Develop Guidelines and Design Program for Hot-Mix Asphalts Containing RAP, RAS, and Other Additives through a Balanced Mix-Design Process

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Conducted for

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16. Abstract

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This project presents an experimental evaluation of different mix design approaches to produced balanced mix designs (BMDs) utilizing locally available pavement materials. The current volumetric-based design method was enhanced with a performance-based analysis that specifies parameters from the overlay tester and Hamburg wheel tracking tests. Four typical Superpave mixes that exhibited poor performance especially in terms of cracking, were selected from different plants for this evaluation. The mixtures were first designed following the current volumetric-based design process and characterized under the proposed performance-based analysis. Two alternative approaches that consider the influence of the asphalt content and aggregate gradation were explored to improve the engineering behavior of the mixtures. From this evaluation, mixtures that could potentially yield optimal volumetric and balanced mechanical properties were developed. Adjusting the aggregate gradation is a promising approach to produce BMD mixtures following a volumetric analysis with performance verification design approach.

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Abstract

Asphalt mixtures must ideally exhibit acceptable cracking and rutting properties to perform well in the field. Improving the durability and long-term performance of asphalt mixtures has become a major concern, especially with the rapidly increasing use of recycled materials, warm mix asphalt additives and modified binders. Given that available mix design approaches rely mainly on stringent criteria for the volumetric properties of asphalt mixtures, mix design approaches that incorporate performance tests are needed to produce asphalt mixtures with balanced durability and stability performance.

This project presents an experimental evaluation of different mix design approaches to produced balanced mix designs (BMDs) utilizing locally available pavement materials. The current volumetric-based design method was enhanced with a performance-based analysis that specifies parameters from the overlay tester and Hamburg wheel tracking tests. Four typical Superpave mixes that exhibited poor performance especially in terms of cracking, were selected from different plants for this evaluation. The mixtures were first designed following the current volumetric-based design process and characterized under the proposed performance-based analysis. Two alternative approaches that consider the influence of the asphalt content and aggregate gradation were explored to improve the engineering behavior of the mixtures. From this evaluation, mixtures that could potentially yield optimal volumetric and balanced mechanical properties were developed. Adjusting the aggregate gradation is a promising approach to produce BMD mixtures following a volumetric analysis with performance verification design approach.

Implementation Statement

This research project comprehensively evaluated the concept of balanced mix design (BMD) for Superpave mixtures in Texas. In close collaboration with TxDOT personnel and project advisory committee (PAC), this study investigated the strengths and weaknesses of implementing the BMD concept into current mix design practices. The key findings and outcomes from this research project can be potentially used to produce durable and stable asphalt mixtures.

This research project provides implementable products and feasible modifications to mix design practices that will benefit TxDOT with solutions in engineering, environmental and economical areas. The proposed test protocols, design specifications and guidelines can be implemented to produce BMDs using locally available pavement materials. The implementation of the process is especially timely since TxDOT districts are incorporating more recycled materials, modified binders and additives to produce their asphalt mixtures.

To incorporate fully the BMD testing protocols, design specifications and guidelines generated from this research project, a comprehensive pilot study is recommended for investigating the field performance of BMD mixtures. An implementation project can be carried out to document thoroughly the formulation, production and construction of BMD mixtures containing different mix design variables such as aggregate gradation, aggregate types, binder source and grade, recycled material, and additives. The implementation project will provide assistance to districts to implement the concept and will establish specifications for quality control and acceptance, and construction of BMD mixtures.

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CHAPTER 1 – INTRODUCTION

Executive Summary

Most asphalt mixtures are primarily designed using Superpave system. The rutting problems have been minimized due to refined Superpave specifications leading to more appropriate asphalt binder and higher quality mineral aggregates (*Tran et al., 2019*). Unfortunately, many highway agencies are still concerned with premature cracking of their asphalt mixtures. While cracking problems may not be caused directly by Superpave design method, the ability of Superpave to discriminate the quality of current complex mix designs containing high recycled materials, modified asphalt binders and additives has been questioned. Superpave system originally included laboratory performance tests. However, the proposed performance test methods were not considered practical for routine use during the mix design process. Today, it is recognized that the current mix design system has some shortcomings including the need for performance testing and selection of optimum asphalt content for asphalt mixtures. Assessing the possibility of enhancing current practices by including performance tests in the design process is paramount to identify the underperforming asphalt mixtures and extend the performance of asphalt pavements.

With the goal of implementing the balanced mix design (BMD) concept in Texas, this project evaluated the strengths and weaknesses of current mix design process, performance testing protocols and design specifications. Challenges with the current mix design processes to yield BMD were documented through several typical mixes. The effectiveness of alternative design approaches proposed to improve the mechanical performance of the asphalt mixtures was also evaluated. Since more than 90% of the mix is the mineral aggregates, a rigorous evaluation of the aggregate gradation was carried out to improve the stability of the asphalt mixtures. Finally, the impact of selecting a wide range of mix design variables during the mix design process was assessed with a parametric evaluation of essential design variables such as aggregate type, binder type and source, and recycled material type and content. The study clearly demonstrates that BMD mixtures can be produced with acceptable volumetric and mechanical properties using a *volumetric design with performance verification approach*.

Objectives and Scope of Work

The main goal of this project was to provide TxDOT with a mix design program, testing protocols and corresponding specifications to produce BMD mixtures without significantly compromising the constructability of the final product. To achieve this goal, the following objectives must be addressed:

1. Evaluate current mix designs, design processes and guidelines in Texas and worldwide to identify the weaknesses and strengths of the current practices for balanced mix designs.
2. Collect laboratory data using test methods such as the overlay tester and Hamburg wheel tracking to assess the cracking and rutting performance of asphalt mixtures, respectively.

3. Evaluate a representative number of asphalt mixtures used by TxDOT through an experiment design process.
4. Develop specifications and guidelines that can be readily used to produce BMD with available local materials, recycled materials and additives.

The project was divided into the following three broad phases:

1. Phase I (*Feasibility*), which reported the state of the practice in TxDOT and other national and international agencies to select the most promising approaches.
2. Phase II (*Development*) consisted of a systematic effort to evaluate the performance of a large number of asphalt mixtures and to develop a program and testing protocols for designing balanced mix designs with specific raw materials, recycled materials and additives.
3. Phase III (*Verification*) included finalizing the guidelines and proposed specifications to properly account for the performance of the asphalt mixtures.

Report Organization

Aside from this introductory chapter, this report contains eight chapters. Chapter 2 presents a comprehensive review of relevant literature concerning the posed topic. Chapter 3 describes the experiment design plan and pavement materials studied in this project. Chapter 4 covers an assessment of two main design approaches that can be used to produce BMD mixtures. Chapter 5 consists of a parametric study conducted to optimize the aggregate gradation systematically for BMD mixtures. Chapter 6 reports the results from different aggregate gradations for BMD mixtures. Chapter 7 describes the process of formulating BMD mixtures with available pavement materials. Chapter 8 summarizes the results from testing BMD mixtures with varying mix design variables. Chapter 9 contains a summary of general conclusions and practical recommendations derived from this project.

The following appendices complement this report:

- Appendix A volumetric analysis of asphalt mixtures.
- Appendix B proposed BMD specifications.
- Appendix C pilot study for pavement field test sections.

CHAPTER 2 – LITERATURE REVIEW

Implementation of Superpave Design Method

The Superpave mix design method, implemented under the Strategic Highway Research Program (SHRP), has been used routinely to proportion asphalt mixtures (*Kennedy et al., 1994*). The incorporation of Superpave provided new opportunities for the selection of raw pavement materials, aggregate gradation and laboratory compaction method that were significantly different from the traditional dense-graded (DG) asphalt mixtures. Many Departments of Transportation (DOTs) have implemented the Superpave and corresponding acceptance specifications to produce asphalt mixtures. Superpave consists of three basic steps including selection of the aggregate structure, the asphalt binder performance grade (PG), and determination of optimum asphalt content based on a volumetric based analysis. Since the Superpave relies on volumetric properties (including voids in mineral aggregates, VMA, and voids filled with asphalt, VFA) and a target lab-molded density to determine the quality of an asphalt mixture (*McDaniel and Levenberg, 2013*), it may not provide enough information related to the engineering performance of the final product (*e.g., Witczak et al., 2002, Bonaquist et al., 2014, and Zhou et al., 2016*). The key to determining reliably the volumetric properties is a precise calculation of the aggregate bulk specific gravity (G_{sb}). However, the accuracy and repeatability of current laboratory procedures associated with the calculation of aggregate bulk specific gravity brings up a concern about whether the correct amount of asphalt is used in the mix design and production (*West et al., 2018b*). Asphalt mixtures with excessive asphalt binder can lead to permanent deformation (i.e., rutting), while those with lower asphalt binder content than the optimum can lead to cracking and other durability related pavement distresses (*Fee et al., 2018*). Due to the increase in the use of recycled materials, diverse recycling agents, warm mix asphalt additives, and modified asphalt binders, many organizations including TxDOT have questioned whether the Superpave volumetric-based design method alone is enough to ensure appropriate engineering performance for the asphalt mixtures.

State of Practice to Increase Asphalt Content of Asphalt Mixes

To improve pavement durability and long-term performance, many highway agencies have adopted strategies that focus on increasing the asphalt content. Some of these approaches include lowering the design air voids, lowering the design gyrations (N_{design}), and increasing the minimum VMA criteria (*West et al., 2018b*).

Lowering Design Air Voids

This approach requires a lower laboratory molded density. While the target air void content is decreased, the compaction effort and specimen preparation process are kept constant. By only decreasing the target air void content during the mix design process, the optimum asphalt content is consequently increased. The target air void content can be decreased from 4.0 percent, as required by AASHTO M323, to 3.0 or 3.5 percent if allowed by DOTs (*Tran et al., 2019*).

Lowering Gyration Level (N_{design})

Lowering the design gyration level (N_{design}) will generally result in an increase in the asphalt content. The research findings from NCHRP Project 9-9 indicated that the compaction efforts set by AASHTO R 35 using the Superpave gyratory compactor (SGC) were too high as compared to the densification of flexible pavements achieved due to traffic (*Prowell and Brown, 2007*). Lowering N_{design} can enable the use of asphalt mixtures with fine gradations, which sometimes are considered very dry due to the absorption of the asphalt binder as well as the limited space to accommodate effective asphalt binder in the aggregate skeleton. Several highway agencies have reduced the compaction efforts during mix design to increase the optimum asphalt content of an asphalt mixture (*Maupin, 2003*).

Increasing Minimum VMA

The voids in mineral aggregates (VMA) describes the inter-granular space between the aggregate particles in a compacted asphalt mixture, which includes the air voids and asphalt binder not absorbed by the mineral aggregate. Increasing the minimum VMA requirement tends to increase the optimum asphalt content. A 1% increase in VMA without changing the design air voids results in an increase in the optimum asphalt content of approximately 0.4% to 0.5% (*Tran et al., 2019*).

Air Voids Regression

This is a similar approach to lowering design air voids. In this approach, a mix is designed to meet all volumetric requirements including a target air void content of 4.0 percent. The asphalt content is then increased to achieve a reduced target air voids of 3.5 or 3.0 percent. A one-percent change in the design air voids with a constant VMA can increase the design asphalt content by up to 0.5 percent (*Tran et al., 2019*). The main concerns with this approach are that with the increased asphalt content the mixture may become susceptible to rutting (*West et al., 2018a*). Besides, even with the added binder the mixture may still not have satisfactory cracking resistance.

Several highway agencies have adopted some of these approaches to improve the quality of asphalt mixtures when using the volumetric-based design. Based on a survey by Aschenbrener (*2014*), seven DOTs had lowered the target design air voids, sixteen DOTs had decreased N_{design}, and eight DOTs had increased the minimum VMA requirement. Although those measures have resulted in potential improvements in the asphalt pavement performance, it is difficult to determine which approach is the most effective. In addition, those approaches may not be considered long-term solutions when advanced laboratory test methods have been developed and proposed to determine the engineering properties of asphalt mixtures.

Balanced Mix Design

Balanced mix design (BMD) is defined by the Federal Highway Administration (FHWA) Expert Task Group as (*Cox et al., 2017*):

"asphalt mix designed using performance tests on appropriately conditioned specimens that address multiple modes of distresses taking into consideration mix aging, traffic, climate, and location within the pavement structure"

Although performance testing is always central to BMD, the following three design approaches are the most common (*Aschenbrener et al., 2016*): 1) volumetric design with performance verification, 2) performance-modified volumetric mix design, and 3) performance design. Figure 2.1 depicts the steps associated with the alternative design approaches to produce BMDs.

