crystalline quartz (SiO_2). Hydrated lime is produced by reacting quicklime with approximately 33% water resulting in dry, powdered hydrated lime. This powder is 92-97% passing 325 mesh (45µm).

Lime Kiln Dust (LKD)

Calciment®, obtained from Carmeuse, is a high calcium lime kiln dust (LKD) that was used in this study to evaluate the use of alternative chemical binders in CMRB. According to Carmeuse, high calcium lime kiln dust is a fine powder containing of mix of calcium oxide (CaO), magnesium oxide (MgO), and other pozzolans including calcium hydroxide, calcium magnesium carbonate, calcium magnesium oxide, magnesium carbonate, and magnesium oxide, as well as less than 10% silica-crystalline quartz by weight. Lime kiln dust is a byproduct of the lime manufacturing process that is screened out of fumes produced by heating limestone.

Base soil

A total of four different base soils were selected from throughout South Carolina for use in experimental work. These will be referred to by their source locations of Walhalla, Lugoff, Myrtle Beach, and Clemson. Walhalla soil is used for the majority of experimental work to evaluate the effects of variables on the performance of CMRB. Base soils were prepared first by drying for 24 hours in the oven at 110°C and then passing through a No. 4 sieve (4.75mm) to separate larger RAP particles. Sieve analysis for soil classification is provided in Table 5 and Figure 18.

Table 5: Classification of the four base soils based on the percent passings.

Sieve	Size, mm	Walhalla	Lugoff	Myrtle Beach	Clemson
No. 10	2	67.04	96.03	98.95	90.23
No. 40	0.425	7.23	38.22	52.14	49.41
No. 200	0.075	0.66	4.10	0.18	5.60
AASHTO M 145		A-1-b	A-1-b	A-3	A-1-b

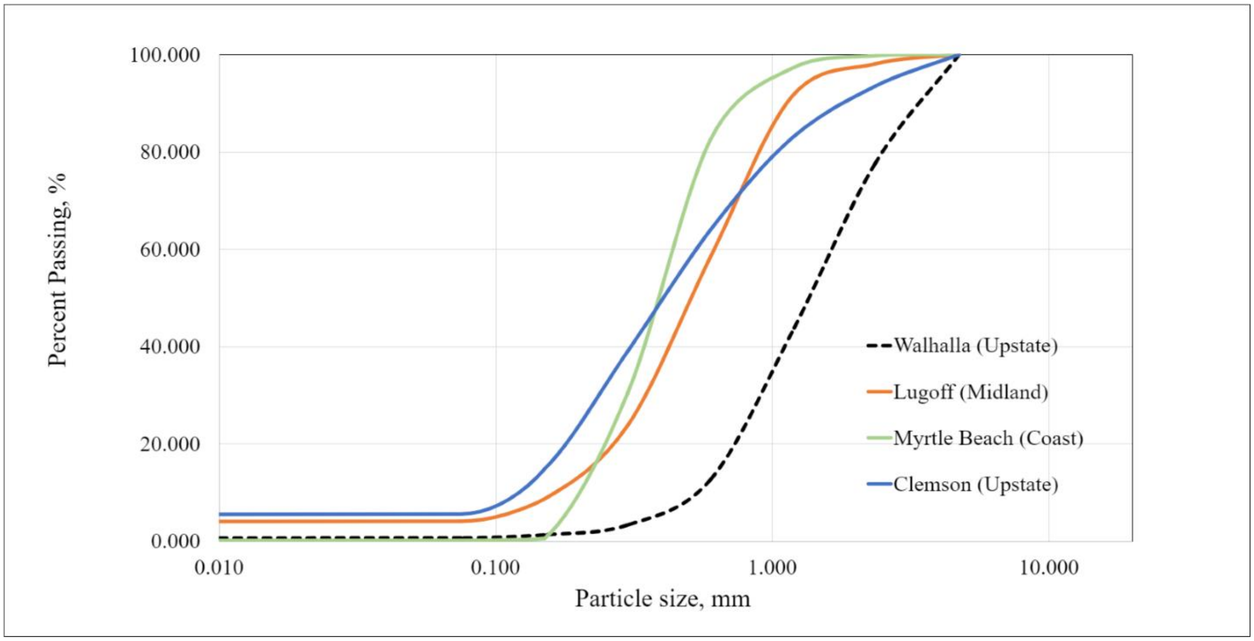

Figure 18 PSD of the different base soils.

Reclaimed Asphalt Pavement

Reclaimed Asphalt Pavement (RAP) was obtained from a local road construction site for use in this study. The RAP was prepared by drying for 24 hours in an oven at 110°C and then sieved into the following particle sizes: 3/4" (19 mm), ½" (12.5 mm), 3/8" (9.5 mm), and the retained-on No. 4 (4.75 mm). The different sizes were stored separately and then blended at the same proportions for each round of casting. Sieve analysis of the RAP is provided in Table 6.

Table 6: Sieve Analysis of RAP

Sieve Size, in.	Size, mm	% Retained	% Passing
3/4"	19	0	100
1/2"	12.5	30	70
3/8"	9.5	60	40
No. 4	4.75	100	0

RAP specific gravity and absorption ratio were evaluated as per ASTM C127. The absorption percent was 6.60% and the specific gravity was 2.1. Although these physical properties depend largely on the source of the coarse aggregate used in the asphalt concrete mixture, the asphalt coating could affect the values of both.

Ball Clay

An external source of clay, a ball clay from Imerys was selected to study the effects of clay content on the performance of CMRB. Ball clays are fine-grained, highly plastic clays consisting of primarily kaolinite, mica, and quartz minerals, as well as organic matter. The ball clay particle size distribution provided by the supplier is provided in Table 7 and plotted in Figure 21.

Table 7: Particle Size Distribution of Ball Clay

Particle Size, mm	Percent Passing, %
0.075	100
0.02	96
0.01	91
0.005	83
0.002	68
0.001	57
0.0005	46
0.00001	0

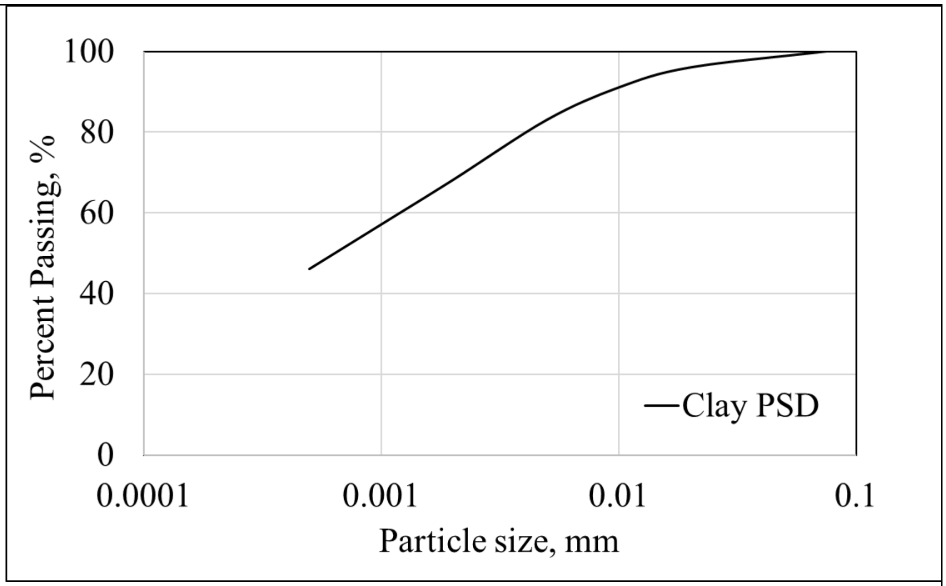

Figure 19 Particle Size Distribution of the Ball Clay.

The ball clay was blended with the granular base soil sourced from Walhalla, SC to create varying mixtures with clay contents of 10%, 20%, 30%, and 40% by weight of the base soil. The particle size distribution and the classification of these mixtures are represented in Table 8 and plotted in Figure 20.

Table 8 Varying Clay Mixtures PSD and Classification

Sieve #	**Size**	**00%Clay**	**10%Clay**	**20%Clay**	**30%Clay**	**40%Clay**
No. 10	2 mm	67.0	60.3	53.6	46.9	40.2
No. 40	0.425 mm	7.2	6.5	5.8	5.1	4.3
No. 200	0.075 mm	0.7	10.6	20.5	30.5	40.4
Class:		**A-1-b**	**A-1-b**	**A-2**	**A-2**	**A-4**

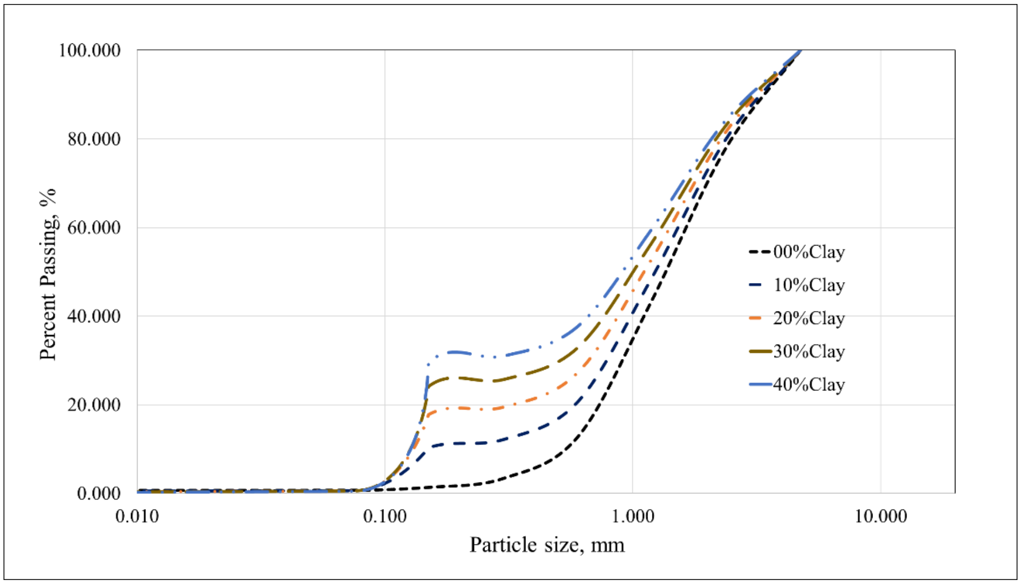

Figure 20 The PSD of the varying clay mixtures

Test Methods

Base Soil Characterization:

The specific gravity of base soils

ASTM D854 method B test procedures were followed to calculate the SG of the base soil. The soil is a granular, non-plastic material. The calculated SG for the different base soils sourced for this study was 2.10, 2.50, 2.54, and 2.62 for Walhalla, Lugoff, Clemson, and Myrtle Beach respectively.

Particle size distribution of base soil (ASTM D6913)

A well-graded soil with minimal amounts of clay and silt requires less cement content to produce a strong and durable recycled base layer. Whereas clayey soil or gap-graded soil requires more cement content to get the required strength and durability. After a representative sample was obtained from the base soil, different particle sizes were separated over the No. 8, No. 16. No. 30, No. 50, No. 100, and No. 200 standard set of sieves (8-inch diameter sieves).

Test Methods of CMRB:

Optimum moisture content for the cement-treated base material (AASHTO T 99).

The purpose of this test is to determine the moisture content required to result in the maximum density of blended materials. According to SCT-26, this test should be performed on a blend that has medium cement content, which is 6% of the total weight of RAP and base soil. The optimum moisture content (OMC) obtained using this proportion should be used for all other binder ratios (i.e. 3% and 9%).

Unconfined Compressive Strength for cement-treated RAP and base soil (SC-T-26 and SC-T-142).

SCT-26 requires two specimens for each tested mixture. The specimens were prepared using a 4-inch (100 mm) diameter proctor mold and 5.5 lbs. (2.495 Kg) rammer. Each specimen was made by compacting three equal layers using 25 blows of proctor rammer. Following the compaction of each specimen, it was extruded using a manual sample extruder.

All specimens were covered and cured in a 100% humidity room at 23°C until tested. On the night the test was due, specimens were soaked overnight according to SCT-26 (for consistency, a period of 10-12 hours of soaking was maintained). Although SCT-26 requires testing CMRB specimens at the age of 7 days, it was decided to test them at both 7 days and 28 days to explore the strength development.

To investigate the effects of cement application methods (dry vs. slurry) on CMRB samples, a comparative analysis was conducted. In the slurry application method, the cement slurry was prepared using the amount of water required to achieve the optimum moisture content (OMC%). The slurry was then thoroughly mixed with the base soil and RAP materials before molding the CMRB samples. This approach was briefly tested against the traditional dry application method to evaluate any differences in performance and effectiveness.

Test Methods to Assess the Tensile Strength of CMRB

Flexural Strength (ASTM D1635-00(2006)):

Flexural strength is a critical property for CMRB, especially in pavement design. It measures the material's ability to resist bending stresses and indicates its overall structural integrity and resistance to cracking under traffic loads. The third-point loading test on 3 in. × 3 in. × 11.25 in. prisms provide data on the material's ability to withstand flexural forces, which is vital for evaluating its suitability as a load-bearing layer in pavements.

Indirect Tensile Strength (ITS) (ASTM D6931-17):

Though not a soil-cement-specific procedure, the indirect tensile strength (ITS) is a widely used test for assessing the tensile strength of various materials, including CMRB. The use of 6-inch-diameter, 2-inch-thick CMRB pills allows for quick and efficient evaluation of the material's resistance to cracking and tensile stresses perpendicular to the loading axis. ITS is important for pavement design as it helps to understand the material's ability to resist tensile forces from traffic loads and temperature-induced stresses.

For the ITS, CMRB pills were cut from CMRB cylinders with dimensions of 6in. diameter by 8in. length. The thickness of the CMRB pills was about 2in. the actual thickness was measured before the test by taking an average of four readings around the perimeter. Also, the actual diameter was measured by taking the average of three readings along the diameter. All samples were submerged for 24 hours before testing. Once the CMRB is placed in the loading frame, a constant loading rate was applied to induce 50±5 mm/min deformation.

The ITS was performed on samples prepared using base soils from Walhalla, Clemson, and Lugoff. The Myrtle Beach sand failed while cutting the CMRB pills. All mixtures contained 35% RAP by weight of the pavement materials, 6% Cement, and water content at the OMC level.

See the appendix for some pictures of the test.

Splitting Tensile Strength (STS) (ASTM C496-17):

Similar to ITS, STS is not specifically designed for soil cement but is commonly applied to evaluate the tensile strength of cementitious materials, including CMRB. The use of standard proctor-sized samples (4in diameter, 4.58in length) allows for a reliable assessment of the material's tensile strength parallel to the loading direction. STS is vital for pavement design, as it provides data on the material's resistance to cracking and tensile forces within the pavement layers.

Durability tests for the stabilized base material

Wetting and Drying (W-D) (AASHTO T135 or ASTM D559)

In this test, two cylindrical specimens of 4 in. dia. x 4.5 in. height were prepared. Following preparation, they were cured for seven days in a curing room. After that, specimens are subject to what consists of one cycle of wetting and drying, which is achieved by submerging the specimens for 5 hours followed by placing them in a 71°C oven for 42 hours. The testing duration includes 12 cycles. At the end of each cycle, wire brushing is applied to all of the surface areas of the specimens twice to remove any loosened materials. The pressure applied by the wire scratch brush should be about 3 lbs. Weight loss is monitored at each cycle and the final weight loss is used to indicate durability. AASHTO T135 – method B was followed here since the maximum size of the used materials was 19 mm (3/4").

The first specimen (labeled No. 1 specimen) in the durability test is used to monitor volume change after each wetting and drying cycle. The volume of specimens was calculated by taking the average diameter and average height by digital caliper measurements taken at the same points each time. The wire brushing is applied on the second specimen (labeled No. 2 specimen). The 3-lb pressure applied while brushing was achieved by placing a 3-lb object on top of the wire scratch brush. At the end of all cycles, specimens were put in a 110°C oven for 24 hours and the final oven-dry masses were obtained. These masses were corrected for the amount of water of hydration retained in specimens which -according to AASHTO T135- is estimated to be 1.5% for A-1 soil.

Freezing and Thawing of Soil-Cement (ASTM D 560)

In this test, after compacting and extruding the two samples from a 4-in. diameter standard proctor mold, initial measurements for the mass and volume are taken. Then, all samples are cured for seven days in a standard curing room. Next, the samples are subjected to 12 cycles of freezing and thawing. Each cycle consists of freezing at -23℃ ± 2℃ for 24 hours, followed by thawing at 21℃ in the standard moist room for another 24 hours. Measurements of volume and mass are taken after each half-cycle. At the end of each cycle, a brushing using a wire brush is performed on one of the samples. The weight loss and volume changes are to be calculated at each cycle. Not among the ASTM D560 requirements, the UCS values are usually measured after the completion of all F-T cycles and compared to the original UCS.

Tube Suction Test (TST)

The tube suction test (TST) procedures from Texas DOT specification (TEX-144-E, 2020) were followed in this investigation. The cylindrical sample dimensions used in these procedures are 6in. diameter by 8in. height. At the beginning of this study, a smaller sample with dimensions that are similar to the standard proctor sample was explored (4in. diameter by 4.58in. height). However, it was concluded that the TST requires larger samples to provide longer passages for capillary suction. The dielectric values measured from the smaller sample size increased gradually but became constant after a day or two from the test initiation.

The mixture proportion chosen to be tested for TST contained 35% RAP by mass of the base soil, 6% cement by mass of the RAP+base soil, and a water level at the OMC of the tested materials based on the OMC results obtained previously. The test procedures involve preparing two samples at the OMC level, and then drying these samples at 60 °C for 48 hours. Once taken out of the oven and cooled down at room temperature, the initial dielectric values are taken. Next, a porous stone and a filter paper are placed at the bottom of the sample, and a porous stone and a plastic disk are placed on top of the sample. Then, a latex membrane is wrapped around the whole set to prevent evaporation during the 10-day test period. The sample set is then placed in a steel or plastic pan with water covering 0.25" on top of the bottom porous stone. The dielectric values are monitored daily at the same time for the next 10 days.

To compact the sample as per the TEX-144-E, five layers are needed, and each layer must be tamped 56 times (to deliver a compaction effort energy equivalent to 750 ± 15 ft-lb) by the 10-lb modified proctor hammer at a free fall of 18 inches. The compaction of the sample was done by applying static pressure to an amount of CMRB materials enough to produce a 1.6in. (40mm) layer. The materials were determined based on the wet density corresponding to the OMC that was obtained previously. Once each layer is compacted, groves on the surface are made using a straight edge to ensure good inter-layer bonds. The compacted sample then was extruded, its weight was measured, and then it was placed in a 60°C oven.

Shrinkage of CMRB

It is well known that some cracks on the CMRB pavement surface are propagated from the base course and are caused by drying shrinkage of the CMRB [4], [14]. There are many contributing causes to the drying shrinkage including moisture content, clay content, cement content and low-quality compaction [4]. In this study, two aspects of the CMRB shrinkage behavior were studied: the free shrinkage and the restrained shrinkage.

Free shrinkage test

To assess the length change caused by drying shrinkage of CMRB, the same standards associated with Portland cement concrete (ASTM C157 [75] and ASTM C490 [76]) were followed in this study.

Free drying shrinkage of CMRB was evaluated by molding and testing 3 in. x 3 in. x 11.25in prisms, as shown in Figure 49. Each CMRB specimen was compacted to yield the maximum wet density at OMC. Three cement contents—3%, 6%, and 9%—were evaluated. An environmental chamber at 23 °C and 50%RH was used to store the samples. After 48 hours of curing the samples in molds in the typical curing environment, the length change was monitored until no significant drying occurred.

Restrained Shrinkage test

Traditionally, the restrained shrinkage ring test, per ASTM C1581 / AASHTO T334-08 has been used to evaluate and quantify the shrinkage cracking sensitivity of cement-based materials when restrained. The test procedure consists of casting concrete in an annular region of two concentric steel rings where the inner steel ring provides a uniform restraint to the concrete contraction when it is exposed to drying. The restraint to the contraction from shrinkage results in the development of compressive stress and accordingly compressive strain in the inner steel ring when the concrete ring shrinks. The inside of the inner steel ring is equipped with strain gauges for monitoring the strain variation as the concrete specimen shrinks against it. When the tensile stresses in concrete due to the restraint exceed the tensile strength of concrete, the concrete ring cracks resulting in a sudden decrease in strain in one or more of the strain gages. By continuously monitoring the strain development in the steel ring, it is possible to calculate a corresponding stress and, from mechanical equilibrium considerations, the average stress in the concrete ring can be computed. In the present investigation, the restrained shrinkage test was adapted to assess the shrinkage behavior of CMRB. In this method, instead of concrete or mortar, CMRB is placed in the mold surrounding the steel ring in four layers and compacted to produce a ring of CMRB having the same density obtained at the OMC level. After compacting the CMRB ring, the outer cover is removed and the CMRB is allowed to dry in a chamber maintained at a 50% relative humidity environment and 23℃, while the strain in the inner steel ring is monitored. The time to cracking is observed and recorded.

Other Test Methods

Isothermal Calorimetry

The heat output from the chemical reactions of the cement hydration can be monitored and measured by conducting an isothermal calorimetry test. The objective of this test is to evaluate the heat generated during cement hydration in CMRB samples, with the assumption that this heat production could serve as an indicator of CMRB strength. For this investigation, the heat evolution in CMRB was assessed using the Calmetrix iCal HPC 4000 isothermal calorimeter. A comparative analysis was conducted between CMRB and Cement mortar in terms of heat evolution. The calibration of the instrument was executed using a standard Portland cement sample with a known heat evolution pattern.

The test materials encompassed base soil passing through a No. 4 standard sieve, Type I cement, and water at the OMC level; Recycled Asphalt Pavement (RAP) was not incorporated into the mixture. Before the mixing process, all materials were pre-conditioned to a temperature of 23°C.

