University of Nevada, Reno

Impact of Aggregate Gradation on Airfield (P-401) Asphalt Mixture

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in
Civil and Environmental Engineering

By

Naveen Parameswaran

Dr. Adam Hand / Thesis Advisor

August 2025

THE GRADUATE SCHOOL

We recommend that the thesis
prepared under our supervision by

Naveen Parameswaran

entitled

Impact of Aggregate Gradation on Airfield (P-401) Asphalt Mixtures

be accepted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE

Adam J.T. Hand, Ph.D.
Advisor

Peter E. Sebaaly, Ph.D.
Committee Member

Elie Y. Hajj, Ph.D.
Committee Member

Anna Panorska, Ph.D.
Graduate School Representative

Markus Kemmelmeier, Ph.D., Dean
Graduate School

August, 2025

Abstract

The Federal Aviation Administrations' (FAA) current asphalt mixture gradation specification limits are finer, and the allowable ranges are more restrictive than control points for similar nominal maximum aggregate size mixtures within the Superpave mix design methodology. Ensuring the gradation specification limits requirements are allowing asphalt mix designers to produce the best performing, most economical, and lowest carbon footprint mixtures will safeguard airfield pavements into the future and were goals of this research.

This research utilized three material sources, one each from Arizona, Nevada and Washington to develop mix designs using the Baily Method inside the P-401 gradation specification limits requirements (in spec) and outside the P-401 gradation specification limits requirements (out spec). In and out of spec mix designs within each source were developed with the same asphalt cement (AC) and volume of effective binder. The rutting, moisture susceptibility, top-down cracking, low temperature cracking, durability (Cantabro abrasion loss) and permeability performance of each mixture were evaluated. However, broadening the FAA P-401 gradation specification limits did not compromise mixture volumetric requirements or affect the rutting performance, moisture susceptibility, durability or the permeability of the mixtures from the three states.

This work was part of a national effort by three laboratories including the Western Regional Superpave lab at UNR, the National Center for Asphalt Technology at Auburn University and the Heritage Research Group in Indiana. The final proposed adjustments to the gradation specification limits are anticipated to take place in the near future with the goal of providing the least restrictive gradation specification limits possible while maintaining the mixture performance expected of FAA P-401 mixtures.

Acknowledgments

I would like to express my sincere appreciation to Dr. Adam Hand, my advisor at the University of Nevada, Reno, for his constant guidance and support in my study. Dr. Hand's assistance and encouragement have allowed me to gain a tremendous amount of confidence and opened many opportunities for me in my academic career. I am extremely grateful toward Dr. Peter Sebaaly for being the great leader that you are, pushing the limits of the team and advancing our development as a collective in the program. Your excitement and dedication always drove toward betterment and continue to motivate me today. I wish to acknowledge Dr. Elie Hajj for his expertise and dedication as a driving force in motivating everyone in our team. Your expertise and significant contributions through our research have been so valuable on this journey. I would also like to thank Dr. Ashraf Alrajhi for his support and leadership as a lab manager.

I want to thank Bill Pine from the Heritage Research Group for being always there to help and assist through the Baily Method. His generous and structural expertise were a bridge of success for overcoming challenges on mix design development. I would also like to recognize all of the research team at the National Center for Asphalt Technology at Auburn University and Heritage Research Group that were involved and active engagement and shared insight and knowledge to make this research happen. I would like to thank my fellow graduate students for their warm welcome during my time here, family and friends for their support and efforts in providing input.

Table of Contents

List of Tables

List of Figures

Abbreviations and Acronyms

AAPTP – Airport Asphalt Pavement Technology Program

AASHTO - American Association of State Highway and Transportation Officials

AC – Asphalt Cement

ASTM - American Society for Testing and Materials

BMD – Balance Mix Design

DCT - Disc-Shaped Compact Tension

FAA – Federal Aviation Administration

FM - Florida Method of Test

HWTT – Hamburg Wheel Tracking Test

Ideal CT - Indirect Tensile Asphalt Cracking Test

I-FIT – Illinois Flexible Index Test

NCAT - National Center for Asphalt Technology

NMAS - Nominal Maximum Aggregate Size

Superpave - Superior Performing Asphalt Pavements

TSR - Tensile Strength Ratio

VMA – Voids Mineral Aggregate

WRSC – Western Regional Superpave Center

Chapter 1

Introduction

1.1 Background

Many airfield taxiways, runways and aprons are constructed with asphalt mixtures. The performance of these asphalt mixtures is crucial for aircraft operations in a safe and efficient manner. These asphalt pavements must resist deformation under high loads to maintain the drainage and the smoothness of the surface, and resist against weathering, raveling, and cracking to prevent the occurrence of the foreign object debris (FOD) [1]. The Federal Aviation Administration (FAA) outlines detailed mix design and construction requirements in Item P-401 of Advisory Circular 150/5370-10H, "Standard Specifications for Construction of Airports" to meet the above performance requirements [2].

The FAA P-401 specifications are used to design civilian airports (with the exception of non-primary airports serving aircraft with a gross weight less than 60,000 pounds) pavement. These designs are typically made of dense grade asphalt mixtures. Mix designs are conducted based on volumetric criteria using either Marshall or Superpave gyratory compaction [3], supplemented with the Tensile Strength Ratio (TSR) test [4] for evaluating moisture susceptibility. Furthermore, asphalt mixtures are designed for airports serving aircraft over 60,000 pounds must be tested with the Asphalt Pavement Analyzer (APA) or Hamburg Wheel Tracking Test (HWTT) to ensure adequate rutting resistance [5]. The P-401 specification asphalt mix design criteria are shown in Table 1.1.

Table 1.1: Asphalt Mix Design Criteria in P-401 Specification

Test Property	**Value**	**Test Method**
Number of blows or gyrations	75	N/A
Air Void (%)	3.5	ASTM D3203 [6]
Percent voids in mineral aggregate (VMA), minimum	14 (NMAS[1] =1 inch) 15 (NMAS =3/4 inch) 16 (NMAS = 1/2 inch)	ASTM D6995 [7]
Tensile Strength Ratio (TSR)[2]	Not less than 80 at a saturation of 70-80%	ASTM D4867 [4]
Asphalt Pavement Analyzer (APA)[3], HWTT[4]	Less than 10 mm @ 20000 passes	AASHTO T324 [5] at 50°C

[1] Nominal Maximum Aggregate Size

[2] Test specimens for TSR shall be compacted at 7 ± 1.0% air voids. In areas subject to freeze-thaw, use freeze-thaw conditioning in lieu of moisture conditioning per ASTM D 4867.

[3] AASHTO T 340 at 100 psi hose pressure at 64$_o$C test temperature may be used in the interim. If this method is used, the required Value shall be less than 5 mm @ 8000 passes.

[4] Where APA is not available, use Hamburg Wheel test (AASHTO T 324) 10 mm @ 20,000 passes at 50°C.

A critical component of the mix design process is aggregate selection and blending. The aggregate requirements of the P-401 specification include crushed aggregates, fine aggregates, and mineral fillers, all of which must meet strict standards of shape, angularity, toughness, soundness, and cleanliness. The content of natural sand is limited to 15% by weight in order to reduce rutting risk [2]. The specified gradation classes, now referred to as Gradations 1, 2, and 3, establish the maximum sizes and nominal maximum sizes of aggregates, and therefore ensure compliance with the operational requirements of airport pavements [2].

As good as P-401 specifications are in providing pavement performance and durability, there are difficulties that arise in harmonizing these standards with local supply of aggregates. Gradation specification requirements can create difficulty for mix producers, which will most likely result in modification that may compromise volumetric requirements and add costs [2]. This research was intended to explore these intricacies by collecting the experiences of industry practitioners and exploring potential improvements to P-401 mix design gradation specification requirements to enhance the workability and efficiency of asphalt pavements for airport conditions. The current P-401 gradation specifications requirements are summarized in Table 1.2.

Table 1.2: P-401 Aggregate Gradation Specification Requirements

Sieve Size	**Percentage by Weight Passing Sieves**		
	Gradation 1	**Gradation 2**	**Gradation 3**
1 inch	100	--	--
3/4 inch	90-100	100	--
1/2 inch	68-88	90-100	100
3/8 inch	60-82	72-88	90-100
No. 4	45-67	53-73	58-78
No. 8	32-54	38-60	40-60
No. 16	22-44	26-48	28-48
No. 30	15-35	18-38	18-38
No. 50	9-25	11-27	11-27
No. 100	6-18	6-18	6-18
No. 200	3-6	3-6	3-6

1.2 Research Objective

This research aims to investigate the effects of changes in aggregate gradations on the performance and volumetric properties of FAA P-401 asphalt mixtures. The project focuses on two key objectives:

1. Evaluating the impact of moving aggregate gradation outside the P-401 gradation specification limits while maintaining the volumetric and binder content requirements.
2. Evaluating the impact of aggregate gradation changes on volumetric and performance test results of P-401 mixtures, by comparing the volumetric properties and performance test results of In Spec gradations (In Spec 1 and In Spec 2) with Out Spec gradations (Out Spec 1 and Out Spec 2). All gradations were tested using the same volume of effective binder contents within a given mixture design.

This research includes laboratory testing of the volumetric properties and performance of the mixes, particularly the assessments of rutting, cracking, moisture susceptibility, and other mechanistic properties. The results will help to determine the sensitivity of P-401 mix performance to aggregate gradation changes and potentially establish broader gradation specification limits.

1.3 Research Scope

The intent of this research is to determine if it is possible to make changes to the FAA P-401 gradation specifications without compromising the volumetric mix design criteria or airfield asphalt mixture performance requirements. It focuses on widening the upper gradation limits of all sieves except the No. 200 sieve and lowering the limits for the No.

16 sieve and smaller, without changing the No. 8 sieve and larger sizes to prevent increasing mixture permeability.

This research is planned to offer measures for assessing the effects of mixture gradation and recommend methodology for the adjustment of regional aggregate gradation standards, thereby enhancing performance and optimizing resource utilization in FAA specified P-401 mixtures.

Chapter 2

Literature Review

2.1 Importance of Gradation

In the asphalt pavement performance aggregate gradation plays a vital role. Gradation of the aggregate affects the workability of the mix and several key performance properties like durability, stability, resistance to moisture susceptibility, resistance to rutting and cracking. While designing and optimizing airfield pavement mix designs it is mandatory to consider the effects of gradation on performance related parameters.

2.1.1 Workability

Workability is an important characteristic of P-401 airfield pavement mixtures designed to withstand the high demands of aircraft traffic. Gradation significantly impacts the workability of asphalt mixture. A well-graded gradation ensures that the mixture can be easily placed and compacted, which is critical for achieving the desired density and smoothness of the pavement surface [8]. Fine-graded mixes typically offer better workability due to their higher asphalt binder content, which acts as a lubricant during compaction. This is particularly important in P-401 mixes, where achieving the required density is essential for performance [9].

2.1.2 Durability

A certain amount of asphalt pavement performance loss under the load and environmental stress through time refers to the durability of asphalt pavement. Aggregate gradation affects aggregate interlocking, air voids and VMA of the mix which leads to changes in the durability of the mix. Raveling generates foreign object debris (FOD), which could lead to damaging jet engines and threaten aircraft safety. A dense graded mix ensures a low permeable asphalt surface which leads to lower water and air movement resulting in lower damage due to raveling, stripping, aging of the asphalt binder, and loss of the surface over time [10].

2.1.3 Stability

Aggregate gradation has a very significant effect on stability in the form of an aggregate skeleton that will transmit the load and evenly distribute the load while maintaining the initial shape and configuration of the pavement surface. Coarse graded mixes typically have better load distribution which leads to rutting resistance. However, it can lead to reduced cohesion and increased segregation when gradation is too coarse. Fine-graded mixes offer a better surface finish and compaction compared to coarse-graded mixes. Nevertheless, they may deform more than coarse-graded mixes if not properly designed [11].

2.1.4 Resistance to Distress

Various modes of asphalt pavement distress including raveling, rutting, cracking, and moisture damage are influenced by aggregate gradation:

- **Raveling**: Loss of aggregate particles from the pavement surface is referred to as raveling. Raveling is caused by a number of factors including, but not limited to, poor compaction upon construction, poor quality of materials used in construction, oxidation of the asphalt binder and environmental elements, such as water and thermal cycling. Raveling can result in FOD, rough surface texture, and reduced skid resistance particularly in areas with aircraft operations. Addressing raveling is important to protect jet engines from FOD, and thus for passenger safety and engine longevity. Stripping of asphalt mixture can contribute to generation of FOD as well.

- **Rutting**: As a result of repeated traffic loading permanent deformation occurs. It is referred to as rutting of pavements. Optimal gradation provides a stable aggregate framework that resists shear deformation. The coarse aggregate framework is essential to resisting rutting; it promotes stone-to-stone contact to enhance load transfer [11].
- **Cracking**: Thermal distresses, fatigue, or reflection from underlying lifts can cause cracking. Fine-graded mixtures tend to resist thermal cracking since they have a tighter surface texture and have higher binder content compared to coarse graded. [12].
- **Moisture Damage**: Stripping occurs when water penetrates the asphalt pavement surfaces leading to breaking the bonds between the asphalt binder and aggregates. Altering gradation could lead to lower air voids and less water intrusion, allowing the pavement to be less susceptible to moisture damage. Additionally, using aggregates with angularity can lead to a rougher surface which leads to decreasing stripping [13].

2.1.5 Optimizing Gradation for Performance

The best gradation of aggregate for asphalt mixtures achieves particle packing that is the densest, creates the most interparticle contacts, and minimizes voids in the mineral aggregate, which provides a more stable and durable mixture as long as volumetric and performance test requirements are met. The Superpave mix design method originally used control points to help choose gradation to assure an appropriate ratio of coarse and fine aggregates, and to help assure the pavements meet the performance criteria of the specifications [13].

2.2 Historical Context and Evolution

The FAA developed the P-401 gradation specification which has a basic guideline for a durable and stable asphalt airfield pavement construction withstanding the demand of aircraft loads. Throughout the years, it has evolved to take advantage of new material technologies and best practices in pavement engineering. There have been major changes to specifications, such as those occurring in Advisory Circular 150/5370-10H [14], where specifications were synchronized with the Department of Defense's Unified Facilities Guide Specifications, thus eliminating inconsistencies between civilian and military airfield specifications [14]. These developments, including an emphasis on narrow gradation specification limits, are to deliver the best densification of the aggregate, thereby improving the pavement durability, surface smoothness, and resistance to deformation and cracking.

2.2.1 Development of P-401 Specifications

The P-401 specification has always been an important element in airfield pavement construction, and guidelines for the design and construction of hot-mix asphalt (HMA) pavements. The FAA developed these specifications based on the aircraft traffic subject to heavy loads and high tire pressures internationally not typically seen for highway pavements.

The first P-401 specification was primarily concerned with ensuring sufficient durability and stability using material and construction requirements. The initial intent of the P-401 specification also addressed a less than typical circumstance for pavements, in that airfields are subjected to rutting, cracking, and moisture damage results from the stress induced by aircraft traffic and loadings. As such, the specification provided material component gradation sizes, binder contents, and compaction [15]. The rationale behind the gradation specification limits currently outlined in the P-401 specifications is to achieve a balance that ensures both gradation and pavement structural integrity while maintaining an appropriate surface texture and durability for aircraft operations and traffic. The gradation specification limits were established to enhance the interlock of aggregates, reduce voids, and provide a dense mix to resist deformation and cracking.

2.2.2 Revisions and Updates

Throughout the years, changes to the P-401 specification have included advancements in material science, and the refinement of best practices in pavement engineering. The most significant revisions to the specification have focused primarily on improving the gradation specification limits for material performance and improving the specification to articulate adaptability to different environments and operational conditions.

Changes recently introduced in Advisory Circular 150/5370-10H [14], which included changes to the gradation specification limits with tighter gradation specification limits making it easier to compare to the UFGS, were intended to be used in revised specifications as aggregate blends began to move toward finer blends. These changes are intended to result in aggregates that were more intentionally packed to increase durability and surface smoothness. The updated specification will align with the current state of knowledge and practice and will be useful in meeting challenges associated with airfield pavement construction [14].

Through their efforts to align the FAA specifications with UFGS, the FAA was able to create specifications that represented the best knowledge of the behavior of the materials and the performance of the pavements. Along with the latest knowledge and practices, aligning the UFGS with FAA specifications allows the FAA, as well as the DoD, to share resources and knowledge and ultimately create effective airfield pavement design and construction methods that apply uniformly across all agencies.

2.3 Current Gradation Specification Requirements

Airfield pavements must meet gradation specification requirements under the P-401 specification for optimal performance and properties [1]. Aggregate materials that are used in P-401 mix designs consist of crushed aggregate (stone, gravel, and/or slag) fine aggregate (screenings and or natural sand), and mineral filler as required. The aggregates materials must meet particle angularity, shape, toughness, soundness, and cleanliness specifications. While natural (uncrushed) sand can be used to achieve the required gradation or improve the workability of a mixture, it is limited to a maximum of 15% by weight of the total aggregate due to concerns of rutting under heavy aircraft loads. After aggregates that meet the physical property requirements are selected, they are blended into the gradation specification limits outlined in the P-401 specifications. These gradation specifications include three types, 1 through 3, which are coarse, medium, and fine. Table 2.1 shows the gradation type details. Gradation 1 is the coarser mix among three and used for base layers. Gradation 2 is a medium gradation used for intermediate layer construction, and it embodies a balance of stability and surface texture. Gradation 3 is the finest of the three and will be used in the surface layer with emphasis on smoothness and fine texture.

The specification for all three gradations requires 3.0-6.0% passing the No. 200 sieve (0.075 mm) [14].

Table 2.1: P-401 Mixture Aggregate Gradation Specifications

Sieve Size	Percentage by Weight Passing Sieves		
	Gradation 1	Gradation 2	Gradation 3
1 inch	100	--	--
3/4 inch	90-100	100	--
1/2 inch	68-88	90-100	100
3/8 inch	60-82	72-88	90-100
No. 4	45-67	53-73	58-78
No. 8	32-54	38-60	40-60
No. 16	22-44	26-48	28-48
No. 30	15-35	18-38	18-38
No. 50	9-25	11-27	11-27
No. 100	6-18	6-18	6-18
No. 200	3-6	3-6	3-6

2.4 Comparison of P-401 and Superpave Gradation Specification Requirements

The Superpave mix design system is more flexible in terms of aggregate gradation compared to the FAA's specifications in P-401. However, there are many similarities between highway and airfield pavement gradation. In the Superpave mix design method, aggregate gradation is controlled by control points for only four sieves [17]. The objectives of the Superpave mix design method are to maximize the performance parameters for asphalt mixtures across a range of environmental and loading conditions. In terms of flexibility Superpave's use of control points creates a broader range of possible gradation design combinations and gives mix designers more flexibility to design specific mixes with unique parameters. The FAA keeps strict narrow gradation specification limits in the P-401 specification to ensure a reliable and uniform mix for use in airfield conditions. In the context of performance expectations both Superpave and the FAA P-401 specifications try to enhance the performance of flexible pavements; however, P-401 mixes rely on volumetric properties and performance tests such as resistance to rutting and moisture damage. This system accounts for variations in material properties and exploits regional environmental conditions.

The FAA specifications prioritize developing a durable and stable surface tailored to the unique loading conditions of airfield pavements. These specifications emphasize resisting the generation of FOD and withstanding the heavy loads and tire pressures of aircraft, while not focusing on the need for resistance to light residential passenger vehicles. [16]. In addition, the minimum VMA requirements for the P-401 specifications are 1.0 percent higher than those in the Superpave specifications and the design air voids requirement is 3.5 percent compared to the Superpave requirement of 4.0 percent. While the differences are useful to ensure that the P-401 mixtures will provide a higher design binder content and potentially additional durability, they make it very difficult to design mixtures, especially with some aggregate materials due to the restrictive gradation specification limits. Both the Superpave and FAA P-401 gradations aim to optimize the performance of the pavement in terms of durability, service life and stability of asphalt pavement. However, the FAA P-401 specification has well defined narrow gradation specification limits, while Superpave offers a wide range of gradation choice flexibility.

2.5 Regional and Environmental Considerations

Aggregates are highly affected by regional variations in sources and types; therefore, aggregate specifications in asphalt mix design and performance are variable. The geological variability between regions provides a wide range of aggregate characteristics, such as size, shape, texture, mineral characteristics, etc. Consequently, gradation specification limits can be optimized across a range of gradations to allow for acceptable pavement performance based on the local availability of materials.

In certain areas, aggregates may be primarily obtained from limestone, granite or basalt, or some combination of these aggregates, and thus have unique characteristics that affect the performance of the mix. For example, limestone aggregates are often softer, and tend to polish under traffic, which reduces skid resistance. In contrast, granite aggregates are typically harder and better able to resist wear [18]. Additionally, aggregate angularity and particle shape are important to the stability and compaction of asphalt mixtures [19].

Due to these differences, flexible gradation specification limits are necessary to accommodate local materials while still achieving satisfactory performance. With local accommodations of gradation specification requirements, mix designers can adapt in a way that decreases weaknesses and maximizes the strengths of local aggregates. This flexibility can also result in cost savings via less imported materials to achieve similar specifications [20].

Climate influences the selection of appropriate mix of design and materials. For example, cold regions with large temperature swings require mixes with better thermal cracking resistance, whereas locations with high levels of rain require mixes with better performance properties for moisture susceptibility. Mix selection and binder source must take the environmental loading factors into consideration to make the pavement more durable and last longer [15].