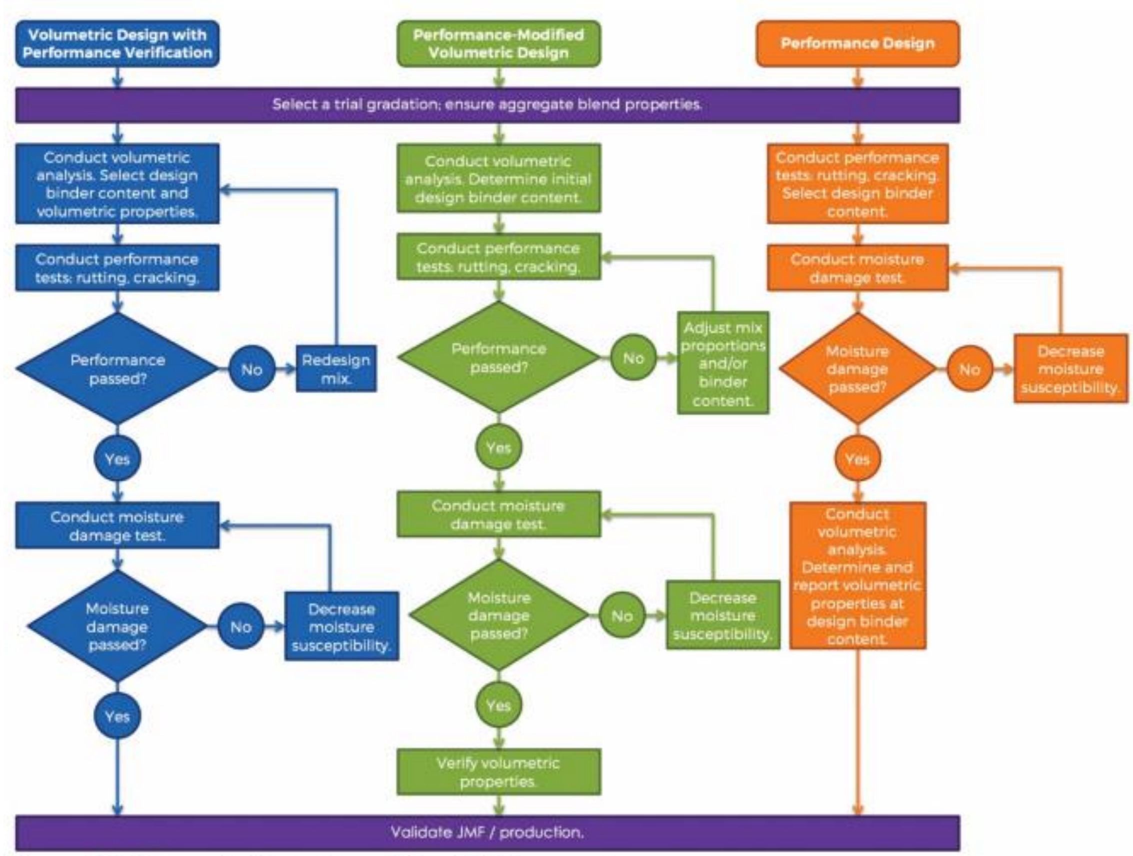


Figure 2.1 – Illustration of Design Approaches for BMD (Aschenbrener et al., 2016)

The *volumetric design with performance verification* consists of the commonly used volumetric-based design followed by performance testing of the mixture. If the trial mixture does not meet the performance criteria, the entire mix design process must be re-formulated. *Performance-modified volumetric design* approach starts with a volumetric-based design to estimate the feasible asphalt content and aggregate structure. The performance test results are then used to adjust the asphalt content to meet the performance requirements. This design approach focuses on meeting the performance test criteria since the final mix may not require meeting all volumetric requirements. Lastly, *performance-based design* approach produces mixtures based on a performance-based analysis alone. Once the laboratory test results meet the performance criteria, volumetric properties may be considered for the initial construction control.

Performance tests have been used more frequently due to the attention paid to the BMD concept. Several rutting and cracking tests have been developed and standardized to address pavement distresses. The rutting potential of asphalt mixtures can be characterized with performance test methods such as the Hamburg wheel tracking (HWT), asphalt pavement analyzer (APA) or permanent deformation tests. The crack susceptibility of these mixtures can be assessed using one of the several test methods available (*Zhou et al, 2016*). Zhou et al. (*2006*) recommended using the overlay tester (OT) and HWT tests to determine the cracking and rutting potentials of asphalt mixtures, while Cooper et al. (*2014*) proposed the energy release rate from the semi-circular bend (SCB) and HWT tests. Al-Qadi et al. (*2015*) proposed the HWT test and flexibility index from the SCB tests. Buttlar et al. (*2017*) utilized the disk-shaped compact tension (DCT) and HWT tests. They use a performance space diagram to simultaneously analyze the rutting and cracking performance indices and identify asphalt mixtures with balanced performance.

State of the Practice of Balanced Mix Design

With the popularity of more complex asphalt mixtures, the reliance of Superpave has become tenuous incurring the need for alternative approaches to design and select asphalt mixtures. From NCHRP Synthesis 492 "Performance Specifications for Asphalt Mixtures" (*McCarthy et al., 2016*), many DOTs highlighted that current volumetric mix design approach does not ensure long-term performance. To avoid durability and long-term performance problems, the incorporation of performance tests has been recommended for enhancing the mix design procedure (*Bhasin et al., 2004*). Although Superpave volumetric design approach does not require any performance tests, several highway agencies have investigated and implemented performance test methods to complete the selection of asphalt mixtures.

Texas Department of Transportation (TxDOT)

The Texas DOT (TxDOT) currently uses volumetric design with performance verification approach. The HWTT is used to evaluate the rutting resistance and moisture sensitivity and the OT to assess the cracking resistance. The BMD concept was originally developed by the Texas Transportation Institution (TTI) researchers. This approach sets a maximum asphalt content where the rutting criterion is exceeded and a minimum asphalt content to satisfy the cracking criterion, as shown in Figure 2.2. An asphalt content that lies between the minimum and maximum will represent the optimum asphalt content for a BMD. For most mixtures, it is possible to find a range where both rutting and cracking criterion are satisfied, but if a binder and aggregate combination do not pass performance testing criteria, the mix design must be re-formulated (*Zhou et al., 2014*).

California Department of Transportation (Caltrans)

Caltrans uses the performance-based specifications and the CalME (Caltrans' Mechanistic Empirical Design Program) to carry out a mix design. Performance testing includes repeated shear (AASHTO T 320), bending beam fatigue test (AASHTO T 321) and HWTT (AASHTO T 324). A short-term conditioning protocol of four hours at 135°C is required for repeated shear and HWTT (*Tsai et al., 2012*).

Illinois Department of Transportation (IDOT)

The Illinois DOT uses the Volumetric Design with Performance Verification approach with HWTT and I-FIT method to evaluate rutting and cracking resistance (*Al-Qadi et al., 2015*). To satisfy the performance criteria, the asphalt binder content, the asphalt binder source and the amount of recycled materials can be adjustments. However, the final volumetric properties must meet the Superpave mixture design system requirement.

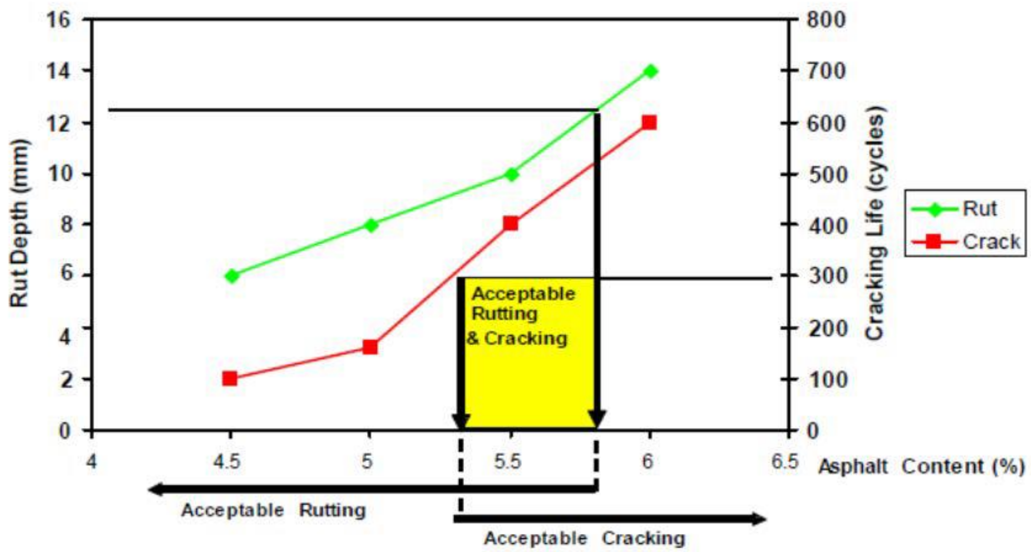


Figure 2.2 - Balancing Rutting and Cracking Requirements (*Zhou et al., 2014*)

Louisiana Department of Transportation and Development (LADOTD)

The Louisiana Department of Transportation and Development has complemented the conventional volumetric criteria with HWT test to asses rutting resistance and SCB tests for intermediate temperature cracking performance. Louisiana mixtures generally show adequate rutting resistance, so the balanced mixture design often result in increased asphalt content. Additionally, LADOTD changed specification requirements in 2013 to lower the number of gyrations at N_{design} and to increase the minimum VMA requirements (*Cooper et al., 2014*).

Wisconsin Department of Transportation and Development (WisDOT)

The Wisconsin DOT in association with the Wisconsin Asphalt Producers Association developed specifications to pilot the use of performance tests for mixtures with higher recycled materials content (*Hanz et al., 2017*). Following the BMD concept, the HWT test was selected to address the rutting resistance and moisture sensitivity, and the DCT test for low temperature cracking, and the SCB test for intermediate temperature cracking. Performance grading of the recovered asphalt binder is also required.

CHAPTER 3 – EXPERIMENT DESIGN

Review of Design Approaches and Specifications

The current TxDOT procedure (Tex-204-F), which includes Items 340 through 346A, contains a thorough explanation of the mix design process based on a volumetric analysis. The current mix design process consists of the following four steps:

- Step 1: Selecting Materials,
- Step 2: Preparing Laboratory Mixed Specimens,
- Step 3: Determining Optimum Asphalt Content (OAC), and
- Step 4: Evaluating Asphalt Mixture at OAC using Performance Tests (Optional)

Step 1 consists of selecting the binder source and performance grade, aggregate source and gradation, and additives and recycled materials. The designer tries out different trial aggregate gradations that best suits the intended use and the local experience. Step 2 requires the preparation of laboratory-prepared specimens utilizing a Superpave gyratory compactor (SGC), while Step 3 consists of evaluating the volumetric properties of the laboratory-prepared specimens to determine optimum asphalt content (OAC) at the selected target density. The VMA is considered as the main volumetric parameter since the requirement limits have already been established and extensively used. For the selected mix design type and gradations, a minimum VMA of 15% must be achieved to accept the mix design. **Equation 3.1** is used to compute the VMA parameter.

$$VMA = 100 - \frac{Gmb*100}{Gmm} + \frac{G_{mb}*P_b}{G_b} \tag{3.1}$$

where G_{mb} is mixture bulk specific gravity, G_{mm} is mixture theoretical maximum specific gravity, P_b is percent binder content, and G_b is asphalt binder specific gravity.

Several other parameters were considered in this study. The equations for the film thickness (FT), dust to binder (DB) ratio, percent of binder effective (P_{be}), voids in coarse aggregate from the mixture (VCA_{mix}), and voids filled with asphalt (VFA) are presented in ***Appendix A*** Step 4 was recently incorporated to evaluate the mechanical properties of the asphalt mixture utilizing the indirect tension test (Tex-227-F) and Hamburg wheel-tracking test (Tex-242-F). Since each of these steps may provide insight into the performance of mix, it is paramount to evaluate and enhance them in order to effectively implement the concept of balanced mix design into current design and evaluation processes. In this study, the overlay tester test (Tex-248-F) was also included to assess the cracking resistance of the asphalt mixtures.

In addition to the *volumetric design with performance verification*, the *performance-based design* introduced in the previous chapter was evaluated. Same mix designs, pavement materials and performance tests methods were used to compare the effectiveness of both design approaches.

Mixture and Pavement Materials Characteristics

Mix design and corresponding pavement raw materials were collected from different locations in Texas. The selection of the mix designs was done based on the experiments to be conducted. For the evaluation of aggregate gradation, four mixes that specify a single aggregate source were selected. Four typical Superpave mix designs that exhibited poor performance in terms of cracking, rutting or both, were selected from different plants to investigate the implementation of the BMD concept into current practices. The mixtures were first designed following the current volumetric analysis with performance verification design approach outlined under ITEM 344 "Superpave Mixtures."

Mixes typically used by four different asphalt plants in different regions of Texas were included in this evaluation. To properly simulate the production of this mix design in the laboratory, the specified aggregate sources, binder type and source, recycled material, and additives were collected for the selected mix designs. These Superpave mixes had a nominal maximum aggregate size (NMAS) of 12.5 mm (1/2 in., designated as SP-C). The mixtures were originally designed following TxDOT Item 344 specification (similar to AASHTO M 323). Detailed mix design information including binder performance grade (PG), number of gyrations, aggregate type and recycled material content is summarized in Table 3.1. The mix from Plant 1 (hereafter referred to as "TMD 1") exhibited poor cracking properties, the mix design from Plant 2 (hereafter referred to as "TMD 2") exhibited poor cracking and rutting properties, the mix design from Plant 3 (hereafter referred to as "TMD 3") exhibited poor cracking properties and the mix design from Plant 4 (hereafter referred to as "TMD 4") exhibited poor rutting properties.