The mixing procedure was carried out within a 5-quart Hobart mixer. The sequence of material addition was as follows: base soil (including clay in cases of varying clay mixtures), followed by cement. After one minute of dry material mixing, water was introduced. A brief pause of one minute allowed any materials adhering to the sides of the mixing drum to be scraped down into the batch. Subsequently, a final mixing phase of one minute was performed. All mixing operations were conducted at a low speed, approximately 140 rpm. Following the preparation of the batch, a 100 g portion was transferred into a 150 mL plastic vial. This plastic vial containing the mixture was then inserted into the calorimeter for analysis. The entire measurement process was conducted at an ambient temperature of 23°C.

4. Findings

Pavement Materials Characterization:

The specific gravity of base soils

ASTM D854 method B test procedures were followed in order to calculate the SG of the base soil. The soil is a granular, non-plastic material. The calculated SG for the different base soils sourced for this study were 2.10, 2.50, 2.54, and 2.62 for Walhalla, Lugoff, Clemson, and Myrtle Beach respectively.

Particle size distribution of base soil (ASTM D6913)

To determine the particle size distributions of the four base soils, representative samples were taken and sieved over the No. 8, No. 16. No. 30, No. 50, No. 100, and No. 200 standard set of sieves. The particle size distributions of the four base soils are shown in Figure 21. It should be noted that the two constituents of the imported pavement materials (base soil + RAP) were separated by sieving over a No. 4 standard sieve (4.75 mm size).

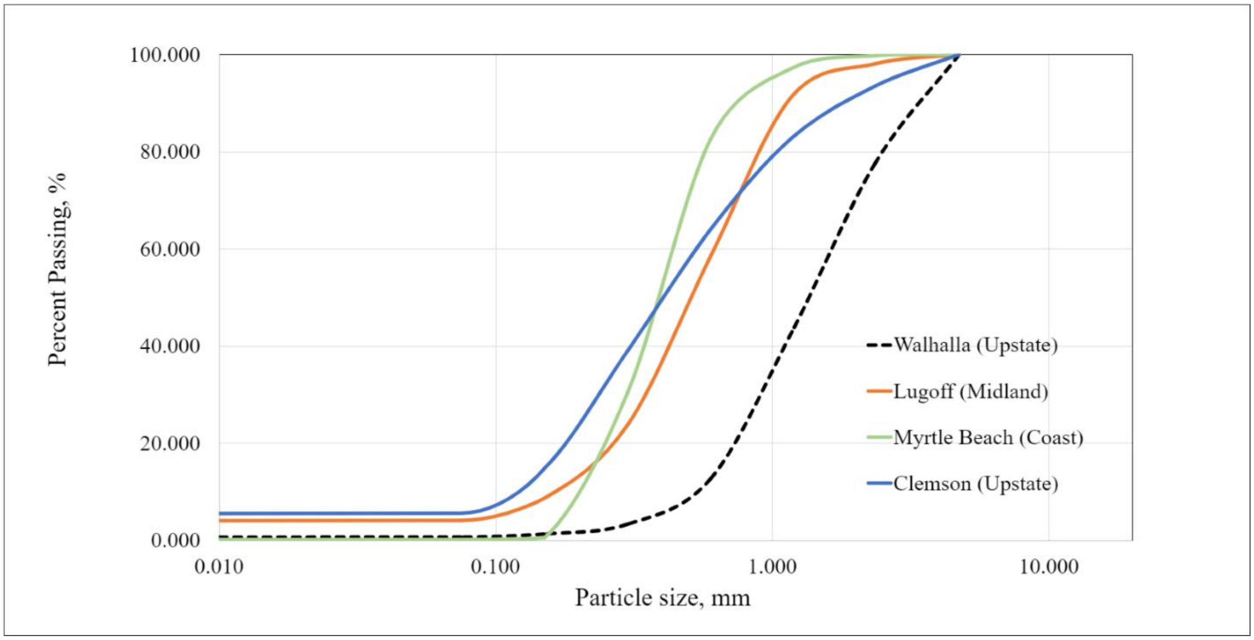

Figure 21: Particle Size Distributions of the Four Base Soils

RAP characterization

RAP specific gravity and absorption ratio were evaluated as per ASTM C127. The absorption ratio was 6.60% and the specific gravity was 2.1. Although these physical properties depend largely on the source of the coarse aggregate used in the asphalt concrete mixture, the asphalt coating could affect the values of both. No testing was undertaken to evaluate the thickness of the asphalt coating on the crushed stones, but the binder content can be estimated based on the AASHTO T308. These procedures were tried earlier at the start of the project but were not successful because of some complications with the oven.

Atterberg limits

Table 9 Atterberg Limits for Clay/Soil Blends

Blending ratio	Avg. Plastic Limit (PL)	Average Liquid Limit (LL)	Plasticity Index
00%Clay+100%Soil	--	--	--
30%Clay+70%Soil	12.12%	25.62%	13.88%
50%Clay+50%Soil	21.00%	32.00%	11.00%
100%Clay+00%Soil	35.00%	66.50%	28.50%

Test Methods for Stabilized Base Soil and RAP:

Optimum moisture content for the cement-treated base material (AASHTO T 99).

The results of this testing are illustrated in Figure 224. For variable clay testing, the optimum moisture contents of blends with 0-40% clay replacement of soil are presented in Table 10: Optimum Moisture Contents of Variable Clay Mixes

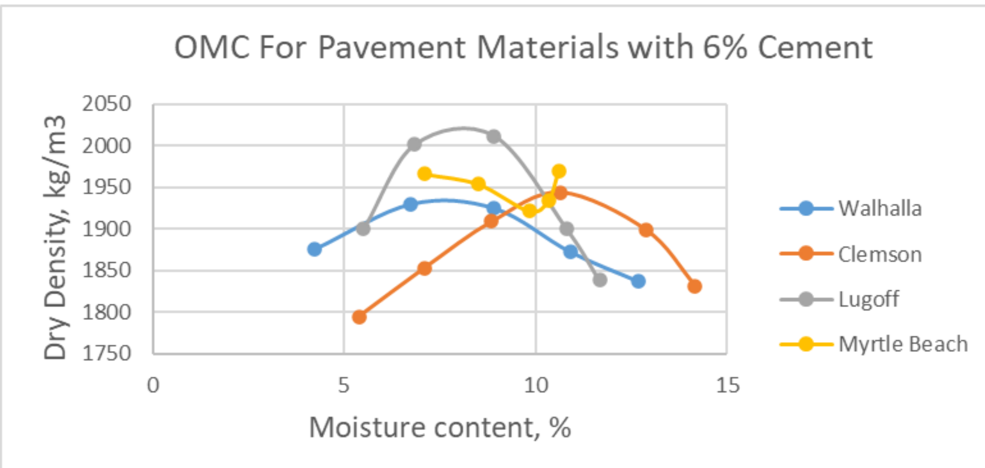

Figure 22: Dry Density vs. Moisture Content, 6% Cement Blends of RAP and Base Soils

Table 10: Optimum Moisture Contents of Variable Clay Mixes

Clay Content	OMC, %	Max. Dry Density, pcf	Max. Dry Density, kg/m3
0%	8.0%	120.0	1935.0
10%	9.0%	126.2	2035.1
20%	9.5%	127.6	2057.3
30%	10.0%	124.1	2001.7
40%	10.5%	120.0	1935.0

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Unconfined compressive strength for cement-treated RAP and base soil (SC-T-26 and SC-T-142)

To determine a baseline RAP proportion to use in subsequent testing, CMRB mixtures at variable RAP contents were tested at 3, 6, and 9% cement, as shown in Figure 23. At 6% cement, UCS peaked at 35% RAP and so this mix design was selected for evaluation of all other variables in UCS and durability testing. These values were taken after 7-days of curing.

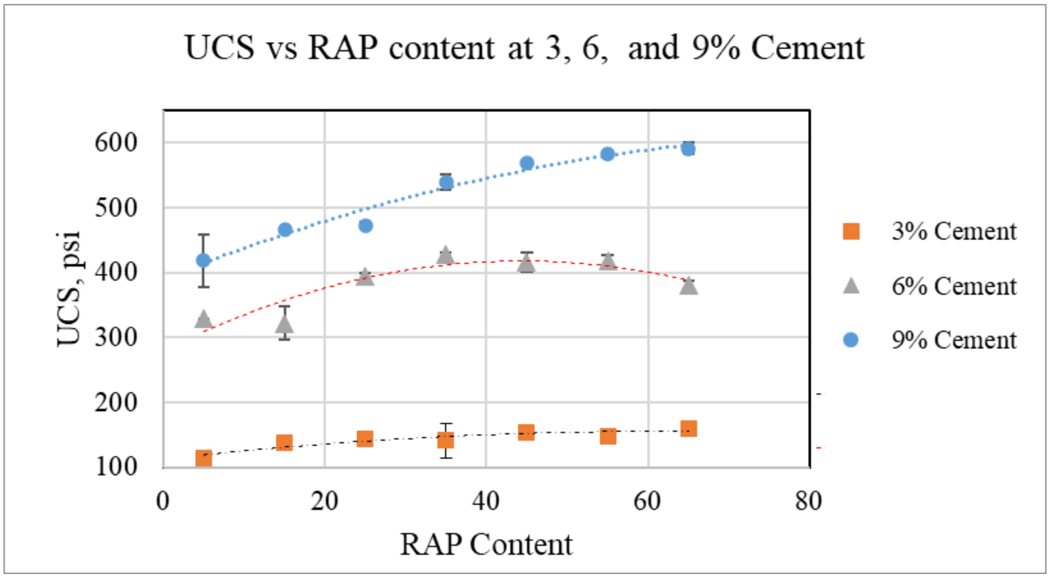
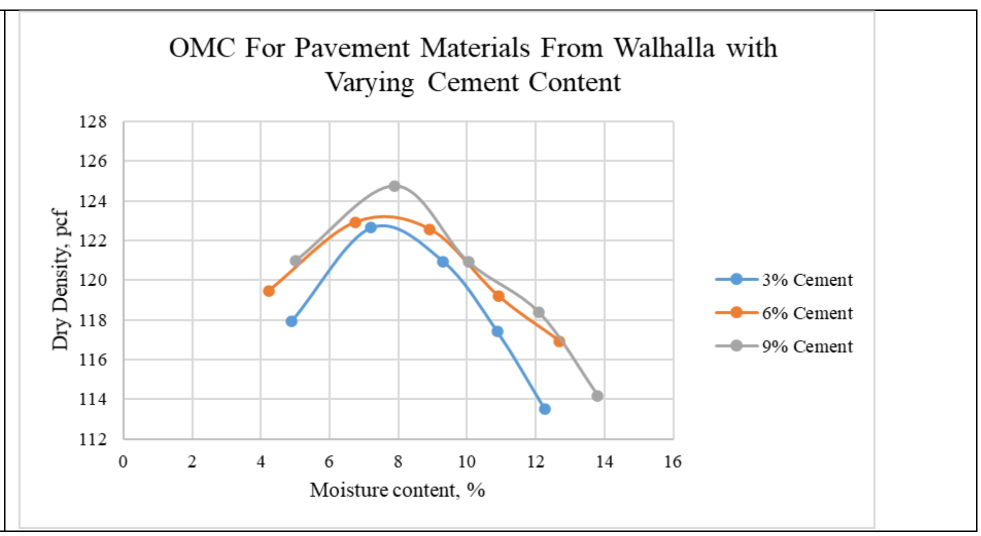


Figure 23: UCS vs RAP Content at 3, 6, and 9% Cement.

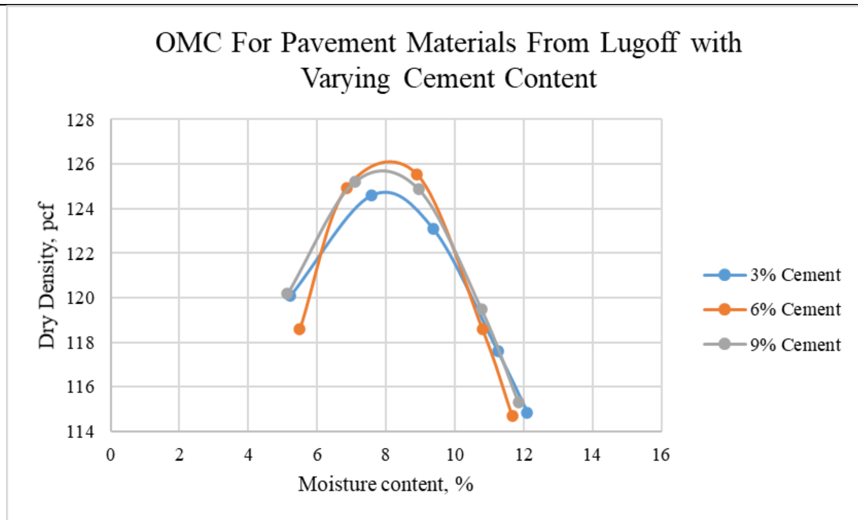
The effect of varying cement content on the OMC

The OMC was measured at the three different cement dosages of 3%, 6%, and 9% at a fixed RAP content of 35% and using all sources of base soil. The results are shown in Figure 24a, b, c, and d for base soils from Walhalla, Lugoff, Clemson, and Myrtle Beach, respectively. As can be seen, there was not a significant variation of OMC at 3%, 6%, and 9% cement for all the tested base soils. However, the sandy soil of Myrtle Beach tends to vary more, with lower OMC at higher cement content.

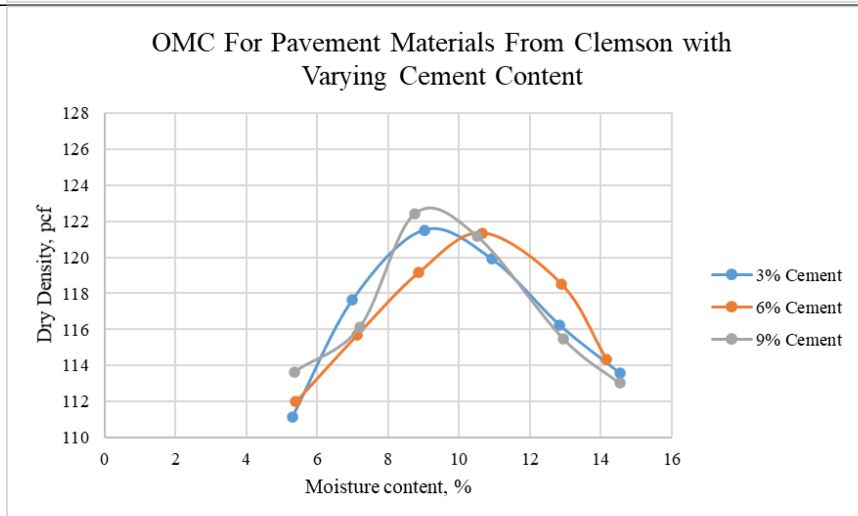
(a)



(b)



(c)



(d)

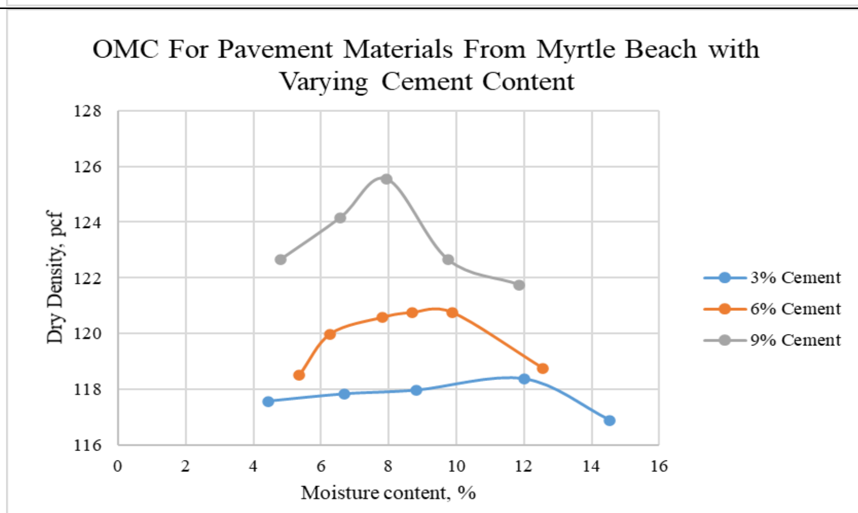
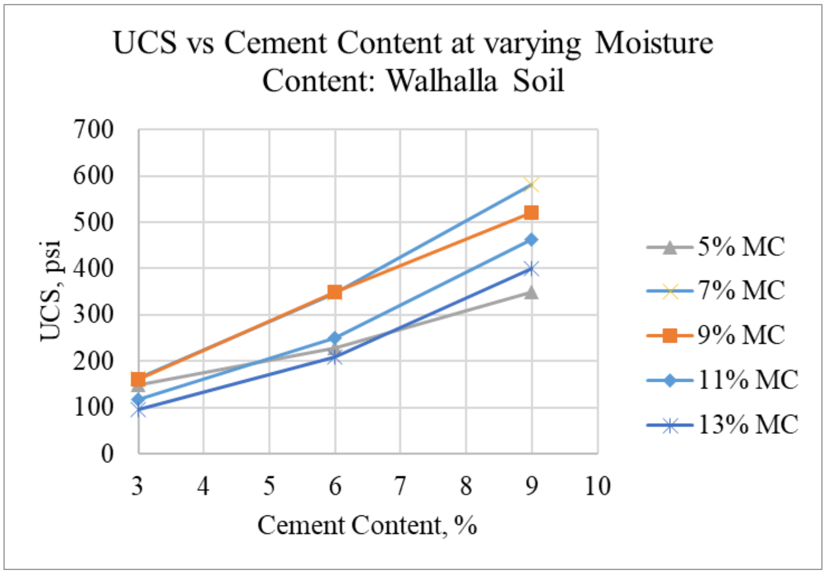


Figure 24 The effect of varying cement content on the OMC of the CMRB for base soils from (a) Walhalla, (b) Lugoff, (c) Clemson, (d) Myrtle Beach.

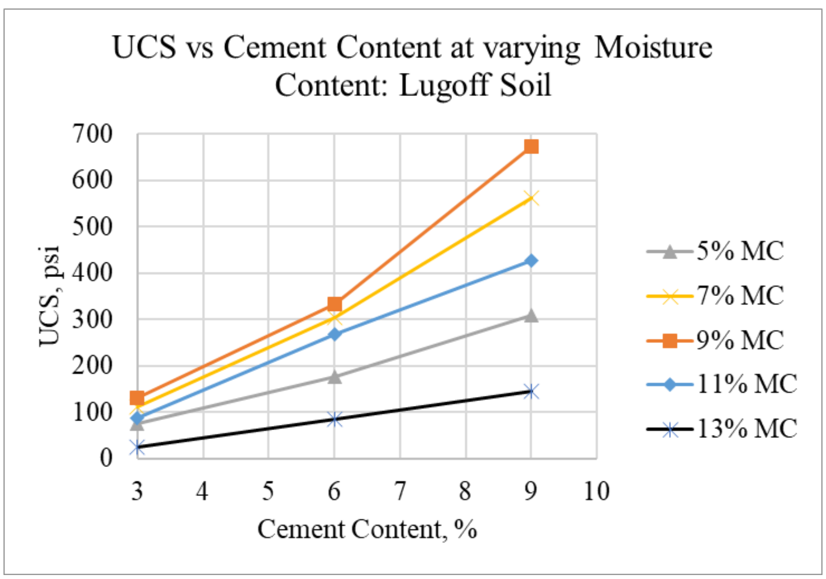
Effect of varying cement content on UCS at different moisture contents

It is well recognized that the moisture content of CMRB plays an important role in achieving maximum density. While the use of optimum moisture content in the preparation of test specimens is justified in lab evaluation, precisely achieving the optimum moisture content in the field can be difficult, and in some cases, the moisture content may exceed the optimum moisture content. In this investigation, the UCS was conducted for samples molded at different moisture content with a range of about 4% below and above the OMC level of 9%. This test was completed for all four base soils blended with 35% RAP and at the three cement contents of 3%, 6%, and 9%. The results are presented in Figure 257.