2.6 Challenges and Opportunities in Current Gradation Practices

The current FAA P-401 gradation specification requirements have several challenges associated with aggregate availability and cost-effectiveness. Suitable aggregate availability, which meets the P-401 gradation specification requirements, is one of the major challenges faced by contractors. Natural aggregate does not meet the FAA specified requirements in some regions of the country, therefore aggregate processing or aggregate blending with different sources is needed, which increases cost and can lead to supply chain challenges [21,22].

2.6.1 Opportunities for Improvement

There are challenges with the current P-401 gradation specification requirements. However, there are several ways to improve the gradation specification requirements focusing on pavement performance and sustainability. Altering the current P-401 gradation specification requirements to a performance-based specification leads to flexibility in material choice. There are many considerations that need to be understood in conjunction with one another. They include the interactions between the properties of the aggregates used, the binder that is selected, and the conditions under which the material and/or pavement will have to perform. Engineers interested in mixing materials can begin focusing on achieving performance objectives with respect to moisture damage, rutting resistance and cracking resistance rather than being constrained to gradation specification limits. This flexibility could provide more innovative, cost-effective, and sustainable practices for airfield pavements [25].

Chapter 3

Experiment Plan

3.1 Design of Experiment

The experimental plan is structured into six key tasks as presented in Figure 3.1, each contributing to the overall aim of evaluating and potentially modifying the P-401 asphalt mixture specifications. Task 1 is to conduct a survey of airport mix designers and practitioners to discuss their challenges with designing P-401 asphalt mixtures and gather existing P-401 mix designs and aggregate information to develop a database for further evaluation in the project. In Task 2, the collected data was analyzed to determine sieve sizes and associated allowable ranges that limit the use of local aggregate materials in different regions of the country.

Aggregates from the various Long-Term Pavement Performance (LTPP) climate regions were incorporated into the research. In this research, six P-401 mixtures used for constructing airfield pavements in the LTPP climate zones were selected, and raw materials were obtained from these mixture producers. This encompassed a total of 24 P-401 mixtures, representing one from each of the four LTPP climate regions. For each of the six P-401 mixture designs, new asphalt mixtures were developed by altering the gradation to fall outside the current P-401 gradation limits, as long as the volumetric properties were acceptable. The Bailey Method [11] guided these modifications. Both the original and newly designed P-401 mixtures were subjected to testing for rutting, cracking (including top-down and low-temperature), moisture damage, raveling, and permeability. The objective was to evaluate whether the performance characteristics statistically showed no significant difference from the established P-401 criteria.

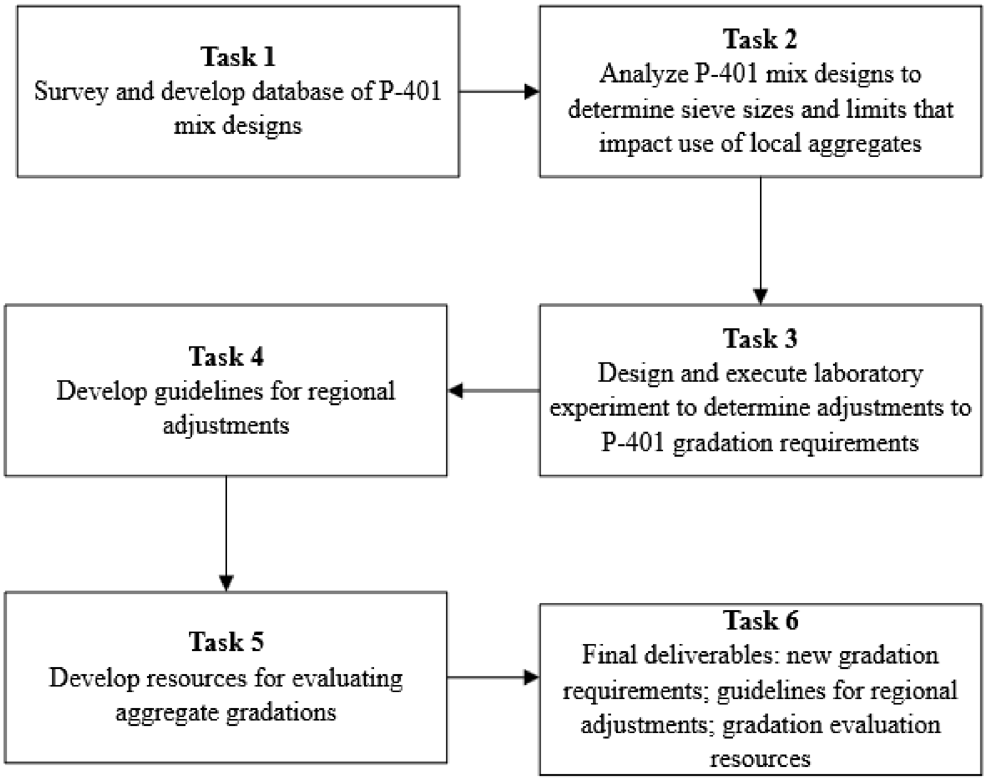

Figure 3.1: Illustration of Design of Experiment

If the gradation adjustments vary between the LTPP climatic zones, the fourth task will be to evaluate and develop guidelines for development of appropriate adjustments to aggregate requirements for that region. These adjustments may be patterned by gradation design so that the recommendations are relevant to the regional issue.

The fifth task will use mix design information and laboratory test data to determine the influence of aggregate gradation parameters on volumetric and performance properties of the mixtures.

Finally, the sixth task involves compiling and submitting project deliverables. This will include documentation of the research findings, proposed specification adjustments, and any recommended guidelines for implementation. The detailed execution of these tasks will address the research objectives and potentially lead to improved P-401 specifications that accommodate a broader range of aggregate materials while ensuring performance and durability.

3.2 Laboratory Evaluation Approach

The laboratory evaluation approach, as illustrated in Figure 3.2, uses the existing P-401 mix design as a control to design a new mix with a gradation that deviates outside the standard P-401 gradation specification limits while still meeting specified volumetric requirements. Performance testing will be conducted on both mix designs, ensuring they have similar volumetric properties that adhere to P-401 requirements. If the new mix design delivers equivalent or superior performance test results compared to the existing P-401 mix design, or if it meets the established performance test criteria (such as the rutting and moisture susceptibility criteria defined in the P-401 specifications), the gradation of the new mix design will be considered a feasible option for adjusting gradation limits without negatively impacting mixture performance.

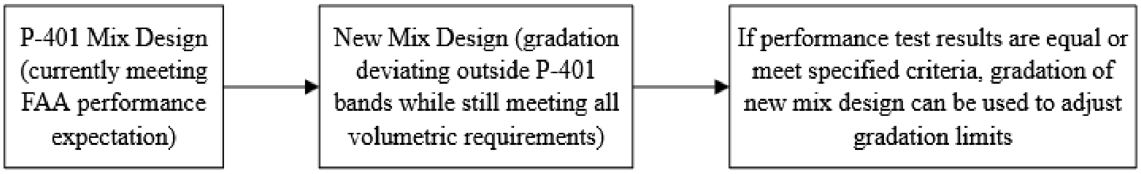

Figure 3.2: Illustration of laboratory evaluation approach

The selection of existing P-401 mix designs for laboratory testing was guided by several conditions. Initially Gradations that were close to or at the gradation limits on certain sieve sizes and can deviate outside the gradation specification limits while still meeting P-401 volumetric requirements, were prioritized. The selection of existing P-401 mixes was evaluated based on the Bailey Method. Secondly, the materials should represent a variety of aggregate types used across the four LTPP climatic zones, covering mix designs with varying aggregate sizes and gradations (Gradations 1, 2, and 3), and designed for different airport loading conditions and incorporating different asphalt binder grades.

The P-401 specifications currently require 75 blows or gyrations for airports serving aircraft over 60,000 lbs, and 50 blows or gyrations for airports serving lighter aircraft. The selection of mix designs was prioritized to those requiring 75 blows or gyrations. Higher compactive effort typically poses more challenges with meeting the mix design requirements, assuming other factors remain constant. Additionally, the availability of mixture production data was also considered. The project selected six P-401 mix designs, incorporating various aggregate sources and mixture types, for they were representative of the four LTPP climatic zones. The National Center for Asphalt Technology (NCAT) conducted testing on materials from the wet, no-freeze, and dry, no-freeze LTPP climatic zones. The Western Regional Superpave Center lab at UNR tested materials from the dry, freeze zone and part of the wet, freeze LTPP climatic zone, and the Heritage Research Group tested materials from the remaining part of the wet, freeze LTPP climatic zone.

3.3 Materials and Methods

Each mix design had different NMAS and different grades of binder according to the high pavement temperature of the region. Aggregate property tests, gradation type selections, mixture volumetric testing and the conducted performance tests for each mix design are shown in Figure 3.4.

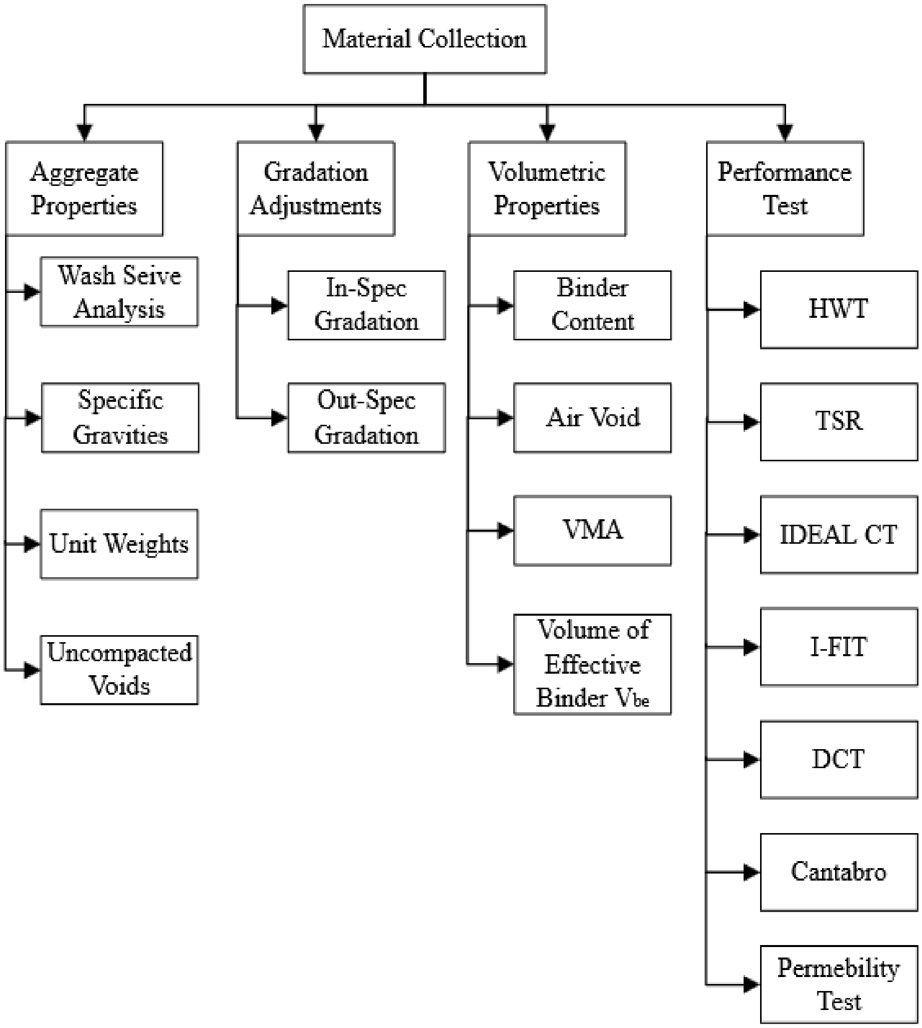

Figure 3.3: Performed Tests

Required materials and mixture designs were collected from Granite Construction Company in Tucson Arizona for the Tucson International Airport (TUS), Granite Construction Company in Reno Nevada for the Reno Tahoe International Airport (RNO) and Lakeside Industries in Issaquah Washington for the Skagit Regional Airport (KBVS).

3.4 Aggregate Testing and Evaluation

Asphalt mixture blend aggregate gradations and changes in gradations were developed, evaluated and adjusted using the Baily Method throughout the research [11]. The Bailey Method is a tool used by asphalt technologists to develop and adjust gradations to achieve desired volumetric properties and optimize mixture cost, volumetrics and performance properties. In order to perform the Baily Method analysis aggregate gradation, specific gravity and unit weight, as well as other inputs are needed. The Bailey Method was also used to develop In Spec and Out Spec gradations that resulted in asphalt mixtures with similar effective asphalt contents [11]. This made it possible to compare performance test results of In Spec and Out Spec mixtures without bias due to different asphalt contents. In other words, to be able to isolate the difference in performance test results due to changes in gradation.

3.4.1 Washed Sieve Analysis

The gradations of the stockpile aggregates were tested using washed sieve analysis in compliance with ASTM C117 and ASTM C136 standards [26,27]. Two samples from each stockpile were prepared following ASTM C117 [26], and the washing process was conducted for seven minutes using a mechanical washer. Afterwards, the samples were dried overnight at a temperature of 235°F, after which their weights were measured to carry out the sieve analysis as per ASTM C136 [27] standards.

3.4.2 Specific Gravity

Specific gravity is an indicator of the density of the aggregate which is crucial factor in the asphalt performance. The specific gravity of each stockpile aggregate was tested in accordance with ASTM standards. ASTM C127 [28] was followed to obtain the specific gravity of the coarse aggregate following a 16 -19 hours of saturation period and ASTM C128 [29] was followed to obtain the specific gravity of the fine aggregate following a 16 -19 hours of saturation period at least 6% water absorption by weight of fine aggregate.

3.4.3 Fine Aggregate Angularity (FAA)

The angularity of fine aggregate was obtained for each mix design blend in accordance with the ASTM C1252 [31]. FAA is an indication of the aggregate angularity, surface texture and grading. The FAA P-401 specification requires that Method A of the standard be used.

3.4.4 Unit Weights

Both loose and rodded unit weight were run on each stockpile in accordance with ASTM C29/C29M [30]. For coarse aggregate, a 1/2 ft^3 metal unit weight bucket was used. For fine aggregate, a 1/30ft^3 metal unit weight bucket was used.

3.5 Gradation Adjustment

The mix designs from contractors were initially adopted for the In Spec mix design. However, those jobs mix formulas (JMF) had different gradations and volumetrics due to several factors like sampling timing from the quarry between the airport pavement project construction to the laboratory testing at UNR and variability associated with the testing methods. Therefore, In Spec 1 mix design gradation was adjusted as closely as possible to JMF blend consistently with the FAA specification using the Baily Method. Then these gradations were modified using the Baily Method to fall outside the specification limits (Out Spec 2) to develop new mix designs with volumetric properties like those of the In Spec 1 mixtures. Except the RNO mix all other mixes have In Spec 2 and Out Spec 2 mix designs (in excess to In Spec 1 and Out Spec 1). This process ensured that the changes in performance properties would not depend on the differences in volumetrics and binder contents.

3.6 Superpave Mix Design

The Superpave mix design process was conducted according to the FAA specification [1]. Aggregates were batched according to the JMF gradation and then mixed with binder at the recommended temperature for each mixture. Table 3.1 summarizes mixture identifications, which are the airport codes for them, the LTPP climatic region, state, asphalt binder grades used for each mix and temperature used for mixing and compaction. Mixed samples were then compacted with a Superpave Gyratory Compactor (SGC) at the recommended temperatures for each mix in 150mm diameter molds. The resulting compacted samples achieved heights ranging from 115 ± 5 mm.

Table 3.1: Mixture IDs, Binder Grades and Temperatures

Mix ID	LTPP Climatic Region	State	Binder Grade	Mixing Temperature	Compaction Temperature
TUS	Dry No Freeze	Arizona	PG76-22PM	337°F – 354 °F	289°F – 301 °F
RNO	Dry Freeze	Reno	PG76-28M	321°F – 328 °F	308°F – 314 °F
KBVS	Dry Freeze	Washington	PG70-22	320°F – 335 °F	305°F – 320 °F

Figure 3.5 illustrates the volumetric adjustment procedure followed in summary. When designing the Out Spec 1 mixture, the targeted VMA difference of ±0.5% compared to In Spec 1 was maintained. Since both mixtures were designed with the same asphalt cement

(AC), the corresponding V_{be} difference between In Spec 1 and Out Spec 1 was also ±0.5%. For Out Spec 2, the allowable VMA difference of ±1 to 2% relative to Out Spec 1 was used, again using the same binder content. Similarly, In Spec 2 was designed with a VMA difference of ± 1 to 2% compared to In Spec 1, with the same binder content as well. The V_{be} difference of ± 0.2% was used between either the In Spec mixtures or the Out Spec mixtures. According to the mixture job mix formulas mineral fillers were used in addition to the stockpile aggregates. The TUS mixture included Type 2 Portland cement and the RNO mixture included lime per the mix designs. All the gradations reported in Chapter 4 included mineral fillers.

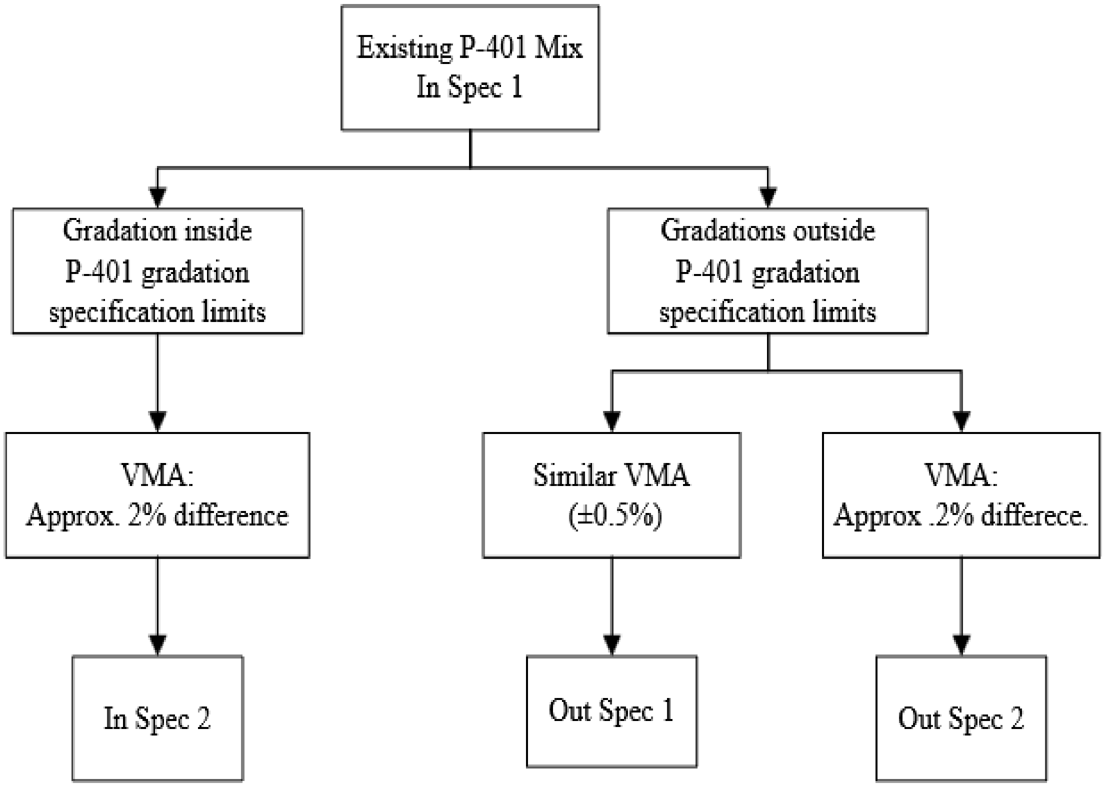

Figure 3.4: Mix Design Gradation Development Summary

3.7 Performance Tests

Performance test specimens were prepared using a Superpave gyratory compactor based on the In Spec and Out Spec designs and assessed to evaluate the impact of gradation changes on mixture resistance to rutting, top-down cracking, low-temperature cracking, moisture damage, raveling, and permeability. These performance properties were evaluated based on the test methods summarized in Table 3.3.

Table 3.2: Asphalt Performance Test Details

Mixture Performance	Test	Aging Condition	Air Void (%)	Specimen Thickness (mm)	Test Standard
Rutting	[1]Hamburg Wheel Tack Test (HWTT)	2 hours at compaction temperature	7.0 ± 0.5	62 ± 1	AASHTO T 324 [5]
	Ideal Rapid Shear Rutting Test (IDEAL-RT)		7.0 ± 0.5	62 ± 1	ASTM D8360 [43]
Moisture Susceptibility	Tensile Strength Ratio (TSR)		7.0 ± 0.5	95 ± 5	ASTM D 4867 [4]
Top-down Cracking	Illinois Flexible Index Test (I-FIT)		5.0 ± 0.5	50 ± 1	AASHTO T 393 [36]
	Indirect Tensile Asphalt Cracking Test (IDEAL-CT)		5.0 ± 0.5	62 ± 1	ASTM D 8225 [35]
Low-Temperature Cracking	Disc Shaped Compact Tension Test (DCT)		5.0 ± 0.5	50 ± 1	ASTM D7313 [39]
Durability	Cantabro Test		7.0 ± 0.5	115 ± 5	AASHTO T401 [38]
Permeability	Florida Permeability Test		7.0 ± 0.5	62.5 ± 2.5	FM 5-565 [40]
[1] The rutting test used was the test that was required for the original mix design, which could have been the HWTT or asphalt pavement analyzer (APA). All the mixture tested by UNR were designed with HWTT requirements.					