Table 3.1 Summary of mix design information and pavement material characteristics

Parameters		TMD 1	TMD 2	TMD 3	TMD 4
Design Information	NMAS	12.5 mm (1/2")			
	Specified Binder PG	PG 70-22		PG 64-22	PG 58-28
	Number of Gyrations	50		75	50
	Target Density, %	96			
	Aggregates Types	Granite/Dolomitic-Limestone	Soft Limestone	Granite/ Dolomitic-Limestone	
	RAP, %	16	20	20	10
	RAP Asphalt Content, %	5.9	4.2	4.6	6.6
	RAS, %	-	-	-	3
	RAS asphalt content, %	-	-	-	20.4

Four different aggregate types including a dolomite, granite, gravel and soft limestone aggregates were included in this study in order to evaluate the influence of the gradation on the volumetric and mechanical properties of the mixtures. Detailed information about the aggregate properties is provided in Table 3.2. Figure 3.1 illustrates the typical aggregate shape of the selected aggregates. Item 344 "Superpave Mixtures" was followed to conduct a separate mix design for each of the selected gradations and aggregate types. The mixtures were designed using 50 gyrations (N_{des}=50 gyrations at 1.25° angle of gyration). The optimum asphalt content (OAC) was determined as the asphalt content required to achieve 4% air voids at N_{des}. A single source of asphalt binder that met a performance grade (PG) 64-22 was used to produce all mixtures with different gradations.

Table 3.2 - Properties of Mineral Aggregates

Parameter	Aggregate Type			
	Dolomite	Granite	Gravel	Soft Limestone
Los Angeles Abrasion (LA)	27	28	19	32
Soundness Magnesium (SSM)	3	14	4	18
Micro-Deval (SMD)	11	10	4	21
Acid Insoluble (SAI)	2	94	93	2
Aggregate Crushing Value (ACV), %	25	21	14	30
Aggregate Impact Value (AIV), %	27	28	22	22
Surface Aggregate Classification (SAC)	B	A	A	B

Figure 3.1 - Illustration of Aggregate Shape from 3/8" Sieve Size

Performance Tests

The overlay tester (OT, as per test procedure Tex-248-F) and Hamburg wheel-tracking (HWT, as per test procedure Tex-242-F) tests were used to evaluate the mechanical properties in terms of durability and stability, respectively. The indirect tension (IDT, as per test procedure Tex-226-F) test was also included in this study for reference purposes.

Overlay Tester (OT) Test

The OT test can be seen in Figure 3.2 along with an insight of the actual test specimen being placed for testing. The OT test is conducted in a displacement control mode at a loading rate of one cycle per 10 sec. The movement of the sliding platen follows a cyclic triangular waveform at a test temperature of 77°F (25°C). The OT specimens are nominally 6 in. (150 mm) long, 3 in. (75 mm) wide and 1.5 in. (38 mm) thick compacted to nominal target air voids of 7±1.0%. The crack progression rate (CPR) parameter from the OT test was used in this study (*Garcia et al., 2016*). CPR represents the flexibility of the mixture to attenuate the propagation of a crack as shown in Figure 3.5a. The acceptance limit for CPR was selected as 0.45 for Superpave mixtures.

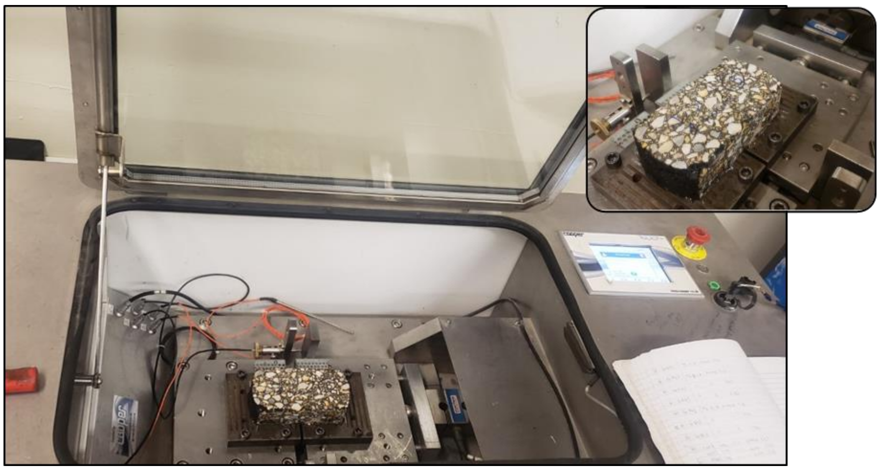


Figure 3.2 - OT Device and Specimen Setup

Hamburg Wheel Tracking (HWT) Test

The HWT test is conducted to determine the permanent deformation and moisture susceptibility of asphalt mixtures. Figure 3.3 depicts two sets of specimens on the HWT device. A load of 158 ± 5 lb (705 ± 22 N) is applied through a steel wheel at 50 passes across the specimen per minute. A water bath with a temperature of 122 ± 2°F (50 ± 1° C) is used to condition the specimens. The specimens are nominally 6 in. (150 mm) in diameter and 2.5 in. (62 mm) in height. The main output parameters from the HWT test are the number of passes and rut depth (Figure 3.5b). The requirements for HWT test are shown in Table 3.3. Wu et al. (*2017*) recommended the rutting resistance index (RRI) for the HWT test using:

$$\mathrm{RRI} = \mathrm{N} \times (1 - \mathrm{RD}) \tag{3.1}$$

where N is the number of cycles and RD is the rut depth (in.).

The minimum RRI requirement for each PG is also shown in Table 3.3. For convenience, RRI is normalized with respect to the minimum RRI for comparing mixes with different PG binders. Normalized RRI (NRRI) is calculated from:

$$\text{NRRI} = \frac{Actual\ RRI}{Minimum\ RRI\ for\ Specified\ PG} \tag{3.2}$$

NRRI of unity or greater means an acceptable mix in terms of rutting.

Figure 3.3 - HWT Device and Specimen Setup

Table 3.3 - Hamburg Wheel Tracking (HWT) Test Requirements

High-Temperature Performance Grade	Minimum Number of Passes	Minimum RRI
PG 58	5,000	2,600
PG 64	10,000	5,100
PG 70	15,000	7,600
PG 76	20,000	10,100

PG = performance grade; RRI=rutting resistance index

Indirect Tension Strength Test

The IDT specimens, which are nominally 6 in. (150 mm) in diameter and 2.4 in. (62 mm) in height, are placed in an environmental controlled chamber at a temperature of 77 ºF (25 ºC) for preconditioning before testing. The IDT test is performed on a displacement-controlled mode at a rate of 2 in./min (50 mm/min) until the specimen completely fractures. During the overall testing period, the time, load, and displacement are recorded. A universal testing frame was used for application of the load, whereas an IDT jig was used for testing as can be seen in Figure 3.4. The indirect tensile strength (ITS) is the main output from the IDT test that is calculated from

$$\text{ITS} = \frac{2P_{max}}{\pi t D} \tag{3.3}$$

where P_{max} is the maximum peak load, and *t* and *D* are the thickness and diameter of the specimen, respectively. TxDOT specifies a minimum and maximum tensile strength of 85psi and 200 psi for mixtures with any asphalt binder PG.

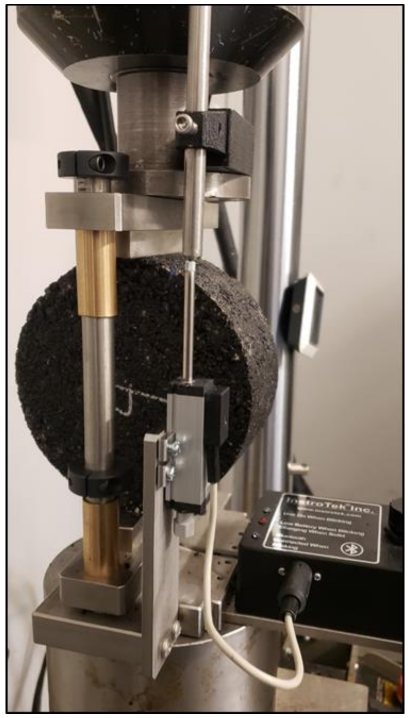


Figure 3.4 - IDT Device and Specimen Setup

In addition to the ITS parameters, the cracking tolerance (CT) index was calculated from the IDT test data. The work of failure (W_f) can be calculated as the area under the load versus displacement curve. The failure energy (G_f) can be evaluated using the work of failure and the cross-sectional area of the specimen using:

$$G_f = \frac{W_f}{Dt} \qquad (3.4)$$

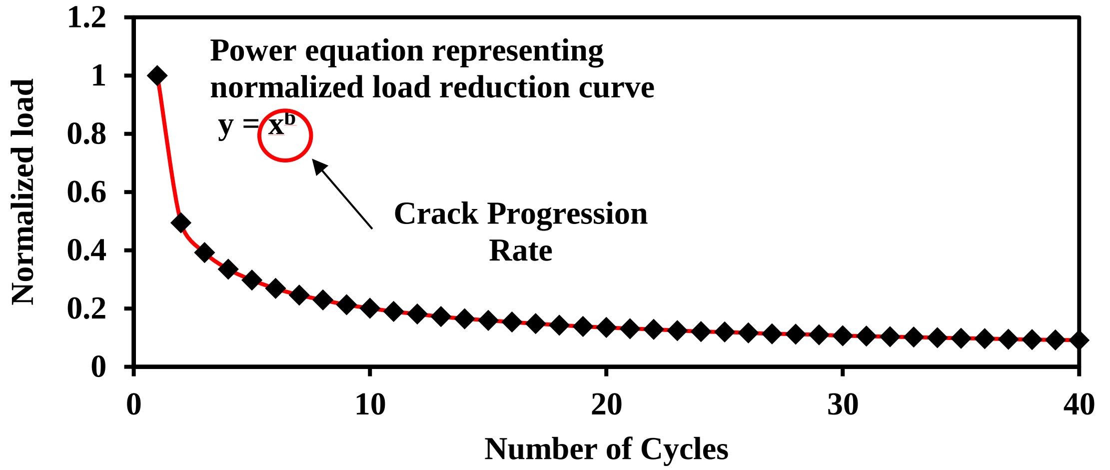
where t and D are the thickness and diameter of the specimen, respectively.

Eventually, CT Index is calculated using the parameters obtained from the load-displacement curve Zhou et al. (*2017*) using:

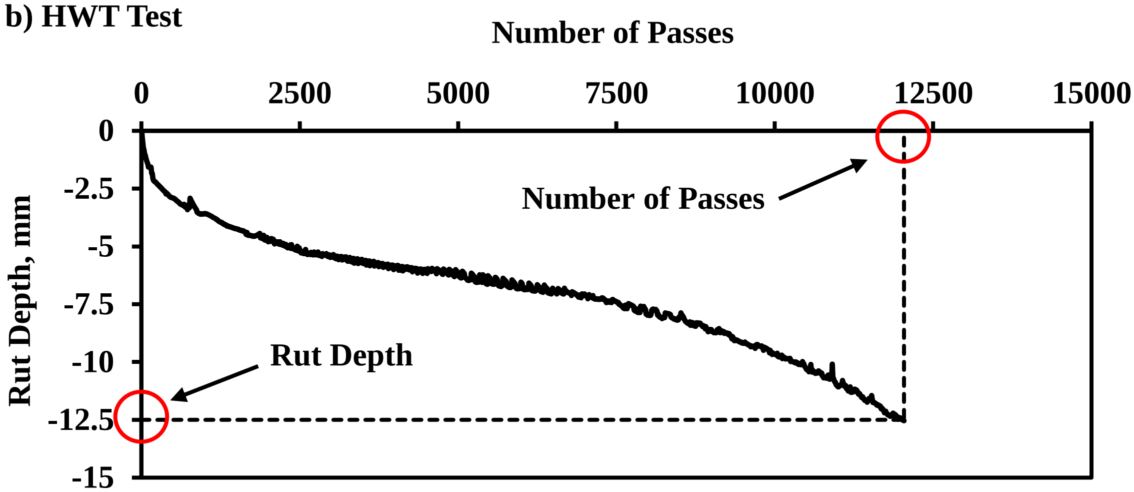
$$CT_{Index} = \frac{t}{2.4} \times \frac{l_{75}}{D} \times \frac{G_f}{|m_{75}|} \times 10^6 \qquad (3.5)$$

where, |m75| is the absolute value of the post-peak slope and l75 is the associated displacement at 75% of the peak load located after the peak.

a) OT Test



b) HWT Test



c) IDT Test

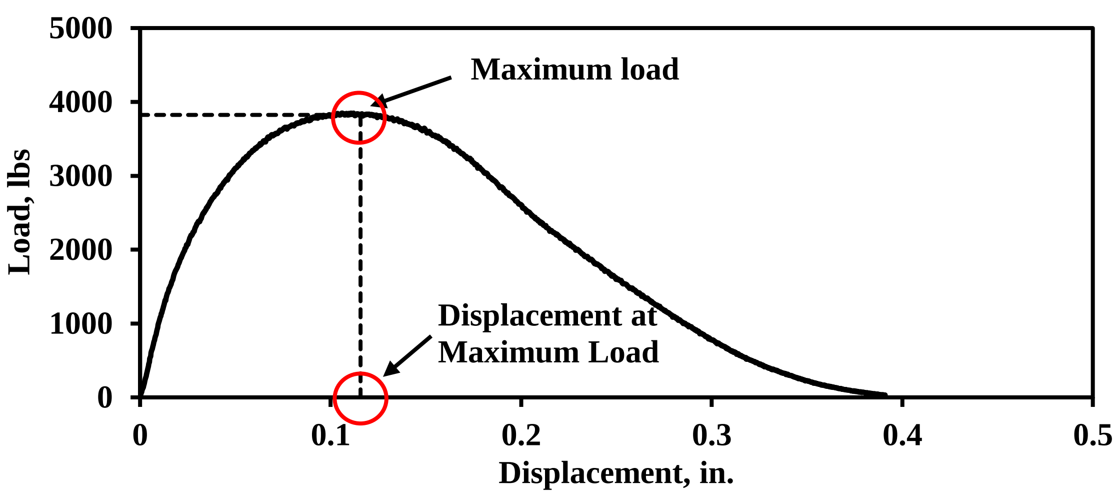


Figure 3.5 - Performance Tests Data and Analysis Methodologies

Performance Space Diagram

The performance space diagram provides a multifaceted analysis of the mechanical properties of asphalt mixtures in terms of cracking, rutting and toughness. As shown in Figure 3.6, CPR from OT test is plotted on the abscissa with a corresponding acceptance limit of 0.45, while NRRI from HWT test is plotted on the ordinance with an acceptance limit of 1.0. The performance indicators from IDT are shown as a data label.