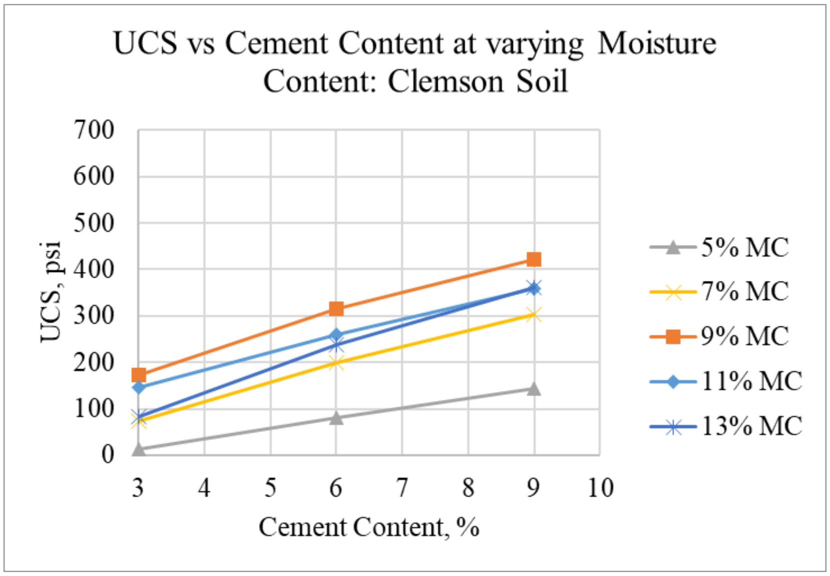
(a)



(b)



(c)



(d)

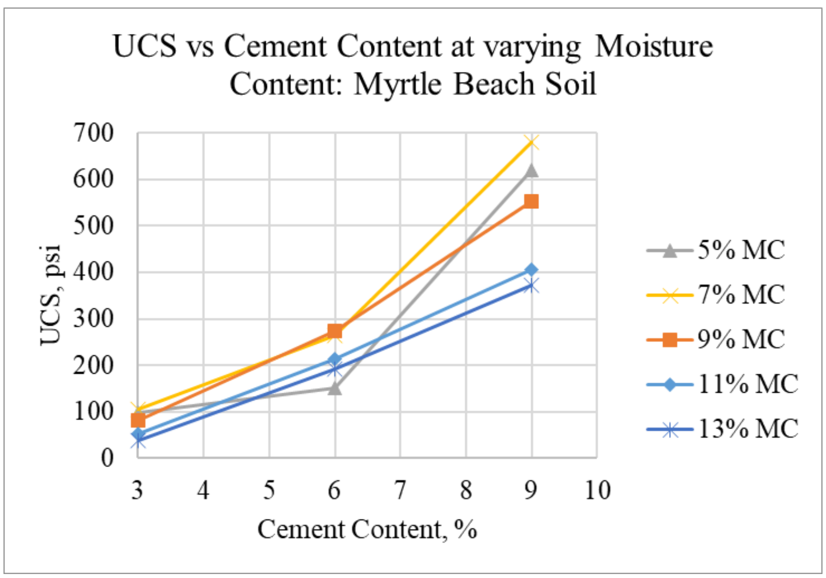
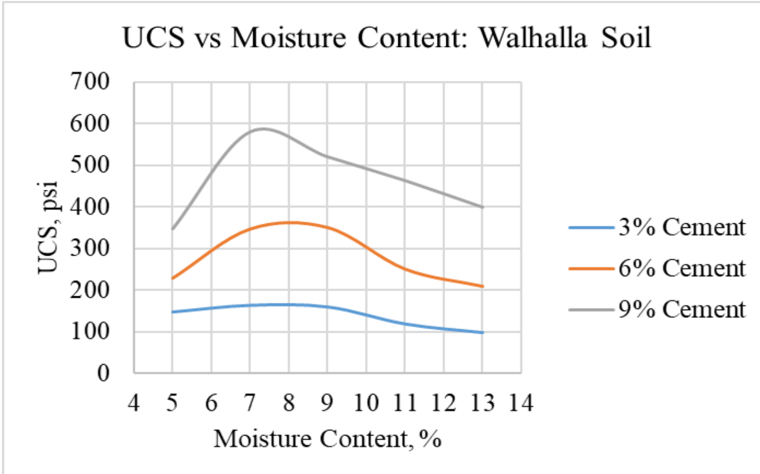
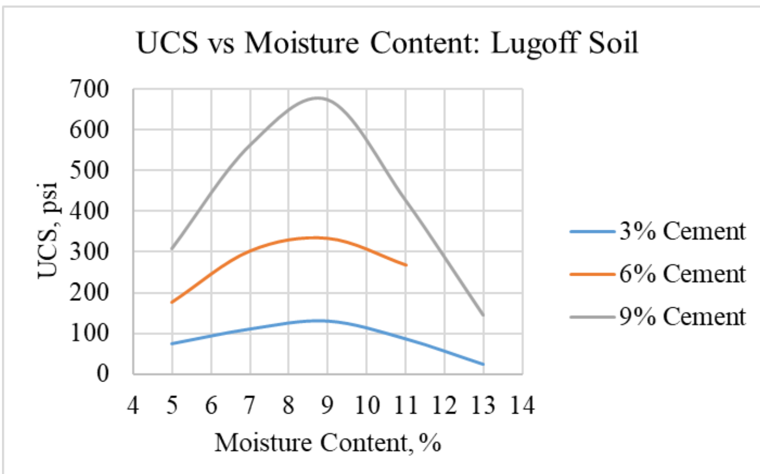
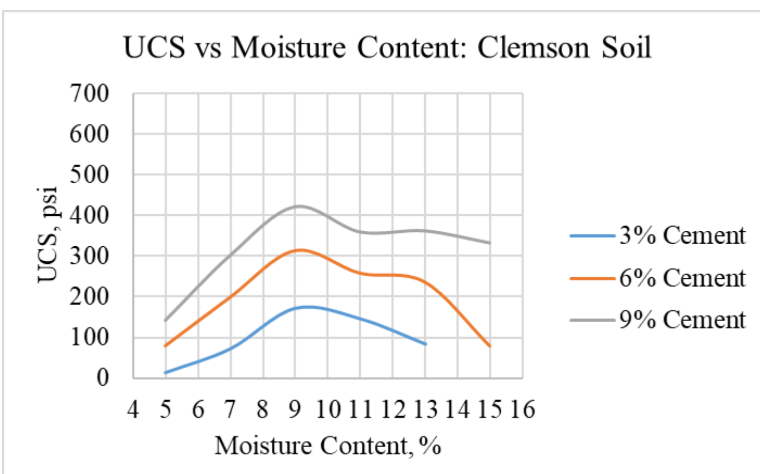


Figure 257 The effect of varying cement content and moisture content on UCS of different base soils: (a) Walhalla, (b) Lugoff, (c) Clemson, and (d) Myrtle Beach.

The effect of varying Moisture Content on UCS

Figure 26 illustrates the UCS trend of CMRB mixes of each base soil with variable moisture content at 3%, 6%, and 9% cement. The peak strengths of each soil/cement set correspond closely to the optimum moisture contents determined using the AASHTO T99 methodology. The UCS values reported here are for 7 days of CMRB age.

(a)	
(b)	
(c)	

UCS vs Moisture Content: Walhalla Soil
UCS, psi
Moisture Content, %
0 100 200 300 400 500 600 700
4 5 6 7 8 9 10 11 12 13 14
3% Cement
6% Cement
9% Cement

UCS vs Moisture Content: Lugoff Soil
UCS, psi
Moisture Content, %
0 100 200 300 400 500 600 700
4 5 6 7 8 9 10 11 12 13 14
3% Cement
6% Cement
9% Cement

UCS vs Moisture Content: Clemson Soil
UCS, psi
Moisture Content, %
0 100 200 300 400 500 600 700
4 5 6 7 8 9 10 11 12 13 14 15 16
3% Cement
6% Cement
9% Cement

(d)

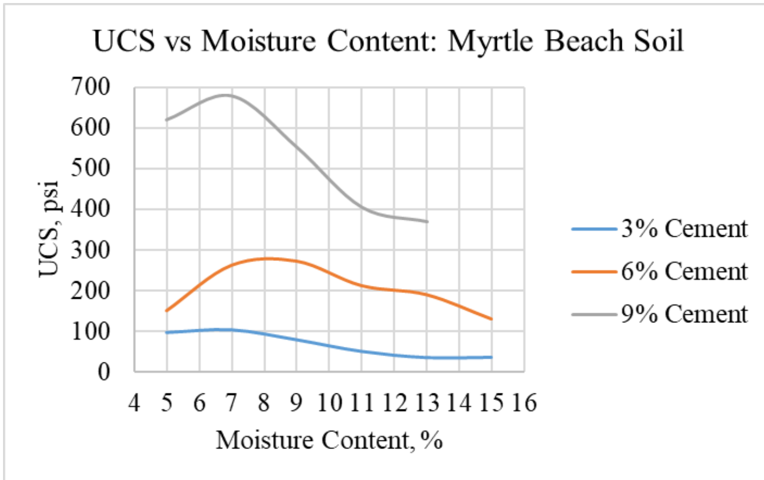


Figure 26 The effect of varying moisture content on the UCS of CMRB made out of 35%RAP and different base soil from: (a) Walhalla, (b) Lugoff, (c) Clemson, and (d) Myrtle Beach.

The effect of maximum particle size of RAP on UCS

According to SCT-26, only RAP particles that pass a 3/4" sieve are to be used for testing. To evaluate the effects of larger RAP particles on the UCS of CMRB samples, three mixes containing a replacement of large RAP at 4%, 8%, and 12% of the total RAP were tested at 7 days. The RAP replacement with larger particles involved an equal mix of particles retained on 1-inch and particles retained on 3/4-inch, all passing through a 1.5-inch sieve. These mixes used Walhalla base soil at OMC and 6% cement. The results are illustrated in Figure 29.

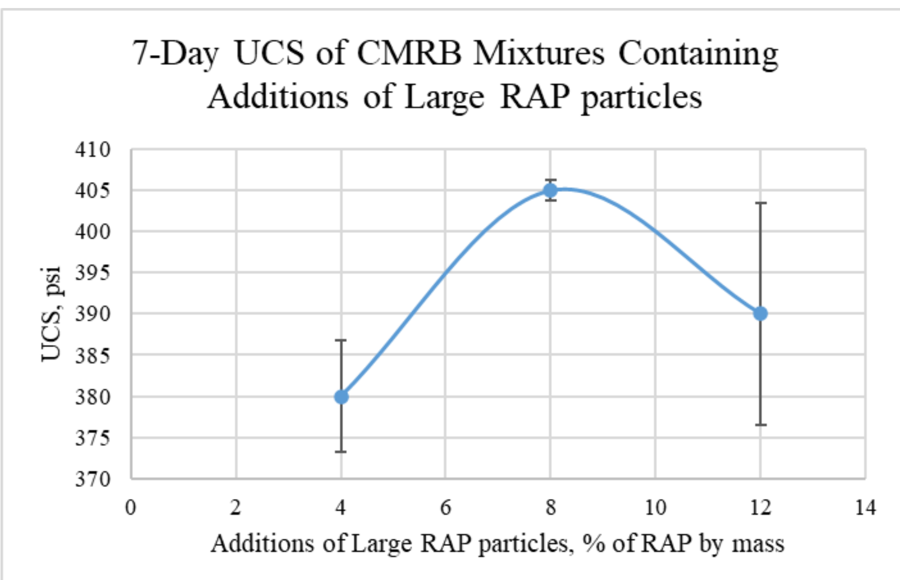


Figure 29: UCS, Additions of Large RAP Particles

UCS Development

CMRB Samples were prepared for each base soil at OMC using 3%, 6%, and 9% cement and tested at 7, 28, and 120 days in order to evaluate strength development over time. The results for 6% cement mixes are shown in Figure 27.

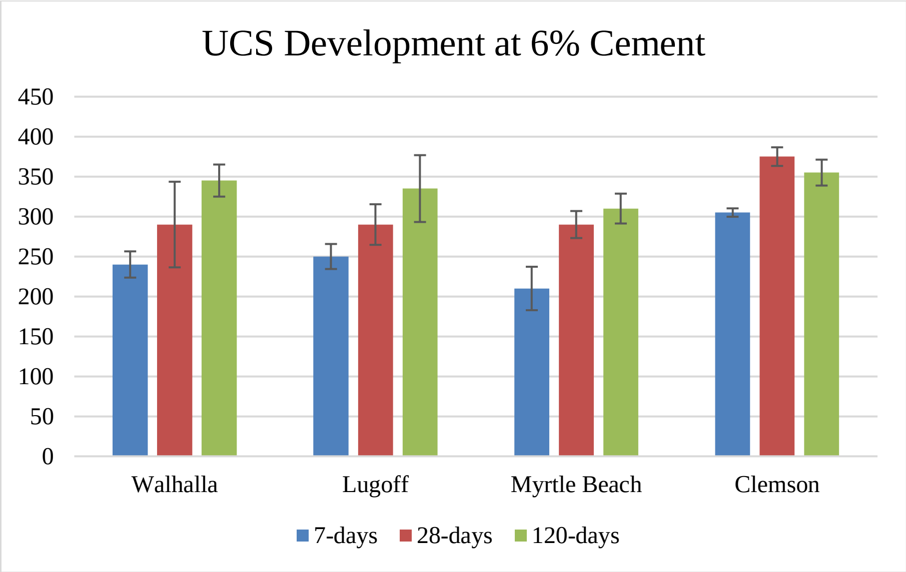


Figure 270: UCS Development over 120 days, All Base Soils, 6% Cement

Effect of clay content on UCS

To evaluate the effects of clay content on the UCS of CMRB samples, variable clay mixes were prepared using Walhalla base soil with a percentage of soil replaced with ball clay. The 7-day strengths for these mixes at 3, 6, and 9% cement are presented in Figure 281. UCS development over 120 days for 6% cement at variable clay contents is shown in Figure 292.

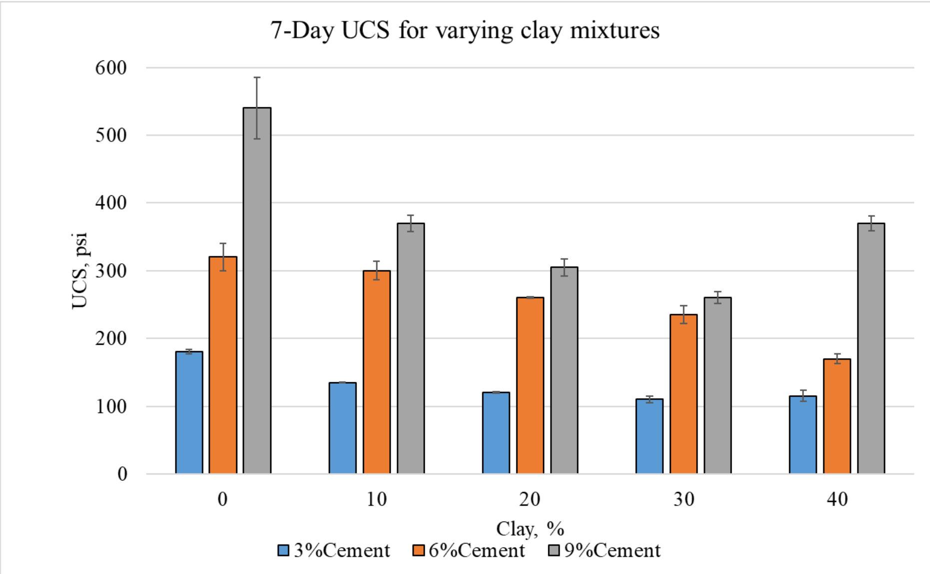


Figure 28: 7-Day UCS of Variable Clay Mixes, 3,6,9% Cement

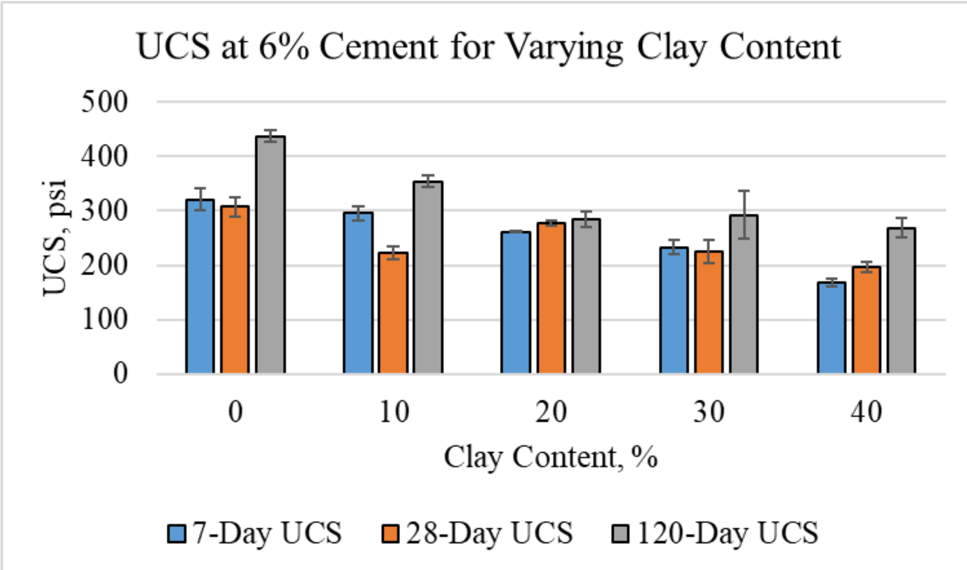


Figure 292: UCS Development over 120 days, Variable Clay Content, 6% Cement

Effect of dry versus slurry cement application on UCS

In order to evaluate the effects of a slurry cement application compared to dry application on the UCS of CMRB samples, four samples were cast of each base soil using both methods to be tested at 7 and 28 days. Both results are shown in Figure 30. Slurry samples tended to outperform the dry application except for the Clemson samples, which were of approximately equal strength at 7 days. Myrtle Beach samples saw the most extreme increase of 73%.

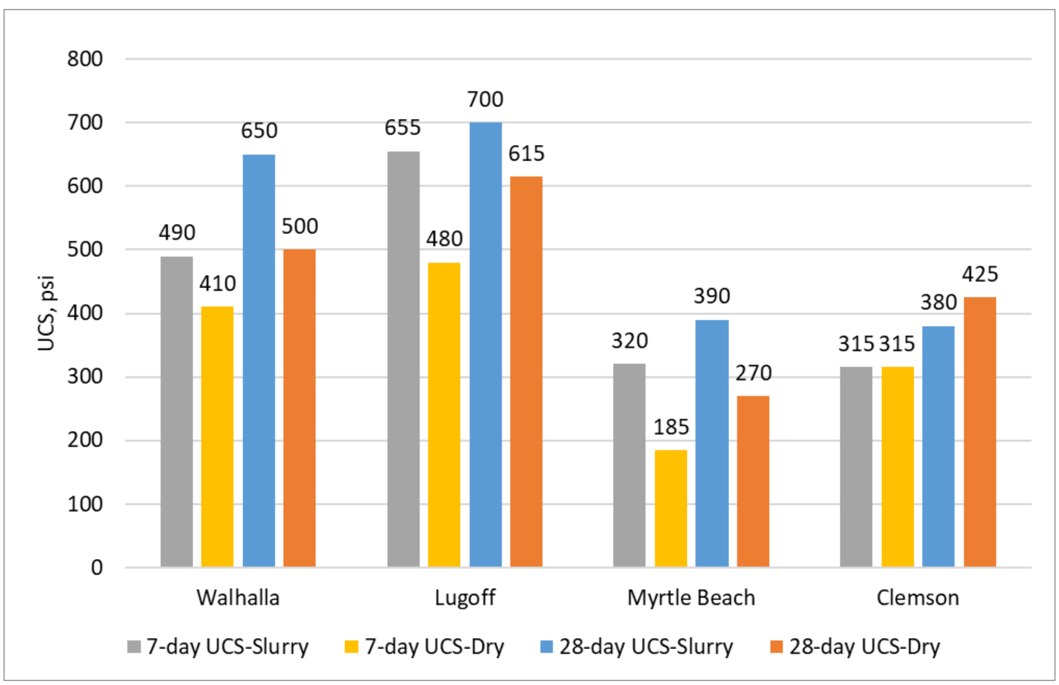


Figure 30: 7-Day UCS for Different Soils Stabilized by Type IL cement (PLC), Dry vs. Slurry

Alternative Chemical Binders

As a part of this investigation into CMRB, alternative chemical binders were also tested. Figure 31 shows the UCS of QL stabilized samples for all base soils, as well as variable dosages with Walhalla soil, at 7 and 28 days. Figure 32 shows the 7-day UCS of Walhalla pavement materials stabilized by Quicklime (QL), hydrated lime (HL), and lime kiln dust (LKD) compared with OPC and PLC. The QL, HL, and LKD samples perform poorly as stabilizing chemical agents at the dosages tested, compared to OPC and PLC stabilized CMRB. In particular, high heat of hydration of QL resulted in variable results.

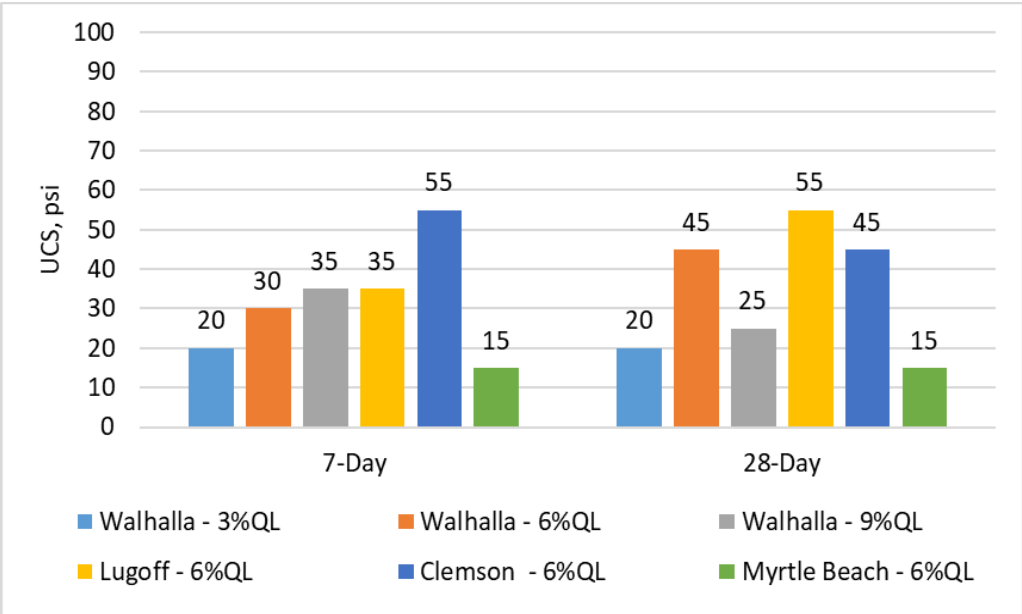


Figure 31: UCS of Quicklime Stabilized Samples, All four base Soils.