Even though they are not mentioned in the RFP (Request for Proposal), permeability and raveling tests were added to the experimental plan. Permeability affects the infiltration of air and water into an asphalt pavement, which can lead to durability issues, including raveling which generates FOD that is a primary safety concern with airport asphalt pavements.

All mixture performance testing was conducted in accordance with the FAA P-401 specification, which included specimen fabrication and aging. There was also some additional rutting performance testing performed. Specifically, IDEAL-RT for the KBVS In Spec 1 mix.

The HWTT was used for the rutting evaluation, TSR was conducted for moisture susceptibility evaluation, I-FIT and IDEAL-CT were conducted to evaluate top-down fatigue cracking, and DCT was performed to evaluate thermal cracking. These tests were included as they are the three most popular cracking tests that have been implemented or are being considered for BMD implementation among many agencies. They correlate well with cracking data collected on highway asphalt pavements. Specifically, the IDEAL-CT and I-FIT have shown a strong correlation to top-down cracking data based on the Cracking Group (CG) experiment on the NCAT Test Track [33], and the DCT had the best correlation to the thermal cracking data from the CG experiment at the Minnesota Road Research Facility (MnROAD) [34]. The Cantabro test was conducted to assess the overall durability of the P-401 asphalt mixtures. In the past, this test was used to evaluate raveling resistance of open-graded friction courses, but several recent studies have shown that it can be used to discriminate range of dense-graded asphalt mixture durability as well [44]. The Florida

Permeability Test was conducted to assess the permeability of P-401 asphalt mixtures with the In Spec gradation versus Out Spec gradation.

3.7.1 Hamburg Wheel Track Test (HWTT)

The Hamburg Wheel Track Test was performed in accordance with AASHTO T 324 [5] to evaluate the rutting and moisture susceptibility of compacted mixtures. The objective of the test is to simulate the conditions that an asphalt pavement would experience in the field to predict its performance in terms of resistance to rutting and moisture-induced damage. The test assesses the potential of an asphalt mixture to undergo permanent deformation under repeated loading as illustrated in Figure 3.6. This is critical because rutting is a common form of distress in asphalt pavements, especially in high-temperature environments under heavy traffic loads.

Figure 3.5: HWTT test specimen in Water

The test also evaluates asphalt mixture susceptibility to moisture damage, which can lead to stripping. Stripping is the loss of bond between the asphalt binder and the aggregates due to the presence of water, which can significantly reduce the pavement's durability and lifespan.

Superpave gyratory compacted cylindrical samples (150 mm diameter and 62 mm height) with air voids of 7 ± 0.5 percent were tested in a water bath at elevated temperature of 50ºC. This simulates the high temperatures that pavements experience during hot weather conditions, which can accelerate rutting. The test applies a repeated rolling load using a steel wheel, simulating the effect of traffic loads on the pavement. The load and speed simulate the stresses that pavements endure under actual traffic conditions.

Four samples are prepared to perform the test as two compacted samples are required to make a single HWTT test specimen, and the test method requires that two test specimens be performed to obtain a single reported test result. The specimens were subjected to 45 minutes of conditioning in the HWTT under water at 50 ºC prior to testing. During the test, rut depth is measured at eleven points along wheel path travel distance. The test terminates, upon reaching either 20000-wheel passes or a maximum rut depth of 10 mm (average points between points 4 and 8) per FAA P-401 requirements.

3.7.2 Indirect Tensile Asphalt Cracking Test (IDEAL-CT)

The Indirect Tensile Asphalt Cracking Test was performed in accordance with ASTM D8225 [35] to evaluate the cracking resistance of asphalt mixtures under intermediate temperature conditions. This test is designed to be simple, quick, and cost-effective, making it suitable for routine use in both laboratory settings and field quality control processes. It aims to assess the potential of asphalt mixtures to resist intermediate-temperature fatigue cracking, which is a critical factor affecting the longevity of asphalt pavements.

The test is conducted on cylindrical asphalt specimens, typically compacted using a Superpave gyratory compactor. The test applies a monotonic load at a constant rate to induce tensile failure in the specimen. The test is usually conducted at intermediate temperatures, typically around 25 °C (77 °F), which are representative of the conditions where thermal and fatigue cracking are most likely to occur.

The test specimens were Short-Term Oven Aging (STOA) conditioned prior to testing. All asphalt mixtures were conditioned at the compaction temperature for 2 hours. After 2 hours of conditioning all four samples were compacted to 150 mm diameter and 62 mm height at the required air void of 5 ± 0.5 percent.

Compacted specimens were conditioned for 2 hours at 25 ºC (77 °F) prior to the testing. CT-Index is calculated using Equation 3.1 and Figure 3.7 represents the typical Ideal CT graph.

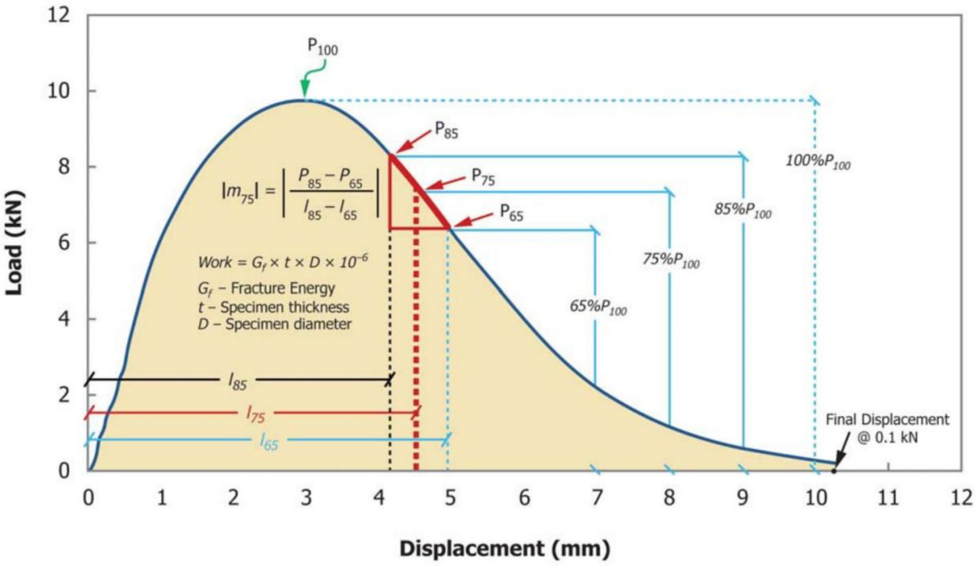

Figure 3.6: Typical Ideal-CT Graph

$$CT_{Index} = \frac{t}{62} \times \frac{G_f}{|m_{75}|} \times \frac{l_{75}}{D} \times 10^6 \qquad \textit{Equation 3.1}$$

t : Specimen thickness, mm

G_f : Fracture energy, J/m^2

$|m_{75}|$: Absolute value of post-peak slope m75, N/m

l_{75} : Displacement at 75% of peak load after the peak, mm

D : Specimen diameter, mm

3.7.3 Illinois Flexible Index Test (I-FIT)

I-FIT was performed according to AASHTO T 393 to assess the top-down cracking performance of asphalt mixture (36). Laboratory mixed samples were compacted to 160 ± 1 mm height and 150 mm diameter using Superpave gyratory compactor. The compacted samples were then cut at their center, and both the top and bottom were trimmed to obtain 2 disk shaped samples with a height of 50 ± 1 mm after the disk sample was cut through their diameter using a saw to obtain 2 semicircular specimens with a target air void of 5.0 ± 0.5 percent. A tile saw was used to make a 15 ± 1.25 mm long by 2.5mm wide notch on the center of the flat side of the semicircular specimen. Figure 3.8 shows an I-FIT sample before testing.

Figure 3.7: I-FIT Sample

I-FIT was performed at 25 °C to represent the intermediate temperature condition. Prior to the testing all 4 test specimens were conditioned in an environmental chamber at 25 °C for 2 hours. A loading piston applied a load of 0.1 ± 0.01 kN (22.48 ± 2.25 lbf) to the semicircular sample during the test in stroke control mode. The loading rate was programmed at a constant rate of 0.05 kN/s (11.24lbf/s). Once the load reached 0.1 kN

(22.48 lbf) the load control switched to displacement control and applied a displacement rate of 50 mm/min.

As a result of the applied displacement, specimens started cracking at the notch in the test specimens and propagated through them, then the applied load started to decrease and once the applied load was below 0.1 kN (22.48 lbf) the test was stopped automatically. The raw data was analyzed using I-FIT analysis tool 2017 V1.1 [37]. Figure 3.9 represents a typical load distribution curve which is used to calculate the Illinois Flexibility Index. The slope in the post-peak region of the load-displacement curve indicates the rate of energy dissipation and provides insight into the material's ductility. A steeper slope in this region typically suggests that the material is more brittle, meaning it loses load-carrying capacity quickly after peak load is reached. Conversely, a shallower slope indicates a more ductile material, as it retains more load-carrying capacity over a greater displacement after the peak load, dissipating energy more gradually.

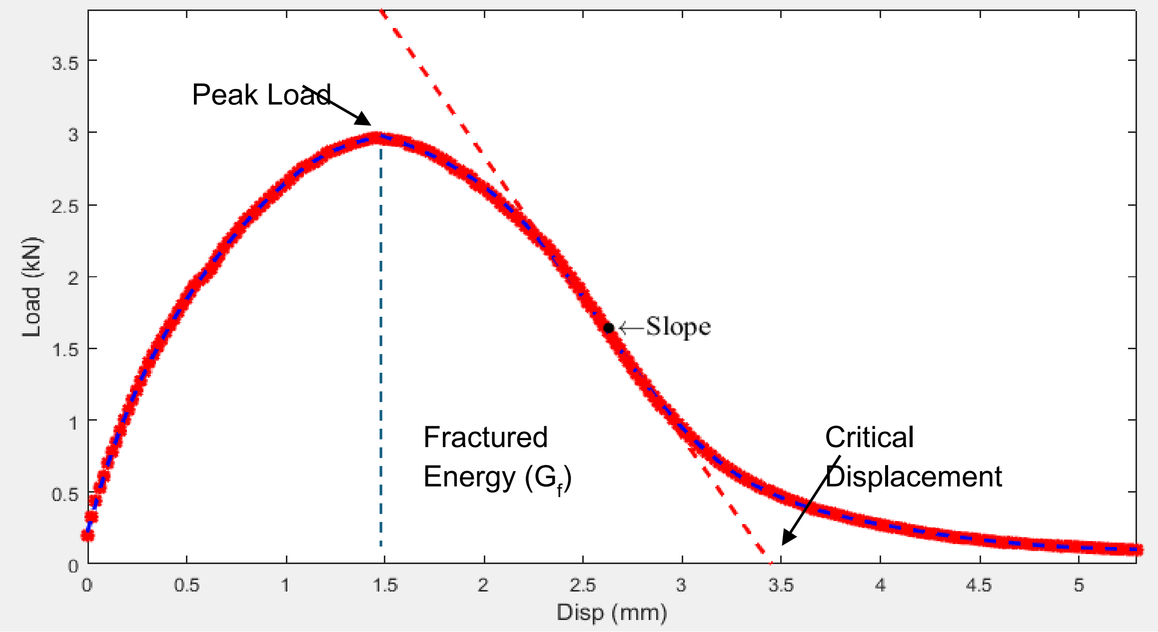

Figure 3.8: Recovered Load (P) vs Load Line Displacement (u) Curve in I-FIT Test

The fracture energy is affected by both the peak load and post peak load. The flexibility index is calculated by dividing the fracture energy by the post-peak slope. According to the Illinois Department of Transportation the minimum threshold value of flexibility index is 8.

3.7.4 Tensile Strength Ratio (TSR)

The TSR test was performed in the laboratory based on ASTM D4867 [4] procedure. The TSR test is designed to evaluate the moisture susceptibility of asphalt mixtures which can lead to stripping. Stripping is the breakdown of the bond between aggregate particles and the asphalt binder coating them due to moisture damage. The TSR test is used to assess the damage in asphalt mixture due to moisture infiltration combined with freeze and thaw conditioning and the results from the TSR test can be used to anticipate the long-term performance of asphalt pavements, particularly in environments where moisture and temperature fluctuations are prevalent. It helps in predicting the pavement's ability to withstand moisture-induced damage over time. This is achieved by comparing the tensile strength of unconditioned and conditioned asphalt specimens.

The TSR test provides a quantifiable measure of the potential for moisture-induced damage in asphalt pavements, which is critical for designing pavements that can withstand the environmental conditions in which they are placed. By understanding how different asphalt mixtures respond to moisture damage, engineers can select materials and design mixes that minimize the risk of stripping and extend a pavement's service life. And, the test results can be incorporated into performance-based specifications, guiding the selection and approval of asphalt mixtures for specific projects based on their moisture resistance.

Laboratory prepared asphalt mixture is conditioned at the compaction temperature for 2 hour ± 10 min. The mixture is then compact in a Superpave gyratory compactor to create specimens that are 95mm in height and have a diameter of 150 mm. The compacted specimens must possess 7.0 ± 0.5 percent air voids.

Six samples are prepared and divided into two subsets (wet set and dry set). The average air voids of the two subsets should be approximately equal. The wet set of samples is conditioned through the freeze thaw cycle procedure. One set of samples is saturated with up to 70 – 80 % water and frozen at -18 ^{0}C in the freezer at least 16 hours, then they are thawed for 24 hours at 60 ^{0}C in a water bath. Following the freeze thaw cycle, the samples conditioned in a 25 ^{0}C water bath for 2 hours. At the same time, the dry set of samples is conditioned for 2 hours at 25 ^{0}C in the oven. After 2 hours of conditioning both wet and dry set samples were tested. The TSR was obtained for each mix by dividing the wet strength by dry strength multiplied by 100. The TSR value must be greater than or equal to 80%.

3.7.5 Cantabro Test

Cantabro test was performed based on AASHTO T 401[38]. It helps to evaluate the resistance of asphalt mixtures to abrasion and raveling, which are critical aspects for maintaining pavement performance and preventing the design of mixtures. Superpave gyratory compacted samples with 115 ± 5 mm height and 150 mm diameter were used for the test. A minimum of three replicates were used for the test with them having an air void of 7.0 ± 0.5 percent.

The prepared specimens were conditioned in an environmental chamber at the test temperature of 25 ± 1 ^{0}C (77 ± 2 ^{0}F) for at least 4 hours. Once each specimen was conditioned, the mass of them was measured prior to placing the specimens inside the Los Angles Abrasion machine drum without a charge of the steel spheres. The drum was rotated at 30 to 33 rotation/min for 300 revolutions. The specimens were then removed from the drum, the surface was lightly cleaned with a cloth to remove small particles which were loose on outside the specimen, and then the mass of the specimens was measured. The percentage abrasion loss was calculated for each specimen based on Equation 3.2.

$$Percentage\ abrasion\ loss = \frac{W_1 - W_2}{W_1} \times 100 \qquad \textbf{\textit{Equation 3.2}}$$

Where,

W_1 = Initial mass of the specimen, g

W_2 = Final mass of the specimen, g

3.7.6 Disc Shaped Compact Tension Test (DCT)

The DCT test was performed in accordance with ASTM D7313 [39]. The test is used to determine the fracture energy of asphalt mixtures. This test helps to assess the resistance of asphalt mixtures to low-temperature or thermal cracking. Superpave gyratory compacted samples with 150 mm diameter and 160 mm height were prepared, and two test specimens were cut from the compacted samples. The target thickness for the specimens was 50 ± 1 mm and a notch is made along the diameter of the specimens that cannot be wider than 1.5 mm. Also, the flat surface at the crack mouth needs to cut 90 ± 5 degrees to the notch and loading holes cannot be greater than 5 mm from the specified locations. This is illustrated in Figure 3.10.

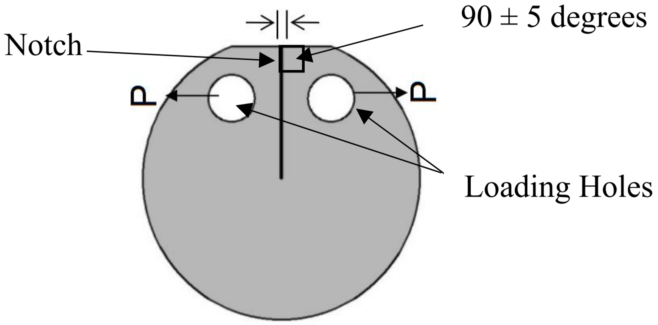

Figure 3.9: DCT Sample with Notch and Hole

The samples prepared were conditioned in a temperature control chamber for a minimum of 2 hours and a maximum of 8 hours at 10 °C warmer than the low PG grade temperature of the binder used in the mixtures. After conditioning, specimens were loaded into the test fixture. The test is performed with a constant crack mouth opening displacement rate of 0.017 mm/s (±5 %). Tests were completed when the post peak load level has reduced to 100N. After the test, the data is analyzed and fractured energy is calculated based on Equation 3.3. The WRSC test specimens were fabricated by the UNR lab shipped to the NCAT lab for testing.

$$G_f = \frac{AREA}{B \times (W-a)} \qquad \textbf{\textit{Equation 3.3}}$$

Where,

G_f = Fracture Energy, J/m^2

AREA = Area under load-CMOD$_{\mathrm{fit}}$ curve

B = Specimen thickness, m

W-a = initial ligament length, m

3.7.7 Florida Permeability Test

Permeability testing was performed in accordance with the Florida DOT Method of Test for Measurement of Water Permeability of Compacted Asphalt Paving Mixtures [40]. The

Florida Permeability test assesses the water conductivity of saturated asphalt mixtures. This test helps to measure how easily water can flow through a compacted asphalt sample, which is crucial for determining the permeability of the asphalt pavement. Permeability is an important factor for durability and performance of the asphalt pavement, because excessive permeability can lead to stripping, raveling or cracking in a pavement structure.

Specimens are compacted with 150 mm diameter and 115 mm height. The ends of compacted samples are trimmed, and the cuts are at least the NMAS of the asphalt mixture. The test allows water from a graduated cylinder to flow through a saturated asphalt sample. During the test the time intervals are recorded to reach known changes in head. The test measures the water flow rate through the specimen and coefficient of permeability is calculated using Equation 3.4. The calculation is based on Darcy's Law. The testing was performed by NCAT.

$$k = \frac{al}{At} ln \; (h_1/h_2) \times t_c \qquad \textbf{\textit{Equation 3.4}}$$

Where:

k = Coefficient of permeability (cm/s)

a =Inside cross-sectional area of the buret (cm^2)

L = Average thickness of the test specimen (cm)

A = Average cross-sectional area of the test specimen (cm^2)

t = Elapsed time between h_1 and h_2 (s)

h_1 = Initial head across the test specimen (cm)

h_2 = Final head across the test specimen (cm)

t_c = Temperature correction for viscosity of water

Chapter 4

Test Results and Analysis

4.1 Aggregate Testing

Prior to doing mixture design verifications and performance testing, each aggregate material used in each of the mixture designs was tested to verify the aggregates received from the contractors had properties similar to those reported in the mix designs. Table 4.1 summarizes the mixture producers that supplied the mix designs and raw materials used by UNR along with their location, the airports the mix designs were originally developed for, the mixture identification and the NMAS of each mixture.

Table 4.1: Material Suppliers, Locations, Mix and NMAS

Suppliers	Locations	Airports	Mix ID	NMAS
Granite Construction Company	Tucson, Arizona	Tucson International Airport	TUS	1”
Granite Construction Company	Reno, Nevada	Reno Tahoe International Airport	RNO	3/4”
Lakeside Industries	Skagit, Washington	Skagit Regional Airport	KBVS	3/4”

Most of the time, materials properties were similar to the mix design, especially gradations. Some specific gravity differences were observed, especially for fine aggregates specific gravities. Gradation, unit weight and specific gravities of each stockpile for each source are presented in Table 4.2 through Table 4.4.