Asphalt mixtures can be preliminarily divided into the following four general categories:

- Quadrant 1: Acceptable cracking resistance (flexible) and rutting resistance (rigid).
- Quadrant 2: Poor cracking resistance (brittle) and good rutting resistance (rigid).
- Quadrant 3: Acceptable cracking resistance (flexible) but poor rutting resistance (unstable).
- Quadrant 4: Poor cracking resistance (brittle) and rutting resistance (unstable).

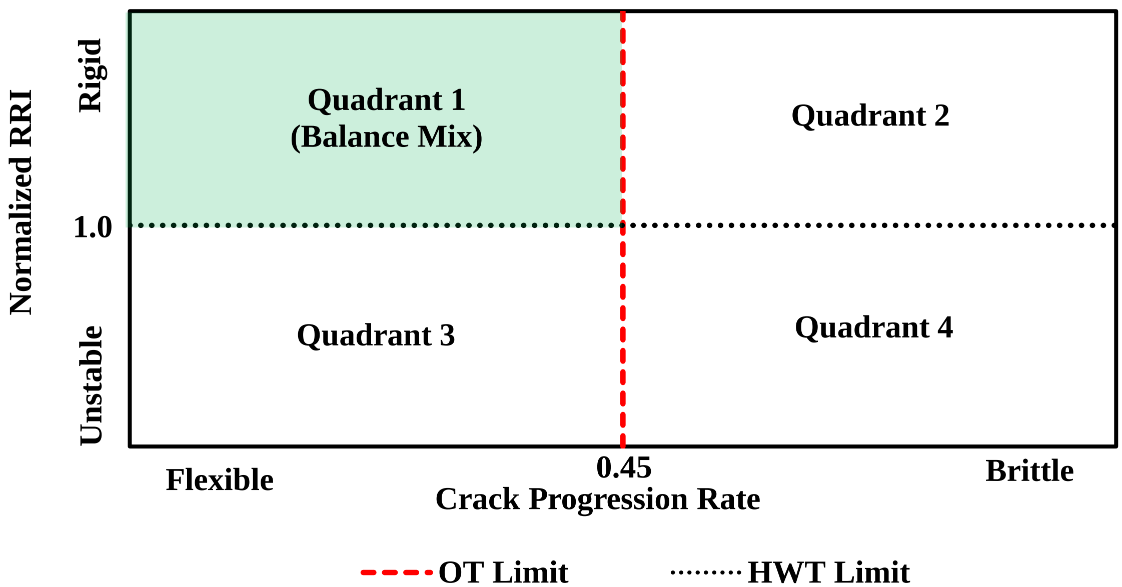


Figure 3.6 - Performance Space Diagram for Balanced Mix Design

CHAPTER 4 – DESIGN APPROACHES FOR BALANCED MIX DESIGN

This chapter reports on a comparison of designing two asphalt mixtures following the *volumetric based design with performance verification* and *performance-based design* approaches. The pavement materials from Plants 1 and 2 (see Table 3.1) were used to reproduce the aggregate gradations shown in Figure 4.1. These aggregate gradations are commonly used by the selected asphalt plants. Regardless of the mix design approach, the OT, HWT and IDEAL CT tests were utilized to assess the cracking, rutting and toughness of the asphalt mixtures. The strengths and challenges of the two mix design approaches are highlighted for further evaluation.

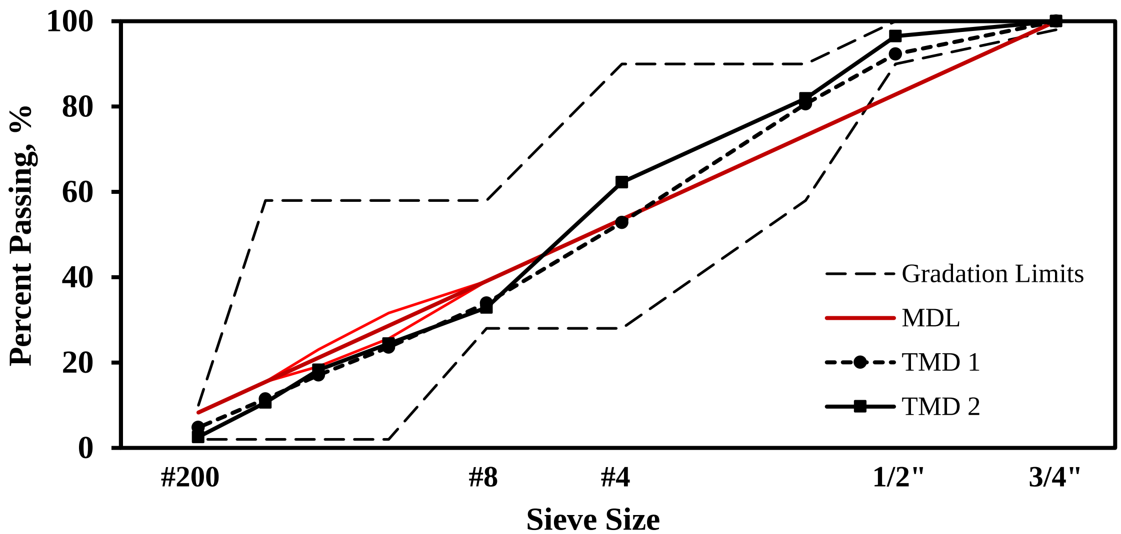


Figure 4.1 - Particle Size Distribution of TMD Mixtures

Volumetric Based Design with Performance Verification Approach

The volumetric properties of TMD 1 and TMD 2 mixtures are shown in Table 4.1. Both TMD 1 and TMD 2 mixes were originally designed following the volumetric-based design process using criteria for a SP C mix as specified in TxDOT Item 344 specifications (similar to AASHTO M 323). The mixtures were designed with a Superpave gyratory compactor to meet a 96% target density at 50 gyrations (N_{design}). The OAC for TMD 1 mix was determined to be 4.7%, while TMD 2 mix yielded an OAC of 4.6%. The VMA for TMD 1 mix was determined to be 15%, while TMD 2 mix yielded a VMA of 14.7%. Only TMD 1 mix met the minimum VMA requirement of 15%.

Although the aggregate gradation for TMD 2 mix would need to be adjusted to meet the minimum VMA requirement, performance testing was still performed for both TMD mixtures. Figure 4.2 depicts the CPR values from the OT tests for the two TMD mixtures. Based on the COVs shown as data labels, the OT test yielded consistent results with acceptable variability (COV < 20%). From the OT test results, TMD 1 mix yielded an average CPR of 0.57, which is greater than the maximum acceptance limit of 0.45. TMD 2 mix yielded an average CPR of 0.49, which is also greater than the maximum acceptance limit of 0.45. Therefore, TMD 1 and TMD 2 mixes can be considered cracking susceptible mixtures.

Table 4.1 - Summary of Volumetric Properties for TMD Mixtures

Parameters		TMD 1	TMD 2
Volumetric Properties	Optimum Asphalt Content, %	4.7	4.6
	Voids in Mineral Aggregates, %	15.0	15.0
	Bulk Specific Gravity	2.369	2.379
	Maximum Specific Gravity	2.470	2.486
	Recycled Binder Ratio	19.1	18.7

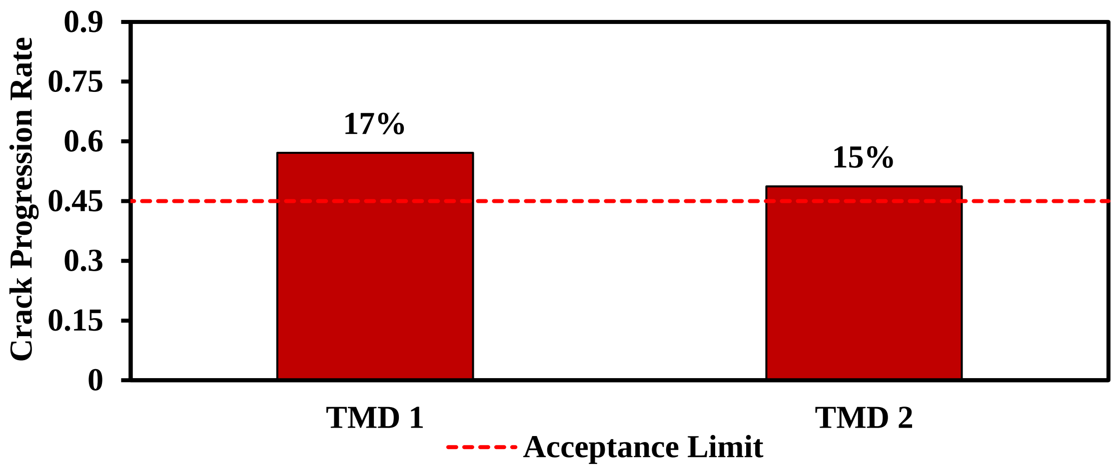


Figure 4.2 - OT Test Results for TMD mixtures

The HWT test results are presented in Figure 4.3. The minimum RRI for mixtures designed with PG 70-22 binder is 7600. NRRI is reflected as a data label. TMD 1 mix yielded an RRI of 14881 and TMD 2 mix yielded an RRI of 5481. TMD 1 mix satisfactorily met the rutting requirements, while TMD 2 mix did not pass the rutting requirement for a PG 70-22 binder.

The mechanical properties of the TMD mixtures are presented in the performance interaction diagram in Figure 4.4. As a reference, CT index is shown as a data label. TMD 1 mix exhibited satisfactory rutting resistance with a NRRI of 1.9 but poor cracking resistance as discussed before. Therefore, TMD 1 mix is categorized as a crack-susceptible mix design. TMD 2 mix did not meet the minimum performance requirement for HWT test with a NRRI of 0.72 and yielded a CPR of 0.49. Therefore, TMD 2 mix is categorized as a rut- and crack-susceptible mix design. Based on CT index values of 65 and 22, TMD 1 and TMD 2 mixtures are also both crack suspectable.