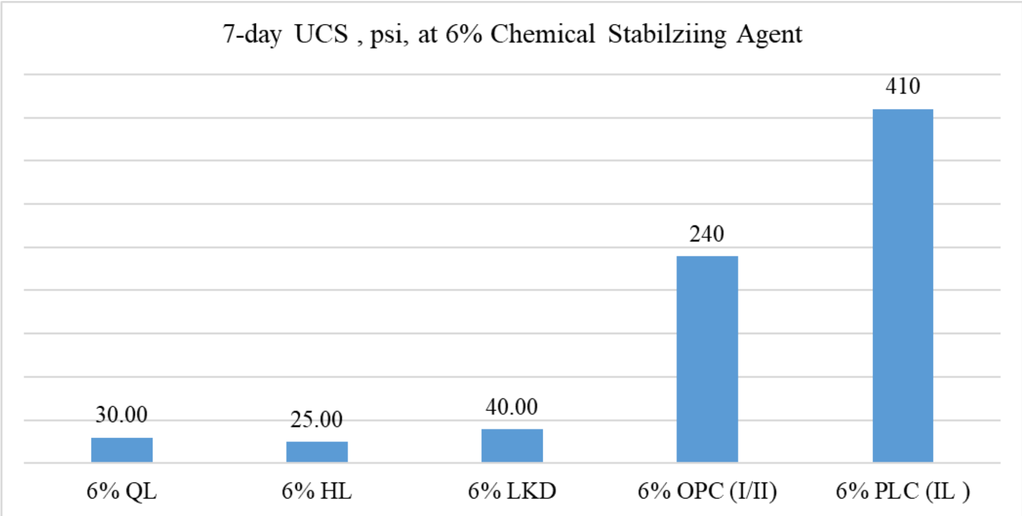


Figure 32: 7-Day UCS of Walhalla Base Soil stabilized by 6% of different stabilizers.

Tensile Strength of CMRB

Flexural Strength (ASTM D1635-00(2006))

To explore the effect of clay content on the flexural strength CMRB, third-point load testing of 3 in. x 3 in. x 11.25 in. prisms of varying clay content with Walhalla base soil and 6% Type I cement was performed following ASTM D1625-00(2006). The results, shown in Figure 33, indicate an increase in the modulus of rupture (f_r) to a peak value of 235 psi at 10% clay, followed by a decrease with additional clay in the mix. When plotted against 7-day UCS, data shows a moderate correlation with an R^2 of 0.7028.

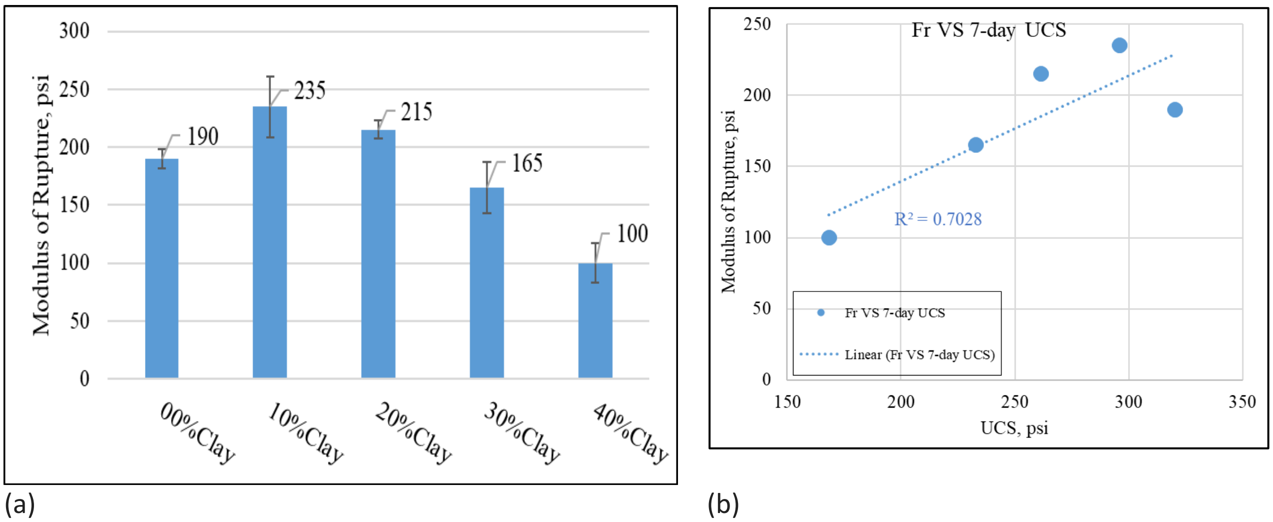


Figure 33 (a) Flexural Strength using a simple beam with third point loading, and (b) correlation with the UCS at 7 days.

Indirect Tensile Strength (ITS) (ASTM D6931-17)

ITS testing was performed on CMRB pills of different base soils as another measure of flexural strength. Results shown in Figure 34 indicate that the Clemson samples outperform the Walhalla and Lugoff samples. Figure 358 shows ITS results from variable clay testing. These values show a pattern that opposes the modulus of rupture pattern, although the variation between ITS values is much less significant with a range of only 25 psi.

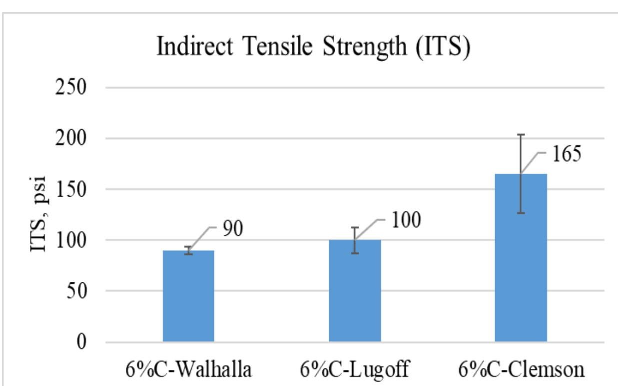


Figure 34 Indirect Tensile Strength Result

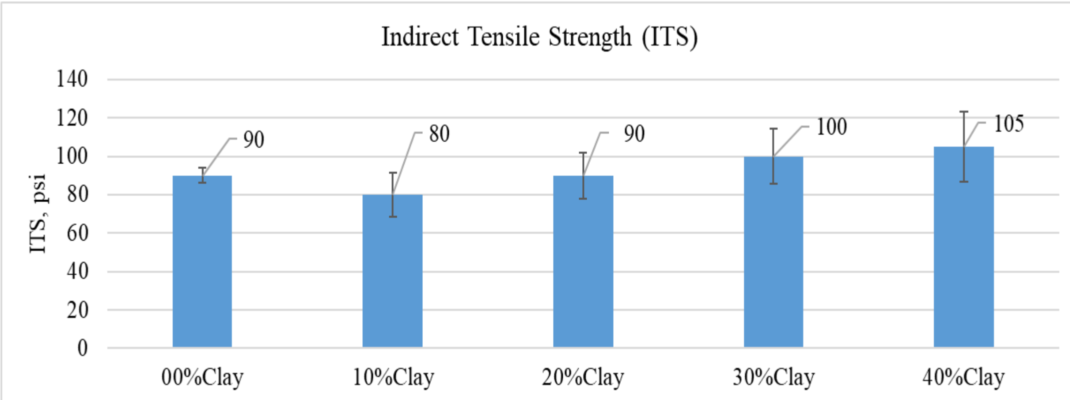


Figure 35 Indirect Tensile Strength Results of Variable Clay Mixes

Splitting Tensile Strength (STS) (ASTM C496-17)

Splitting tensile strength testing in accordance with ASTM C496-17 was performed on CMRB proctor samples of variable clay mixes to evaluate the effect of clay content on the mixtures' tensile strength parallel to the direction of loading. Similar to the ITS results, the STS results, seen in showed a decrease to a minimum of 20% clay, followed by a rise in STS with additional clay in the mixture. However, all STS values were relatively close with a range of only 10 psi in the results. Also shown in Figure 36 are the STS results for the different base soil types at 6% cement. Lugoff and Clemson, the two soils with the most clay content, performed the best. The Myrtle Beach samples were much weaker, with an STS value of 40 psi which is a third of the value obtained by the Lugoff samples.

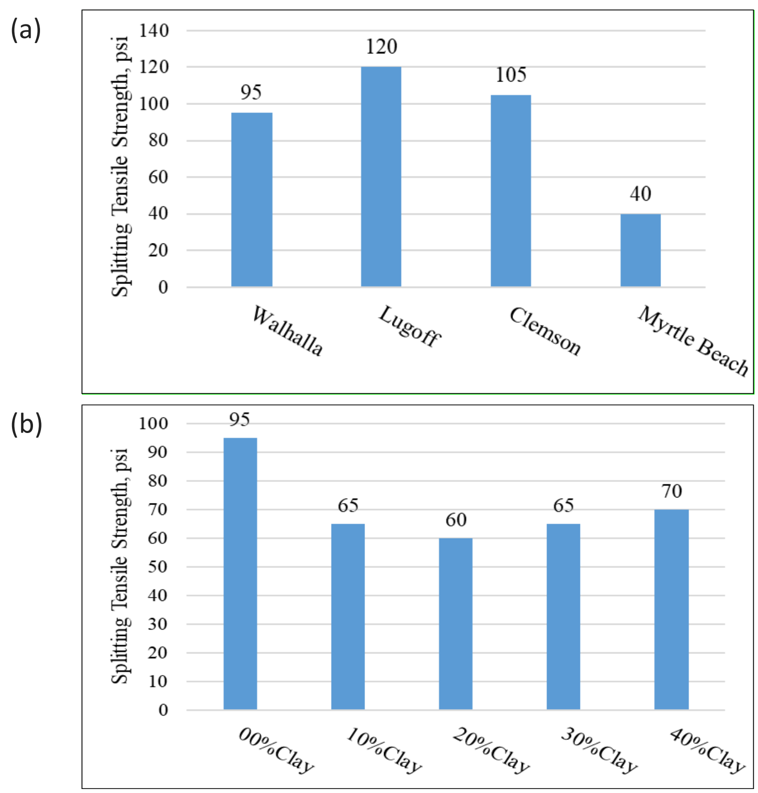


Figure 36 Splitting Tensile Strength test results at 6% Cement for (a) all soils, and (b) varying clay mixtures.

Preliminary Investigation of the Use of Portland Limestone Cement (PLC) (Type IL) on the UCS of CMRB

As part of an initial investigation on the efficacy of Portland Limestone Cement (PLC, Type IL) as compared to Ordinary Portland Cement (OPC, Type I/II), samples using 3%, 6%, and 9% PLC were tested at 7 and 28 days. A 7-day and 28-day UCS comparison are shown in Figure 37 and 41. At 6% and 9% dosages, PLC mixes tend to outperform OPC mixes. As the difference between Lugoff mixes at 6% dosages was significant, further experimentation was done on Lugoff mixes at 6% that were cast on the same day to verify results. These are shown in Figure 42. The verification resulted in strengths that were much closer to each other, with OPC outperforming at 28 days. It is suggested that further investigation is needed to precisely determine the influence of PLCs on the performance of CMRB as a function of base soil type.

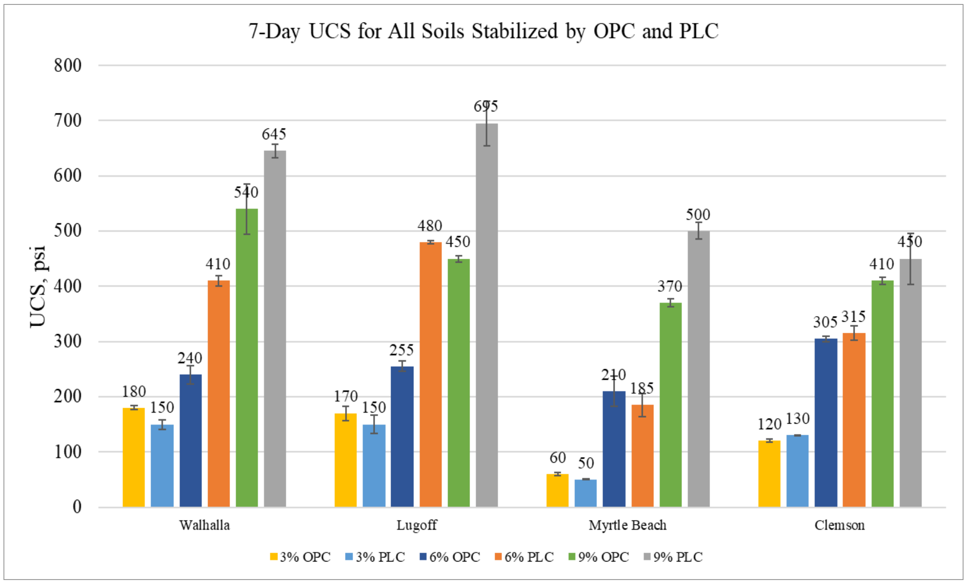


Figure 370: 7-Day UCS Comparison of OPC vs PLC, All Base Soils, 3,6,9% Binder

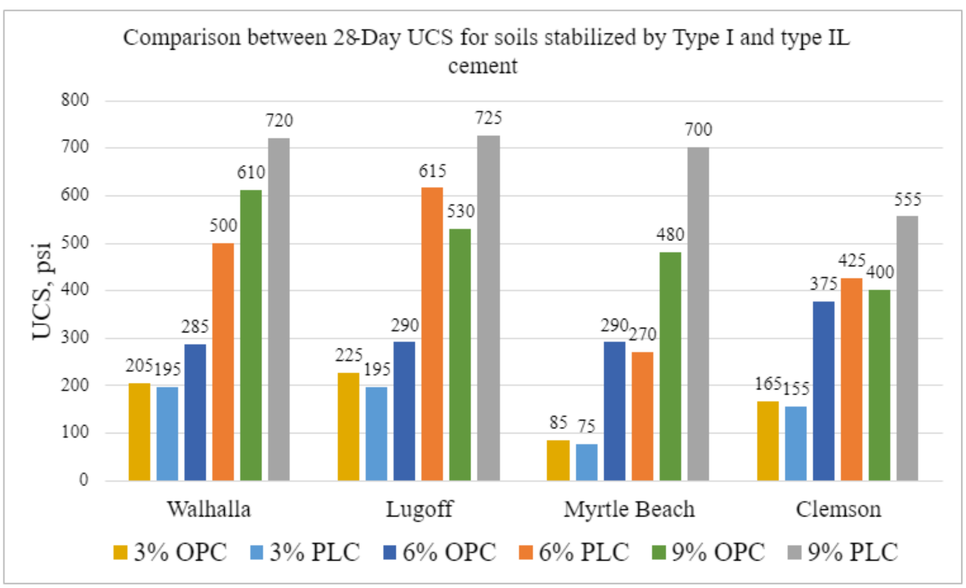


Figure 38:28-Day UCS Comparison of OPC vs PLC, All Base Soils, 3,6,9% Binder

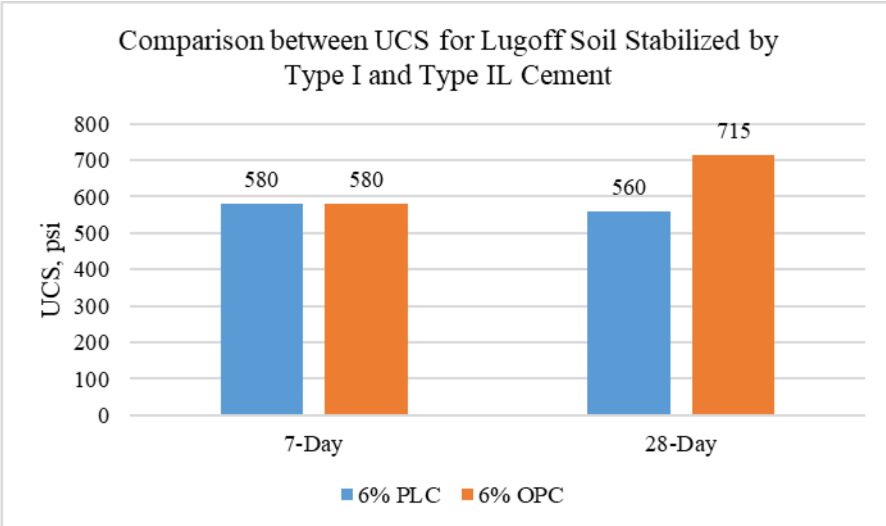


Figure 39: UCS Comparison of 6% OPC and 6% PLC, Lugoff Soil, 7 and 28 Day

Synthetic FDR Testing Results

To determine the effects of replacing RAP with synthetic aggregate, samples were prepared using Walhalla base soil and 3%, 6%, and 9% OPC. Size #67 aggregate was used at 5%, 10%, and 15% of the total mix, replacing an equal mass of RAP. For example, with 5% replacement, the mix proportion used was 65% base soil, 30% RAP with the standard particle size distribution, and 5% size# 67 aggregate. Results are shown in Figure 40. No clear trends are seen as the replacement level does not distinctly affect UCS. Strength values are all near what was seen with no synthetic aggregate used.

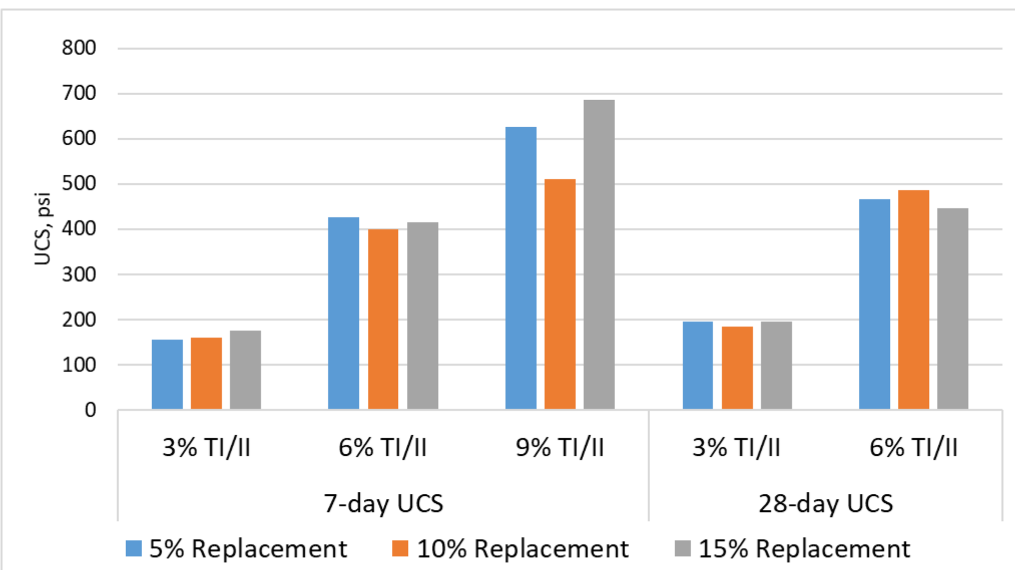


Figure 40: UCS of Synthetic Aggregate Samples, Walhalla Soil, 7 and 28-day

Durability Tests for the Stabilized Base Material

Wetting and Drying (W-D) (AASHTO T135 or ASTM D559)

Samples of the different base soils as well as variable clay contents were put through W-D testing in order to gauge the effects of the soil type on CMRB moisture susceptibility. Results from the different base soil testing are shown in Table 11 and results from variable clay testing are shown in

Table 12. Clemson and Lugoff samples performed the best with a low mass loss of around 1%. Myrtle Beach samples performed the worst, with a mass loss of 13.4%. The variable clay samples had the best performance at 10% clay. Beyond this clay content, the mass loss increased with increase in clay content.

Table 11 Wetting/Drying Durability test results of the different base soils stabilized by 6% cement.

Base Soil source	6%C-Walhalla	6%C-Clemson	6%C-Lugoff	6%C-Myrtle Beach
Mass loss, %	4.33%	1.00%	1.03%	13.40%

Table 12 Wetting/Drying Durability test results of variable clay samples stabilized by 6% cement.

Clay Content	0%	10%	20%	30%	40%
Mass loss, %	3.5%	0.11%	1.29%	2.32%	4.66%

Freezing and Thawing of Soil-Cement (F-T) (ASTM D 560)

Samples of the different base soils as well as samples with variable clay contents were F-T tested to gauge the effects of the soil type on CMRB freezing-thawing resistance. Results from the different base soil testing are shown in Table 13 and results from variable clay testing are shown in

Table 14. Clemson samples performed the best with a low mass loss of 1.72%, with Walhalla and Lugoff samples just behind. Myrtle Beach samples showed the most inferior performance, with a mass loss of 13.35%. Much like with the W-D testing, the variable clay samples had the best performance at 10% clay, beyond which mass loss % increased with clay content.

Table 13 Freezing/Thawing Durability test results of the different base soils stabilized by 6% cement.

Base Soil source	6%C-Walhalla	6%C-Clemson	6%C-Lugoff	6%C-Myrtle Beach
Mass loss, %	2.17%	1.72%	2.52%	13.35%

Table 14 Freeing/Thawing Durability test results of variable clay samples stabilized by 6% cement.

Clay Content	0%	10%	20%	30%	40%
Mass loss, %	1.91%	1.34%	1.84%	1.65%	2.41%

Tube Suction Test (Tex-144-E)

The results obtained from this test are shown for both types of mixtures in Table 15 and Table 16. As opposed to the previous durability tests, Clemson samples performed the worst, being the only sample to fail the test and be deemed moisture-susceptible in accordance with Tex-144-E. The addition of any clay led to a slight increase in Final DV, although each variable clay sample ended with a Final DV less than 10.0.

Table 15 TST Results of different soil sources and correlation with W-D and F-T test results.

Soil Type	Cement, %	Final DV	W/T mass loss	F/T mass loss
Walhalla	6%	3.89	4.33%	2.17%
Lugoff	6%	5.2	1.03%	2.52%
Clemson	6%	15.45	1.00%	1.72%
Correlation with w/d and f/t (R^2)			0.34	0.59

Table 16 TST Results of the varying clay mixtures and correlation with W-D and F-T test results.