Table 4.2: Aggregate Properties of TUS Material

Stockpile	**3/4"**	**3/8"**	**WCD[1]**	**CD[2]**	**WAS[3]**
Sieve Size	**Percentage Passing (%)**				
1”	100	100	100	100	100
3/4"	87	100	100	100	100
1/2"	30	100	100	100	100
3/8"	10	83	100	100	100
#4	5	10	87	92	99
#8	4	4	49	65	88
#16	4	3	26	46	61
#30	4	3	15	34	35
#50	4	2	7	26	15
#100	4	2	5	22	4
#200	3.3	1.8	2.9	17.1	0.6
Specific Gravities (G_{sb})					
Specific Gravity (Dry)	2.666	2.666	2.601	2.453	2.570
Specific Gravity (SSD)	2.684	2.691	2.642	2.547	2.602
Apparent Specific Gravity	2.716	2.734	2.711	2.707	2.656
Absorption (%)	0.689	0.930	1.563	3.827	1.254
Unit Weights (kg/m^3)					
Loose Unit Weight	1456.0	1498.9	1774.0	1685.9	1632.9
Rodded Unit Weights	1548.8	1561.1	1979.0	1777.5	1661.9

[1] WCD – Washed Crusher Dust
[2] CD- Crusher Dust
[3] WAS – Washed Asphalt Sand

Table 4.3: Aggregate Properties of RNO Material

Stockpile	**3/4"**	**1/2"**	**3/8"**	**CF[1]**	**WCF[2]**
Sieve Size	**Percentage Passing (%)**				
3/4"	100	100	100	100	100
1/2"	35	99	100	100	100
3/8"	4	52	100	100	100
#4	1	2	20	100	100
#8	1	1	2	75	67
#16	1	1	1	50	38
#30	1	1	1	34	21
#50	1	1	1	24	12
#100	1	1	1	18	6
#200	0.8	1.0	1.2	13.6	3.4
Specific Gravities (G_{sb})					
Specific Gravity (Dry)	2.794	2.776	2.747	2.661	2.756
Specific Gravity (SSD)	2.820	2.807	2.789	2.734	2.800
Apparent Specific Gravity	2.869	2.866	2.867	2.873	2.882
Absorption (%)	0.937	1.123	1.518	2.772	1.579
Unit Weights (kg/m^3)					
Loose Unit Weight	1419.9	1405.3	1388.5	1684.5	1685.1
Rodded Unit Weights	1546.1	1525.1	1478.1	1789.8	1825.6

[1] CF –Crusher Fines

[2] WCF- Washed Crusher Fines

Table 4.4: Aggregate Properties of KBVS Materials

Stockpile	**3/4”-3/8”**	**3/8"**	**CF**	**Altered CF**	**B. Sand**
Sieve Size	**Percentage Passing (%)**				
3/4"	100	100	100	100	100
1/2"	85	100	100	100	100
3/8"	40	100	100	100	100
#4	5	20	100	100	100
#8	4	2	75	75	93
#16	3	1	50	42	77
#30	3	1	34	29	59
#50	3	1	24	19	28
#100	3	1	18	16	7
#200	2.2	1.2	13.6	11.0	2.0
Specific Gravities (G_{sb})					
Specific Gravity (Dry)	2.785	2.747	2.661	2.685	2.593
Specific Gravity (SSD)	2.809	2.789	2.734	2.752	2.653
Apparent Specific Gravity	2.855	2.867	2.873	2.879	2.757
Absorption (%)	0.790	1.518	2.772	2.500	2.510
Unit Weights (kg/m^3)					
Loose Unit Weight	1510.2	1388.5	1684.5	1684.5	1599.2
Rodded Unit Weights	1693.3	1478.1	1789.8	1789.8	1716.5
[1]CF – Crusher Fine					

4.2 In Spec and Out Spec Gradations

The In Spec and Out Spec gradations for each mix with the FAA P-401 gradation control points are shown in Figures 4.1, Figure 4.2, and Figure 4.3. Appendix A includes the bin percentages of each material and mineral fillers for all the gradations. Figure 4.1 presents the gradations for the Tucson International Airport (TUS) mixtures. In Spec 1, and Out Spec 1 gradations were adopted from previous research [41]. Both of the In Spec gradations were chosen intentionally to lie on the P-401gradation lower end at lower sieves and upper end of coarser sieve limits. Therefore, it was easy to develop an Out Spec 1 gradation without compromising the volumetrics and performance. In the Out Spec gradation coarser sieves (i.e. 3/4”,1/2” and 3/8”) percent passing were designed to fall out of upper limits and for finer sieves (i.e. No 30, No 50, and No 100) designed to fall out of lower limits which maintained the volumetrics the same as the In Spec 1. In Spec 2 and Out Spec 2 gradations were designed far from the max density line compared to the In Spec 1 and Out Spec 1.

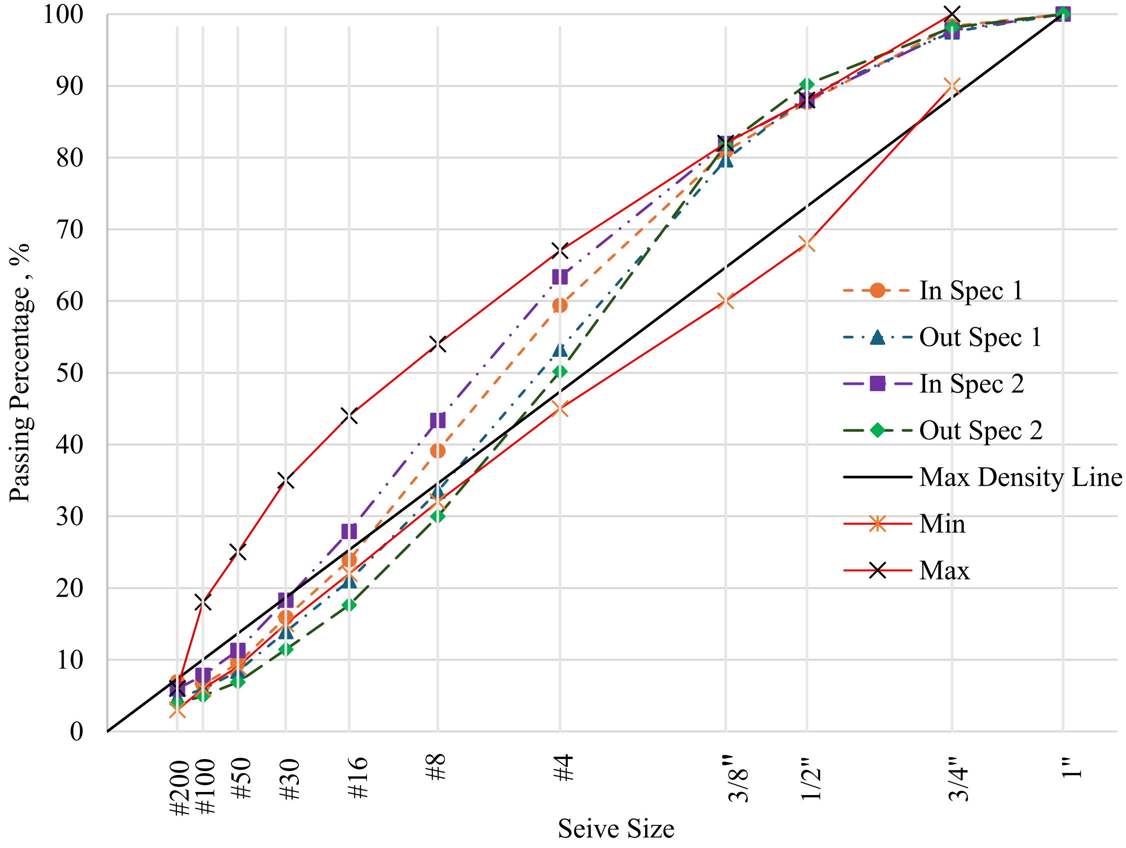

Figure 4.1: In Spec and Out Spec Gradations for TUS Mix

Figure 4.2 represents the gradations for the Reno Tahoe International Airport (RNO) In Spec 1, and Out Spec 1. Like the Tucson International Airport (TUS) gradation, the Reno Tahoe International Airport (RNO) In Spec 1 gradation is also designed to fall on the lower and upper limits of the coarser and finer sieves. The Out Spec 1 gradation was developed to fall below the lower limits of finer sieves (i.e., No 16, No 30, No 50 and No 100).

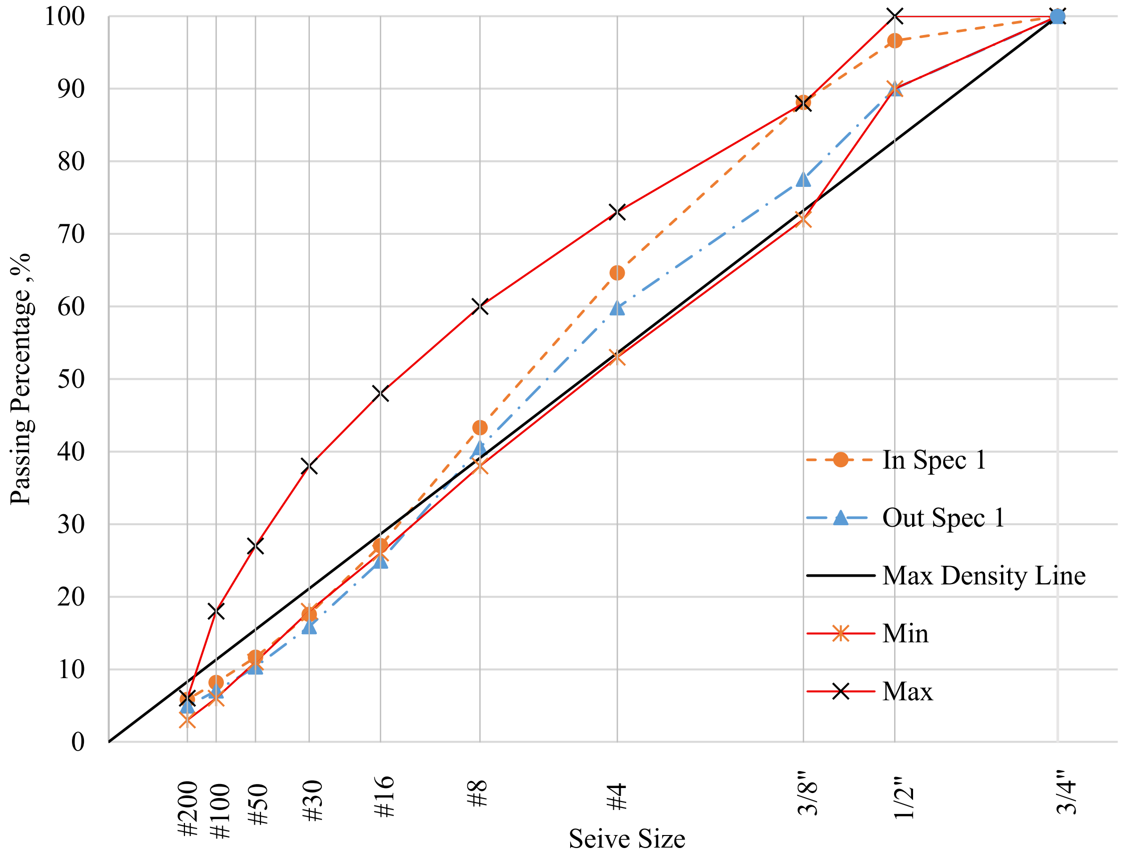

Figure 4.2: In Spec and Out Spec Gradation for RNO Mix

Figure 4.3 represents the gradation for Skagit Regional Airport (KBVS) In Spec 1, Out Spec 1 In Spec 2, and Out Spec 2 gradation designs. The In Spec 1 gradation was designed to be near the maximum density line and In Spec 2 gradation was designed away from the maximum density line. However, both gradations were maintained inside the P-401 specification limits. The Out Spec 1 gradation was developed to fall below the lower limits of finer sieves (i.e., No 16, No 30, and No 50), while the gradation was maintained inside the coarser sieve limits.

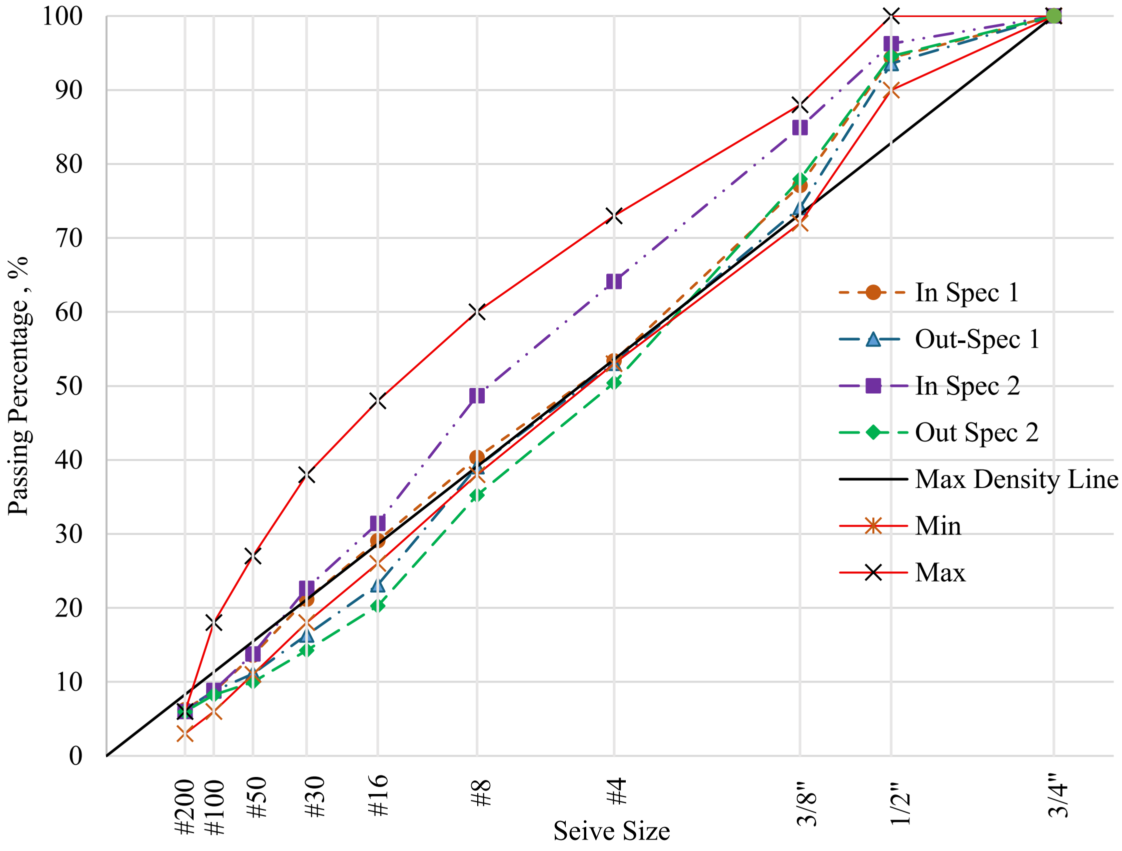

Figure 4.3: In Spec and Out Spec Gradation of KBVS Mix

Because gradations were developed outside P-401 gradation specification limits, ASTM C1252-17 Standard Test Methods for Uncompacted Void Content of Fine Aggregate (as Influenced by Particle Shape, Surface Texture, and Grading) tests were performed on the fine aggregate portion of all mixture gradations used in this research [31]. This test was performed to determine if creating blends outside the P-401 specifications would affect the fine aggregate angularity of the gradations. Table 4.5 shows the fine aggregate angularity values for the mixes. All the gradations met the FAA specification minimum threshold level of 45% except the TUS Out Spec 1 mix gradation. This data illustrates that broadening the current P-401 gradation limits would not significantly affect the fine aggregate angularity [1].

Table 4.5: Uncompacted Air void Content

Mix		Uncompacted Void Content (%)
TUS	In Spec 1	45.3
	Out Spec 1	44.2
	In Spec 2	45.6
	Out Spec 2	45.3
RNO	In Spec 1	47.6
	Out Spec 1	45.8
KBVS	In Spec 1	45.2
	Out Spec 1	47.4
	In Spec 2	46.1
	Out Spec 2	47.9

4.3 Mix Design and Volumetrics

Observed mix design volumetric properties for all mixtures are summarized in Table 4.6. As previously mentioned, all of the In Spec 2 and Out Spec 2 mix designs were intentionally designed not to satisfy the P-401 volumetric air voids and VMA requirements. TUS In Spec 1 and Out Spec 1 were adopted from the previous research [41], TUS In Spec 2 and Out Spec 2 were developed with the same optimum and effective binder contents (i.e., Allowed difference of ± 0.2%) as TUS In Spec 1.

Table 4.6: Mixture Volumetric Properties

Volumetric Properties		NMAS	OBC (%)	Va (%)	VMA (%)	V_{be} (%)
TUS	In Spec 1	1"	5.3	3.5	14.6	11.1
	Out Spec 1		5.3	3.5	14.6	11.1
	In Spec 2		5.3	2.5	13.4	10.9
	Out Spec 2		5.3	5.1	16.1	11.0
RNO	In Spec 1	3/4"	6.2	3.5	15.4	11.9
	Out Spec 1		6.1	3.5	15.4	11.9
KBVS	In Spec 1	3/4"	6.0	3.5	15.3	11.8
	Out Spec 1		6.0	3.6	15.3	11.7
	In Spec 2		6.0	3.4	15.1	11.7
	Out Spec 2		6.0	5.5	17.4	11.9

The RNO In Spec 1 mix design was developed with 6.2% binder content and the Out Spec 1 was developed with 6.1% binder content. However, in both mix designs volume of effective binder content was maintained as 11.9% and VMA was maintained at 15.4%. All four mix designs for Washington mix were developed with the same binder content of 6.0%. However, the volume of effective binder (V_{be}) was allowed differ by ± 0.2% among the mixtures as previously mentioned. The KBVS Out Spec 2 mix had an increase in VMA and air voids. All other volumetric properties including theoretical maximum specific gravities, specific gravities, VFA and dust proportion are summarized in Table B.1 to Table B.8 in Appendix B.

4.4 Performance Test Results and Analysis

All the performance tests were conducted based on the standards described in Chapter 3 with the required minimum number of replicates. A statistical analysis using the t-test assuming equal variances was conducted by NCAT for all the performance test results. The mean performance test results (i.e., Rut depth, CT-Index, Flexibility Index, Coefficient of Permeability, Percentage abrasion loss and Fracture energy) of the In Spec 1 to the Out Spec 1 were used in the t-test. The purpose of these analyses was to determine if a statistically significant mean difference existed between the In Spec 1 and Out Spec 1 mix designs. The null hypothesis (H_0) stated that there is no difference between the population means of the In Spec 1 and Out Spec 1 mix designs, while the alternative hypothesis (H_1) stated that a significant population mean difference existed between In Spec 1 and Out Spec 1 mix designs. The significance level (α) was set at 0.05. As an output of t-test results, if the p-value is less than 0.05 there is no significant difference between the mean performance test results (i.e., Rut depth, CT-Index, Flexibility Index, Coefficient of permeability, Percentage abrasion loss and Fracture energy) of In Spec 1 and Out Spec 1 mix designs.

The t-test revealed no significant mean difference in tensile strength ratio, coefficient of permeability and percentage abrasion loss between In Spec 1 and Out Spec 1 mix designs. Except for the TUS and RNO mix designs all other mix designs were followed with a reduced performance test matrix, which included only the HWTT, IDEAL-CT, I-FIT and DCT tests. The reduced test matrix only focused on cracking and rutting resistance of the mixes.

4.4.1 Hamburg wheel tracking test (HWTT)

Observed HWTT rut depths for all the mixes were less than 10 mm, which satisfies the FAA P-401 requirements. Figure 4.4 shows the rut depths in millimeters after 20,000 passes at 50°C. The stripping inflection point (SIP) was calculated for the individual mixes and reported in Figure 4.4. For TUS mix and RNO mix, when the gradation was moved outside of the specification limits rut depth decreased nearly 1.5 mm and no striping inflection point was identified. Table 4.7 shows p-values, and all the p-values were greater than 0.05, which indicates there is no significant difference between the mean rut depth of In Spec 1 and Out Spec 1. This suggests that broadening the P-401 gradation specification limits while maintaining the volumetric requirements of the mixtures does not affect the rutting performance of the mixture. Rut depth plots for all the mixes tested are presented in Figure C.1 to Figure C.10 in Appendix C.

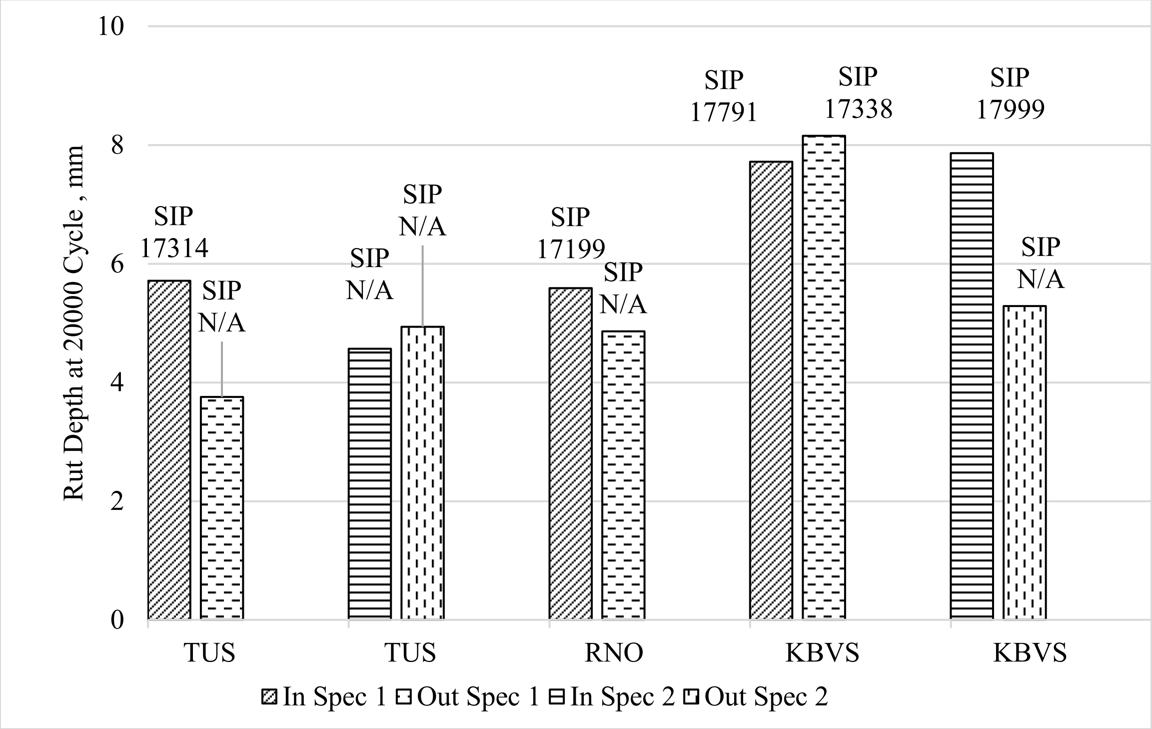

Figure 4.4: Rut depth at 20000 passes and Stripping Inflection Point (SIP) for Different Mixes

Table 4.7: Rut Depth Significance

Mix	p-value	Significance
TUS (Between In Spec 1 and Out Spec 1)	0.15	No
RNO (Between In Spec 1 and Out Spec 1)	0.16	No
KBVS (Between In Spec 1 and Out Spec 1)	0.72	No

4.4.2 Tensile Strength Ratio (TSR)

Figure 4.5 shows Tensile Strength Ratios for the TUS and RNO mixes. Both mixtures satisfy the minimum requirement of 80% indicating they possess good resistance to moisture damage. The standard deviation and coefficient of variation were calculated and are reported in Table C.1 in Appendix C. The single operator within laboratory standard deviation for wet and dry samples were less than 8 psi.