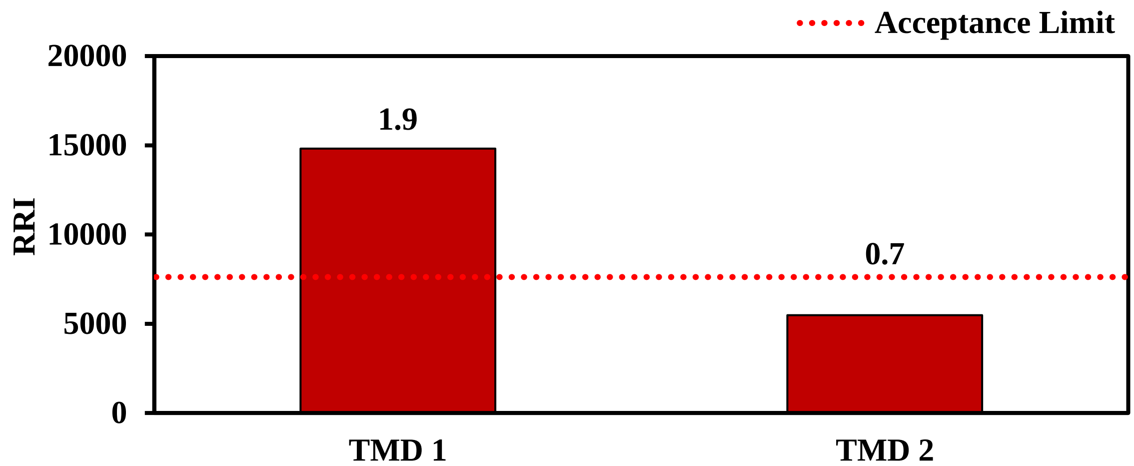


Figure 4.3 - HWT Test Results for TMD mixtures

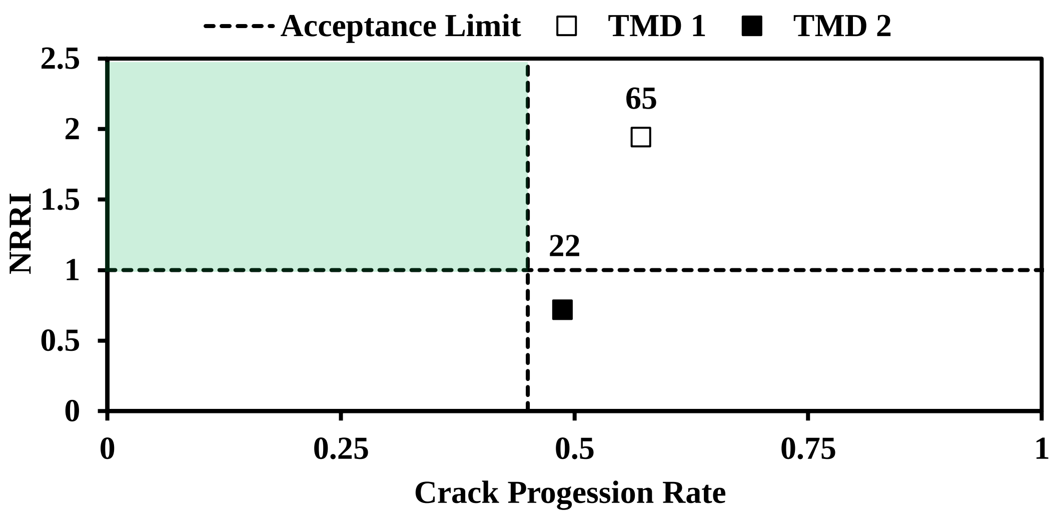


Figure 4.4 - Performance Space Diagram for TMD 1 and TMD 2 Mixtures

Performance Based Design Approach

As part of the *performance-based design* approach, performance tests are carried out at different asphalt contents. The optimum asphalt content (OAC) is then selected based on the performance requirements of the test methods. Laboratory specimens for OT and HWT tests were prepared at four asphalt contents including OAC, OAC-0.5%, OAC+0.5% and OAC+1.0%. Figure 4.5a presents the variations of the CPR and NRRI with respect to asphalt content for TMD 1 mix. Even though NRRI decreased from 2.3 to 1.8 as the asphalt content increased, specimens prepared with all four asphalt contents met the minimum performance requirements for HWT test. CPR decreased from 0.97 to 0.42 as the asphalt content increased. Only specimens at OAC+1.0% (5.7%) passed the OT test requirements of 0.45 or less.

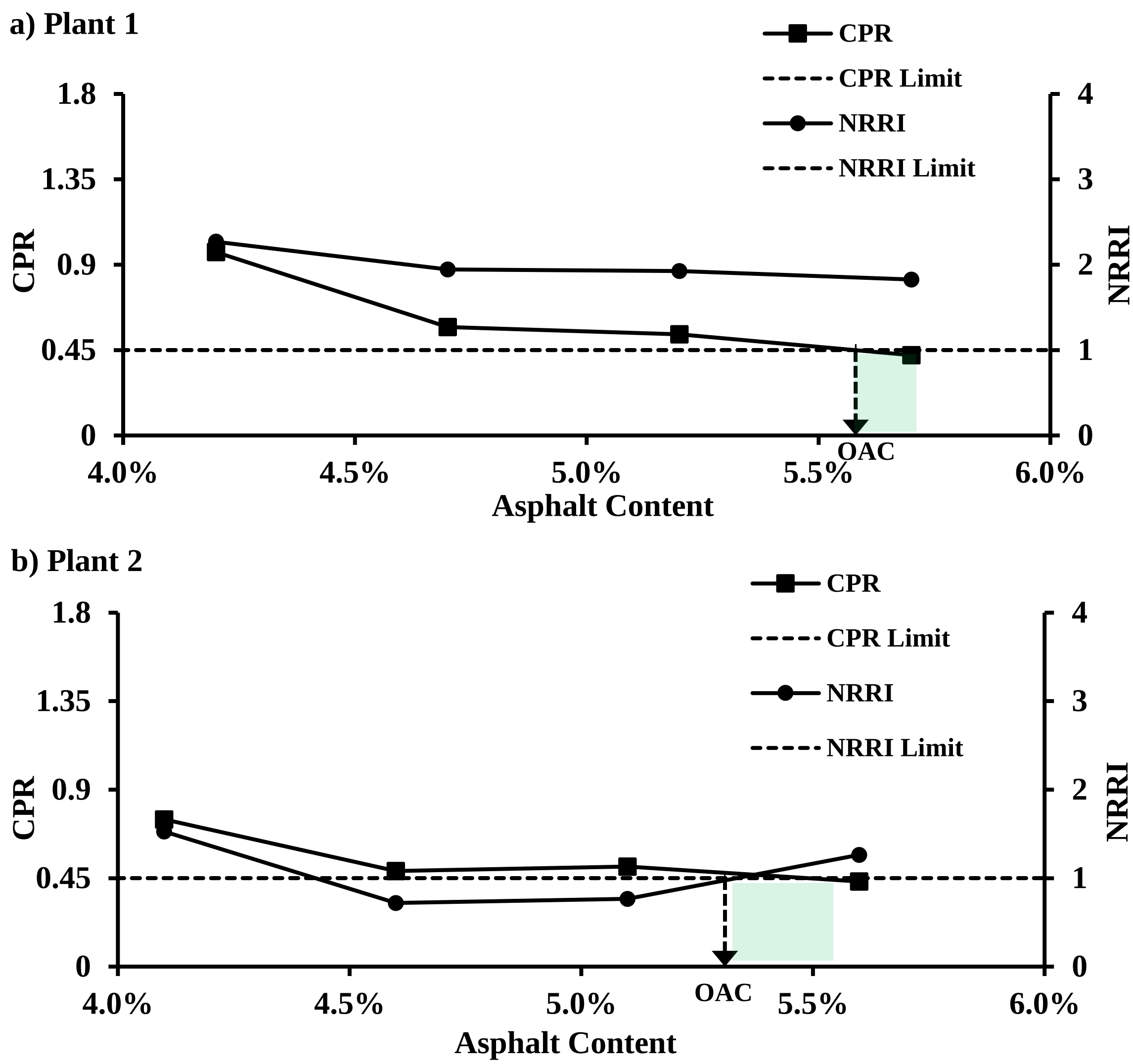


Figure 4.5 - Performance-Based Selection of Optimum Asphalt Content

Similar information is shown in Figure 4.5b for TMD 2 mix. Again, specimens at OAC+1.0% (5.6%) met the performance requirements for OT and HWT tests. The increase in NRRI for specimens at OAC+1.0% can be explained by the fact that when there was enough binder in the mixture to provide a binder film thickness that reduced the aggregate crushing under the HWT test. To produce a mix with balanced cracking and rutting potentials, TMD 1 and TMD 2 mixes must contain a minimum asphalt content of 5.3% and 5.2%, respectively, as illustrated by the shaded regions in Figure 4.5.

A summary of the results from the performance test methods for TMD 1 and TMD 2 is presented in Table 4.2. The OT test results yielded COVs less than 25%, except for TMD 2 produced at OAC-0.5% (4.1%), which was a very stiff mixture. The COVs for IDT tests were between 25% and 10%.

Table 4.2 - Performance Test Results of Mixtures at Different Asphalt Contents

Mix	Parameters			OAC-0.5	OAC	OAC+0.5	OAC+1
TMD 1		Asphalt Content		4.2%	4.7%	5.2%	5.7%
	OT	CPR	Avg.	0.97	0.57	0.53	0.42
			COV	25%	17%	23%	10%
	HWT	RRI	RRI	17283	14811	14677	9278
			NRRI	2.3	1.9	1.9	1.8
	IDT	CT Index	Avg.	22	65	71	142
			COV	21%	23%	10%	19%
TMD 2		Asphalt Content		4.1%	4.6%	5.1%	5.6%
	OT	CPR	Avg.	0.75	0.49	0.51	0.43
			COV	44%	15%	16%	6%
	HWT	RRI	RRI	11630	7419	5843	9624
			NRRI	1.5	1.0	0.8	1.3
	IDT	CT Index	Avg.	13	18	39	75
			COV	19%	22%	18%	25%

The state of the practice in the production and placement of asphalt mixtures during construction requires a quality control process. This is currently done by following a set of pre-defined volumetric criteria, specifically a target lab molded density and VMA. The VMA and lab-molded densities of the TMD mixtures with different asphalt contents are depicted in Figure 4.6. For TMD 1 mix, the minimum VMA of 15% for a SP C mix is achieved irrespective of the asphalt content. In the contrary, only TMD 2 mix with OAC-0.5% (4.1%) met the minimum VMA requirement.

A target lab-molded density of 96% ±1% of theoretical maximum density is currently used in the design to assess the consistency of the asphalt mixture. For the evaluated mixtures, the lab-molded densities varied from 93% to 99%. TMD 1 and TMD 2 mixtures with asphalt contents of 5.2% or more (to satisfy the performance test requirements for a balanced mix design) yielded lab-molded densities of 98.4% and greater of their theoretical maximum densities. These values raise concerns about the durability of the mixtures.

Key Remarks and Findings

The evaluation of two typical mix designs revealed that the current mix design practices tend to produce crack susceptible mixtures. This phenomenon can be attributed to the low asphalt contents selected for the mix designs (typically lower than 5.0%). This low asphalt content is the result from selecting aggregate gradations that are very close to the maximum density line. This type of aggregate gradations is optimized only in terms of volumetric properties, while the asphalt mixture may not exhibit acceptable mechanical performance.

Regardless of the mix design approach, *volumetric design with performance verification* and *performance-based design*, the main challenge to produce asphalt mixtures with improved mechanical performance is to select mix designs with higher asphalt contents.

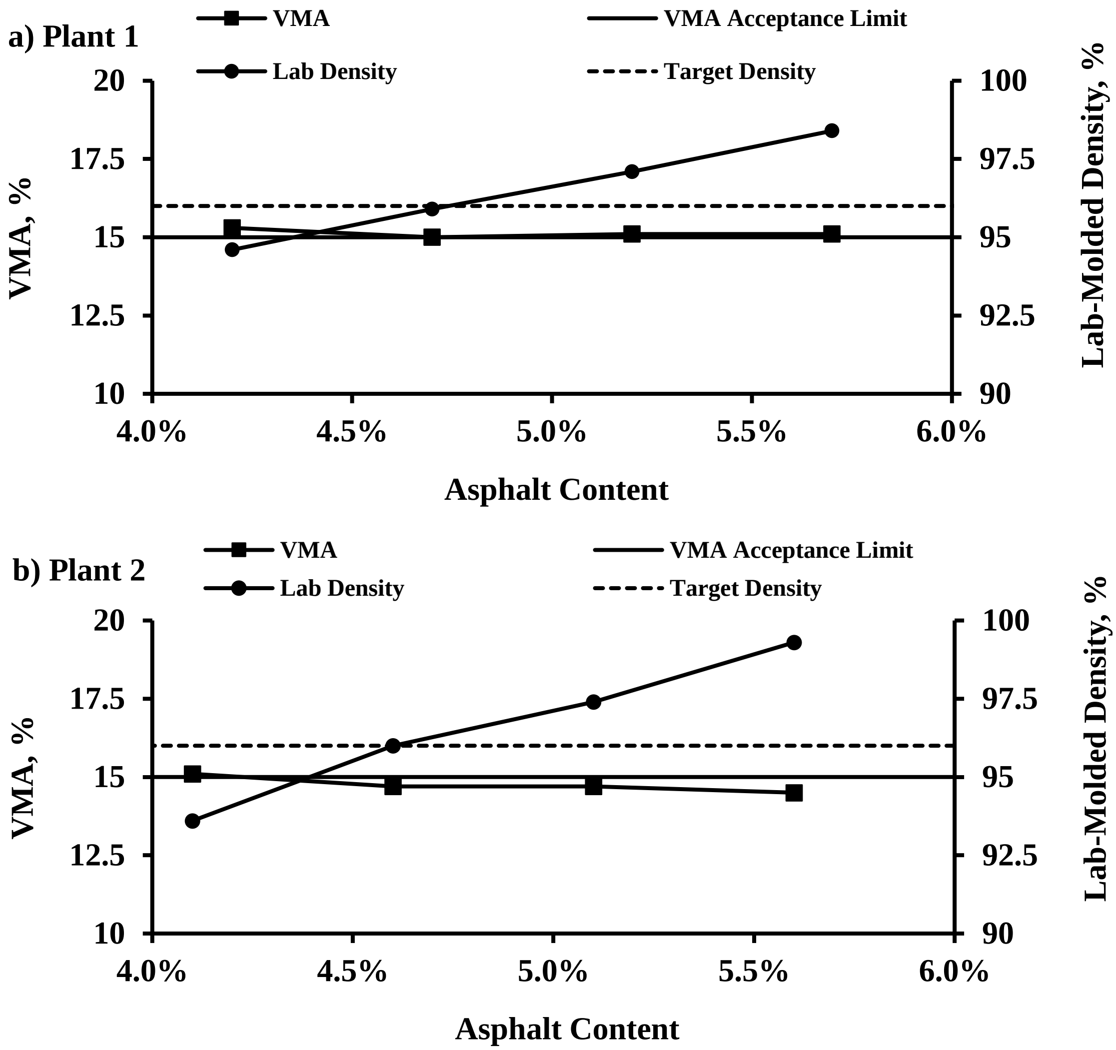


Figure 4.6 - Altered Aggregate Gradations for TMD 1 Mixture

CHAPTER 5 – OPTIMIZATION OF AGGREGATE GRADATION

Review of Superpave Mix Design Method

While Superpave design methods provides detailed information regarding the selection of asphalt binder and aggregate types to produce a high-quality asphalt mixture, these volumetric properties are directly influenced by the packing of the aggregate particles and space created within the aggregate skeletons. Several state highway agencies (SHAs) have implemented guidelines to design properly an aggregate skeleton that can yield desired volumetric properties. Yet, current practices for aggregate gradation selection is mainly driven by optimization of the VMA and OAC of the asphalt mixture.