Clay, %	Cement, %	Final DV	W/T mass loss	F/T mass loss
0%	6%	3.89	4.34	1.91
10%	6%	6.85	0.11	1.34
20%	6%	5.51	1.29	1.84
30%	6%	5.76	2.32	1.65
40%	6%	6.07	4.66	2.41
Correlation with w/d and f/t (R^2)			0.35	0.09

The TST results did not correlate well with the other two durability tests performed on the same materials (wetting and drying (W/T) and freezing and thawing (F/T) tests). However, the TST results are still showing the 20% and 30% clay content as optimum in terms of the dielectric values as both had smaller DV readings among the clay-containing mixtures.

Shrinkage of CMRB

Free Shrinkage

Results of the free shrinkage test performed on CMRB prisms are shown in Figures 44, 45 and 46. It is seen in Figure 414 that an increase in cement content reduces shrinkage over 7 days. Although this is against the general belief, it might be attributed to the fact that additional cement led to a denser and more compacted mixture, reducing the voids within the originally granular soil of Walhalla. As a result, there is less room for moisture to evaporate, which leads to reduced shrinkage during the drying process. Additionally, higher cement content generally means greater binding capacity within the mixture. This improved binding helps hold the particles together more tightly, reducing the tendency for individual particles to move or shift, which is a major contributor to shrinkage. In Figure 425 and Figure 436, results from Walhalla and Clemson base soils at 6% cement and various water contents show that Clemson base mixtures result in more than double the shrinkage of Walhalla base mixtures at each water content. Figure 447 clearly shows that the initial rate of free shrinkage increases as clay content increases.

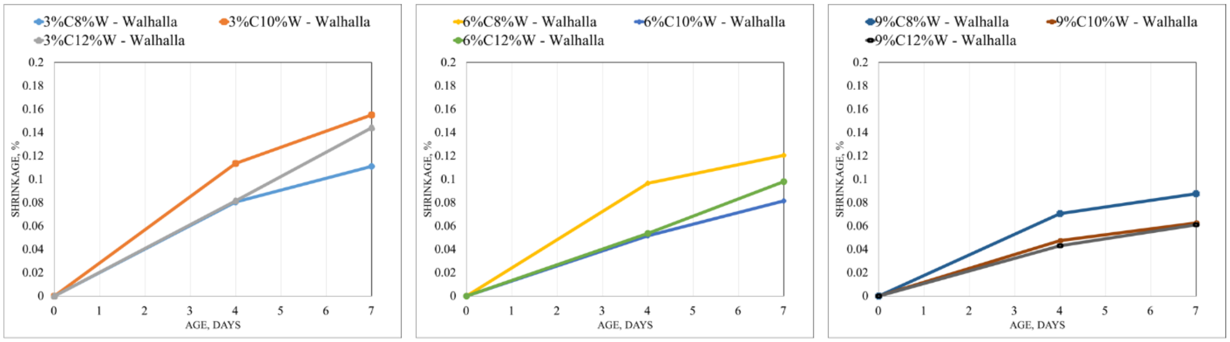


Figure 414 The Effect of Cement Content on Free Shrinkage at 8%, 10% and 12% water content.

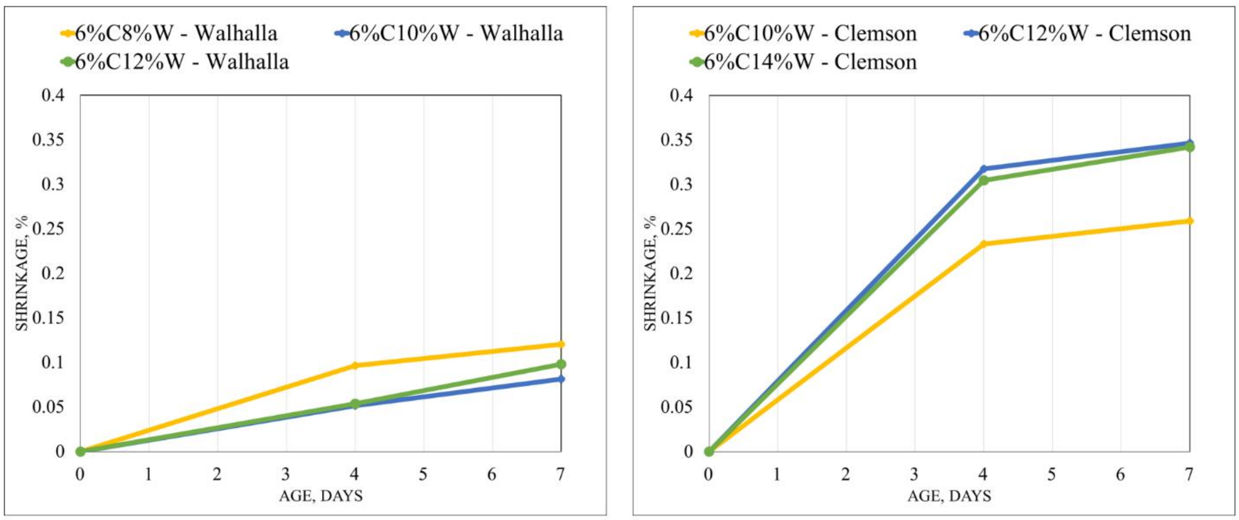


Figure 42 Comparison of Free Shrinkage behavior between two different base soils at 8%, 10% and 12% water content.

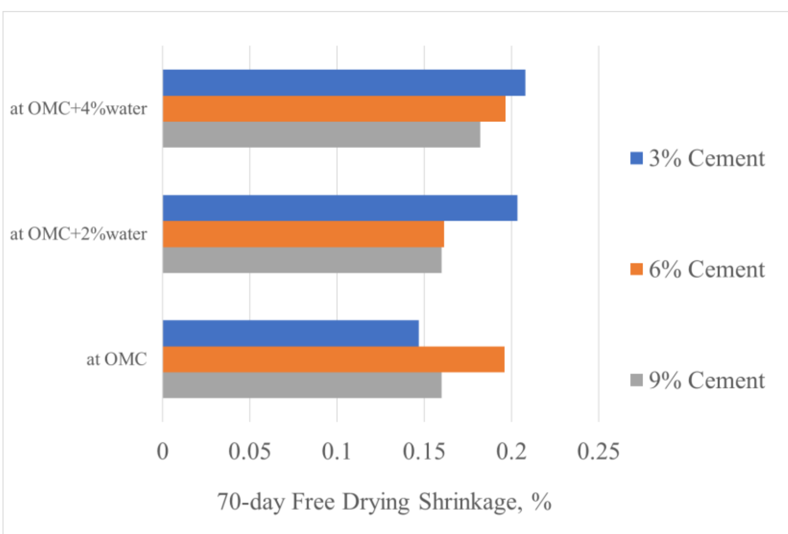
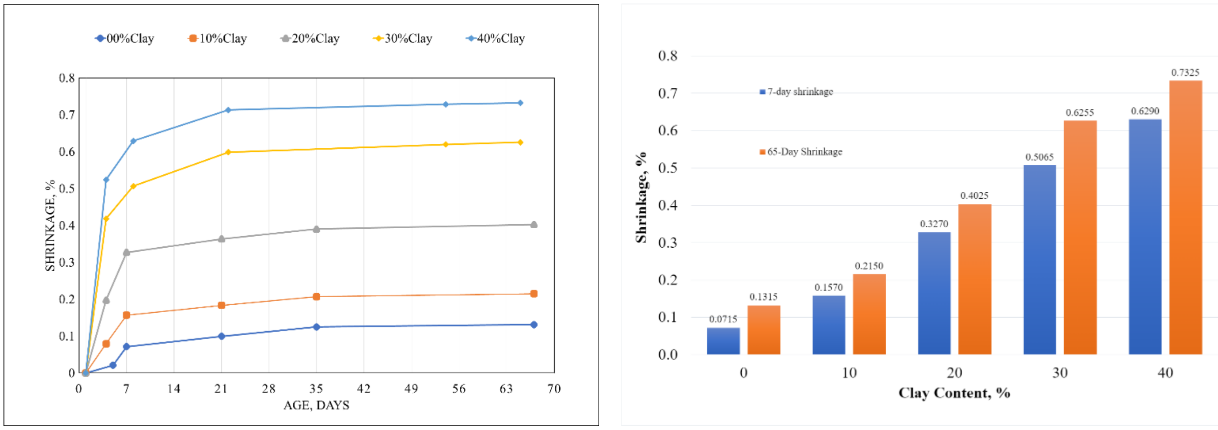


Figure 436 Comparison of the final shrinkage values of Walhalla base soil.



(a) Free Shrinkage

(b) Influence of Clay Content on Free Shrinkage

Figure 44 The Free Shrinkage behavior of variable clay mixes with Walhalla base soil.

Restrained Shrinkage

The results of the restrained shrinkage test performed by the shrinkage ring apparatus are shown in the following figures. The data plotted in Figure 48 shows that the time needed to reach maximum strain (at which a crack is developed) is proportional to the clay content of the CMRB mixture. The exact values of the strain and the time needed to reach this strain are shown below in Table 17 and the relationship is plotted in Figure 45.

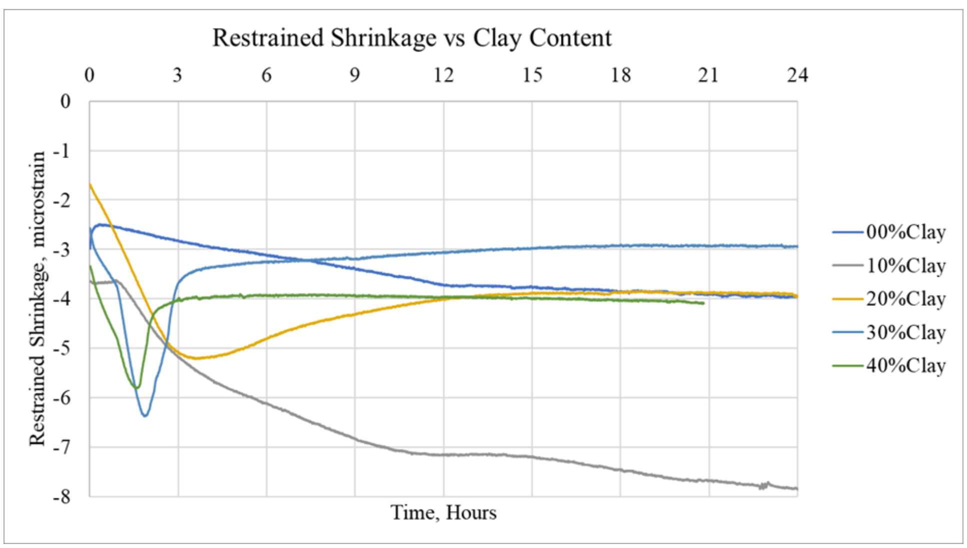


Figure 48 Restrained Shrinkage Test Results.

Table 17 Maximum Strain from the Restrained and Free Shrinkage tests.

Label	Max. Shrinkage		Time to reach max. strain, days	
	Restrained	Free	Restrained	Free
00%Clay	11.40	1315.00	6.4500	65
10%Clay	11.23	2150.00	6.2500	65
20%Clay	5.21	4025.00	0.1483	65
30%Clay	6.37	6255.00	0.0774	65
40%Clay	5.81	7325.00	0.0659	65
R^2	0.69			

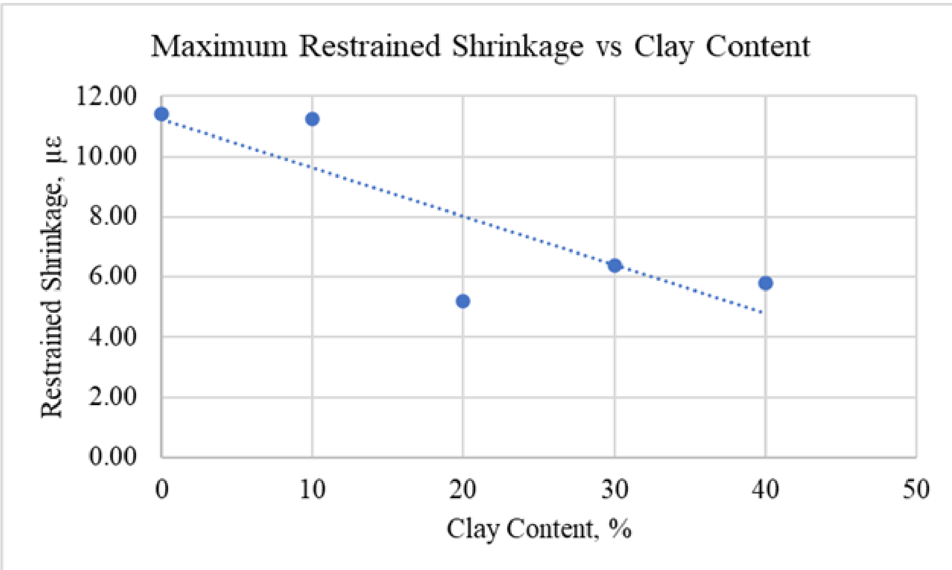


Figure 45 Maximum restrained shrinkage to cause cracking vs Clay Content.

Isothermal Calorimetry

Several factors may affect the `heat generated during the test, including the cement content, the water-to-cement ratio, the base soil composition, and other factors. All the mixtures were tested at 6% and 9% cement content and only the water needed for OMC was added. The results of this investigation are shown below in Table 18 and Figure 46. Additionally, the correlations between the maximum heat released after 7 days of testing with the 7-day UCS, in psi, are shown in the same table. A very weak correlation was observed within mixtures with different base soils having the same cement content. However, the varying clay mixtures at both cement contents of 6% and 9% had good correlations with the 7-day UCS with R2 values of 0.62 and 0.70, respectively.

Table 18 Cumulative heat released from the isothermal calorimetry tested mixtures.

Label	Max. Heat, J/g cement	7-Day UCS, psi	Correlations within same cement content	Overall Correlations
6%C-Walhalla	330	240	0.005	0.33
6%C-Lugoff	390	255		
6%C-Clemson	305	305		
6%C-Myrtle Beach	310	210		
9%C-Walhalla	455	540	0.027	
9%C-Lugoff	545	450		
9%C-Clemson	395	410		
9%C-Myrtle Beach	525	370		
6%C-10%Clay	365	295	0.619	
6%C-20%Clay	370	260		
6%C-30%Clay	335	235		
6%C-40%Clay	335	170		
9%C-10%Clay	430	370	0.703	
9%C-20%Clay	390	305		
9%C-30%Clay	56	260		
9%C-40%Clay	380	370		

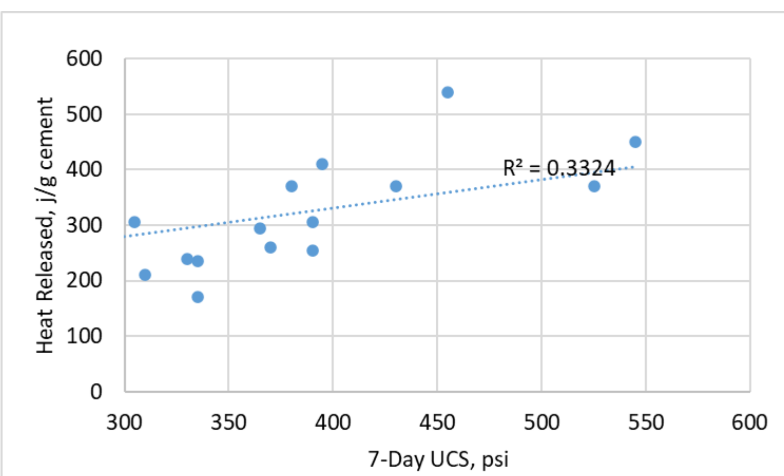


Figure 46 Correlation between the heat released and the 7-day UCS for various CMRB mixtures.

5. Discussion

Base Soil Characterization

The base soils used in this project were classified based on AASHTO M145. Walhalla, Lugoff, and Clemson soils were classified as A-1-b, while Myrtle Beach soil was classified as A-3. The PCA guidelines for FDR with cement [3] suggest selecting a cement content of 6% for A-1-b and 9% for A-3 as a starting point for testing field-sampled soil to determine the optimal mix design. Our UCS data supports this, as 6% cement dosages resulted in strengths near or above 300 psi for A-1-b soils while Myrtle Beach, an A-3 soil, required a 9% dosage to reach 300 psi at 7 days.

UCS Testing for CMRB

As part of this study, CMRB samples were tested to evaluate the effects of many variables, namely RAP content, moisture content, binder content, RAP gradation, age, binder type, aggregate type, clay content, and application type.

CMRB samples at 3%, 6%, and 9% cement dosages were prepared at varying RAP contents from 5% to 65% for 7-day UCS testing. There was a peak strength seen at 35% RAP content for 6% cement, so this mix design was chosen for all subsequent testing. At 3% cement, strengths did not vary more than 50 psi across every sample, suggesting that RAP content had little effect on the UCS at low cement dosages. At 9% cement, sample strengths were seen to increase with increasing RAP content, although the rate of increase began to level off beyond 35% RAP content.

To determine the effects of moisture content on the UCS of CMRB, samples of each base soil were prepared at each cement content with moisture content from 5% to 13%. For each base soil, the peak strengths of cement content were within 1% of each other, further suggesting that the OMC determined from AASHTO T99 testing at 6% can be used for all other binder dosages. Walhalla, Myrtle Beach, and Clemson samples saw peak strengths at a moisture content <1% lower than the OMC determined from dry density testing. Lugoff samples saw the highest UCS values at moisture contents slightly above OMC, but still within 1%.

To test the effects of RAP gradation, samples were prepared using large RAP fragments larger than 3/4" at varying dosages. The RAP ratio to total mix remained unchanged at 35%, but increasing proportions of larger fragments were tested. The samples saw a peak strength at a large RAP replacement level of 8% of the total mix by mass. However, the increase was not very significant especially considering variability, suggesting that RAP gradation does not greatly impact CMRB UCS.

To determine the strength development over time of CMRB, samples of each base soil were prepared at 6% cement content for UCS testing at 7, 28, and 120 days. Walhalla and Lugoff samples behaved similarly, where a strength gain of 50 psi was observed between 7 and 28 days and an additional 50 psi strength gain was observed at 120 days. Myrtle Beach samples exhibited the most strength gain up to 28 days and with less gain beyond 28 days, but the total gain of strength was still around 100 psi. Clemson samples were the outlier, where nearly 70 psi was gained in the first 28 days, but a reduction of strength was seen at 120 days.

To investigate the effects of the clay content of the base soil in a CMRB mix, samples at each cement content were prepared using Walhalla soil with a 0% to 40% replacement of ball clay, at 10% increments, and the samples were tested for UCS at 7 days. Samples with 6% cement and different clay contents were also tested at 28 and 120 days to evaluate strength development over time. At each cement content, a reduction of strength was seen with increasing clay content at 7 days. The 9% cement, 40% clay sample was the exception and it saw an increase of strength to the levels seen at 10% clay. Increasing clay content did not seem to have a significant effect on strength development over time, aside from the base reduction in strength due to increased clay content as seen at 7 days.

The strength development of the median cement content mixture of 6% was further explored. The UCS was measured at 7, 28, and 120 days and the results are shown in Figure 29. It can be seen, first, that there was a significant increase (averaged at 30%) in UCS between 7 days and 120 days, indicating the continuation of the cement hydration. Surprisingly, between 7-day and 28 days, UCS decreased for some mixtures. The UCS reduction occured in mixtures with 0%Clay, 10%Clay, and 30%Clay. Second, the decrease in strength with the increase of clay content is evident from the 7-day UCS results. Although the decrease in UCS is still shown in the UCS at later ages (28 and 120 days) the rate of decrease is less than that of the 7-day UCS results. The results of this investigation, again, do not show any evidence of the beneificial interaction between cement and clay, such as pozzolanic reaction.

As part of a preliminary investigation on the use of Portland limestone cement (PLC) as a chemical binder in CMRB, samples of each base soil were prepared at each cement content for UCS testing at 7 and 28 days. At 3% cement, PLC samples had strengths very similar to those seen from ordinary Portland cement (OPC) samples. Lugoff, Walhalla, and Myrtle Beach samples had significantly higher strengths when using PLC compared to OPC at 6% and 9% dosages. Samples with Clemson base soil showed an increase in UCS when using PLC at 6% and 9%, but not at a level comparable to other base soils. This data seemed suggestive, so the sample with the most extreme increase (6% Lugoff) was selected for verification. This time, samples of OPC and PLC were prepared at the same time for a better comparison between UCS strength at 7 and 28 days. At 7 days, strengths were identical, while 28-day samples showed an increase in strength with OPC. This suggests that mix designs using PLC can follow the same procedure as with OPC, but that more experimentation is needed for further investigation of this relationship. In this preliminary study, the early-age strength behavior of mixtures with PLC was not investigated.

In this study, all samples were prepared using a dry-cement application method, where the cement is added to the soil-RAP mixture before water in the procedure. To investigate the effects of a slurry-application method, cement, and water were mixed separately and then added to the mix as a slurry. Samples of each base soil were cast using each application method (i.e. dry cement and slurry cement) at a 6% binder ratio to be tested for UCS at 7 and 28 days. At 7 days, slurry samples tended to outperform the dry samples with all base soils except for Clemson samples, which were equal. The 28-day samples showed the same pattern for all base soils, but the Clemson samples showed the dry cement samples outperformed the slurry samples. This suggests that the slurry application method should be investigated for some soil types in the state, especially coastal sandy soils which saw the most significant improvement when using the slurry method.

The Clemson samples may not have performed as well as the other samples due to their higher clay content. Clay can interact with cement differently compared to other soil types. In the dry application process, cement is added directly to the soil, and the interaction between clay particles and dry cement can be more effective in terms of bonding and strength development. This is because the fine clay particles can coat the cement particles, aiding in the uniform distribution of the cement and enhancing the hydration reaction once water is added.