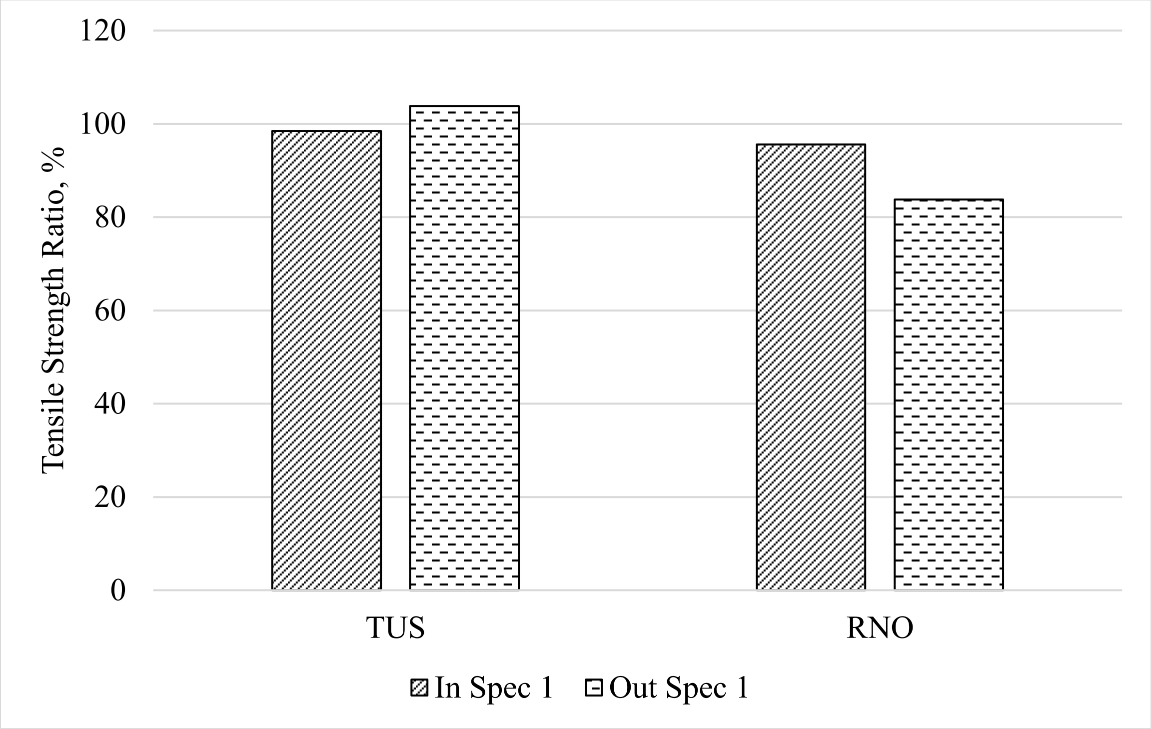

Figure 4.5: Tensile strength Ratio

As mentioned in Chapter 4, 4.4 Performance test between the In Spec 1 and Out Spec 1, there was not significant TSR variation. According to the NCHRP research [45], the Acceptable Range of Two Results for TSR is 0.093. The D2s value between "In Spec 1" and "Out Spec 1" for TUS is 0.070, which is below the acceptable range of 0.093, indicating no significant statistical variation. Conversely, the D2s value for RNO between "In Spec 1" and "Out Spec 1" is 0.120, which exceeds the 0.093 threshold, indicating a statistical variation in TSR. However, it is important to note that the RNO "Out Spec 1" mix still met the TSR criterion with a value of 84%, surpassing the 80% requirement. Therefore, TSR testing was not performed as moving gradations outside the P-401 specification limits did not significantly affect TSR values.

4.4.3 Cantabro Test

Figure 4.6 shows the average percentage abrasion loss of compacted samples after 300 revolutions in the LA abrasion machine. The error bars denote the 95 percent confidence intervals. The difference in confidence intervals between the two mixtures (TUS and RNO) is likely due to gradation NMAS.TUS has a 1-inch NMAS and RNO has a ¾ inch NMAS. The AASHTO T401-22 standard test method does not contain a precision and bias statement. Therefore, the coefficient of variation was calculated and reported in Table C.7 in Appendix C [38]. The Cantabro test results show a trend of reduced percentage abrasion loss as aggregate gradation is moved out the P-401 gradation limits.

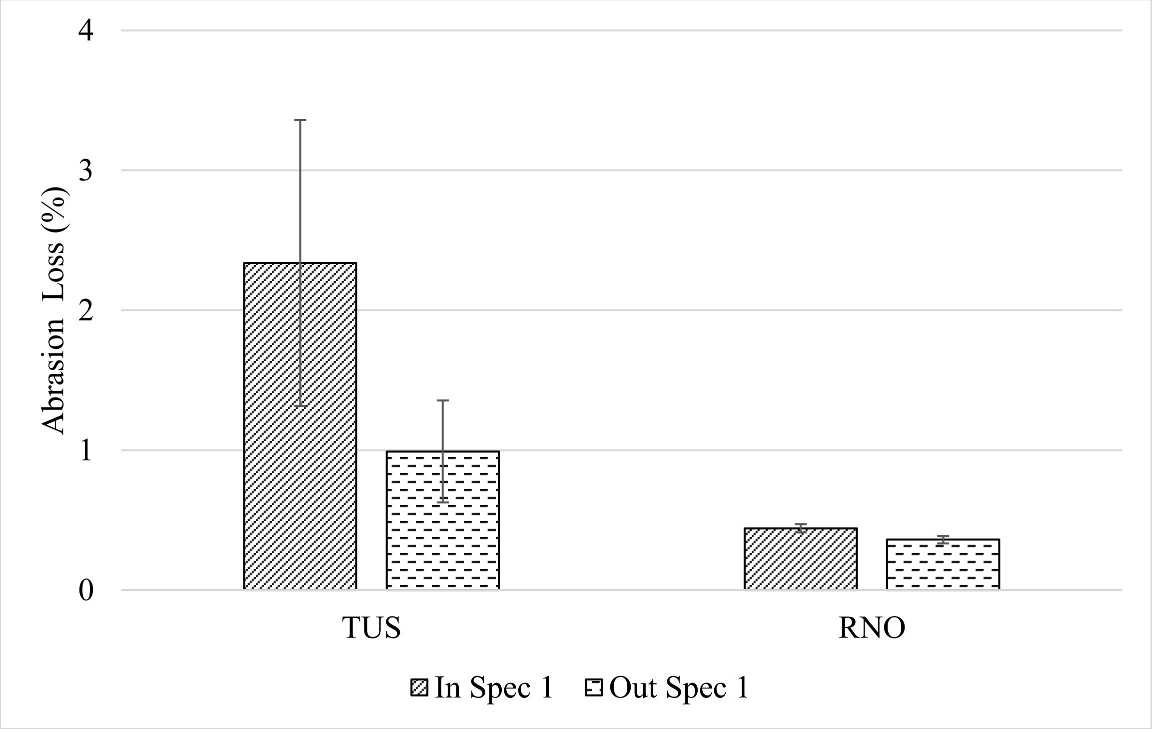

Figure 4.6: Abrasion Loss from Cantabro Test

The p-values are represented in Table 4.8, and the analysis shows no significant difference between the mean percentage abrasion loss of In Spec 1 and Out Spec 1 for all the mixes. Therefore, the Cantabro test wasn't performed on other mixes.

Table 4.8: Cantabro Test Significance

Mix	p-value	Significance
TUS (Between In Spec 1 and Out Spec 1)	0.10	No
RNO (Between In Spec 1 and Out Spec 1)	0.06	No

4.4.4 Disc Shaped Compact Tension Test (DCT)

Table 4.9 shows the PG grade and test temperature used for DCT testing. Figure 4.7 shows the fracture energy in J/m^2 for each mix at the test temperature and the error bars denote the 95 percent confidence intervals. The TUS Out Spec 1 and 2 performed well in the low temperature cracking. In contrast the RNO mix In Spec 1 performed well compared to the Out Spec 1 mix. The p-values for each mix are mentioned in Table 4.10. There is no significant difference between the mean fracture energy of In Spec 1 and Out Spec 1. Ultimately gradation change didn't affect the low temperature cracking resistant significantly.

Table 4.9: Testing Temperature of DCT

Mix	Binder Grade	Test Temperature
TUS	PG76-22PM	-12°C
RNO	PG76-28M	-18°C
KBVS	PG70-22	-12°C

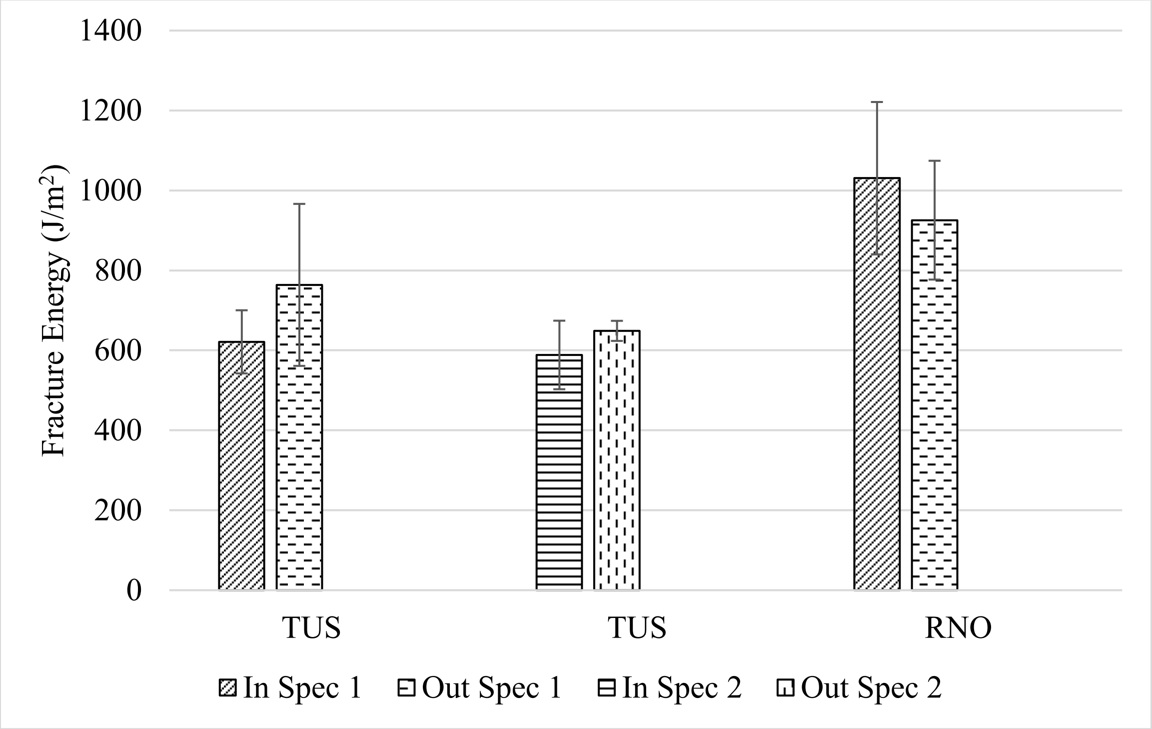

Figure 4.7: DCT Test Fracture Energy

Table 4.10: DCT Test Significance

Mix ID	**p-value**	**Significance**
TUS (Between In Spec 1 and Out Spec 1)	0.25	No
RNO (Between In Spec 1 and Out Spec 1)	0.45	No

4.4.5 Indirect Tensile Asphalt Cracking Test (IDEAL-CT)

The IDEAL-CT test was performed at 25°C to assess intermediate temperature cracking performance among mixtures. Figure 4.8 shows the CT index for all mixtures and the error bars denote the 95 percent confidence intervals. Both the TUS Out Spec 1 and 2 mixtures performed well in terms of intermediate temperature cracking. While comparing the TUS mix's CT Index there is a significant difference between the mean CT Index of In Spec 1 and Out Spec 1(i.e., p-value < 0.05).

On the other hand, the TUS Out Spec 2 mix shows two times the CT Index of the TUS In Spec 2 mix. However, the RNO mix shows similar CT Index results between In Spec 1 and Out Spec 1 mix designs and those CT Index means are not significant. The KBVS In Spec 1 mix CT Index is higher than the Out Spec 1. However, for KBVS Out Spec 2 the CT Index is higher than the In Spec 2. Table 4.11 shows the p-values for all the mixes between In Spec 1 and Out Spec 1 mean CT Index. Coefficient of variance was calculated for each mix and details are reported in Table C.2 to Table C.3 in Appendix C.

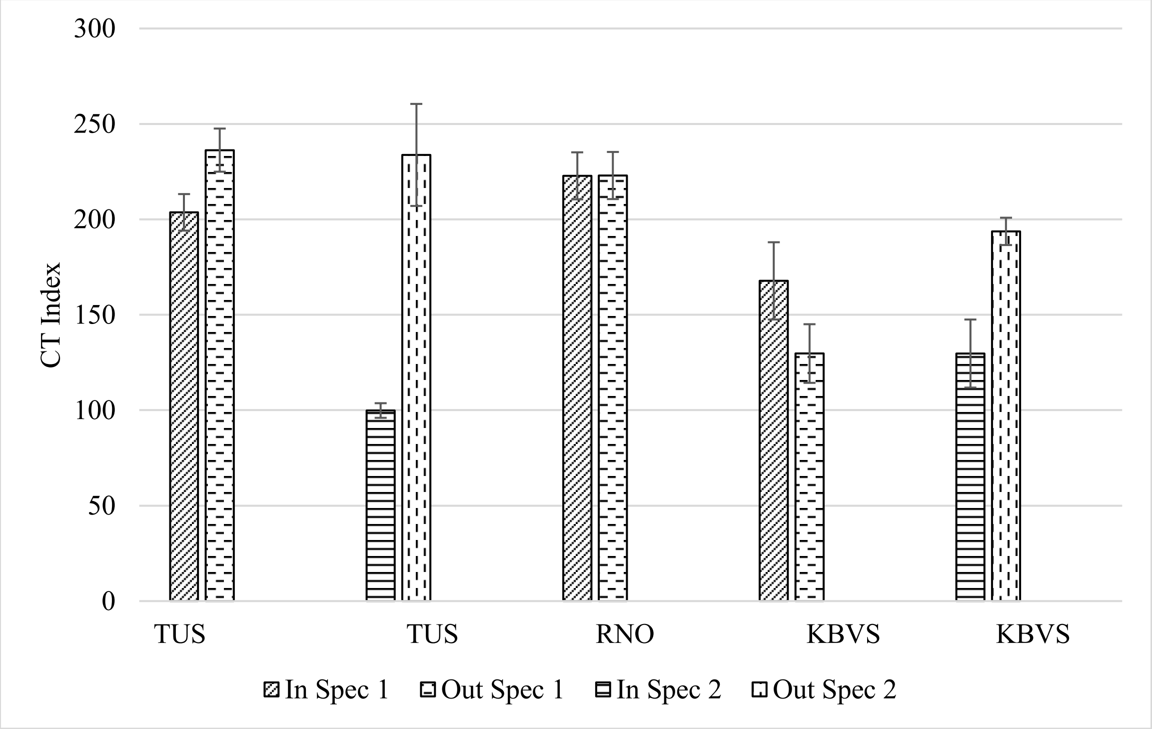

Figure 4.8: CT-Index from IDEAL-CT Test

Table 4.11: IDEAL-CT Test Significance

Mix	**p-value**	**Significance**
TUS (Between In Spec 1 and Out Spec 1)	0.01	Yes
RNO (Between In Spec 1 and Out Spec 1)	0.99	No
KBVS (Between In Spec 1 and Out Spec 1)	0.13	No

4.4.6 Illinois Flexible Index Test (I-FIT)

Figure 4.9 illustrates the Flexibility Index from I-FIT tests, and the error bars denote the 95 percent confidence intervals. The TUS Out Spec 1 mixture performed well compared to TUS In Spec 1. The RNO In Spec 1 and Out Spec 1 exhibited similar Flexibility Index. Statistical analysis reflects there is no significant difference between the mean flexibility index of The KBVS In Spec 1 and Out Spec 1. However, KBVS Out Spec 2 showed a higher Flexibility Index compared to In Spec 2. The p-values are shown in Table 4.12, which shows the gradation adjustment significantly changing the Flexibility Index for TUS mix.

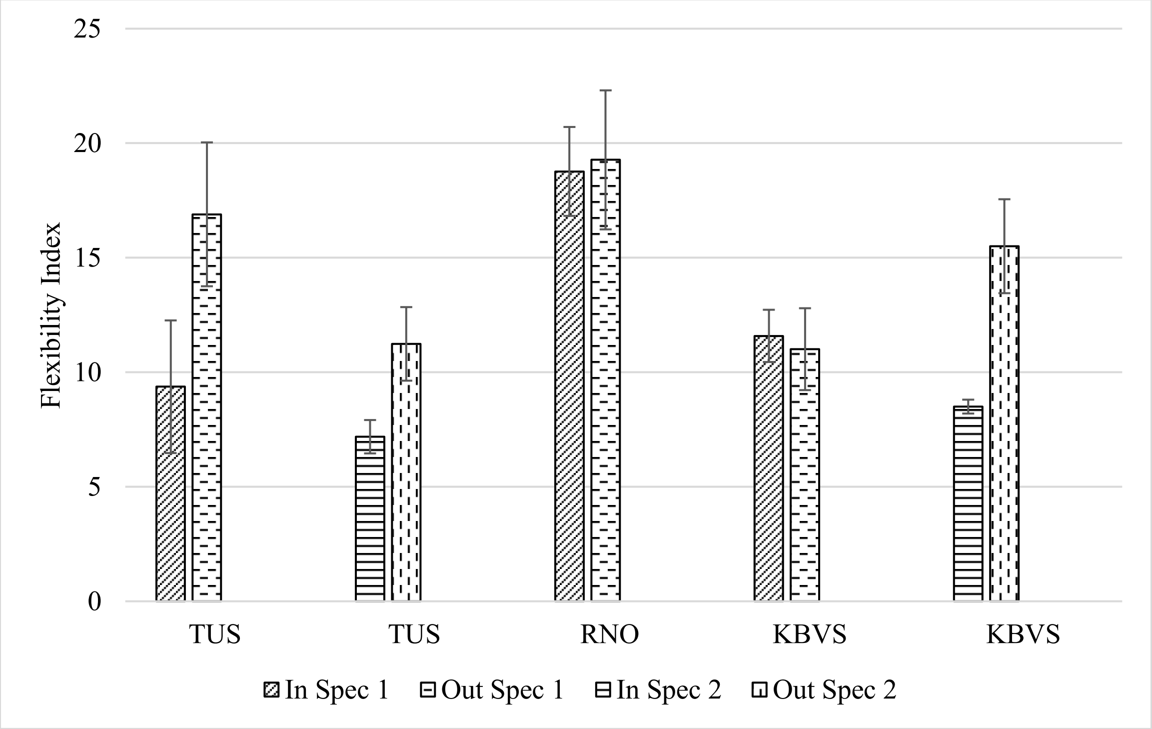

Figure 4.9: Flexibility Index

Table 4.12: I-FIT Test Significance

Mix	p-value	Significance
TUS (Between In Spec 1 and Out Spec 1)	0.01	Yes
RNO (Between In Spec 1 and Out Spec 1)	0.79	No
KBVS (Between In Spec 1 and Out Spec 1)	0.61	No

4.4.7 Florida Permeability Test

The water conductivity of compacted asphalt sample reported as coefficient of permeability for all mixes is shown in Figure 4.10, and the error bars denote the 95 percent confidence intervals of the results. The p-value did not indicate a significant difference between the mean coefficient of permeability of In Spec 1 and Out Spec 1 mix designs for TUS mixtures. However, a significant difference between the mean coefficient of permeability of In Spec 1 and Out Spec 1 was observed for the RNO mix. Table 4.13 shows the p-value and significance of the test for the mixes. Permeability testing was not continued for the remaining mixes. The coefficient of variance was 33% for RNO In Spec 1 mix which was anticipated as it had a coarser gradation than the other mixtures. The detailed results are presented in Table C.8 in Appendix C.