Superpave Specifications for Aggregate Gradation Selection

Current TxDOT design specifications included in test procedure Tex-204-F, Items 340 through 346A, contain a thorough explanation of the mix design process. Items 340 through 346 mix design processes prescribe upper and lower gradation band limits for different mix types. As an example, Figure 5.1 shows the gradation limits for Item 344, Superpave (SP) Type C (12.5 mm NMAS) and Superpave Type D (9.5 mm NMAS) mixtures. The percentages of the aggregates from the available material bins are calculated so that the combined gradation falls within the specified gradation limits for the specific mix type. Several combinations of bin proportions may produce a gradation that lies within the limits. Volumetric requirements are also prescribed in the TxDOT mix design procedures to better constrain the acceptable gradations. More comprehensive guidelines are desirable so that the designers can select an optimal gradation more objectively. An optimized aggregate gradation must provide adequate particle interlock to distribute more effectively the stresses that develop within the pavement structure.

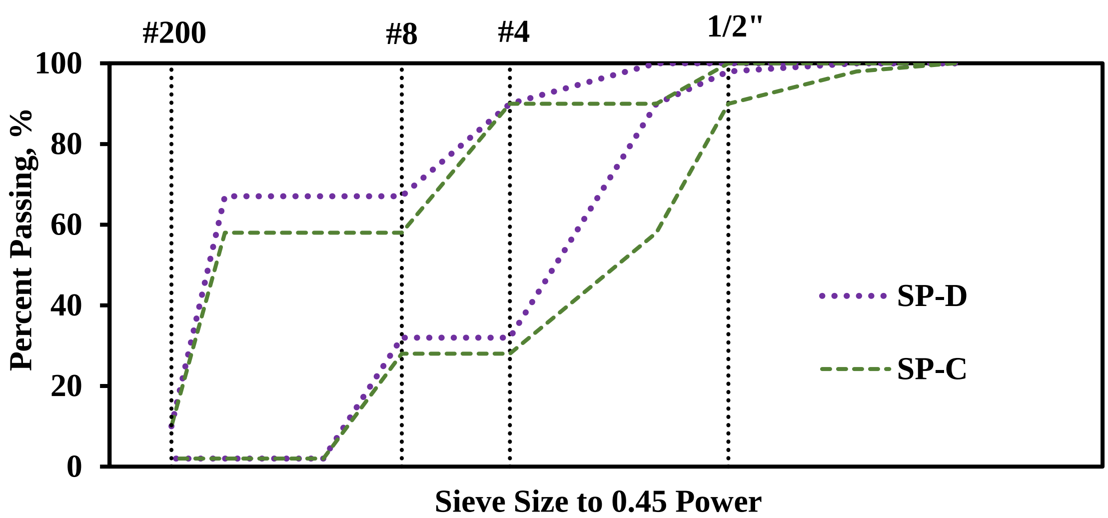


Figure 5.1 - Aggregate Gradation Limits for Item 344 – Superpave Mixes

Selection of Aggregate Gradation for Superpave Mixtures

Vavrik et al. (*2001*) proposed the Bailey method for aggregate gradation selection. The Bailey method takes into consideration the packing characteristics of the coarse and fine aggregates and provides quantifiable criteria that could be used to optimize the volumetric properties of the combined aggregate gradation. As illustrated in Figure 5.2, Bailey method uses the following parameters to characterize the gradation curve:

1. Primary Control Sieve (PCS) that defines the boundary between the coarse and fine aggregates and that controls the aggregate structure;
2. Coarse Aggregate (CA) ratio that influences the packing of the fine fraction;
3. Fine Aggregate Coarse Fraction (FA_c) ratio that impacts the packing of the overall fine fraction in the combined blend; and
4. Fine Aggregate Fine Fraction (FA_f) ratio that influences the packing of the fine portion of the gradation in the blend.

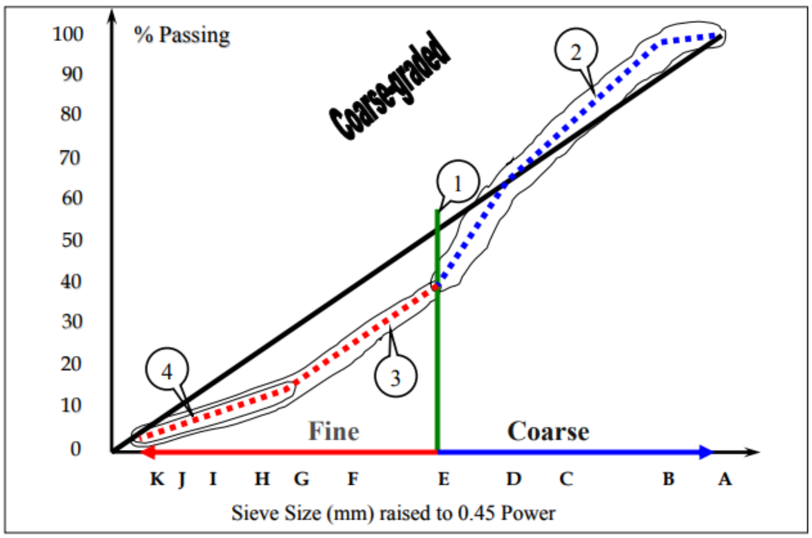


Figure 5.2 - Four Bailey Method Principles (*Vavrik et al., 2001*)

Three parameters are calculated using the following three equations:

$$CA\ Ratio = \frac{\%\,HS - \%\,PCS}{100\% - \%\,HS} \tag{5.1}$$

$$FA_c\ Ratio = \frac{\%\,SCS}{\%\,PCS} \tag{5.2}$$

$$FA_f\ Ratio = \frac{\%\,TCS}{\%\,SCS} \tag{5.3}$$

where SCS = secondary control sieve, TCS = tertiary control sieve (TCS), and HS = half sieve. Briefly, PCS, SCS, TCS and HS are derived from the nominal maximum aggregate size (NMAS).

The Bailey method uses an optimization approach to formulate a combined aggregate gradation and provides established acceptance criteria for the gradation parameters. However, if the proposed aggregate gradation does not satisfy the volumetric requirements, the designer must interactively adjust the input information until the formulated aggregate gradation yields the desired volumetric properties. Like the current practices for designing AC mixtures, the designer's experience will play a crucial role in the proper optimization of an aggregate gradation that can achieve acceptable volumetric properties.

Parametric Study on Aggregate Gradation

A four-level factorial experiment design was developed to investigate the influence of aggregate gradation on the volumetric properties and mechanical performance of AC mixtures. The experiment design plan consisted of a systematic perturbation of the aggregate gradation for a Superpave mix design with a 12.5 mm (0.5 in.) nominal maximum aggregate size (NMAS). Figure 5.3 shows the combined aggregate gradation (referred to as "Control" gradation hereafter) that was formulated to satisfy the acceptance limits for the gradation parameters of the Bailey method. The dashed lines on the figure represent the gradation limits for SP C mixtures. The maximum density line for the formulated gradation was also added and is represented with the solid line in Figure 5.3. Table 5.1 summarizes the gradation parameters. Considering the recommended limits proposed by Vavrik et al., the results were highlighted in green, yellow and red for values that are within, below or above the recommended values, respectively. The influence of the four gradation parameters (e.g. PCS, CA, FA_c and FA_f) was investigated by altering the coarse and fine portions of the gradation as depicted in Figure 5.4. For each gradation parameter, four levels of perturbations were considered as summarized in Table 5.1.

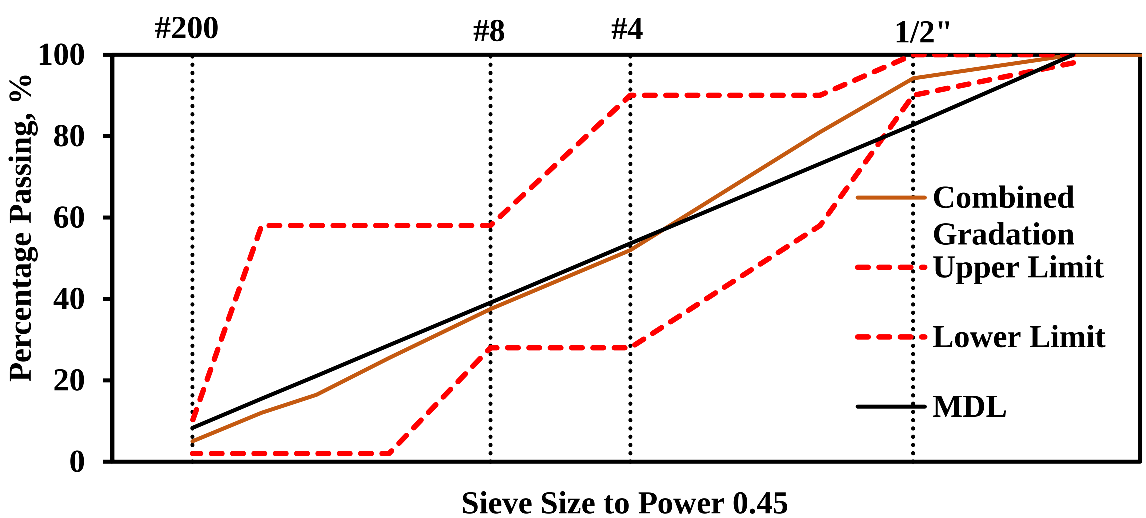


Figure 5.3 - Control Superpave Aggregate Gradation with 12.5 mm NMAS

Table 5.1 - Summary of Gradation Parameters from Altered Gradations

Gradation Parameter	Variation	Parameter			
		PCS	CA	FA_c	FA_f
Recommended Range		**NA**	**0.50 - 0.65**	**0.35 - 0.50**	**0.35 - 0.50**
PCS	Finest	47.5	0.61	0.44	0.45
	Finer	42.5	0.61	0.44	0.45
	Control	37.5	0.61	0.44	0.45
	Coarser	32.5	0.61	0.44	0.45
	Coarsest	27.5	0.61	0.44	0.45
CA	Finest	37.5	0.81	0.44	0.45
	Finer	37.5	0.71	0.44	0.45
	Control	37.5	0.61	0.44	0.45
	Coarser	37.5	0.51	0.44	0.45
	Coarsest	37.5	0.41	0.44	0.45
FA_c	Finest	37.5	0.61	0.54	0.45
	Finer	37.5	0.61	0.49	0.45
	Control	37.5	0.61	0.44	0.45
	Coarser	37.5	0.61	0.39	0.45
	Coarsest	37.5	0.61	0.34	0.45
FA_f	Finest	37.5	0.61	0.44	0.55
	Finer	37.5	0.61	0.44	0.50
	Control	37.5	0.61	0.44	0.45
	Coarser	37.5	0.61	0.44	0.40
	Coarsest	37.5	0.61	0.44	0.35