In contrast, in the slurry application, the cement is pre-mixed with water, initiating the hydration process before it interacts with the clay. This pre-hydration can lead to less effective bonding with the clay particles, possibly resulting in lower strength development.

Additionally, the higher clay content in Clemson soil might cause difficulties in mixing, whether in slurry or dry form. The cohesive nature of clay can make it harder to achieve a uniform mixture, potentially leading to inconsistent test results. Further investigation into the specific interactions between clay and cement in different application methods could provide more detailed insights.

Alternative chemical binders were also evaluated for their use in CMRB in an effort to reduce cement consumption in CMRB projects. Quicklime (QL), hydrated lime (HL), and lime kiln dust (LKD) were all tested using various base soils and dosages. The dosages used were the same as with cement at 3%, 6%, and 9% by weight of the stabilized materials. Compared to OPC, mixtures with alternative chemical binders performed poorly in UCS testing at both 7 and 28 days of age, suggesting that either higher dosages or partial cement substitution should be further investigated. Additionally, the heat generated from QL and LKD was high, which might be a practical issue in the field.

Tensile Strength: Flexural, Indirect, Splitting

Mixtures containing variable clay content were tested to evaluate their flexural strength (modulus of rupture, F_r), indirect tensile strength (ITS), and splitting tensile strength (STS). The general trend observed from the results of this study indicates that the clay content of the base soil improved STS and ITS performance, while hampering the modulus of rupture performance. Flexural strength testing showed the most significant variance in the test results between samples of different clay contents, ranging from 100 psi to 235 psi. ITS and STS test results showed lower variability across the different clay contents, ranging between 80 and 105 psi for ITS, and between 60 psi and 70 psi for STS. Correlations between the results of the three tensile strength tests for variable clay samples are shown in Table 19 along with 7-Day UCS correlations for each test. A strong correlation was observed between ITS and flexural strength testing, although the tests saw inverse trends. The F_r values also correlated strongly with 7-Day UCS values. ITS values were moderately correlated with 7-day UCS values. Finally, the STS results correlations were weak or negligible with the two other tensile strength and 7-Day UCS results, likely due to the difference in the direction of applied tension causing different failure conditions.

ITS testing was also performed on different base soils, where a similar trend was observed where performance improved with additional clay content. Clemson base soil, which has the highest clay content among our base soils, performed the best, followed by Lugoff and finally Walhalla. STS results deviated from this trend. Lugoff samples maintained the highest STS values, followed by Clemson and Walhalla samples. Myrtle Beach soil, which is relatively clean sand with a low clay content among the base soils in this study, made it difficult to form pills or prisms with which to test tensile strength without the samples collapsing under their self-weight.

Table 19 Correlations between Tensile Strength Values and 7-Day UCS, Variable Clay Samples.

R^2	ITS	F_r	STS	7-Day UCS
ITS	1.00	0.81	0.00	0.51
F_r	0.81	1.00	0.10	0.82
STS	0.00	0.10	1.00	0.41

Durability Testing: Wetting/Drying, Freeze/Thaw, Tube Suction Test

Durability testing, i.e. both W/D and F/T testing, was conducted on all mixtures with all base soils and variable clay content, all with a 6% cement dosage, to investigate the effects of soil composition on the performance of CMRB to assess moisture susceptibility and freezing-thawing resistance. Mixtures containing Clemson and Lugoff base soils performed the best in the W/D test, followed by Walhalla. Myrtle Beach samples performed the worst but passed the test based on a limit of 14% mass loss for granular soils. Mixtures with variable clay samples showed the optimal performance at 10% clay, while all mixtures with 10% to 30% clay outperformed the 0% clay mixture. None of the mixtures with clay exceeded 5% mass loss. This suggests that the presence of clay is beneficial to the durability of CMRB up to a certain extent.

The F/T testing yielded similar results to the W/D testing, although Walhalla samples outperformed Lugoff samples in this testing. Clemson, Walhalla, and Lugoff samples were all under a mass loss of 3% while the Myrtle Beach samples again saw a large mass loss of 13.35%, however, this is still under the 14% mass loss metric for failure. Mixtures with clay samples saw the same trend where the 10-30% clay samples outperformed the 0% sample, but the 40% saw a slight increase above the baseline. They all performed well, however, with the largest mass loss being 2.41% at 40% clay. Base soil mixtures with a modest proportion of clay performed the best in these durability tests as well as in tensile strength testing.

Results from TST showed an opposite trend than shown by W/D and F/T test results. Lugoff and Clemson's samples had the highest final DV recordings, with the Lugoff sample failing the guidelines set by Tex-144-E for moisture susceptibility. The variable clay samples also disagreed with previous durability testing results. The 0% clay sample performed the best. The addition of clay in the mix led to an increase in the final DV, although each variable clay sample remained well under a final DV of 10.0. At this point, TST results do not replace the need to do durability testing, although further investigation is recommended.

Shrinkage: Free and Restrained

Samples containing varying levels of clay content blended in with Walhalla base soil were tested for both free and restrained shrinkage. Free shrinkage was seen to steadily increase with increased clay in the base soil. In the restrained shrinkage results, it was observed that the maximum strain was lower in samples above 10% clay, and samples cracked within 4 hours. Samples with 10% clay or lower took 6 days to crack and release strain that was generally around double that of higher clay samples.

The results of the shrinkage ring can be correlated with the free drying-shrinkage results obtained from monitoring the length change of prismatic samples. The results correlated well, and this indicates that the shrinkage ring can be utilized to study the drying shrinkage behavior, especially mixtures with clay contents of 20% or higher in a much faster way than the free shrinkage prisms.

For every 10% increase in clay content, there was an increase of about 0.15% in shrinkage in the first week. This trend can be attributed to the fact that clay improves the blend's plasticity. Therefore, as mix-water evaporates, higher plasticity would increase drying shrinkage. The Atterberg limits were measured for different blends of the clay and granular soil and are shown in Table 9.

The drying shrinkage results are shown in Figure 44. The plot clearly shows that the initial rate of drying shrinkage is increasing as clay content increases. The curves did not start from zero because the curing period is included in the age of the sample, which was one day before the samples were demolded. Also shown in Figure 44b are the shrinkage values at 7 days and at the end of the test which lasted until no significant drying occurred (65 days). The values shown are percent from the original length at zero-day.

6. Conclusion, Recommendations, and Implementation

6.1. Conclusions

The following are the conclusions based on the experimental program conducted as part of this study:

1. The UCS of CMRB samples increased with increasing cement content when either ordinary Portland cement or Portland limestone cement was used.
2. A cement dosage of 3% was found to be insufficient in achieving the minimum UCS for CMRB with all base soils.
3. Increasing RAP content led to an increase in UCS when 9% cement dosage was used. The peak strength was observed at a RAP content of 35% by mass of the mixture at 6% cement content. The RAP content had little effect on UCS at low cement dosages.
4. For each base soil type, peak UCS was observed at a moisture content within 1% of the OMC determined from AASHTO T99 testing.
5. Changes in RAP gradation by the addition of larger RAP particles up to 1.5 inches did not significantly alter the UCS of CMRB samples.
6. Increased curing time from 7 days to 28 days increased the UCS of CMRB samples of all base soil types, at all clay contents, and cement contents. Beyond 28 days, while mixtures with most base soils showed further increase in the UCS, the clay-rich Clemson soil did not show significant improvement in UCS.
7. In general, UCS tends to decrease with increase in clay content in CMRB samples. The impact of higher clay content on reduced UCS was more significant in mixtures with higher cement content.
8. There is a positive linear relationship between OMC and clay content. The MDD reached a peak at 20% clay content due to the interaction of the clay particle packing and increased capillary forces. Beyond 20% clay content, the MDD decreased significantly.
9. The slurry cement application method tended to yield a higher 7-day UCS for each of the base soils tested, with the exception of Clemson base soil, which showed similar strength between the dry and slurry application of cement. Myrtle Beach samples showed the highest increase in UCS of about 73% with slurry cement, as compared to dry cement application.
10. Quicklime, hydrated lime, and lime kiln dust perform poorly as chemical binders at 3%, 6%, and 9% binder contents. In addition, while blending QL or LKD in mixtures, the heat generated was high that it may create a practical issue in the field. Further testing with these alternative binders is required and blending them with another chemical stabilizing agent such as asphalt emulsion may be required.
11. Increasing the clay content of the base soil of CMRB improved splitting tensile strength and indirect tensile strength while decreasing the modulus of rupture.
12. Preliminary testing on the comparison of UCS between OPC and PLC samples yielded mixed results, but it seems to not have a significant impact. More testing is recommended to establish precise impact on early-age setting and hardening behavior of CMRB mixtures.
13. The presence of clay in CMRB base soil improved performance of CMRB mixtures in W/D and F/T testing. This behavior was observed in mixtures with variable clay content and with the different base soils. Myrtle Beach soil, with the least amount of clay, was the only base soil that was close to failure in both tests.
14. Tube Suction Test (TST) does not correlate well with F/T and W/D testing. Further investigation is recommended to determine if TST results can be a viable durability metric.

15. An increase in clay content led to a general decrease in the UCS. No mixtures with variable clay content at 3% OPC dosage passed the minimum UCS of 300 psi at 7 days. At 6% cement, only the 0% clay mixture passed. At a cement dosage of 9%, mixtures of up to 20% clay passed the minimum design requirement.
16. Results from the modulus of rupture testing showed a peak performance at 10% clay content. ITS and STS results showed similar patterns with strength increasing after 10% and 20% clay, respectively. In general, it was observed that the addition of clay added cohesive qualities to the CMRB mixtures, improving tensile behavior.
17. The initial rate of drying shrinkage increased with an increase in clay content. However, when the RAP content was adjusted to 25% and 45% by mass of the base soil, the drying shrinkage was significantly reduced (14%, and 30% reduction, respectively) accompanied by a slight reduction in the UCS.
18. Increasing the clay content reduced the weight loss performance of CMRB samples in the wetting/drying test. Additional clay content slightly improved freeze/thaw test performance up to 30% clay content. At 40% clay, there is a sharp increase of weight loss up to 6%, but it is still well within the guidelines. The TST results correlated very weakly with both the W/D and F/T tests. However, the tests all agreed on the moisture susceptibility of each mixture on a pass/fail basis.
19. The isothermal calorimetry test for base soil-cement mixtures did not correlate well with the UCS of CMRB. Further testing is encouraged.

6.2. Recommendations

Based on the results of this study, the following recommendations are suggested:

Optimizing Mixture Design

These recommendations aim to enhance the mixture design process and establish robust quality control measures, ultimately contributing to the optimization of CMRB for improved pavement performance.

1. In base soil mixtures that contain significant clay or show variable clay content along the project site, conduct detailed assessments of Optimum Moisture Content (OMC) in relation to clay content to achieve an ideal balance for maximum density (MDD).
2. Monitor drying shrinkage rates and adjust Recycled Asphalt Pavement (RAP) content to reduce shrinkage while maintaining acceptable UCS levels.

Quality Assurance Recommendations

1. Implement stringent quality control procedures to ensure that mixtures meet or exceed the minimum design requirement of 300 psi at 7 days for UCS. Molding CMRB samples on the job site is recommended to achieve more representative sample QA purposes.
2. Periodically monitoring weight loss performance in wetting/drying tests and freeze/thaw tests to assess durability and identify potential areas for improvement.
3. Use the Texas Tube Suction Test (TST) as an additional indicator of moisture susceptibility but consider it alongside other more established tests.
4. Consider conducting further research and testing to explore the correlation between TST results and established durability metrics, to determine if TST can serve as a reliable durability metric.

Future Work Recommendations

1. It is recommended that SCDOT conduct a study to investigate how the presence of soluble sulfates and/or chlorides in the base soil affects the performance of Portland cement modified recycled base.
2. It is recommended that the performance of Portland Limestone Cement (ASTM C595 Type IL) cement as the primary chemical binder be studied further to assess any significant impact on UCS and other relevant properties.
3. It is recommended that alternative chemical binders such as LKD, and HL be studied for use in CMRB at higher dosages or blended with other chemical stabilizers such as asphalt emulsion.
4. It is recommended that further study be conducted on the efficacy of the Tube Suction Test as a measure of CMRB durability.
5. Findings from the present study are recommended to be used as a basis to further improve the shrinkage assessment of CMRB. Free and restrained shrinkage tests presented in this report should be considered for developing standardized test methods for assessing the shrinkage behavior of CMRB mixtures and establishing threshold values for mix design purposes.

6.3. Implementation Plan

The primary aim of this implementation plan is to seamlessly integrate the key findings and recommendations from the exhaustive study on CMRB into the existing practices of the SCDOT. This plan encompasses specific steps and recommendations for refining mixture design, establishing robust quality control measures, and advocating for further research to elevate CMRB performance. The following table shows the current practice of SCDOT in FDR mixture design and the suggested modification based on the results of this study:

Table 20 Current practice of SCT-26 and suggested modification based on the results of this study.

Current Practice	**Suggested Modification**
Sampling: 140 lb. of materials.	Sampling should be done at smaller intervals to represent the actual soil composition. Samples should be sieved separately and conduct the UCS test with the samples having the highest clay content.
Pavement materials dried at 140°F, sieved through ¾ in. sieve and retained RAP particles heated and broken up. Materials retained on the ¾ in. sieve are discarded.	RAP particle size can be larger than ¾ in. if needed up to a particle size of 1 in. but not larger than 1.5 in. with no significant effect on UCS.
Cement Content Testing and OMC Determination: Three cement contents (3%, 6%, and 9%) tested unless determined otherwise by the Chemical Stabilization Engineer (CSE). OMC for MDD was established using a blend stabilized with 6% cement.	A cement content of 3% did not meet the minimum UCS for most soil types tested in this study, especially with clay-rich soils. It is suggested to adjust the testing to start at slightly higher cement content, such as 5%.
Mixing and Compaction: Cement, RAP, and base soil were mixed dry, and then water was added at the OMC level for a homogeneous blend. Specimens compacted in three layers into standard proctor mold.	The slurry method application should be explored while preparing UCS samples.
The cement content is selected based solely on the minimum UCS.	Drying shrinkage should be incorporated in the mix design, especially with higher clay-content soil. Monitor drying shrinkage rates and adjust Recycled Asphalt Pavement (RAP) content to reduce shrinkage while maintaining acceptable UCS levels.

Current Practice	**Suggested Modification**
Moisture Content and Density Check: Moisture samples were taken before and after molding to verify moisture content and dry density.	In-situ moisture content should not vary by 1% to 2% from the OMC. Use the lower limit with clay-rich soils, while the upper limit with granular soil.
Quality Control and assurance based solely on checking moisture content and density.	Implement stringent quality control procedures to ensure mixtures meet the minimum design requirement of 300 psi at 7 days for UCS. On-site molding of CMRB samples is recommended.
Curing and Strength Testing: Specimens were cured in a standard room at (73±4) °F and 100% humidity for seven days. After soaking overnight, UCS testing was conducted.	A rational definition of "overnight" is needed. Modify to 24 hours of soaking or set a minimum saturation level with each UCS test.
UCS Analysis and Cement Content Selection: UCS values plotted against cement content. Appropriate cement content was chosen based on the required UCS.	Further study is needed to establish shrinkage thresholds for each soil type to eventually include it in the mixture design.

To enhance the management of drying shrinkage, it is imperative to exercise control over the composition of pavement materials. This can be achieved by strategically modifying and regulating factors such as the depth of treatment, or alternatively, incorporating synthetic FDR techniques. This involves the introduction of foreign materials, such as virgin aggregate, to the existing mix. Additionally, it is advised to exercise caution concerning clay content, ensuring it does not surpass the threshold of 20%-30%. This limitation necessitates an adjustment in cement content to meet the requisite minimum UCS. As the cement content is increased, there arises an opportunity to expand both the size and content of Recycled Asphalt Pavement (RAP) up to 1.5 inches and 50% by mass of the mix, respectively. This comprehensive approach empowers the optimization of drying shrinkage control within the pavement materials, setting the stage for improved overall performance.

References

[1] SCDOT, “SCT-26: Standard Method of Test for Sampling, Preparing and Testing of Cement Modified Recycled Base Compression Specimens in the Laboratory.” Aug. 2017. [Online]. Available: https://www.scdot.org/business/pdf/materials-research/testProcedure/soils/SCT26.pdf

[2] F. Xiao, S. Yao, J. Wang, X. Li, and S. Amirkhanian, “A literature review on cold recycling technology of asphalt pavement,” *Constr. Build. Mater.*, vol. 180, pp. 579–604, Aug. 2018, doi: 10.1016/j.conbuildmat.2018.06.006.

[3] G. D. Reeder, D. S. Harrington, M. E. Ayers, and W. Adaska, “Guide to Full-Depth Reclamation (FDR) with Cement,” National Concrete Pavement Technology Center, Institute for Transportation, Iowa State University, SR1006P, Mar. 2017.

[4] S. Sebesta and T. Scullion, “Effectiveness of minimizing reflective cracking in cement-treated bases by microcracking,” FHWA/TX-05/0-4502-1, Oct. 2004.

[5] T. Scullion, “Evaluating the performance of soil-cement and cement-modified soil for pavements: a laboratory investigation,” Portland Cement Association, RP120, 2005.

[6] H. Wen, M. P. Tharaniyil, B. Ramme, and S. Krebs, “Field Performance Evaluation of Class C Fly Ash in Full-Depth Reclamation: Case History Study,” *Transp. Res. Rec. J. Transp. Res. Board*, vol. 1869, no. 1, pp. 41–46, Jan. 2004, doi: 10.3141/1869-05.

[7] SCDOT, “Technical Memorandum: EXISTINGCONDITIONS,” Apr. 2013. [Online]. Available: https://www.scdot.org/Multimodal/pdf/tech_memo_part1.pdf

[8] Eric Carroll, “A Review of Cement Stabilized Aggregate Base Use in South Carolina,” SCDOT Office of Materials and Research, Nov. 2015.

[9] R. L. Parsons and J. P. Milburn, “Engineering Behavior of Stabilized Soils,” *Transp. Res. Rec. J. Transp. Res. Board*, vol. 1837, no. 1, pp. 20–29, Jan. 2003, doi: 10.3141/1837-03.

[10] K. S. Henry, J. P. Olson, S. P. Farrington, and J. Lens, “Improved performance of unpaved roads during spring thaw (No. ERDC/CRREL-TR-05-1),” *Eng. Res. Dev. Cent. HANOVER NH COLD Reg. Res. Eng. LAB*, no. Journal Article, 2005.

[11] W. S. Guthrie, A. V. Brown, and D. L. Eggett, “Cement Stabilization of Aggregate Base Material Blended with Reclaimed Asphalt Pavement,” *Transp. Res. Rec. J. Transp. Res. Board*, vol. 2026, no. 1, pp. 47–53, Jan. 2007, doi: 10.3141/2026-06.

[12] A. J. Puppala, A. Pedarla, B. Chittoori, V. K. Ganne, and S. Nazarian, “Long-Term Durability Studies on Chemically Treated Reclaimed Asphalt Pavement Material as a Base Layer for Pavements,” *Transp. Res. Rec. J. Transp. Res. Board*, vol. 2657, no. 1, pp. 1–9, Jan. 2017, doi: 10.3141/2657-01.

[13] Z. Si and C. H. Herrera, “Laboratory and Field Evaluation of Base Stabilization Using Cement Kiln Dust,” *Transp. Res. Rec. J. Transp. Res. Board*, vol. 1989–2, no. 1, pp. 42–49, Jan. 2007, doi: 10.3141/1989-47.

[14] H. E. Bofinger, H. O. Hassan, and R. I. T. Williams, “The shrinkage of fine-grained soil-cement,” presented at the Australian Road Research Board Symposium, 1978.

[15] T. Scullion, “Precracking of Soil-Cement Bases to Reduce Reflection Cracking: Field Investigation,” *Transp. Res. Rec. J. Transp. Res. Board*, vol. 1787, no. 1, pp. 22–30, Jan. 2002, doi: 10.3141/1787-03.

[16] H. Wen, B. Muhunthan, J. Wang, X. Li, T. Edil, and J. M. Tinjum, *Characterization of cementitiously stabilized layers for use in pavement design and analysis*, no. Project 4-36. 2014.

[17] K. P. George, *Minimizing cracking in cement-treated materials for improved performance*, no. R&D Bulletin RD123,. 2002.

[18] D. N. Little, *Stabilization of pavement subgrades and base courses with lime*. 1995.

[19] F. Q. Yue and C. F. Yang, “Semi-rigid asphalt pavement thermal reflective crack in finite element method,” *J. Guilin Inst. Technol.*, vol. 24, no. 1, pp. 52–54, 2004.

[20] T. Scullion, S. Guthrie, and S. Sebesta, "Field performance and design recommendations for full depth recycling in Texas," 2003.

[21] I. M. Syed and T. Scullion, "Performance Evaluation of Recycled and Stabilized Bases in Texas," *Transp. Res. Rec. J. Transp. Res. Board*, vol. 1757, no. 1, pp. 14–21, Jan. 2001, doi: 10.3141/1757-02.

[22] C. Berthelot, B. Marjerison, G. Houston, J. McCaig, S. Warrener, and R. Gorlick, "Mechanistic Comparison of Cement- and Bituminous-Stabilized Granular Base Systems," *Transp. Res. Rec. J. Transp. Res. Board*, vol. 2026, no. 1, pp. 70–80, Jan. 2007, doi: 10.3141/2026-09.

[23] I. Syed, T. Scullion, and R. E. Smith, "Recent developments in characterizing durability of stabilized materials," presented at the 82nd TRB Annual Meeting, 2003.

[24] Y. Yang *et al.*, "Comprehensive Laboratory Evaluations and a Proposed Mix Design Procedure for Cement-Stabilized Cohesive and Granular Soils," *Front. Mater.*, vol. 7, p. 239, Jul. 2020, doi: 10.3389/fmats.2020.00239.