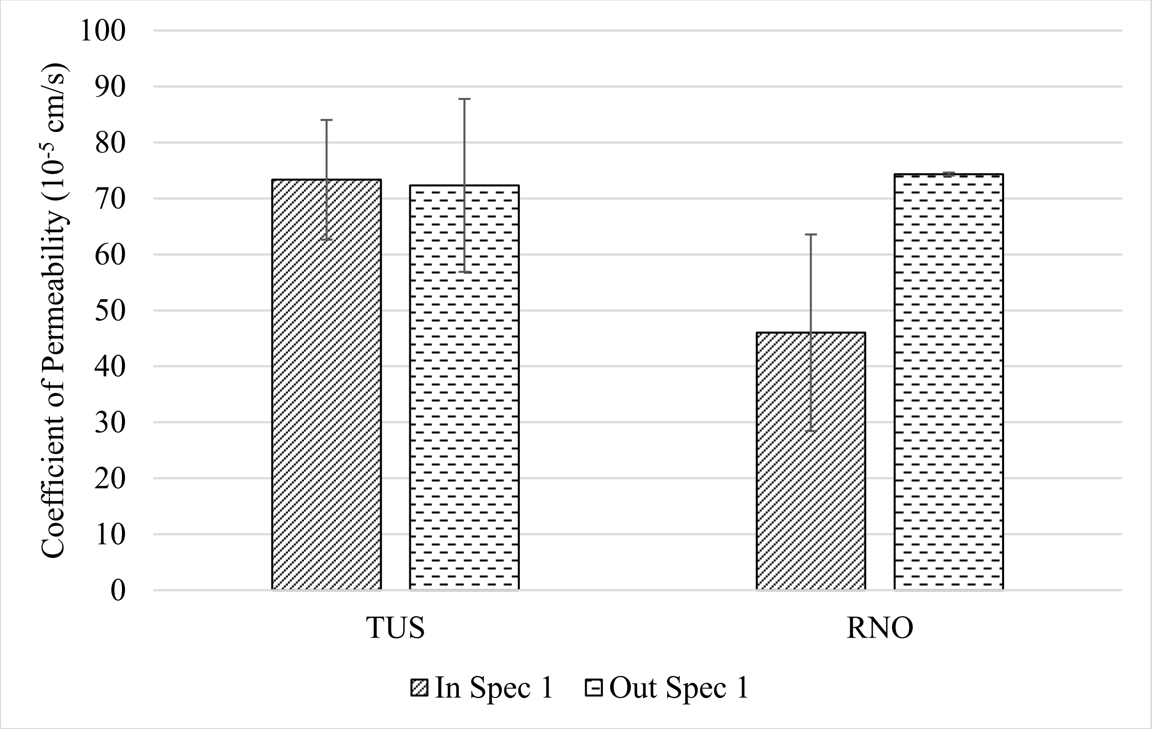

Figure 4.10: Coefficient of Permeability

Table 4.13: Permeability Test Significance

Mix ID	p-value	Significance
TUS (Between In Spec 1 and Out Spec 1)	0.88	No
RNO (Between In Spec 1 and Out Spec 1)	0.01	Yes

Chapter 5

Findings and Conclusions

5.1 Findings

An experimental plan was executed in the laboratory using 3 aggregates sources to develop mixtures with gradations both within and outside the P-401gradation Specification requirements. The volumetrics and performance tests results observed led to following key findings.

5.1.1 Volumetric Properties

- While moving gradation outside of the P-401 limits, to either coarser or finer gradations, VMA was higher than the In Spec gradations.
- Regardless of the gradation adjustment, the developed Out Spec mix designs achieved volumetric properties (i.e. Binder content, Air void and Volume of effective binder) indicating volumetric requirements will be achievable with gradations outside of the current FAA P-401 gradation limits.

5.1.2 Intermediate-Temperature Cracking Resistance

- Statistical analysis confirmed that Out Spec gradation mixes exhibit similar or greater cracking resistance compared to In Spec gradations.
- Intermediate temperature cracking resistance based on Ideal CT and I-FIT results showed coarser gradations provided better intermediate temperature cracking resistance compared to the finer gradations. This suggests that aggregate structure does influence the ability of a mixture to resist crack propagation under intermediate temperature loading.

5.1.3 Low-Temperature Cracking Resistance

- Low temperature cracking resistance DCT results analysis showed that both coarser and finer gradations provided similar results, suggesting that expanding aggregate gradation limits should not affect pavement performance in cold conditions.

5.1.4 Rutting Resistance

- Adjusting the gradations outside the P-401 specification limits did not significantly affect mixture rutting resistant. Both the In Spec and Out Spec mix designs showed similar rutting performance.

5.1.5 Moisture Susceptibility

- Statistical analysis of moisture susceptibility results did not indicate significant difference in tensile strength ratio between In Spec and Out Spec mixtures. The binder and the aggregate sources were the same, suggesting that aggregate gradation alone does not significantly affect resistance to moisture damage.

5.1.6 Durability

- The abrasion losses observed in the Cantabro test were similar for both In Spec 1 and Out Spec 1 for TUS and RNO mixes. This indicates that variations in gradation outside of specified requirements do not significantly impact the Cantabro abrasion loss (durability) performance of the mixtures.

5.1.6 Permeability

- The coefficient of permeability tests revealed similar results across different gradations. However, the coarser gradation mixture exhibited high variability.

5.2 Conclusions

The results of the research indicate that aggregate gradation, which is an important design factor in the FAA P-401 specifications, could be modified outside of the current standard specification limits without adverse impacts on performance of mixtures, as long as volumetric requirements and binder content requirements are fulfilled. Specifically:

- Coarse gradations show potential performance benefits in intermediate temperature cracking resistance, without any negative implications for rutting resistance, moisture susceptibility or durability (Cantabro abrasion loss).
- VMA increases on either side of the maximum density gradation line, for coarser and finer gradations, and may result in additional binder film thickness contributing to the improvement in cracking resistance.
- Except for deformation (i.e. rutting, which is not addressed here), low-temperature cracking resistance, moisture susceptibility, durability (Cantabro abrasion loss), and permeability appear to remain unchanged with modest gradation adjustments outside the current P-401 limits. This suggests that the gradation limits for P-401 mixtures could be broadened.

The results from this research suggest that gradation adjustment is a way to improve some specific performance of airport pavements while conforming to current P-401 volumetric and performance test requirements. However, this research focused on material from specific regions (western U.S. that included 2 LTPP climatic zones), so to adjust the entire gradation specification limits of FAA requirements further investigation in other regions of the U.S. is warranted to provide a better understanding of the potential effect of aggregate gradation changes in P-401 specifications.

References

1. Standards for Specifying Construction of Airports. Advisory Circular AC 150/5370-10H. Federal Aviation Administration. (2018).
2. Item P-401 Plant Mix Bituminous Pavements. Part V - Flexible Surface Courses, FAA Advisory Circular No. 150/5370-10H. Federal Aviation Administration. (2018).
3. Federal Aviation Administration. Engineering Brief 59A. Superpave Mix Design for Airfield Pavements.
4. “Standard Test Method for Effect of Moisture on Asphalt Mixtures,” ASTM D4867/D4867M-22, American Society for Testing and Materials. (2022).
5. “Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Asphalt Mixtures,” AASHTO T324-23, American Association of State Highway and Transportation Officials. (2023).
6. “Standard Test Method for Percent Air Voids in Compacted Asphalt Mixtures,” ASTM D3203/D3203M-17, American Society for Testing and Materials. (2017).
7. “Standard Test Method for Determining Field VMA Based on the Maximum Specific Gravity of an Asphalt Mixture (G_{mm}),” ASTM D6995-21, American Society for Testing and Materials. (2021).

8. Hot-Mix Asphalt Paving Handbook 2000: AC150/5370–14A Appendix 1 Corporate Creator(s): United States Army Corps of Engineers; American Association of State Highway and Transportation Officials; National Asphalt Pavement Association; American Public Works Association; National Association of County Engineers;

Corporate Contributor(s): United States. Federal Highway Administration; United States. Federal Aviation Administration; Published Date 2000-01-Report Number: AC 150/5370-14A, Appendix 1 (FAA) URL: /view/dot/42051.

9. Hossain, M. S. and Islam, N. Airfield Asphalt Pavement Construction Best Practices Manual. (Report No. AAPTP 05-01). Airfield Asphalt Pavement Technology Program. Auburn University. (2012).
10. Aschenbrener, T. B. and Bonaquist, R. Bailey Method for Gradation Selection in Hot Mix Asphalt Mixture Design. Transportation Research E-Circular, No. E-C044. (2002).
11. Leiva, J. P. and West, R. C. Introduction to Aggregate Gradation. National Asphalt Pavement Association. (2016).
12. Towards Sustainable Pavement Systems: Chapter 3. Materials Considerations. Federal Highway Administration. (2017).
13. Wu, Y., Parker, F. and Kandhal, P. S. Aggregate Toughness/Abrasion Resistance and Durability Tests Related to Asphalt Concrete Performance in Pavements. National Center for Asphalt Technology. (2003).
14. Anderson, R. M. and Bahia, H. U. Evaluation and Selection of Aggregate Gradations for Asphalt Mixtures Using Superpave. Transportation Research Board. (1994).
15. Standards for Specifying Construction of Airports (Advisory Circular 150/5370-10H). Federal Aviation Administration. FAA.
16. The Asphalt Handbook, Asphalt Institute. (2007).
17. MS-2 Asphalt Mix Design Methods, Asphalt Institute. (2019).

18. “Standard Specification for Superpave Volumetric Mix Design,” AASHTO M323-22, American Association of State Highway and Transportation Officials. (2022).
19. Kandhal, P. S. and Parker, F. Aggregate Tests Related to Asphalt Concrete Performance in Pavements. National Center for Asphalt Technology. (1998).
20. Roberts, F. L., Kandhal, P. S., Brown, E. R., Lee, D.-Y. and Kennedy, T. W. Hot Mix Asphalt Materials, Mixture Design, and Construction. National Asphalt Pavement Association. (1996).
21. Regional Adaptation of Specifications for Hot Mix Asphalt Design and Construction. Federal Highway Administration (FHWA). (2007).
22. Roberts, F. L., Kandhal, P. S., Brown, E. R., Lee, D.-Y. and Kennedy, T. W. Hot Mix Asphalt Materials. National Asphalt Pavement Association. (2000).
23. The Asphalt Handbook. Asphalt Institute. (2007).
24. Sustainable Highways Self-Evaluation Tool. FHWA, Federal Highway Administration. (2010).
25. Hansen, K. R. and Copeland, A. Annual Asphalt Pavement Industry Survey on Recycled Materials and Warm-Mix Asphalt Usage: 2009–2014. National Asphalt Pavement Association. (2001).
26. National Cooperative Highway Research Program (NCHRP). NCHRP Report 455: Recommended Performance-Related Specification for Hot-Mix Asphalt Construction: Results of the Wes Track Project. Transportation Research Board. (2001).

27. “Standard Test Method for Materials Finer than 75-μm (No. 200) Sieve in Mineral Aggregates by Washing,” ASTM C117-17, American Society for Testing and Materials. (2017).
28. “Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates,” ASTM C136/C136M-19, American Society for Testing and Materials. (2019).
29. “Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate,” ASTM C127-24, American Society for Testing and Materials. (2024).
30. “Standard Test Method for Relative Density (Specific Gravity) and Absorption of Fine Aggregate,” ASTM C128-22, American Society for Testing and Materials. (2022).
31. “Standard Test Method for Bulk Density (“Unit Weight”) and Voids in Aggregate,” ASTM C29/C29M-23, American Society for Testing and Materials. (2023).
32. “Standard Test Methods for Uncompacted Void Content of Fine Aggregate (as Influenced by Particle Shape, Surface Texture, and Grading),” ASTM C1252-23 American Society for Testing and Materials. (2023).
33. “Standard Practice for Superpave Volumetric Design for Asphalt Mixtures,” AASHTO R35-22, American Association of State Highway and Transportation Officials. (2022).
34. West, R., Timm, D., Powell, B., Tran, N., Yin, F., Bowers, B. and Rodezno, C. Phase VII (2018- 2021) NCAT test track findings. NCAT Rep, (21-03). 9. (2021).
35. Vrtis, M. NCAT/MnROAD Cracking Group. Presentation at the Fall 2022 NCAT-MnROAD Sponsor Meeting, Bloomington, MN. (2022).

36. “Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature,” ASTM D8225-19, American Society for Testing and Materials. (2019).
37. “Standard Method Test for Determining the Fracture Potential of Asphalt Mixtures Using the Illinois Flexibility Index Test (I-FIT),” AASHTO T393-22, American Association of State Highway and Transportation Officials. (2022).
38. I-FIT analysis tool 2017 V1.1, https://ict.illinois.edu/research/tools/ifit-software
39. “Standard method of test for Cantabro abrasion loss of asphalt mixture specimens,” AASHTO T401-22, American Association of State Highway and Transportation Officials. (2022).
40. “Standard Test Method for Determining Fracture Energy of Asphalt Mixtures Using the Disk-Shaped Compact Tension Geometry,” ASTM D7313-20, American Society for Testing and Materials. (2020).
41. “Florida Method of Test for Measurement of Water Permeability of Compacted Asphalt Paving Mixtures” FM 5-565. (2018).
42. Aad, G, P-401 Mixtures: Aggregate Gradation Bands, University of Nevada, Reno. (2024).
43. Unified Facilities Guide Specification 32 12 15.13: Asphalt Paving for Airfields. Whole Building Design Guide (WBDG). (2020).
44. “Standard Test Method for Determination of Rutting Tolerance Index of Asphalt Mixture Using the Ideal Rutting Test,” ASTM D8360-22, American Society for Testing and Materials. (2022).

45. Watson, A. L., Qureshi, A., Xie, J. and Tran, N. Improvements of open-graded friction course in Alabama (NCAT Report 20-07). National Center for Asphalt Technology. (2020).

46. Azari, H. Precision Statements for AASHTO Standard Method of Test T-148, T-265, T-267, and T-283 (Research Results Digest 351, NCHRP Project 9-26A). Transportation Research Board. (2011).

Appendix A

Table A.1: Bin Percentage and Blend Gradation TUS Mix

Sieve Size	3/4"	3/8"	WCD	CD	WAS	Cement	In Spec 1 Blend	Out Spec 1 Blend
1”	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/4"	86.7	100.0	100.0	100.0	100.0	100.0	97.7	97.7
1/2"	29.6	100.0	100.0	100.0	100.0	100.0	88.0	88.0
3/8"	10.4	83.0	100.0	100.0	100.0	100.0	81.4	79.6
#4	4.8	10.0	87.1	91.5	99.0	100.0	59.5	52.9
#8	4.1	4.0	49.1	65.0	88.0	100.0	38.7	33.8
#16	4.1	3.0	25.6	45.5	60.8	100.0	24.1	20.8
#30	3.7	2.5	15.2	33.5	35.2	100.0	15.7	13.5
#50	3.7	2.2	7.4	26.4	14.6	100.0	9.7	8.2
#100	3.7	2.0	4.5	21.6	3.6	100.0	6.8	5.7
#200	3.3	1.8	2.9	17.1	0.6	100.0	5.2	4.4
In Spec 1 Bin Percentage	17.0%	20.0%	40.0%	12.0%	10.0%	1.0%	100.0%	
Out Spec 1 Bin Percentage	18.0%	28.0%	38.0%	7.0%	8.0%	1.0%		100.0%

Table A.2: Bin Percentage and Blend Gradation TUS Mix

Sieve Size	3/4"	3/8"	WCD	CD	WAS	Cement	In Spec 2 Blend	Out Spec 2 Blend
1”	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/4"	86.7	100.0	100.0	100.0	100.0	100.0	98	98
1/2"	29.6	100.0	100.0	100.0	100.0	100.0	88	90
3/8"	10.4	83.0	100.0	100.0	100.0	100.0	82	82
#4	4.8	10.0	87.1	91.5	99.0	100.0	63	50
#8	4.1	4.0	49.1	65.0	88.0	100.0	43	30
#16	4.1	3.0	25.6	45.5	60.8	100.0	28	18
#30	3.7	2.5	15.2	33.5	35.2	100.0	18	11
#50	3.7	2.2	7.4	26.4	14.6	100.0	11	7
#100	3.7	2.0	4.5	21.6	3.6	100.0	8	5
#200	3.3	1.8	2.9	17.1	0.6	100.0	6	4
In Spec 2 Bin Percentage	17.1%	16.0%	33.2%	17.7%	15.0%	1.0%	100.0%	
Out Spec 2 Bin Percentage	13.9%	34.0%	44.4%	2.8%	3.9%	1.0%		100.0%

Table A.3: Bin Percentage and Blend Gradation RNO Mix

Sieve Size	3/4"	1/2"	3/8"	CF	WCF	Lime	In Spec 1 Blend	Out Spec 1 Blend
3/4"	99.8	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1/2"	35.1	99.4	100.0	100.0	100.0	100.0	96.6	90.0
3/8"	4.4	52.2	99.7	100.0	100.0	100.0	88.1	77.5
#4	1.1	1.5	19.6	99.8	99.8	100.0	64.6	59.8
#8	1.0	1.2	1.8	74.7	66.8	100.0	43.3	40.5
#16	1.0	1.2	1.4	49.8	37.8	100.0	27.0	24.9
#30	1.0	1.1	1.4	34.5	21.4	99.0	17.6	15.9
#50	0.9	1.1	1.3	24.1	11.6	99.0	11.6	10.3
#100	0.9	1.1	1.3	18.1	5.8	99.0	8.2	7.0
#200	0.8	1.0	1.2	13.6	3.4	70.6	5.8	4.9
In Spec 1 Bin Percentage	5.1%	14.5%	19.8%	22.0%	37.0%	1.6%	100.0%	
Out Spec 1 Bin Percentage	15.2%	16.5%	10.9%	14.4%	41.4%	1.6%		100.0%

Table A.4: Bin Percentage and Blend Gradation KBVS Mix

Sieve Size	3/4”–3/8"	3/8"	CF	Altered CF	B.Sand	In Spec 1 Blend	Out Spec 1 Blend
3/4"	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1/2"	85.1	100.0	100.0	100.0	100.0	94.3	93.6
3/8"	39.8	99.7	100.0	100.0	100.0	77.1	74.1
#4	5.1	19.6	99.8	99.8	100.0	53.4	53.1
#8	3.5	1.8	74.7	74.7	92.9	40.4	39.1
#16	3.3	1.4	49.8	41.8	77.2	29.1	23.1
#30	3.2	1.4	34.5	28.5	58.7	21.2	16.3
#50	3.1	1.3	24.1	19.1	28.0	13.6	11.1
#100	2.7	1.3	18.1	15.6	6.5	8.7	8.8
#200	2.2	1.2	13.6	11.0	2.0	6.3	6.3
In Spec 1 Bin Percentage	38.0%	13.0%	37.0%	0.0%	12.0%	100.0%	
Out Spec 1 Bin Percentage	43.0%	7.5%	0.0%	47.0%	2.5%		100.0%

Table A.5: Bin Percentage and Blend Gradation KBVS Mix

Sieve Size	**3/4”–3/8"**	**3/8"**	**CF**	**Altered CF**	**B.Sand**	**In Spec 2 Blend**	**Out Spec 2 Blend**
3/4"	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1/2"	85.1	100.0	100.0	100.0	100.0	96.3	94.6
3/8"	39.8	99.7	100.0	100.0	100.0	84.9	78.0
#4	5.1	19.6	99.8	99.8	100.0	64.1	50.4
#8	3.5	1.8	74.7	74.7	92.9	48.7	35.2
#16	3.3	1.4	49.8	41.8	77.2	31.4	20.3
#30	3.2	1.4	34.5	28.5	58.7	22.6	14.2
#50	3.1	1.3	24.1	19.1	28.0	13.8	10.0
#100	2.7	1.3	18.1	15.6	6.5	8.9	8.2
#200	2.2	1.2	13.6	11.0	2.0	6.0	6.0
In Spec 2 Bin Percentage	25.0%	15.0%	0.0%	45.0%	15.0%	100.0%	
Out Spec 2 Bin Percentage	36.50%	18.50%	0.00%	45.00%	0.00%		100.0%

Appendix B

Table B.1: TUS Mix Maximum Theoretical Specific Gravity Data

Mix	TUS In Spec 2		TUS Out Spec 2	
Sample	1	2	1	2
Empty pycnometer Mass under water (g)	1439.4	1439.4	1439.4	1439.4
Mass of oven dry sample in air (g)	2739.6	2739.0	2740.6	2742.6
Pycnometer + Sample Mass under water (g)	3079.9	3076.9	3074.9	3079.1
Mass of sample under water (g)	1640.5	1637.5	1635.5	1639.7
G_{mm}	2.493	2.487	2.480	2.487
Average	2.490		2.483	
(1s) ≤0.008	0.004		0.005	
(d2s) ≤0.016	0.006		0.007	