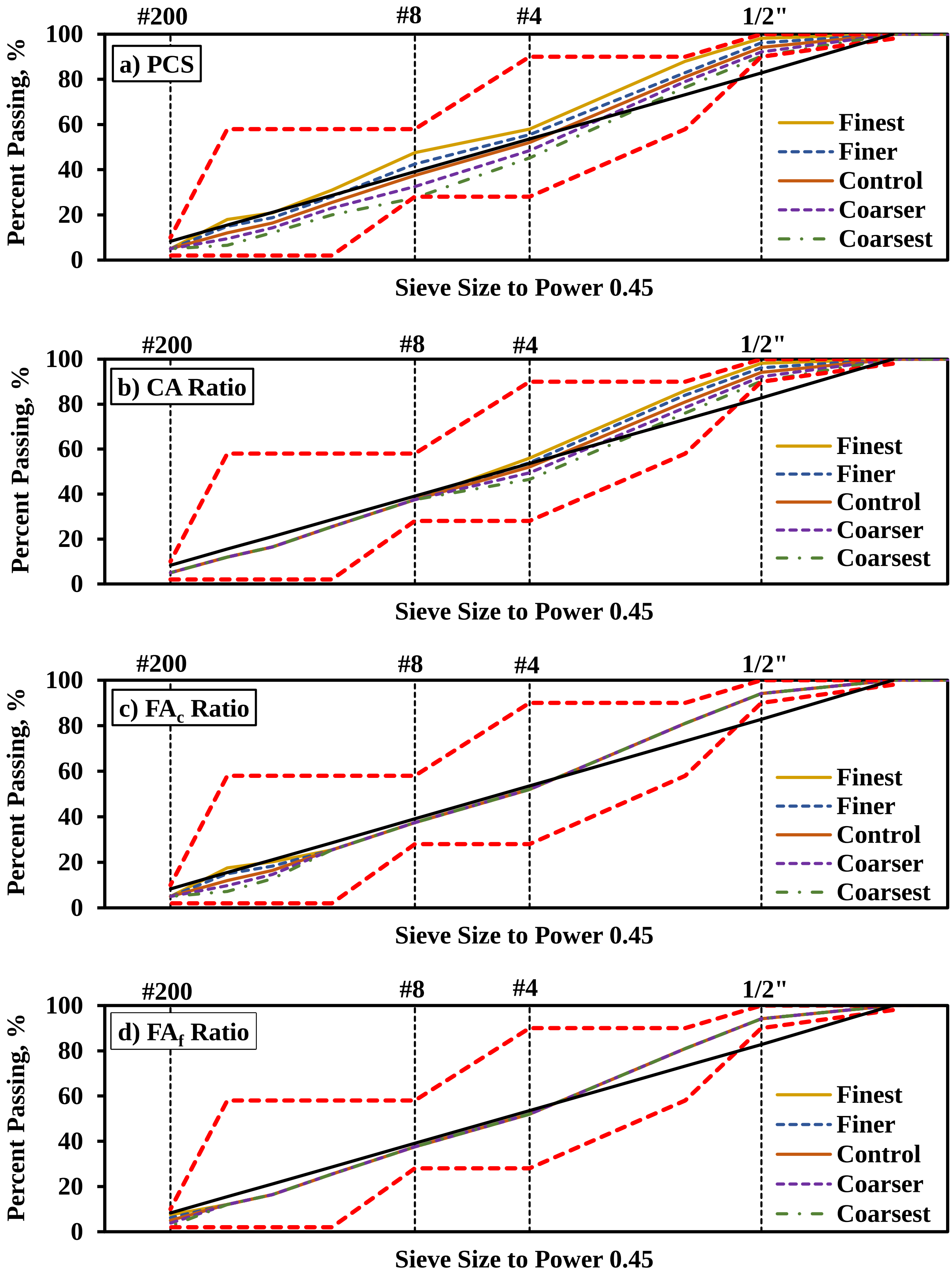


Figure 5.4 - Altered Gradations for Parameter Study

<u>Influence of Primary Control Sieve</u>

The primary control sieve (PCS) defines the boundary between the coarse and fine aggregates and determines whether the aggregate structure is coarse- or fine-grained. PCS was changed between 47.5% and 27.5%, while the CA, FA_c and FA_f ratios were maintained at 0.61, 0.44 and 0.45, respectively. As shown in Figure 5.5, the volumetric properties of the mixtures decrease as the PCS increases except for the mixtures with gravel and soft limestone. The OAC, P_{be}, VMA, VFA and FT for mixtures with gravel and soft limestone are not affected by the perturbation of PCS. The mixtures with the gravel aggregates exhibit greater OAC, P_{be}, VMA, VFA and FT than those for the mixtures with the other aggregates. The mixtures with soft limestone yielded the lowest measured volumetric properties.

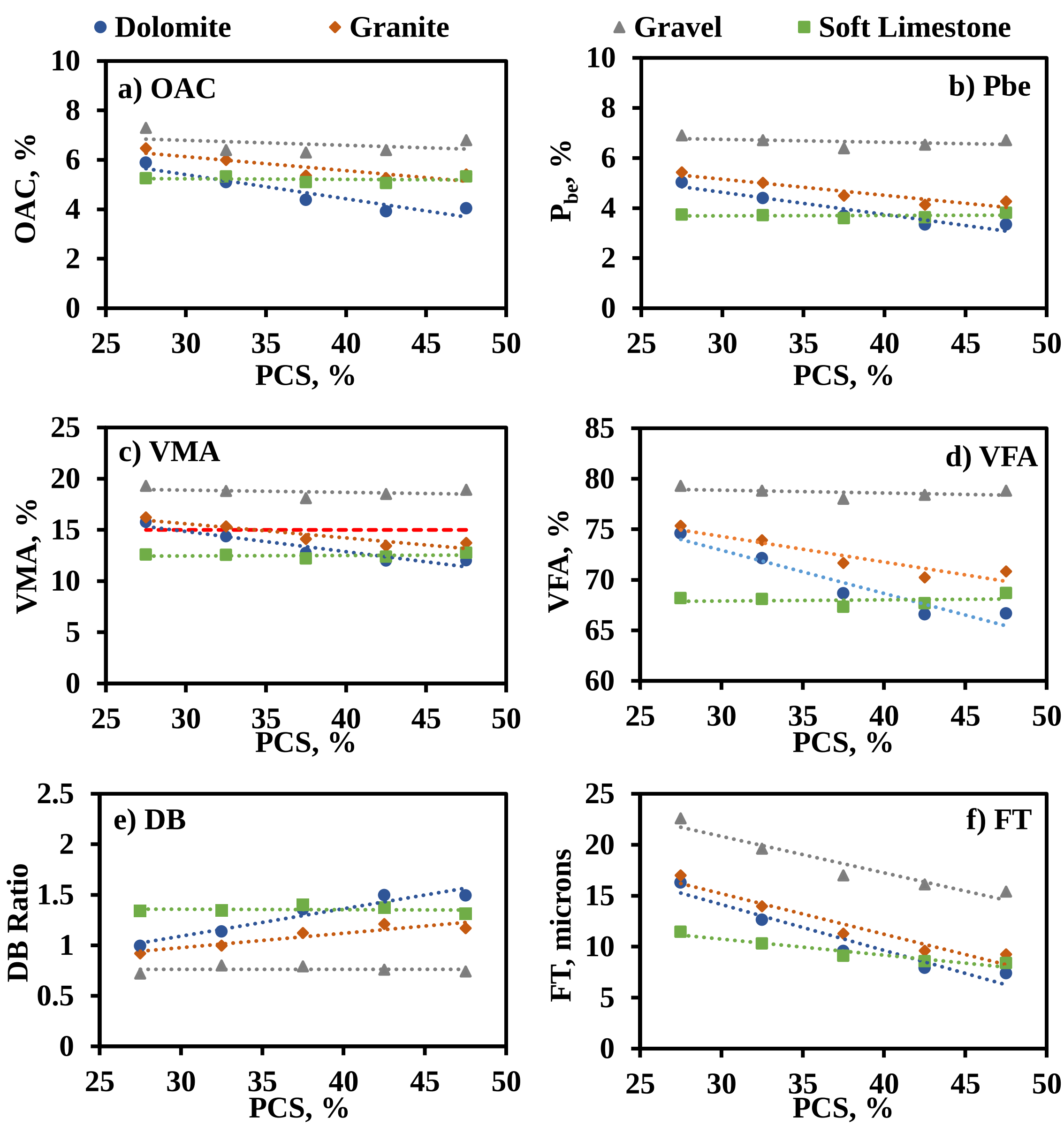


Figure 5.5 - Influence of PCS Parameter on Volumetric Properties of Mixtures

The minimum permissible VMA for SP C mixtures is 15% as per current specifications. Based on the VMA results in Figure 6c, increasing the PCS will decrease the VMA of the mixtures. Mixtures with PCS values lower than 30% met the minimum VMA requirements, except for mixtures with soft limestone. Mixtures with soft limestone yielded VMA values close to 12.5%, while mixtures with gravel exhibit VMA values greater than 18%.

Figure 5.6 presents the IDT and HWT test results along with the associated acceptance limits. As shown in Figure 5.6a, the tensile strength (ITS) increased as the PCS increased for all aggregate types. The mixtures with the granite aggregates presented greater ITS relative to their corresponding mixtures with the other aggregate types. Mixtures with PCS of 40% or greater yielded acceptable or marginally low ITS except for mixtures with soft limestone aggregate.

Figure 5.6b depicts the variations in NRRI with PCS. The mixtures containing the dolomite and granite aggregates yielded greater NRRI. The mixtures with PCS values of approximately 35% to 40% exhibited optimal rutting resistance.

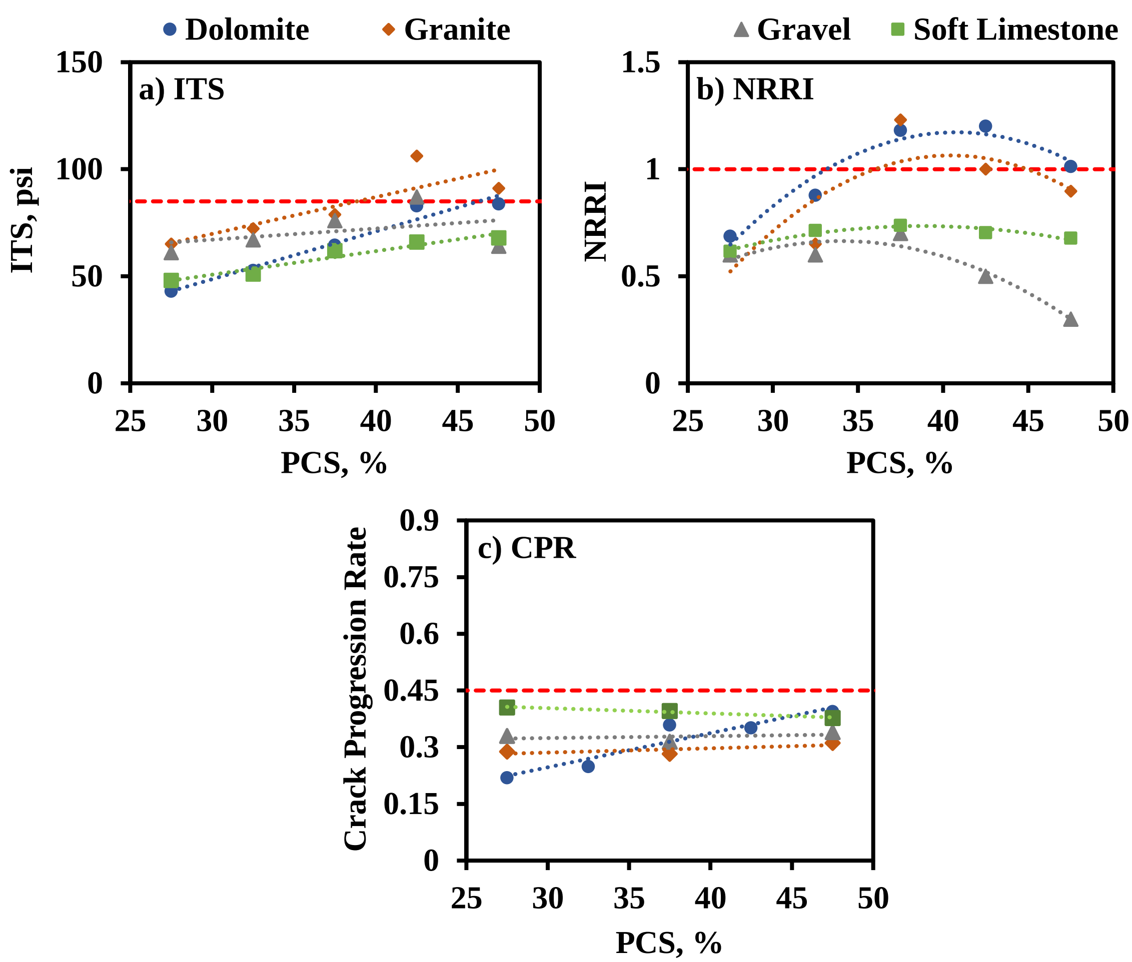


Figure 5.6 - Influence of PCS on Mechanical Performance of Mixtures

Figure 5.6c shows the variations in CPR with PCS. All mixtures presented acceptable CPR values. CPR increased by increasing PCS, except for mixtures containing soft limestone aggregates.

Table 5.2 summarizes the correlation coefficients (denoted as R) from the correlation analyses among the volumetric and mechanical properties of the mixtures. In this study, a strong correlation is defined as conditions when the absolute value of R is greater than 0.70 as highlighted in the table. A positive R greater than 0.7 is highlighted in dark green, and a negative R less than -0.7 is colored in light green. The volumetric properties of mixtures with dolomite and granite are impacted significantly by the changes in PCS. In the contrary, the volumetric properties of the mixtures containing gravel and soft limestone did not correlate strongly with the variation in PCS, except for the FT parameter that presented a strong negative correlation of -0.96. The ITS is directly correlated to PCS. The R values for the correlation between ITS and PCS are greater than 0.84, except for the mixtures containing gravel aggregates. The low R values from the correlations between NRRI and PCS occurs because the relationships between these parameters is not linear. The NRRI parameter is linearly related when PCS is less than 40%, with an optimal PCS value between 35% and 40%. The R values for the correlation between CPR and PCS did not show a consistent trend among the different aggregates. Mixtures containing dolomite and granite aggregates yielded positive and strong R values, while mixture containing soft limestone yielded a negative R value. Mixtures containing gravel aggregates exhibited a poor R value.

Table 5.2 - Correlations of Volumetric and Mechanical Properties of Mixtures to PCS

Aggregate	Correlation Coefficient (R)								
	OAC	**P_{be}**	**VMA**	**VFA**	**DB**	**FT**	**ITS**	**NRRI**	**CPR**
Dolomite	-0.94	-0.95	-0.95	-0.96	0.96	-0.96	0.98	0.71	0.94
Granite	-0.87	-0.93	-0.93	-0.93	0.93	-0.96	0.84	0.58	0.75
Gravel	-0.38	-0.46	-0.39	-0.45	0.00	-0.96	0.39	-0.73	0.40
Soft Limestone	-0.15	0.12	0.17	0.17	-0.10	-0.96	0.97	0.38	-0.98

<u>Influence of Coarse Aggregate Ratio</u>

CA controls the coarse portion of the gradation. All aggregate types were used to design mixtures with the five aggregate gradations presented in Figure 5.4b. CA values of the five mixtures ranged from 0.81 to 0.41, while PCS, FA_c and FA_f were maintained at 37.5%, 0.44 and 0.45, respectively.