[25] Y. Zhang, A. E. Johnson, and D. J. White, "Laboratory freeze–thaw assessment of cement, fly ash, and fiber stabilized pavement foundation materials," *Cold Reg. Sci. Technol.*, vol. 122, pp. 50–57, Feb. 2016, doi: 10.1016/j.coldregions.2015.11.005.

[26] I. Bozbey *et al.*, "Effects of soil pulverization level on resilient modulus and freeze and thaw resistance of a lime stabilized clay," *Cold Reg. Sci. Technol.*, vol. 151, pp. 323–334, Jul. 2018, doi: 10.1016/j.coldregions.2018.03.023.

[27] K. Uddin, A. S. Balasubramaniam, and D. T. Bergado, "Engineering behavior of cement-treated Bangkok soft clay," *Geotech. Eng.*, vol. 28, no. Journal Article, pp. 89–119, 1997.

[28] R. Saadeldin and S. Siddiqua, "Geotechnical characterization of a clay–cement mix," *Bull. Eng. Geol. Environ.*, vol. 72, no. 3–4, pp. 601–608, Dec. 2013, doi: 10.1007/s10064-013-0531-2.

[29] S. Ullah and B. F. Tanyu, "Effect of Variation in Moisture Content on the Mechanical Properties of Base Course Constructed with RAP-VA Blends," in *Geo-Congress 2020*, Minneapolis, Minnesota: American Society of Civil Engineers, Feb. 2020, pp. 612–620. doi: 10.1061/9780784482810.063.

[30] K. P. George, "Characterization and structural design of cement-treated base," *Transp. Res. Rec.*, vol. 1288, no. Journal Article, pp. 78–87, 1990.

[31] P. A. Dixon, W. S. Guthrie, and D. L. Eggett, "Factors Affecting Strength of Road Base Stabilized with Cement Slurry or Dry Cement in Conjunction with Full-Depth Reclamation," *Transp. Res. Rec. J. Transp. Res. Board*, vol. 2310, no. 1, pp. 113–120, Jan. 2012, doi: 10.3141/2310-12.

[32] C. Berthelot and R. Gerbrandt, "Full-Depth In-Place Recycling and Road Strengthening Systems for Low-Volume Roads: Highway No. 19 Case Study," *Transp. Res. Rec. J. Transp. Res. Board*, vol. 1819, no. 1, pp. 32–43, Jan. 2003, doi: 10.3141/1819b-05.

[33] D. Jones, S. Louw, and R. Wu, "Full-Depth Reclamation: Cost-Effective Rehabilitation Strategy for Low-Volume Roads," *Transp. Res. Rec. J. Transp. Res. Board*, vol. 2591, no. 1, pp. 1–10, Jan. 2016, doi: 10.3141/2591-01.

[34] P. Ayar, "Effects of additives on the mechanical performance in recycled mixtures with bitumen emulsion: An overview," *Constr. Build. Mater.*, vol. 178, pp. 551–561, Jul. 2018, doi: 10.1016/j.conbuildmat.2018.05.174.

[35] Brian K. Diefenderfer and Alex K. Apeagyel, "I-81 In-Place Pavement Recycling Project," Virginia Center for Transportation Innovation and Research, Virginia, FHWA/VCTIR 15-R1, Aug. 2014. [Online]. Available: http://www.virginiadot.org/vtrc/main/online_reports/pdf/15-r1.pdf

[36] D. H. Timm, B. K. Diefenderfer, and B. F. Bowers, "Cold Central Plant Recycled Asphalt Pavements in High Traffic Applications," *Transp. Res. Rec. J. Transp. Res. Board*, vol. 2672, no. 40, pp. 291–303, Dec. 2018, doi: 10.1177/0361198118801347.

[37] S. Bemanian, P. Polish, and G. Maurer, "Cold In-Place Recycling and Full-Depth Reclamation Projects by Nevada Department of Transportation: State of the Practice," *Transp. Res. Rec. J. Transp. Res. Board*, vol. 1949, no. 1, pp. 54–71, Jan. 2006, doi: 10.1177/0361198106194900106.

[38] D. E. Lewis, D. M. Jared, H. Torres, and M. Mathews, "Georgia's Use of Cement-Stabilized Reclaimed Base in Full-Depth Reclamation," *Transp. Res. Rec. J. Transp. Res. Board*, vol. 1952, no. 1, pp. 125–133, Jan. 2006, doi: 10.1177/0361198106195200114.
[39] S. Sebesta and T. Scullion, "Implementation of Small Samples for Developing Full-Depth Recycling Mix Designs," Texas A&M Transportation Institute, Texas Department of Transportation, Federal Highway Administration, FHWA/TX-16/5-6271-03-R1, 5-6271-03-R1, Jan. 2019. [Online]. Available: https://static.tti.tamu.edu/tti.tamu.edu/documents/5-6271-03-R1.pdf
[40] K. P. George, "Soil stabilization field trial : interim report I.," no. FHWA/MS-DOT-RD-01-133, Apr. 2001, [Online]. Available: https://rosap.ntl.bts.gov/view/dot/24134
[41] K. P. George, "Soil stabilization field trial : interim report II.," no. FHWA/MS-DOT-RD-02-133, Feb. 2002, [Online]. Available: https://rosap.ntl.bts.gov/view/dot/24135
[42] K. P. George, "Soil stabilization field trial : final report.," no. FHWA/MS-DOT-RD-05-133, Jan. 2006, [Online]. Available: https://rosap.ntl.bts.gov/view/dot/24132
[43] N. Garg and M. R. Thompson, "Lincoln Avenue Reclaimed Asphalt Pavement Base Project," *Transp. Res. Rec. J. Transp. Res. Board*, vol. 1547, no. 1, pp. 89–95, Jan. 1996, doi: 10.1177/0361198196154700113.
[44] W. H. Highter, J. A. Clary, and D. J. DeGroot, "Structural Numbers for Reclaimed Asphalt Pavement Base and Subbase Course Mixes," *Struct. Numbers Reclaimed Asph. Pavement Base Subbase Course Mix.*, no. Journal Article, 1997.
[45] J. A. C. MacGregor, W. H. Highter, and D. J. DeGroot, "Structural Numbers for Reclaimed Asphalt Pavement Base and Subbase Course Mixes," *Transp. Res. Rec. J. Transp. Res. Board*, vol. 1687, no. 1, pp. 22–28, Jan. 1999, doi: 10.3141/1687-03.
[46] G. Colomeier and J. P. Marchand, "The Precracking of Pavement Underlays Incorporating Hydraulic Binders," *Reflective Crack. Pavements State Art Des. Recomm.*, no. Journal Article, p. 273, 2014.
[47] M. Lefort, "Technique for limiting the consequences of shrinkage in hydraulic-binder-treated bases," *Reflective Crack. Pavements Des. Perform. Overlay Syst.*, no. Journal Article, p. 3, 2004.
[48] T. Yamanouchi and M. Ishido, "Laboratory and In-situ Experiments on the Problem of Immediate Opening of Soil-Cement Base to General Traffic," presented at the Austral-new Zeal Conf Soil Mech Efdneng, 1963.
[49] T. C. Teng and J. P. Fulton, "Field evaluation program of cement-treated bases," *Transp. Res. Rec.*, vol. 501, no. Journal Article, pp. 14–27, 1974.
[50] J. Litzka and W. Haslehner, "Cold in-place recycling on low-volume roads in Austria," presented at the Transportation Research Board Conference Proceedings, 1995.
[51] H. Brandl, "Mixed-in-place stabilization of pavement structures with cement and additives," presented at the Twelfth European Conference on Soil Mechanics and Geotechnical Engineering (Proceedings) The Netherlands Society of Soil Mechanics and Geotechnical Engineering; Ministry of Transport, Public Works and Water Management; AP van den Berg Machinefabriek; Fugro NV; GeoDelft; Holland Railconsult, 1999.
[52] S. Sebesta, "Use of Microcracking to Reduce Shrinkage Cracking in Cement-Treated Bases," *Transp. Res. Rec. J. Transp. Res. Board*, vol. 1936, no. 1, pp. 2–11, Jan. 2005, doi: 10.1177/0361198105193600101.
[53] F. Intaj, Y. Liu, and Z. Wu, "Application and Evaluation of Micro-Cracking on Cement-Stabilized Bases at Field Projects in Louisiana," *Transp. Res. Rec. J. Transp. Res. Board*, vol. 2673, no. 9, pp. 355–364, Sep. 2019, doi: 10.1177/0361198119847467.
[54] M. Reza-Ul-Karim Bhuyan and M. Jamal Khattak, "Performance Evaluation of Reflective Crack Mitigation Techniques for Soil-Cement Bases," *Transp. Res. Rec. J. Transp. Res. Board*, vol. 2674, no. 11, pp. 901–914, Nov. 2020, doi: 10.1177/0361198120949879.

[55] E. Zube, C. G. Gates, E. C. Shirley, and H. A. Munday, “Service performance of cement-treated bases as used in composite pavements,” *Highway. Res. Rec.*, vol. 291, no. Journal Article, pp. 57–69, 1969.
[56] D. J. Atkinson, “Evaluation of rehabilitation measures for cracked cement treated pavements,” presented at the Road Engineering Association of Asia and Australasia (REAAA), Conference, 6th, 1990, Kuala Lumpur, Malaysia, 1990.
[57] D. H. Chen, “Field and lab investigations of prematurely cracking pavements,” *J. Perform. Constr. Facil.*, vol. 21, no. 4, pp. 293–301, 2007.
[58] R. Luo and J. A. Prozzi, “Benefit of Lime Treatment for Controlling Longitudinal Pavement Cracking Due to Expansive Subgrade,” presented at the 87th Annual Meeting of the Transportation Research Board, Washington, DC, 2008.
[59] J. R. Wise and W. R. Hudson, “An examination of expansive clay problems in Texas,” 1971.
[60] Y. Li, J. B. Metcalf, S. A. Romanoschi, and M. Rasoulian, “Performance and Failure Modes of Louisiana Asphalt Pavements with Soil-Cement Bases Under Full-Scale Accelerated Loading,” *Transp. Res. Rec. J. Transp. Res. Board*, vol. 1673, no. 1, pp. 9–15, Jan. 1999, doi: 10.3141/1673-02.
[61] M. De Beer, “Behaviour of cementitious subbase layers in bitumen base road structures,” University of Pretoria, 2009.
[62] J. Casmer, “Fatigue cracking of cementitiously stabilized pavement layers through large-scale model experiments,” 2011.
[63] P. C. Pretorius and C. L. Monismith, “Fatigue crack formation and propagation in pavements containing soil-cement bases,” *Highway Res. Rec.*, no. 407, 1972.
[64] K. N. Naji and M. M. Zaman, “Flexural Properties of Stabilized-Aggregate Beams Subjected to Freeze-Thaw Cycles,” presented at the 84th Annual Meeting of the Transportation Research Board, Washington, DC, 2005.
[65] R. S. Ashtiani and J. Tarin, “Testing Procedures for Long Life Heavy Duty Stabilized Bases,” University of Texas at El Paso. Center for Transportation Infrastructure Systems, 2020.
[66] R. Yeo, *The development and evaluation of protocols for the laboratory characterization of cemented materials*, no. AP-T101/08. 2008.
[67] Md. A. Khan, N. Biswas, A. Banerjee, and A. J. Puppala, “Field Performance of Geocell Reinforced Recycled Asphalt Pavement Base Layer,” *Transp. Res. Rec. J. Transp. Res. Board*, vol. 2674, no. 3, pp. 69–80, Mar. 2020, doi: 10.1177/0361198120908861.
[68] S. K. Pokharel, J. Han, D. Leshchenko, and R. L. Parsons, “Experimental evaluation of geocell-reinforced bases under repeated loading,” *Int. J. Pavement Res. Technol.*, vol. 11, no. 2, pp. 114–127, Mar. 2018, doi: 10.1016/j.ijprt.2017.03.007.
[69] A. M. George, A. Banerjee, A. J. Puppala, and M. Salahi, “Performance evaluation of geocell-reinforced reclaimed asphalt pavement (RAP) bases in flexible pavements,” *Int. J. Pavement Eng.*, vol. 22, no. 2, pp. 181–191, Jan. 2021, doi: 10.1080/10298436.2019.1587437.
[70] J. Han *et al.*, “Performance of Geocell-Reinforced RAP Bases over Weak Subgrade under Full-Scale Moving Wheel Loads,” *J. Mater. Civ. Eng.*, vol. 23, no. 11, pp. 1525–1534, Nov. 2011, doi: 10.1061/(ASCE)MT.1943-5533.0000286.
[71] R. Taha, A. Al-Harthy, K. Al-Shamsi, and M. Al-Zubeidi, “Cement stabilization of reclaimed asphalt pavement aggregate for road bases and subbases,” *J. Mater. Civ. Eng.*, vol. 14, no. 3, pp. 239–245, 2002.
[72] W. S. Guthrie, S. Sebesta, and T. Scullion, “Selecting optimum cement contents for stabilizing aggregate base materials.,” Texas Transportation Institute, Texas A & M University System, 2002.
[73] W. H. Wilson Jr., “Strength Assessment of Soil Cement,” Auburn University, United States -- Alabama, 2013. [Online]. Available: https://www.proquest.com/dissertations-theses/strength-assessment-soil-cement/docview/2800161621/se-2?accountid=6167

[74] E. J. Bittar Marin, R. A. Quinones Samaniego, A. Techane Neto, and N. C. Consoli, "Cement Stabilized Soil Field Samples: Quality Control for Bases and Sub-bases," *Geotech. Geol. Eng.*, vol. 41, no. 7, pp. 4169–4184, Sep. 2023, doi: 10.1007/s10706-023-02514-5.

[75] ASTM International, "C157/C157M-17 Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete," ASTM International, West Conshohocken, PA, 2017. doi: 10.1520/C0157_C0157M-17.

[76] ASTM International, "C490/C490M-17 Practice for Use of Apparatus for the Determination of Length Change of Hardened Cement Paste, Mortar, and Concrete," ASTM International, West Conshohocken, PA, 2017. doi: 10.1520/C0490_C0490M-17.

Appendixes

Regional Experience with CMRB

A summary of some of the regional experiences and research studies related to the design, planning, and construction of FDR is presented below.

Virginia

In a study performed by Virginia Center for Transportation Innovation and Research [35], the conditions of three trial road sections rehabilitated by FDR were evaluated. One used bituminous stabilization of both asphalt emulsion and foamed asphalt, and the other two used OPC as stabilizer with FDR. The assessment included different mechanical properties such as indirect tensile strength and resilient modulus, and a life cycle cost analysis (LCCA). The results showed improved structural capacity of the section repaired by FDR, and significant savings were achieved by implementing FDR over the other traditional methods.

In the past, FDR and other pavement recycling techniques have been viewed as suitable only for lower volume roadway applications. Recently, work sponsored by the Virginia Department of Transportation at the National Center for Asphalt Technology Test Track has shown that FDR can be suitable for higher volume facilities [36]. In addition, research conducted as part of NCHRP 9-51 showed that stiffness properties of FDR can be similar to other pavement recycling techniques (such as cold in-place recycling and cold central plant recycling). Although FDR is often given a lesser stiffness and/or layer coefficient value in design by many US highway agencies, research is beginning to show that design values for FDR may be overly conservative. In addition, a recent construction project by the Virginia Department of Transportation on I-64 near Williamsburg, VA has shown that FDR can be used to stabilize imported materials to create a foundation for added lanes (a process that has been referred to as either *imported* or *synthetic* FDR).

Acceptance of the FDR material is most often performed by assessing the density, thickness, and moisture content. While these parameters have a history of use and a comfort level among agency practitioners, these parameters do not always correctly identify acceptable material. The nearly complete, NCHRP 9-62 study looks to address this topic by proposing simple and repeatable field tests that can be used for product acceptance. *We plan on taking advantage of this experience in our research project to make use of the results of the 9-62 project.*

Nevada

The work of Bemanian et al. 2006 [37] reviewed the state of the practice in Nevada DOT (NDOT) regarding the use of cold-in-place recycling (CIR) and FDR in pavement rehabilitation. At the time of the report, NDOT had successfully used both CIR and FDR for 20 years, during which a saving of $600 million was achieved implementing these strategies in pavement maintenance over the option of reconstruction. This work studied how to effectively select, design, and perform both CIR and FDR projects. The selection of CIR and FDR was related to the nature and source of the pavement distress as either being functional or structural, respectively. Therefore, the first two steps that this work suggested were to identify the type and cause of the distress. Next, determine the field conditions by performing field tests. The final step was to do laboratory work to optimize the mix design. A life cycle cost analysis was carried out comparing CIR, FDR, and the traditional pavement rehabilitation methods of overlay, mill and overlay, and reconstruction. The LCA study proved how cost-effective both CIR and FDA strategies were.

Georgia

In a study by the Georgia DOT [38], a road section of 1.8-Km in length in the rural area in the southeast of GA was reconstructed using FDR, while another 3-Km of the same road was repaired by an asphalt overlay over the old pavement. The sandy clay base required 6% cement in FDR to achieve the design strength as the laboratory test indicated. Results of this study favored FDR with Portland cement over the other stabilization methods and the study recommended the use of FDR for non-state road networks. More than 40% reduction of cost and lower Falling weight deflectometer readings were achieved for the FDR section.

TxDOT

A recent report by TxDOT [39] investigated the possibility of designing FDR mixtures using small samples tested by the indirect tensile strength (ITS). The reason for such investigation was that the FDR potential is realized through a good mix design, which often is done by a considerable effort and time in the lab using huge amounts of sample materials from the project site to come up with a suitable design. This process usually utilizes large sample sizes that are tested for UCS. Therefore, the implementation of a reduced sample size would allow for the inspection of a wide range of stabilizers and variable materials, and, at the same time, results would be expected in a shorter time of five days as per the suggested method. Both sample sizes are shown in Figure 2.4. The study concluded that stabilizing with cement or other stabilizers, the results gained from both sample sizes were in an acceptable agreement. However, there is a need for a full review of the small sample procedure to improve its repeatability and reproducibility. Correlation with the existing specification is also needed for further investigation. This study was performed using cement and asphalt-based stabilization, and it recommended further study for the use of a small sample method with lime-based stabilization [39].

Mississippi

In a comprehensive study conducted by University of Mississippi and the Mississippi DOT from 2001 to 2005 and covered in three reports [40]–[42], six 1000 ft test sections were constructed with varying chemical stabilizers to investigate the shrinkage cracks performance. Different techniques of shrinkage cracks mitigation were studied including precracking and grooving. Other binders were also investigated including cement and fly ash, a blend of slag and lime, and a blend of fly ash and lime which, at that time, was the current technique followed by MDOT. The precracked section was obtained by utilizing a vibratory roller after 24 hours of placement of the treated base. The cracking potential was monitored for 5 years by conducting falling weight reflectometer (FWD), testing of 4in. diameter cores for strength, and a manual crack survey. The FWD data were interpreted by software and the modulus was back calculated for each section.

The first report covered the early age performance in terms of the UCS of the treated bases and the initial development of shrinkage cracks [12]. At an age of 3 days, moderate cracking occurred in all section except the precracked section and the lime-fly ash stabilized section, and cracks continued to propagate steadily up to 28 days. The cracks were attributed to drying shrinkage as a result of the hot weather surrounding the test site and a possible improper curing. The higher strength bases were subject to more shrinkage cracks.

The second report summarized the results obtained for monitoring the gain of strength gain and the reflection of cracks in the pavement surface over a period of more than 14 months [41]. For the sections stabilized with cement and lime, the moduli of the subgrade continuously increased after 28 days up to the 440 days of the monitoring period. The percentage increase ranged from 40% to 57% between 28 days and 440 days. However, the sections stabilized with cement-fly ash and lime-slag showed a reduction of the moduli. The reduction of the moduli was attributed to the cracks developed in these two sections. Although there was a reduction in the modulus of some sections, the UCS did not follow the same trend and had increased for all sections.

The final report of this study, numbered FHWA/MS-DOT-RD-05-133 [42], covered the results of FWD tests and cracks survey after 5 years of construction. Again, the moduli of all sections increased steadily up to the monitored period (1654 days) except for the cement-fly ash stabilized section. The cement-fly ash section had a levelled off modulus after 440 days and its value was lower than what it was at 28 days, as mentioned in the second report. Although the UCS had increased with time for all sections, the control section (5.5% cement only) settled after 440 days, and it did not reach the design strength of 300 psi. among all the other sections, the lime-fly ash stabilized section had the lower UCS.

Additionally, the control section was subject to extreme shrinkage cracks. The technique of grooved sections in the treated base resulted in a sound layer but the report questioned its applicability on the field. The report indicated that the precracked CMRB outperformed all the other sections in all of the aspects of the study.

Illinois

For the Illinois Department of Transportation Garg and Thompson (1996) [43] assessed the performance of an Illinois Department of Transportation project involving a 1200-ft-long two-lane demonstration. This project featured an 8-inch compacted RAP base under a 3-inch dense graded AC surface, with a control section of 200 feet using dense-graded crushed stone aggregate. After two years of monitoring, they found comparable performance between the RAP and crushed stone base sections. Deflectometer tests showed adequate structural support and subgrade protection from the RAP base. Minor rutting was the only observed distress. Laboratory triaxial rapid shear and resilient modulus tests confirmed RAP's satisfactory response, aligned with the crushed aggregate used in their research.

Massachusetts

A research study was carried out on behalf of the Massachusetts Highway Department to explore the utilization of RAP/aggregate blends. This investigation, undertaken by Highter et al. in 1997 [44], [45], encompassed a series of laboratory tests that focused on assessing the hydraulic conductivity and resilient modulus of nine distinct RAP/aggregate compositions. The test scenarios involved both a crushed stone base and a naturally occurring granular borrow soil, with RAP content ranging from 0 to 100%. The findings from their laboratory experiments reveal the following key insights:

- An elevated percentage of RAP corresponds to a reduction in the maximum dry density, as determined through the standard Proctor compaction approach.
- The specific gravity and optimal water content exhibit minimal variation in relation to the RAP content, displaying neither significant increase nor decrease in a consistent manner.