Table B.2: TUS Mix Design Volumetric Data

Properties	TUS In Spec 2		TUS Out Spec 2	
Binder Content Used [%]	5.3		5.3	
Sample ID	1	2	1	2
Number of Gyrations	75		75	
G_b	1.034		1.034	
G_{se}	2.704		2.695	
G_{sb}	2.655		2.660	
Air Mass [g]	4816.2	4819.6	4818.9	4815.6
Underwater Mass [g]	2855.2	2860.2	2809.9	2809.6
SSD Mass [g]	4836.6	4848.6	4856.9	4849.6
G_{mb}	2.431	2.424	2.354	2.361
Average G_{mb}	2.427		2.357	
Air Voids [%]	2.4%	2.6%	5.2%	4.9%
Average Air voids [%]	2.5%		5.1%	
VMA (%)	13.3	13.6	16.2	16.0
Average VMA [%]	13.4		16.1	
VFA [%]	82.2	80.5	67.9	69.0
Average VFA [%]	81.4		68.5	
P_{ba}	0.70	0.70	0.50	0.50
P_{be}	4.7	4.7	4.8	4.8
DP	1.3	1.3	1.3	1.3

Table B.3: RNO Mix Maximum Theoretical Specific Gravity Data

Mix	RNO In Spec 1		RNO Out Spec 1	
Sample	1	2	1	2
Mass of empty pycnometer under water (g)	1440.7	1440.7	1439.7	1439.7
Mass of oven dry sample in air (g)	1680.1	1714.1	1756.9	1756.4
Mass of pycnometer + Sample under water (g)	2464.5	2484.6	2511.5	2512.2
Mass of sample under water (g)	1023.8	1043.9	1071.8	1072.5
G_{mm}	2.560	2.558	2.564	2.568
Average	2.559		2.566	
(1s) ≤0.008	0.002		0.003	
(d2s) ≤0.016	0.002		0.004	

Table B.4: RNO Mix design Volumetric Data

Properties	RNO In Spec 1		RNO Out Spec 1	
Binder Content Used [%]	6.2		6.1	
Sample ID	1	2	1	2
Number of Gyrations	75		75	
G_b	1.026		1.026	
G_{se}	2.839		2.843	
G_{sb}	2.737		2.749	
Air Mass [g]	4806.1	4796.9	4819.1	4823.2
Underwater Mass [g]	2860.2	2859.2	2879.1	2883.2
SSD Mass [g]	4808.1	4800.4	4824.8	4829.5
G_{mb}	2.467	2.471	2.477	2.478
Average G_{mb}	2.469		2.477	
Air Voids [%]	3.6	3.4	3.5	3.4
Average Air voids [%]	3.5		3.5	
VMA (%)	15.4	15.3	15.4	15.6
Average VMA [%]	15.4		15.4	
VFA	76.9	77.6	77.3	77.6
Average VFA	77.2		77.5	
P_{ba}	1.35	1.35	1.24	1.24
P_{be}	4.9	4.9	4.9	4.9
DP	1.2	1.2	1.2	1.2

Table B.5: KBVS Mix Maximum Theoretical Specific Gravity Data

Mix	KBVS In Spec 1		KBVS Out Spec 1	
Sample	1	2	1	2
Mass of empty pycnometer under water (g)	1440.1	1440.1	1427	1427
Mass of oven dry sample in air (g)	2074.3	2079.4	1975.1	1986.2
Mass of pycnometer + Sample under water (g)	2694.1	2698.2	2629.2	2633.6
Mass of sample under water (g)	1254	1258.1	1202.2	1206.6
G_{mm}	2.529	2.532	2.555	2.548
Average	2.530		2.552	
(1s) ≤0.008	0.002		0.005	
(d2s) ≤0.016	0.003		0.008	

Table B.6: KBVS Mix Design Volumetric Data

Properties	KBVS In Spec 1		KBVS Out Spec 1	
Binder Content Used [%]	6.0		6.0	
Sample ID	1	2	1	2
Number of Gyrations	75		75	
G_b	1.025		1.025	
G_{se}	2.792		2.820	
G_{sb}	2.710		2.731	
Air Mass [g]	4859.3	4858.2	4849.0	4852.5
Underwater Mass [g]	2876.1	2872.1	2882.9	2884.9
SSD Mass [g]	4864.4	4865.5	4854.2	4856.3
G_{mb}	2.444	2.437	2.460	2.461
Average G_{mb}	2.441		2.461	
Air Voids [%]	3.4	3.7	3.6	3.5
Average Air voids [%]	3.5		3.6	
VMA (%)	15.2	15.5	15.3	15.3
Average VMA [%]	15.3		15.3	
VFA [%]	77.6	76.2	76.5	76.9
Average VFA [%]	76.9		76.7	
P_{ba}	1.11	1.11	1.18	1.18
P_{be}	5.0	5.0	4.9	4.9
DP	1.2	1.2	1.2	1.2

Table B.7: KBVS Mix Maximum Theoretical Specific Gravity Data

Mix	KBVS In Spec 2		KBVS Out Spec 2	
Sample	1	2	1	2
Mass of empty pycnometer under water (g)	1427	1440.1	1427	1440.1
Mass of oven dry sample in air (g)	2074.6	2078.6	2075	2069.7
Mass of pycnometer + Sample under water (g)	2682.5	2697	2684.4	2696.2
Mass of sample under water (g)	1255.5	1256.9	1257.4	1256.1
G_{mm}	2.533	2.530	2.538	2.544
Average	2.531		2.541	
(1s) ≤0.008	0.002		0.004	
(d2s) ≤0.016	0.003		0.006	

Table B.8: KBVS Mix Design Volumetric Data

Properties	KBVS In Spec 2		KBVS Out Spec 2	
Binder Content Used [%]	6.0		6.0	
Sample ID	1	2	1	2
Number of Gyrations	75		75	
G_b	1.025		1.025	
G_{se}	2.793		2.806	
G_{sb}	2.707		2.735	
Air Mass [g]	4875.4	4874.8	4874.8	4873.8
Underwater Mass [g]	2887.6	2887.3	2858.5	2862.2
SSD Mass [g]	4882.2	4881.4	4889	4889.7
G_{mb}	2.444	2.445	2.401	2.404
Average G_{mb}	2.444		2.402	
Air Voids [%]	3.4	3.4	5.5	5.4
Average Air voids [%]	3.4		5.5	
VMA (%)	15.1	15.1	17.5	17.4
Average VMA [%]	15.1		17.4	
VFA [%]	77.3	77.4	77.3	77.6
Average VFA [%]	77.3		68.7	
P_{ba}	1.17	1.17	0.95	0.95
P_{be}	4.9	4.9	5.1	5.1
DP	1.2	1.2	1.2	1.2