- The hydraulic conductivity of the granular borrow soil demonstrates an upward trend as the RAP content in the mixture increases. Incorporating RAP into the crushed stone base material exerts marginal influence on the aggregate's hydraulic conductivity.
- The resilient modulus of the aggregate blends shows an upward trajectory in tandem with higher RAP percentages, indicating an increase in structural integrity.

Survey Questionnaire Design:

The survey questionnaire was carefully crafted to gather comprehensive data on the usage and mix design procedures of CMRB. The questions were designed to capture essential information such as the frequency of CMRB utilization, the types and sources of recycled materials used, the selection criteria for mix designs, the testing methods employed, and any challenges or limitations faced in implementing CMRB. The questionnaire was distributed to all state DOTs to ensure a representative sample of jurisdictions.

The following are the questions included in the survey:

Information about the responding agency

Q1 - Name of your organization

Q2 - Name of the department

Q3 - Name of the person completing the questionnaire.

Q4 - Contact Information — Email and Phone Number:

Information about FDR Process

Q5 - Has your state performed a Full-Depth Reclamation (FDR)? If you select YES, please continue with completing the rest of the survey. If you select NO, you can go to the end of Survey.

Q6 - Please select the primary stabilizing agent(s) your agency has used on FDR projects within the past 5 years.

Q7 - How much FDR does your state do each year (in terms of lane-miles or square yardage; 70,000 square-yards is equal to 10 lane miles) with Portland cement, lime or LKD-based stabilizing agents?

Q8 - In projects where your agency has used FDR within the last 5 years, what is the highest traffic volume (either AADT or ADT)?

Q9 - What percentage of the traffic is truck traffic on these routes?

Information about FDR Specification and Mix Design

Q10 - Please provide links to your state specifications for CMRB/FDR where Portland cement, lime or LKD are used as primary stabilizing agents.

Q11 - Does your agency require or conduct a mix design prior to construction? If you select "no", skip to Question 14

Q12 - If you selected "yes" in Q.11, does your agency use the same stabilizer agent content for all projects or determine the stabilizer agent content based on a strength value or any other parameter?

Q13 - If you have answered "Other" in Question 12, please provide a brief description of the criteria.

Q14 - What is the required stabilizer content or strength range (whichever is applicable) based on your response in Question 12?

Q15 - Does your agency assess the durability of the FDR mixture either during mix design or during production? For example, durability criteria may include characteristics such as Shrinkage, or mass-loss under wet-dry cycles or freeze-thaw cycles. If so, please include the name of any applicable local or national standard test methods.

Q16 - What is the most typical mode of deterioration with FDR that is encountered in your state? For instance, is it shrinkage cracking or rutting or other?

Q17 - Which structural design procedure(s) is(are) used by your agency when designing a pavement with FDR?

Q18 - What is the typical structural/stiffness value in the design procedure (based on Question 17)

Information about Quality Control and Assurance

Q19 - Does your state have any specific sampling procedures for collecting material for mix design of FDR?

Q20 - If you have answered "Yes" in Q.19, how does your agency collect materials in the field?

Q21 - If you have selected "Other" in Question 20, please provide additional information.

Q22 - If you have selected "Yes" in Q.19, how is the material processed after collection from field?

Q23 - If you have selected "Other" in Question 22, please provide additional information.

Q24 - Does your agency determine the Optimum Moisture Content for use in mix design of FDR?

Q25 - How do you ensure the optimum moisture content is achieved in the mix in the field?

Q26 - What is the allowable window of variability (+ or -) in your optimum moisture content as a percentage value in the field?

Q27 - Do you use any testing to evaluate the quality of FDR in the field from a QA/QC perspective?

Q28 - If you selected yes in Q.27, please elaborate on what tests you conduct.

Q29 - What is the best way to contact you?

Summary of Key Findings of the survey

1. **High FDR Adoption Rate**:
    - The survey reveals a significant adoption of Full-Depth Reclamation (FDR) practices among states, with 20 out of 22 responding states actively engaging in FDR projects. This demonstrates a widespread recognition of FDR as a viable pavement rehabilitation technique.
2. **Prevalence of Cement as Primary Stabilizing Agent**:
    - A substantial majority (75%) of the participating states prefer cement as the primary stabilizing agent for FDR projects. This indicates a strong industry consensus on the efficacy and reliability of cement in enhancing the structural integrity of reclaimed pavements.
3. **Diverse Criteria for Chemical Stabilizing Agent (CSA) Selection**:

- States employ various criteria for selecting the chemical stabilizing agent (CSA) content. The most common criterion is the UCS, used by 11 DOTs. Five DOTs opt for alternative stabilizing agents, while others did not specify their criteria. This diversity reflects a range of approaches and considerations in CSA selection.

4. **Variability in Design UCS Ranges**:
    - The design UCS exhibits significant variability across states. For instance, Texas specifies a range of 150-250 psi, whereas Montana sets a broader range of 500-1500 psi. The majority of states fall within the range of 300-450 psi. This diversity suggests tailored approaches based on local conditions and preferences.
5. **Additional Criteria for CSA Design**:
    - Several states incorporate additional criteria such as Marshall Stability, Resistance to Moisture Damage, and Historical Performance/Experience for CSA design. This indicates a comprehensive consideration of factors beyond UCS, highlighting a holistic approach to pavement design.
6. **Durability Assessment Practices**:
    - Montana is distinguished for its thorough durability assessment, performing both AASHTO T135 (Wet/Dry) and T136 (Freeze/Thaw) tests.
7. **Recognition of Common Deterioration Modes**:
    - Shrinkage cracking emerges as the most commonly recognized deterioration mode among states. However, some states, such as NDDOT, identify Freeze/Thaw (F/T) cycles as a significant factor. Vermont also highlights the potential issue of tent cracking due to elevated UCS values.
8. **Diverse Pavement Design Standards**:
    - While most states rely on AASHTO 1993 or earlier standards for pavement design, Texas, California, Florida, and Alaska employ locally developed specifications. This diversity of standards suggests a regionalized approach to pavement design.
9. **Structural Coefficient and Resilient Modulus Usage**:
    - States utilize a range of structural coefficients, with values spanning from 0.16 to 0.26. Additionally, some states employ Resilient Modulus, with values ranging from 20,000 psi to an impressive 150,000 psi in Texas. These variations reflect nuanced approaches to pavement design based on differing material properties.
10. **Quality Control Measures**:
    - Quality control plans encompass a comprehensive array of tests, including Thickness, Gradation (AASHTO T27), Moisture Content (T255), In-Place Density (T310), Indirect Tensile Strength (ITS), and Surface Irregularities. This detailed quality assurance process ensures the integrity and performance of reclaimed pavements.

In conclusion, the survey results underscore the dynamic and nuanced nature of Full-Depth Reclamation practices among participating states. The diversity in stabilizing agents, selection criteria, design standards, and quality control measures highlights the need for adaptable and context-specific approaches to FDR projects. This wealth of information provides valuable insights for the advancement and refinement of sustainable and efficient road infrastructure across the United States.

Comparison between the FDR specification for the DOTs that responded to the Survey.

State/ Year	Mix Design/ Cement Content	Performance Tests	QC Measures
CA 2018 foamed asphalt	• CA test 313: Wet and Dry Indirect Tensile Strengths, Tensile Strength Retained of Asphalt Concrete Samples. Select lowest asphalt content with test results of minimum $ITS_d \geq 30$ psi, $ITS_w \geq 15$ psi and $TSR \geq 0.5$ • Binder must be PG 64-10 • Binder not to exceed 375-degree F	• Visual Inspection of surface • CA test 231: 98% relative compaction at the 3 specified elevations • Thickness within 0.6" of design - 3 cores per lot • CA test 371 for TSR, within 90% of design • CA test 202 for gradation: 100% passing 3", 95%+ passing 2", 85%+ passing 1.5" • CA test 226: Less than 50% of OMC before paving, within 2% OMC after	• **Daily report:** • Weather: air and road surface temp • Binder: Injection rate, temp • Water application rate • Average speed of pulverizing equipment • Foamed asphalt core thickness and location • Moisture Content at mid depth • Water sulfates, chlorides • Binder expansion ratio and half-life • Wet Density • **Per test Strip:** • Gradation • ITS_d, ITS_w, TSR

CA
2018
cement
	• 7-day UCS tests on 3 specimens at OMC
	  ○ Must be 300-600 psi, with exceptions
	• 1 at specified cement content, 1 at -1% content, and 1 at +1% content
	• CA test 202 for gradation: 100% passing 3", 95%+ passing 2", 85%+ passing 1.5
		• Visual inspection of surface
		• ASTM D1633 for UCS.
		• CA test 216 for max wet density
		• CA test 226 for Moisture content, within 2% of mix design
		• Thickness of base course
		• CA test 231 for relative compaction:
		  ○ Max 5% retained on 2"
		  ○ Max 15% retained on 1.5"
		  ○ If relative compaction is less than 97% from lab wet density, additional tests required
			• **Daily report:**
			• Weather: air and road surface temp
			• Average speed of pulverizing equipment
			• Water sulfates, chlorides
			• Gradation
			• Moisture Content
			• Laboratory max wet density
			• Relative Compaction
			• UCS
			• Depth of pulverization

State/ Year	Mix Design/ Cement Content	Performance Tests	QC Measures
GA 2021 [CSRB]	● Pulverize base mixture until 100% passes 3" and 55% passes No. 4 ● Moisture between 100-120% of OMC	● Surface checked with surveyor's tools to ensure no deviation greater than 0.5" ● GDT 19 or 67 for max dry density ● GDT 20, 21, or 59 for finished, in-place density ASAP after compaction, before the cement sets ● Thickness of base course can't deviate by more than 0.5"	● Max Dry density ● In-place density ● Gradation ● A test section is constructed to evaluate: ○ Compaction ○ Moisture ○ Homogeneity ○ Thickness of stabilization ○ Finished base surface
IN 2020 CSFDR	● ● Class C or higher Coarse or Dense Graded Aggregate ● Type 1 Portland cement ● RAP from cold milling or crushing ○ 100% passing 1.5"	● ITM 510: sulfate content less than 1,000 ppm ● ASTM D1633 A for 7-day unconfined strength ○ 300 psi minimum if HMA overlay ≥330 lb/sq yd ○ 400 psi for 165-330 ○ 500 psi for less than 165 lb/sq yd	● Non-pavement materials shall be removed as observed from the pulverization process ○ Rubber, wires, fabric etc. ● Depth of Pulverization ● Gradation ● Moisture of pulverized material ● Max Density/ Moisture content of stabilized material ○ Moisture within -1 to +2% of design ● Cement Application Rate ● Compacted in-place density ○ Within 2" of layer bottom
KY 2018 CSFDR	● Base course shall not contain roots or topsoil ● Gradation: ○ 100% passes 3" ○ 95%+ passes 2" ○ 55%+ passes No.4 ○ 20% max passes No. 200	● Core samples taken to test for mix design: ● AASHTO T265: Moisture content ● AASHTO T88: Particle size ● AASHTO T89: Liquid Limit ● AASHTO T90: Plastic Limit ● AASHTO T99: Moisture Density ● AASHTO T308: UCS	● Moisture with 2% of OMC ● Gradation ● Compaction: average of at least 98% of maximum dry density among 5 consecutive tests

State/ Year	Mix Design/ Cement Content	Performance Tests	QC Measures
MS 2017	● Gradation: ○ 98%+ passes 2” ○ 95%+ passes 1.5”	●	● Slope remains within 0.5% of design ● Test section is first 500 feet of the project ○ Gradation, moisture content, density ● Depth of pulverization remains within .5” of design ● Compaction: average of at least 97% of maximum dry density among 5 consecutive tests
MT 2020	● Cement either Portland Type 1 or 11 or: (blended hydraulic cement) ○ AASHTO M 240 Type IP or Type IP (MS) ○ ASTM C1157 Type GU or Type MS ● AASHTO M 295 Class C Fly Ash can be replace up to 25% of cement weight ● Fine Aggregate passing No. 40: LL less than 30, PI less than 7 (AASHTO T 89 & 90) ● Cementitious materials at least 4.5% the weight of dry aggregate	● MT 216: 7-day UCS of 500-1500 psi ● AASHTO T 134: OMC and max density ● MT 202: Aggregate Gradations ● AASHTO T 135: wet and dry changes ● AASHTO T 136: freeze-thaw changes ● AASHTO T 176 alt No. 2: (with formaldehyde solution): Sand equivalent ● MT 212: Moisture and Density tests ● MT 201 to test compressive strength	● Material quantities remain within 0.5% of design ● Compaction within 98% of max dry density ● Visual surface inspection ● Re-process un-compacted sections where the moisture content has risen more than 1% above OMC ● Max freeze-thaw weight loss is 14% ○ Be sure not to lower cement content without re-checking this

State/ Year	Mix Design/ Cement Content	Performance Tests	QC Measures

ND
2020
(not 2014)
	• Gradation
	  ○ 97%+ passing 2”
	  ○ 90%+ passing 1.5”
		•	•

SC
2018
(2021)
	• Portland cement
	• Gradation
	  ○ 100% passing 3”
	  ○ 95% passing 2”
		• SC-T-1-6.6 for gradation
		• SC-T-26 for rate of cement (5% tolerance)
		• SC-T-23,26,27, or 29 for maximum density, to show compaction is within 95% of max
			• Ensure: structural integrity throughout depth
			• ...surface quality
			• Monitor in-site moisture conditions (within 2% OMC)
			• Test strip to evaluate moisture, compaction, cement tolerances, pulverization, depth

TN 2015	• Portland type 1, 1P, or 1L	• ASTM D1633 method A for 7-day UCS, need 300-500psi • AASHTO T 134 for max dry density and OMC • AASHTO T 310 for moisture content prior to compaction, within 2% of OMC	• Test strip to verify pulverization, cement & water application, compaction, and shaping • Compact to 100% max dry density • Slope • Surface deviations not to exceed .5”
TX 2014	• DMS-6350&6330 Lime products can be used, but not when 3000+ ppm sulfates are present • DMS-4600 Hydraulic Cement can be used • PG64-22 binder can be used	• Tex-103-E for moisture content and max dry density • Tex-115&121-E to test MC and MDD for Lime treatment • Tex-127-E for OMC with fly ash • Tex-101-E for gradation • Tex-120-E to test OMC with cement • Tex-148-E tests sulfate content • Tex-145-E tests organic content	• Compact to 98% dry density • Thickness within 1” of design

	• DMS-4615 Class CS or FS fly ash can be used solo or with lime, not with high sulfates or 1%+ organic content of the base ○ Limit RAP to 50% of the mix		

Sample Pictures from the experimental program

		a. The CMRB pill placed in the loading frame ready to be tested for ITS.
		b. The CMRB pills before and after the ITS test.
		c. Remaining pieces from the sample after the test and collecting all the samples to measure the average moisture content.

Figure 47 Images taken at different stages of the ITS test.

		a. Materials preparation for casting TST samples
		b. Extruding and measuring the mass of the TST sample.
		c. Drying TST Samples at 60 °C, then the samples were wrapped with a latex membrane with bottom and top porous stones.
		d. At the end of the TST test, the first image shows the column of capillary-absorbed moisture, and the second image is the dry weight of the sample after 24 hour drying in 110 °C.

Figure 48 Tube suction test procedures.

a *b* *c*

Figure 49 Shrinkage Prisms: a) Length Change Monitoring, b) Drying Shrinkage Samples showing the end studs, c) Shrinkage Prisms stored in the Environmental Chamber.

(a)

(b)

(c)

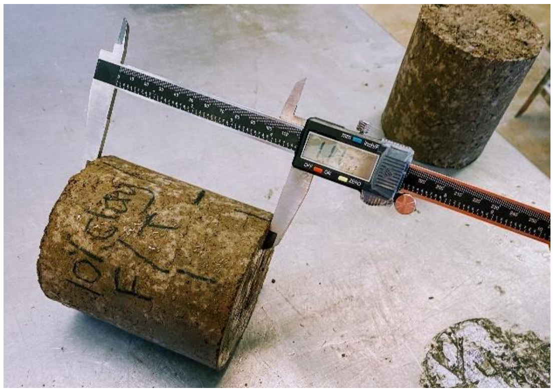
(a) The shrinkage ring after removing the outer ring.
(b) The shrinkage ring in the environmental chamber.
(c) The ring after it is cracked.

Figure 50 Different stages of testing the shrinkage ring.

(a)

(b)

(c)



(d)

(e)

(a) The wire brush and the 3-lb weight used in W/D and F/T testing;
(b) The W/D samples in 71°C for 42 hrs.
(c) The F/T Samples labeling
(d) Measuring dimension change after F/T cycle.
(e) F/T samples just taken from the freezer set at -25 °C.

Figure 51 Durability testing for W/D and F/T (repeated from last report).

Table 21 CMRB Projects Data per County received from SCDOT.

Prevalent Soil Code	County	Data Points (number of projects)	*ADT*	*% Trucks*	*Maximum Dry Density (pcf)*	*Optimum Moisture Content (%)*	*Design Cement Content (%)*	*Depth of CMRB (in)*	UCS, psi		
									3% Cement	*6% Cement*	*9% Cement*
1	Abbeville	25	940.46	6.58	124.84	9.50	7.80	9.92	200	360	510
2	Aiken	2	650.00	13.41	121.55	10.15	7.50	9.00	253	445	688
3	Allendale	2	1200.00	32.86	125.55	5.40	5.25	10.00	285	580	795
1	Anderson	65	2410.92	5.81	123.77	10.03	7.89	10.28	189	349	487
3	Bamberg	1	650.00	2.60	125.00	10.00	5.50	10.00	275	545	830
3	Barnwell	1	1500.00	3.50	121.70	6.60	4.50	10.00	340	580	900
4	Berkeley	43	2213.24	9.20	122.83	9.54	7.55	10.09	192	378	588
3	Calhoun	6	1291.67	12.68	127.18	8.67	5.75	10.67	260	492	735
4	Charleston	5	1532.50	5.54	119.64	8.74	8.10	9.20	139	340	559
1	Cherokee	62	10919.92	10.98	125.29	10.18	7.56	10.35	211	385	546
1	Chester	59	581.09	5.80	127.29	9.63	6.74	9.15	254	496	761
2	Chesterfield	37	965.68	6.48	125.58	9.41	5.95	10.21	248	502	739
3	Clarendon	12	1750.00	9.97	124.22	7.89	4.67	11.00	341	657	960
4	Colleton	24	1135.42	12.32	123.86	8.35	6.10	10.83	228	474	694
3	Darlington	20	1442.50	7.63	125.20	7.94	4.90	11.35	342	667	986
3	Dillon	40	855.29	6.09	124.35	9.43	5.08	10.83	308	626	936
4	Dorchester	14	4078.57	10.52	124.48	9.56	7.32	11.14	175	391	593
1	Edgefield	26	456.73	6.76	124.13	9.67	7.55	9.92	213	398	574
1	Fairfield	31	1366.25	8.34	124.02	9.51	6.84	9.56	250	492	729
4	Florence	82	1469.40	6.73	125.20	8.64	5.51	10.37	305	624	935
4	Georgetown	32	982.58	9.11	122.15	9.72	6.23	10.75	290	524	799
1	Greenville	55	4232.33	5.19	125.04	9.28	7.31	10.67	206	383	528
1	Greenwood	36	824.81	5.55	124.72	10.23	7.64	10.17	208	370	515
4	Hampton	2	1850.00	10.26	125.00	7.60	5.25	9.00	318	560	845

4	Horry	31	970.44	5.70	122.50	10.05	5.63	11.63	248	529	821
4	Jasper	15	4267.19	9.29	123.24	10.29	8.16	11.25	153	303	445
2	Kershaw	35	1834.32	6.95	124.76	8.78	6.24	9.54	274	564	855
1	Lancaster	90	1584.08	6.38	124.60	9.34	7.13	9.89	245	460	691
1	Laurens	59	967.65	6.36	123.71	10.14	7.25	10.31	220	404	570
3	Lee	11	422.31	7.35	125.51	8.86	5.85	10.15	315	591	882
2	Lexington	71	2403.70	6.20	124.20	9.01	6.37	10.31	248	525	797
3	Marion	18	2156.39	9.37	123.91	9.72	5.61	11.11	263	522	758
3	Marlboro	13	386.92	5.93	124.32	8.75	4.58	11.69	317	657	941
1	McCormick	10	277.60	8.26	127.62	8.98	8.00	8.40	228	409	566
1	Newberry	47	752.26	7.30	124.75	9.50	7.41	9.92	224	413	607
1	Oconee	64	2130.23	6.40	123.55	9.67	7.84	10.67	179	331	460
3	Orangeburg	8	4018.75	13.72	126.33	7.85	4.44	11.00	348	703	1076
1	Pickens	50	2051.64	5.49	123.76	9.70	7.87	10.16	204	366	502
2	Richland	67	1322.21	6.08	123.98	9.39	7.19	8.74	257	482	697
1	Saluda	46	345.71	6.96	122.63	10.80	8.05	10.09	177	341	499
1	Spartanburg	70	5123.80	5.56	123.92	9.98	7.68	10.66	201	377	532
3	Sumter	32	1976.38	7.87	125.28	8.39	5.36	10.13	360	697	1039
1	Union	42	673.64	6.54	122.20	10.23	8.21	8.76	206	378	533
4	Williamsburg	60	687.51	6.46	122.98	9.44	5.75	10.93	293	567	858
1	York	199	1447.33	5.43	126.08	9.79	6.93	10.10	247	458	672