Appendix C

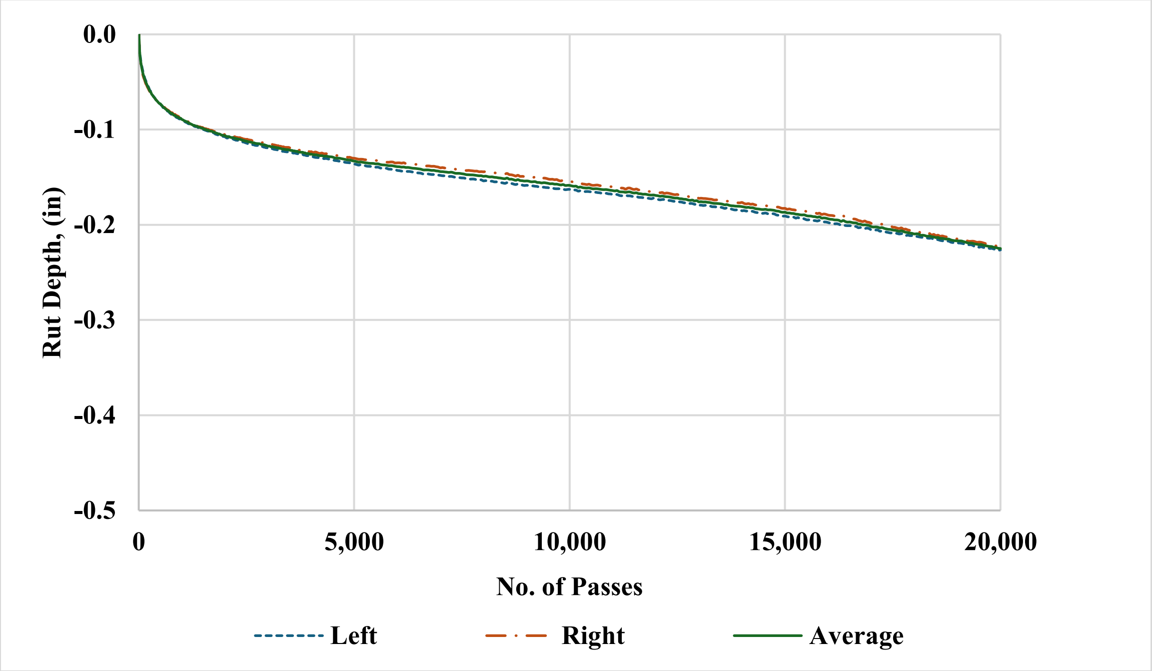

Figure C.1: HWTT Data TUS In Spec 1

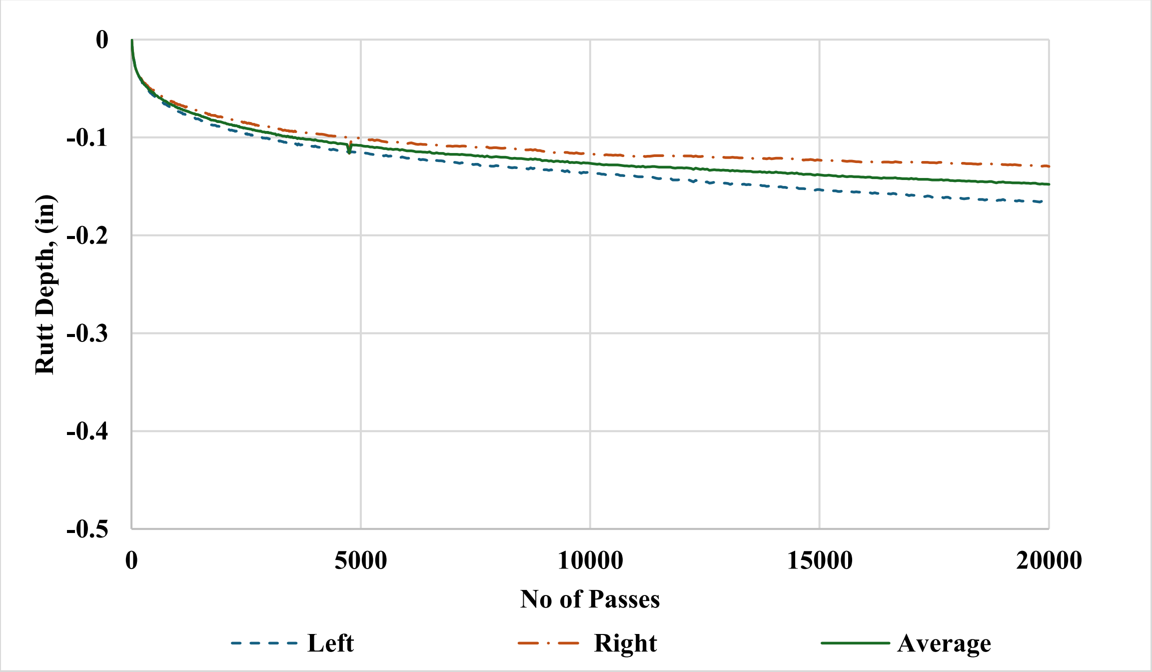

Figure C.2: HWTT Data TUS Out Spec 2

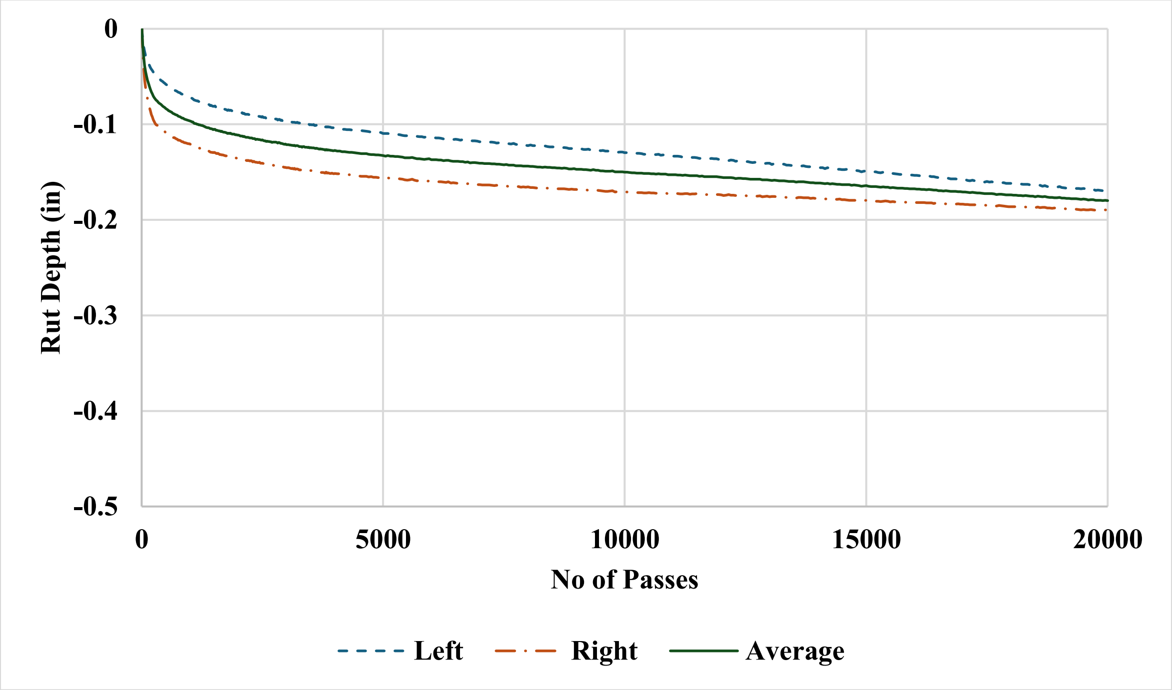

Figure C.3: HWTT Data TUS In Spec 2

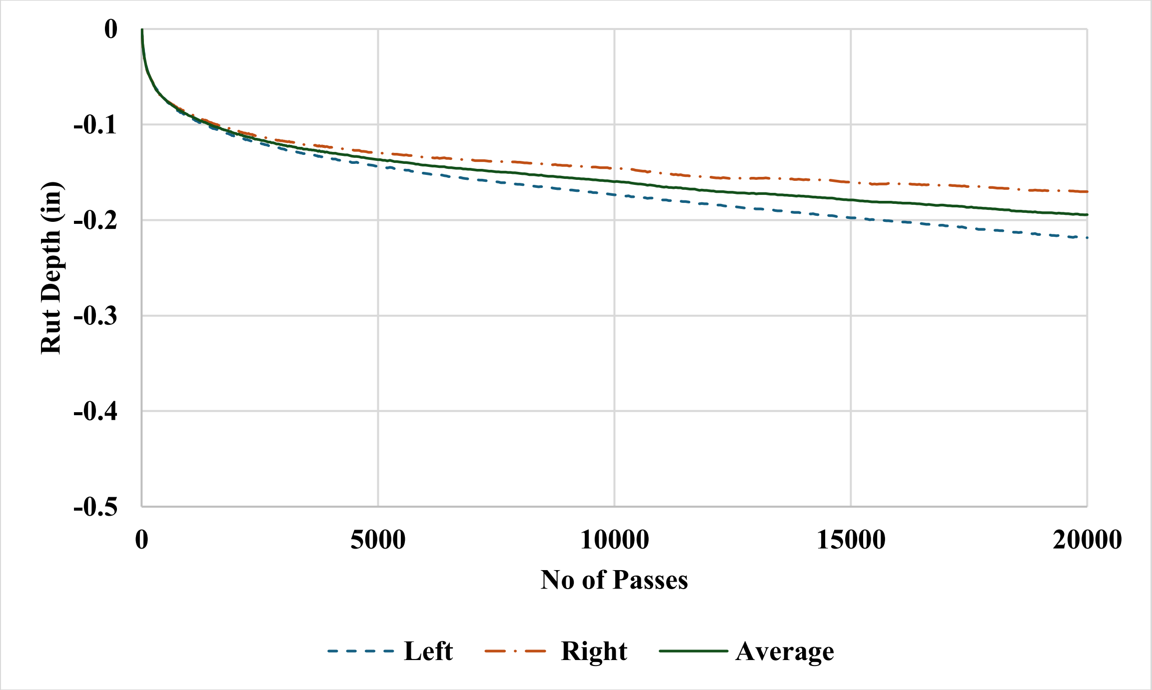

Figure C.4: HWTT Data TUS Out Spec 2

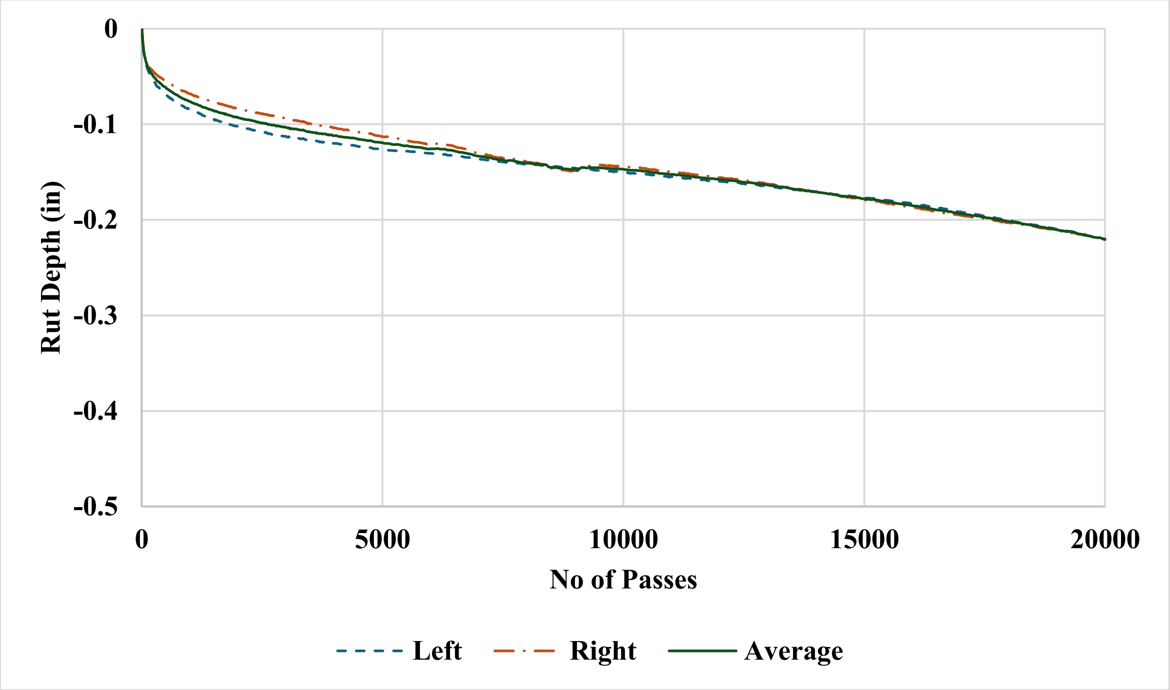

Figure C.5: HWTT Data RNO In Spec 1

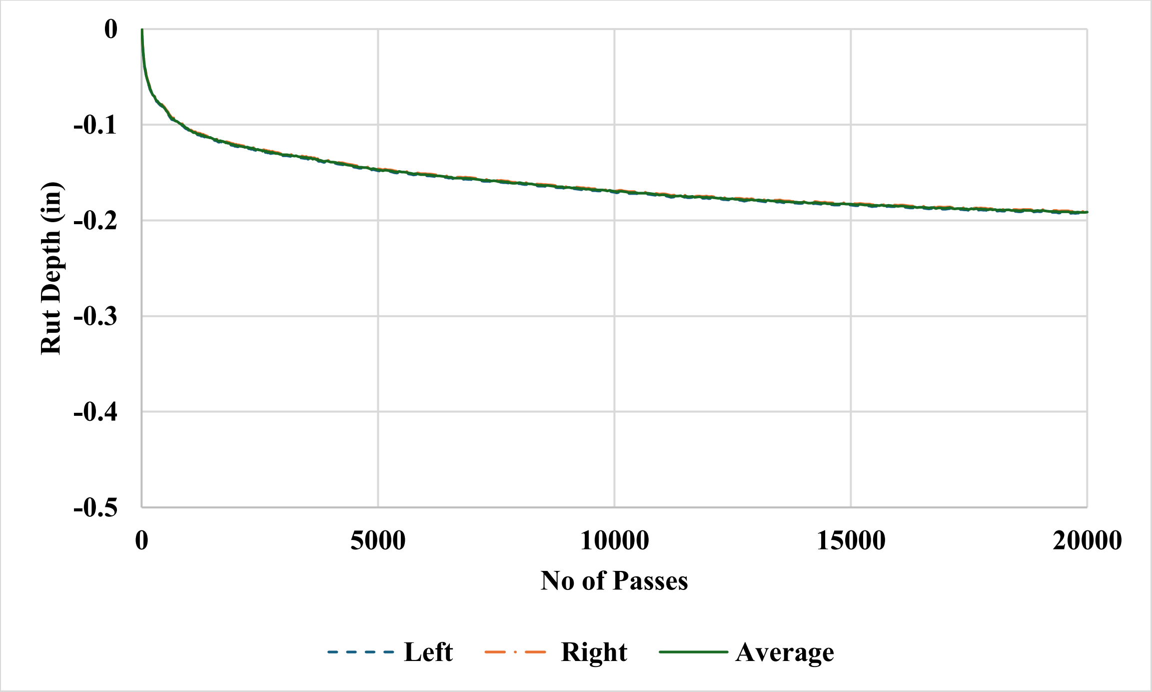

Figure C.6: HWTT Data RNO Out Spec 1

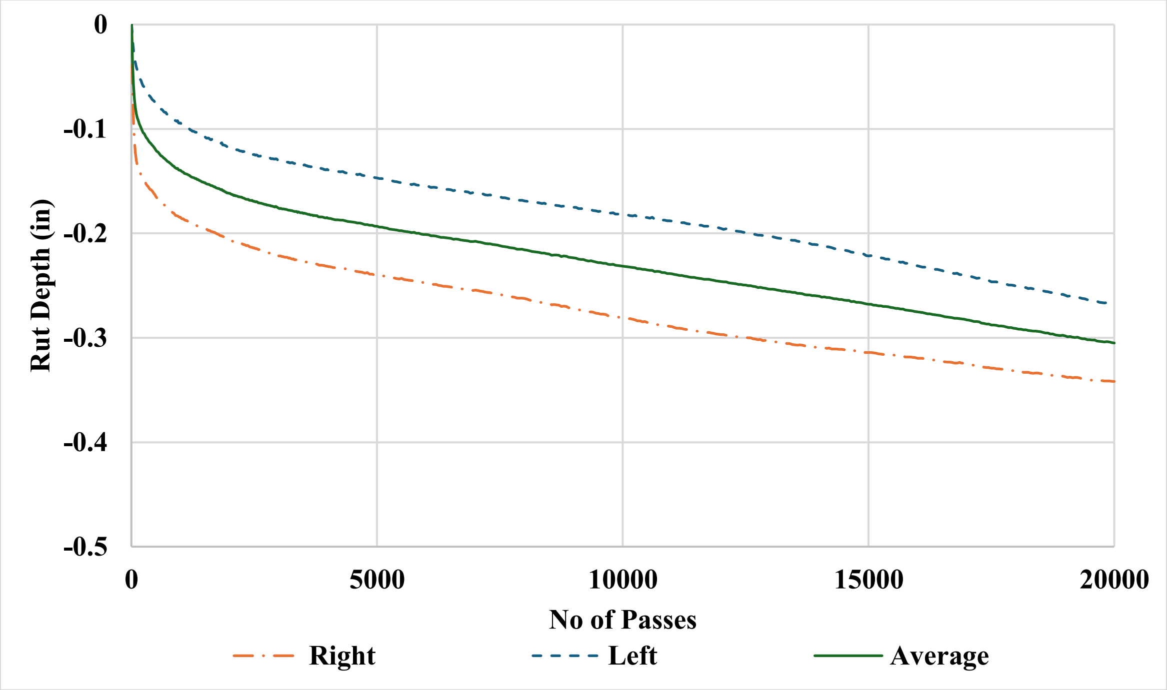

Figure C.7: HWTT Data KBVS In Spec 1

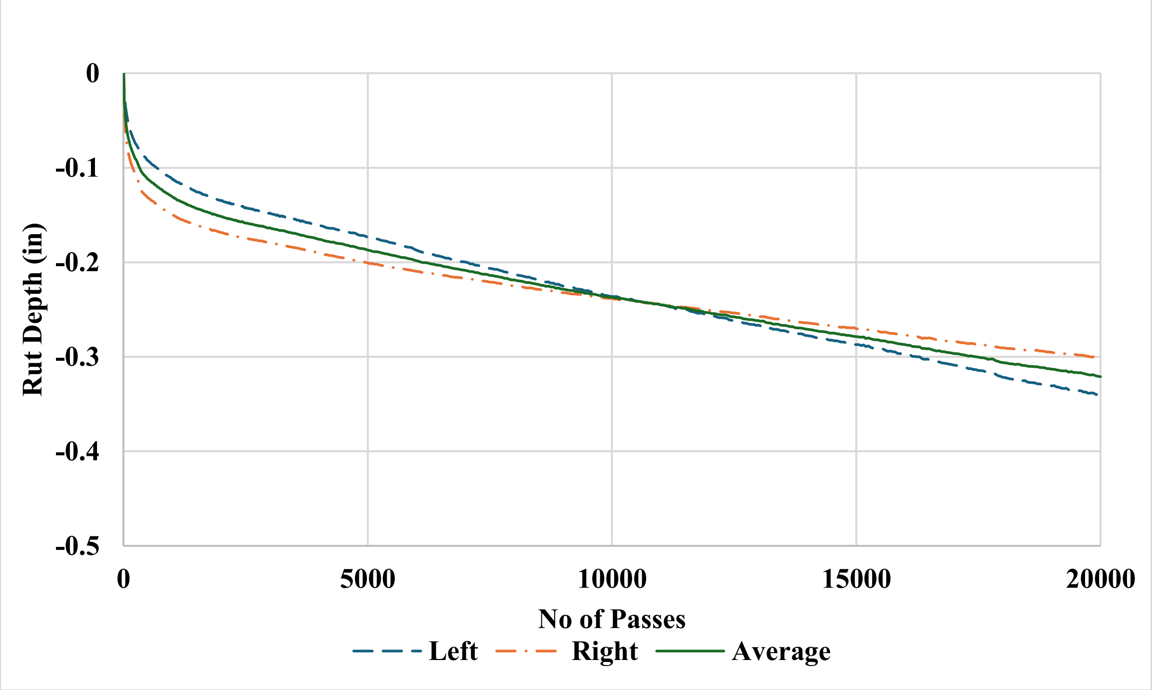

Figure C.8: HWTT Data KBVS Out Spec 1

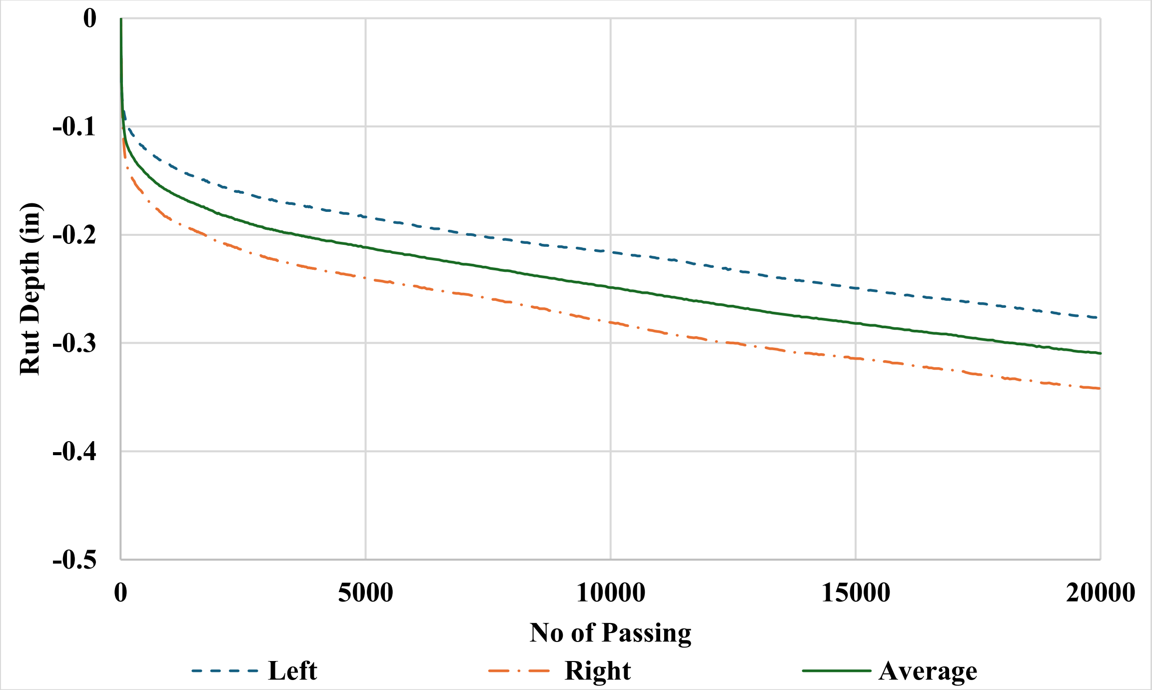

Figure C.9: HWTT Data KBVS In Spec 2

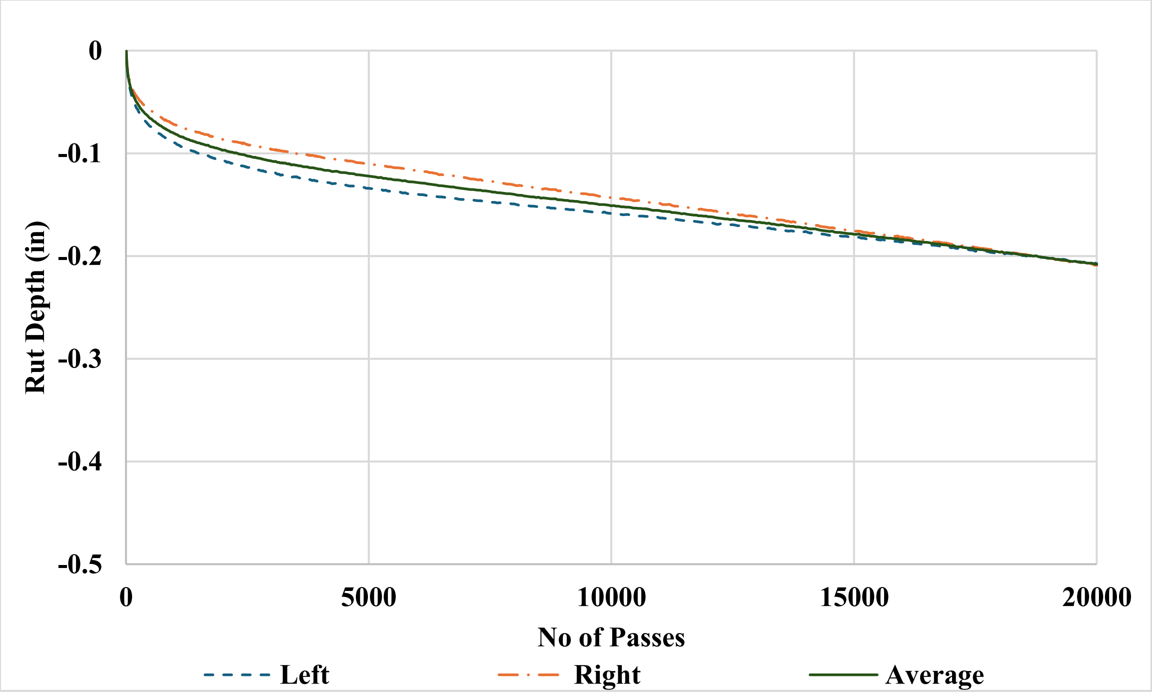

Figure C.10: HWTT Data KBVS Out Spec 2

Table C.1: TSR Data

Mix	Specimen ID	Condition	Tensile Strength (psi)	Avg	Std dev	Coefficient of Variance (%)	95% Confidence Interval
TUS In Spec 1	1	Wet	124.4	123.8	2.8	2.3	121.5 to 126.1
	2		120.7				
	3		126.2				
	1	Dry	127.9	125.7	2.3	1.8	123.9 to 127.5
	2		123.3				
	3		126.1				
TUS Out Spec 1	1	Wet	145.3	134.4	10.0	7.5	126.9 to 141.9
	2		125.5				
	3		132.5				
	1	Dry	135.0	129.5	5.3	4.1	125.4 to 133.6
	2		129.2				
	3		124.3				
RNO In Spec 1	1	Wet	89.0	93.0	3.6	3.9	89.1 to 96.9
	2		96.0				
	3		94.0				
	1	Dry	96.0	97.3	3.2	3.3	94.0 to 100.6
	2		95.0				
	3		101.0				
RNO Out Spec 1	1	Wet	79.6	81.5	1.7	2.0	79.5 to 83.5
	2		82.4				
	3		82.6				
	1	Dry	93.2	97.3	3.8	3.9	93.4 to 101.2
	2		100.7				
	3		98.2				

Table C.2: IDEAL-CT Data

MIX	Specimen ID	CT Index	Avg	Std dev	Coefficient of Variance (%)	95% Confidence Interval	Air Void (%)	Post Peak Slope (kN/mm)	Disp . At 75% (mm)
TUS In Spec 1	1	213.8	203.7	9.8	4.8	194.1 to 213.3	5.5	1.706	5.468
	2	196.5					5.1	1.961	5.544
	3	210.2					5.1	1.729	5.288
	4	194.2					4.8	2.060	5.578
TUS Out Spec 1	1	253.3	236.3	11.5	4.9	225 to 247.6	5.1	1.802	5.907
	2	230.8					5.0	1.785	5.487
	3	228.0					5.4	1.933	6.02
	4	233.0					5.0	1.847	5.893
TUS In Spec 2	1	102.0	99.9	3.9	3.9	96.1 to 103.7	5.1	3.371	4.88
	2	100.0					5.2	2.892	4.113
	3	103.1					5.1	3.101	4.592
	4	94.3					5.2	3.145	4.757
TUS Out Spec 2	1	253.1	233.8	27.3	11.7	197.1 to 270.5	5.2	1.746	6.15
	2	239.1					5.1	1.781	5.441
	3	249.0					5.1	1.551	5.438
	4	193.8					5.2	1.815	4.707
RNO In Spec 1	1	214.4	222.8	10.9	4.9	210.5 to 235.1	5.4	1.355	5.947
	2	218.9					5.2	1.336	5.808
	3	235.1					5.1	1.521	6.190

Table C.3: IDEAL-CT Data

MIX	Specimen ID	CT Index	Avg	Std dev	Coefficient of Variance (%)	95% Confidence Interval	Air Void (%)	Post Peak Slope (kN/mm)	Disp . At 75% (mm)
RNO Out Spec 1	1	210.5	223.0	10.9	4.9	210.6 to 235.4	5.1	1.344	5.876
	2	227.6					5.1	1.346	6.372
	3	230.8					5.2	1.785	5.487
KBVS In Spec 1	1	156.5	167.8	20.6	12.3	147.6 to 188	5.5	2.394	6.028
	2	163.7					5.4	2.143	5.399
	3	198.0					4.6	2.042	5.894
	4	152.9					4.7	2.713	6.036
KBVS Out Spec 1	1	125.0	144.5	15.7	10.8	129.1 to 159.9	5.1	2.647	4.865
	2	161.5					4.7	2.376	5.537
	3	140.0					4.5	2.614	5.416
	4	151.4					4.5	2.532	5.17
KBVS In Spec 2	1	155.4	129.7	18.2	14.0	111.9 to 147.5	5.5	2.394	5.477
	2	112.5					5.1	3.159	5.251
	3	124.9					5.3	3.02	5.304
	4	126.0					5.0	3.035	5.125
KBVS Out Spec 2	1	193.0	193.7	7.3	3.8	186.5 to 200.9	5.0	1.944	5.654
	2	189.5					4.7	1.874	5.672
	3	204.2					5.1	1.837	5.734
	4	188.1					4.7	1.978	5.585

Table C.4: I-FIT Data

MIX	Specimen ID	Flexibility Index	Avg	Std dev	Coefficient of Variance (%)	95% Confidence Interval	Slope	Fracture Energy (J/m^2)	Strength (Psi)
TUS In Spec 1	1	6.3	9.4	3.0	31.5	6.5 to 12.3	-2.67	1679.32	55.6
	2	7.4					-1.9	1409.65	47.46
	3	12.3					-1.66	2036.6	52.94
	4	11.5					-1.46	1676.92	45.44
TUS Out Spec 1	1	16.1	16.9	3.2	19.0	13.8 to 20.0	-1.27	2042.66	48.82
	2	18.8					-1.07	2011.71	44.35
	3	12.8					-1.52	1938.49	44.41
	4	20.0					-1.26	2513.64	50.69
TUS In Spec 2	1	6.5	7.2	0.7	10.3	6.5 to 7.9	-2.52	1642.44	61.96
	2	8.3					-2.25	1856.63	59.86
	3	7.0					-2.46	1713.72	59.79
	4	7.0					-2.61	1826.63	62.31
TUS Out Spec 2	1	10.7	11.2	1.6	14.6	9.6 to 12.8	-1.83	1951.03	52.07
	2	12.2					-1.56	1905.23	46.77
	3	12.9					-1.5	1930.17	51.57
	4	9.2					-1.79	1648.97	49.7
RNO In Spec 1	1	19.4	18.8	2.0	10.6	16.9 to 20.7	-0.8	1555.18	30.79
	2	18.2					-0.91	1653.15	32.19
	3	21.1					-0.85	1790.88	35.33
	4	16.4					-0.99	1622.47	34.68

Table C.5: I-FIT Data

MIX	Specimen ID	Flexibility Index	Avg	Std dev	Coefficient of Variance (%)	95% Confidence Interval	Slope	Fracture Energy (J/m^2)	Strength (Psi)
RNO Out Spec 1	1	19.7	19.3	3.1	16.1	16.3 to 22.3	-0.74	1456.02	27.89
	2	15.8					-0.82	1298.71	27.38
	3	23.3					-0.73	1697.63	34.11
	4	18.3					-0.76	1391.81	28.79
KBVS In Spec 1	1	10.1	11.6	1.2	10.0	10.5 to 12.7	-1.75	1759.21	47.70
	2	12.4					-1.72	2131.09	52.14
	3	11.3					-1.71	1937.91	49.73
	4	12.6					-1.68	2113.83	54.82
KBVS Out Spec 1	1	12.4	11.0	1.8	16.6	9.2 to 12.8	-1.71	2124.04	56.59
	2	10.7					-2.17	2315.36	59.78
	3	12.4					-1.96	2426.32	55.17
	4	8.6					-2.09	1788.23	49.61
KBVS In Spec 2	1	8.1	8.5	0.3	3.6	8.2 to 8.8	-2.41	1958.74	57.13
	2	8.4					-2.40	2010.53	65.29
	3	8.7					-2.41	2087.88	63.91
	4	8.8					-2.02	1783.38	53.75
KBVS Out Spec 2	1	17.3	15.5	2.1	13.5	13.4 to 17.6	-1.31	2267.65	49.29
	2	16.7					-1.49	2488.66	52.27
	3	15.4					-1.07	1647.68	42.55
	4	12.6					-1.71	2155.18	54.43

Table C.6: DCT Data

Mix	Specimen ID	Peak Load (kN)	Energy (J/m^2)	Avg	Std dev	Coefficient of Variance (%)	95% Confidence Interval	Air Void (%)
TUS In Spec 1	1	4.337	595	621	80.5	13.0	542.1 to 699.9	5.5
	2	4.227	728					5.1
	3	4.283	541					5.5
	4	4.592	586					5.5
TUS Out Spec 1	1	3.753	609	764	206.7	27.1	561.4 to 966.6	5.0
	2	3.951	636					5.1
	3	4.332	750					5.0
	4	4.287	1060					5.1
TUS In Spec 2	1	4.205	518	589	87.5	14.9	503.3 to 674.7	5.4
	2	4.967	657					5.1
	3	4.073	508					5.5
	4	4.443	671					5.4
TUS Out Spec 2	1	4.290	640	649	25.6	4.0	623.9 to 674.1	4.8
	2	3.724	620					4.8
	3	4.171	681					5.0
	4	3.891	654					5.3
RNO In Spec 1	1	4.203	1155	1031	168.4	16.3	840.4 to 1221.6	5.3
	2	4.346	839					5.5
	3	4.972	1098					5.5
RNO In Spec 1	1	4.996	962	926	131.3	14.2	777.4 to 1074.6	4.8
	2	3.977	780					4.7
	3	4.791	1035					5.1

Table C.7: Cantabro Test Data

Mix	Specimen ID	Abrasion Loss (%)	Avg	Std dev	Coefficient of Variance (%)	95% Confidence Interval
TUS In Spec 1	1	2.3	2.3	0.9	38.6	1.3 to 3.3
	2	3.3				
	3	1.5				
TUS Out Spec 1	1	0.7	1.0	0.3	32.5	0.6 to 1.4
	2	0.9				
	3	1.3				
RNO In Spec 1	1	0.45	0.44	0.03	5.9	0.4 to 0.5
	2	0.46				
	3	0.41				
RNO Out Spec 1	1	0.34	0.36	0.02	6.4	0.3 to 0.4
	2	0.38				
	3	0.36				

Table C.8: Permeability Test Data

Mix	Specimen ID	Coefficient of Permeability (10^{-5} cm/s)	Avg	Std dev	Coefficient of Variance (%)	95% Confidence Interval
TUS In Spec 1	1	66	73	9.5	12.9	62.3 to 83.7
	2	70				
	3	84				
TUS Out Spec 1	1	88	72	13.7	18.9	56.6 to 87.4
	2	63				
	3	66				
RNO In Spec 1	1	30	46	15.5	33.7	28.4 to 63.6
	2	47				
	3	61				
RNO Out Spec 1	1	74	74	0.2	0.3	73.7 to 74.3
	2	74				
	3	74				