As shown in Figure 5.7, OAC, P_{be}, VMA, VFA and FT for each aggregate type increase and DB ratio decreases as CA increases. Again, the mixtures with gravel exhibited greater volumetric properties than those from the corresponding mixtures with the other aggregates. The mixtures with soft limestone yielded the lowest P_{be}, VMA, VFA and FT even though their OAC values were similar to those from mixtures with granite or dolomite. This may be attributed to the high absorptive properties of the soft limestone aggregates.

As shown in Figure 5.7c, most mixtures did not meet the minimum VMA requirements except for mixtures with gravel that yielded VMA values ranging from 16.5% to 18.5%. Increasing the CA will result in a greater VMA. This means that as the coarse aggregates content increases, the aggregate skeleton provides more space to accommodate binder. Therefore, the volumetric properties, especially VMA, will increase.

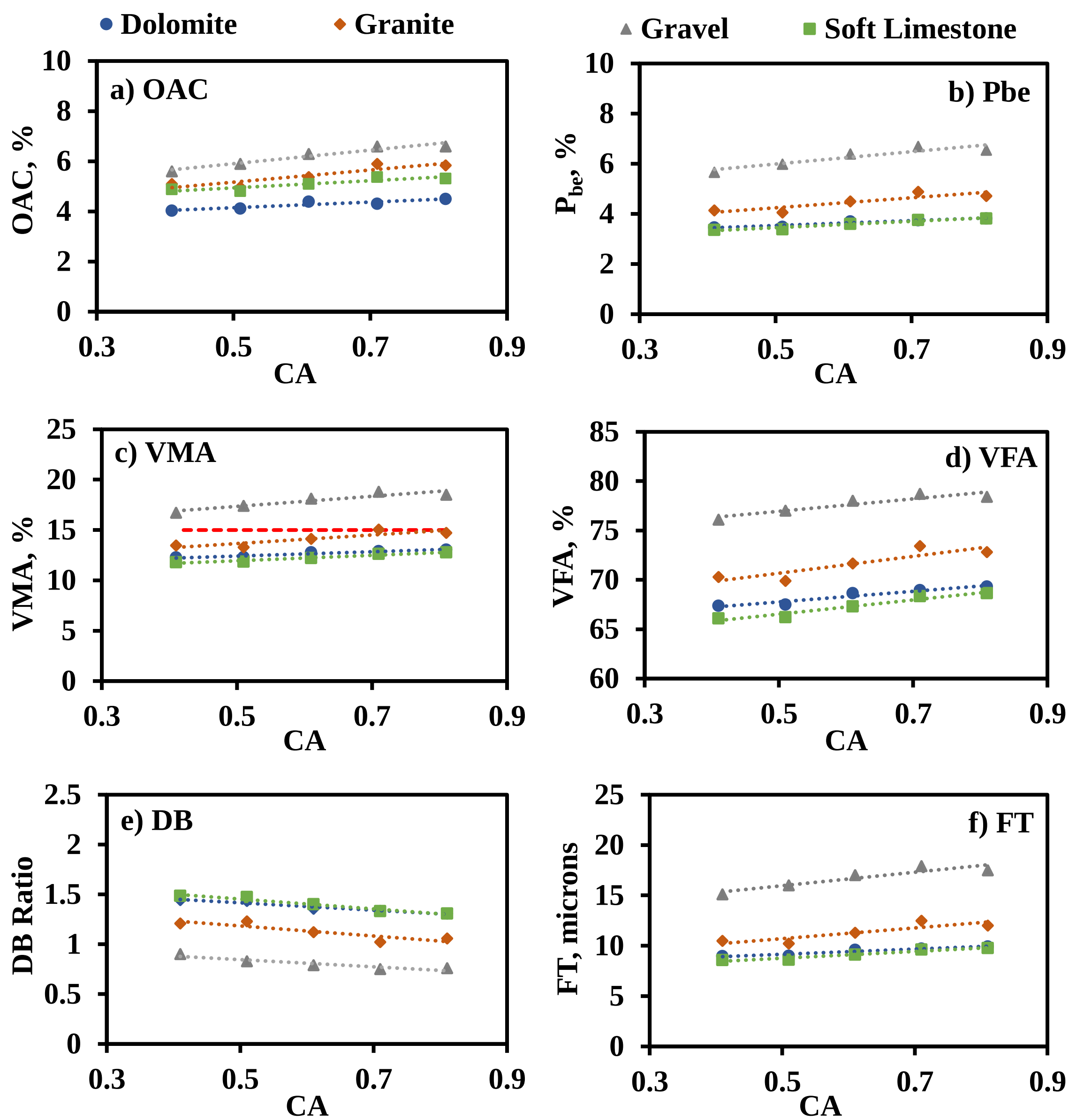


Figure 5.7 - Influence of CA on Volumetric Properties of Mixtures

The mechanical properties of the mixtures are presented in Figure 5.8. Figure 5.8a illustrates the variations in the ITS with respect to CA for the four aggregate types. Overall, the mixtures with the four aggregates yielded similar ITS results. Although ITS decreases slightly when CA increases, the effects of CA ratio on ITS was minimal. To the contrary, CA ratio significantly impacts the rutting resistance of the mixtures (Figure 5.8b), except for the mixtures designed with gravel aggregates. The mixture becomes more rut susceptible (NRRI decreases) as CA ratio increases. Mixtures with CA ratio of less than about 0.70 passed the rutting resistance requirements. The mixtures containing gravel aggregates yielded considerably poor rutting resistance. This phenomenon can be attributed to the poor adhesion properties of this gravel aggregate that can cause significant stripping between the aggregate and binder. The effect of CA ratio on CPR was minimal with the mixtures showing a slightly smaller or similar CPR as CA ratio increased. All mixtures exhibited satisfactory CPR values.

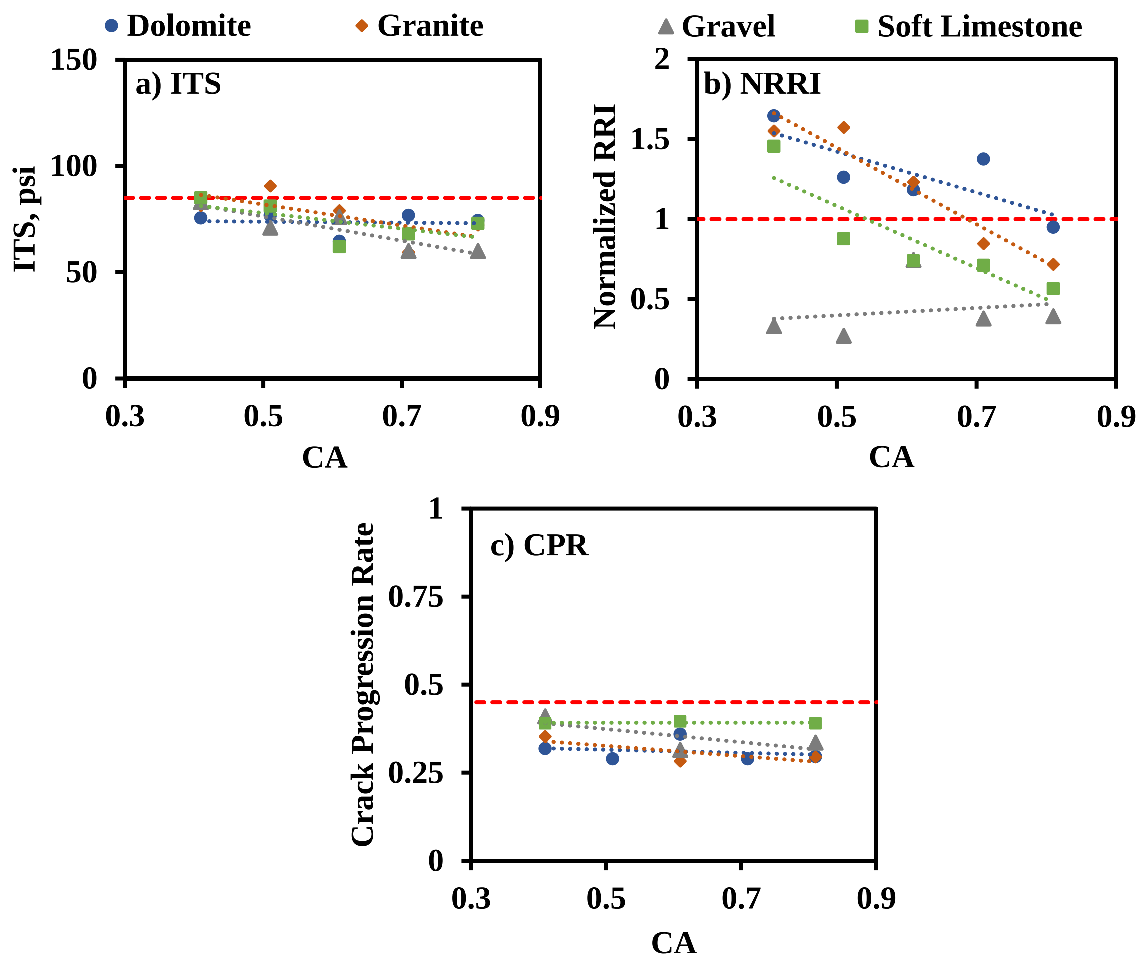


Figure 5.8 - Influence of CA on Mechanical Performance of Mixtures

As shown in Table 5.3, the volumetric properties of the mixtures are strongly correlated to CA (yielded R that are significantly greater than 0.7). The OAC, P_{be}, VMA, VFA and FT are positively correlated to CA, while DB presented a negative correlation. The ITS and NRRI parameters are negatively correlated to CA. The low R values for ITS parameter confirms the minimal impact that CA has on the strength of the mixtures. NRRI presented absolute R values that are greater than 0.79, except to mixtures designed with gravel aggregates. Only mixtures containing granite and gravel aggregates yielded strong R values for the correlations between CPR and CA ratio. The mixtures containing the other aggregate types were not sensitive to the change in CA ratio as per the similar CPR values.

Table 5.3 - Correlations of Volumetric and Mechanical Properties of Mixtures to CA

Aggregate	Correlation Coefficient (R)								
	OAC	P_{be}	VMA	VFA	DB	FT	ITS	NRRI	CPR
Dolomite	0.93	0.96	0.97	0.96	-0.96	0.96	-0.07	-0.79	-0.24
Granite	0.90	0.88	0.88	0.88	-0.88	0.87	-0.68	-0.96	-0.77
Gravel	0.97	0.92	0.93	0.93	-0.93	0.93	-0.89	0.20	-0.74
Soft Limestone	0.90	0.98	0.97	0.97	-0.98	0.97	-0.62	-0.89	0.02

Influence of Fine Aggregate Coarse Fraction

FA_c impacts the packing of the overall fine fraction in the combined aggregate blend. The five gradations shown in Figure 5.4c were used to study the influence of FA_c on the volumetric properties of the mixtures with the four aggregate types. These gradations yielded FA_c values ranging from 0.54 to 0.34 while PCS, CA and FA_f were maintained at 37.5%, 0.61 and 0.45, respectively.

Figure 5.9 shows the variations on OAC, P_{be}, VMA, VFA, FT and DB as FA_c changes. As FA_c increases, the volumetric properties of the mixtures decrease except for the DB ratio. From Figure 5.9c, mixtures with FA_c less than 0.35 yielded VMAs greater than 15%, except for mixture with soft limestone that had a marginal VMA of 14.2%. Since FA_c controls the packing and the amount of the fine particles, fine particles occupy the space that can be used to accommodate more binder. Mixtures with high FA_c are not desirable since they will produce mixtures with low VMA and OAC that can potentially generate issues with their compactability and durability.

Figure 5.10 presents the IDT and HWT test results for FA_c gradations. As shown in Figure 5.10a, ITS increased as FA_c increased for all aggregate types. The mixtures with the granite aggregates presented slightly greater ITS relative to their corresponding mixtures with the other aggregate types. A few mixtures with FA_c of 0.5 or greater yielded acceptable or marginally low ITS. Figure 5.10b depicts the variations in NRRI with respect to FA_c. The mixtures containing the dolomite and granite aggregates yielded greater NRRI. The mixtures with FA_c of approximately 0.4 to 0.5 exhibited optimal rutting resistance, except for the mixtures containing soft limestone aggregates that showed an increasing trend with respect to FA_c. As shown in Figure 10c, CPR increased as FA_c increased for all mixtures except for the mixture containing gravel aggregates. Most mixtures yielded acceptable CPR values.

Table 5.4 summarizes the coefficients of correlation for FAc. The volumetric properties of mixtures with the four aggregates are significantly impacted by the changed in FA_c. The ITS is directly and strongly correlated to FA_c, with R values greater than 0.86. Again, the R values from the correlations between NRRI and FA_c are low because the relationship between these parameters is not linear. The NRRI parameter is linearly related when FA_c is less than 0.45. The R values from the correlations between CA and FA_c were greater than 0.74. Mixtures containing gravel aggregate yielded a poor R value from the correlation analysis.

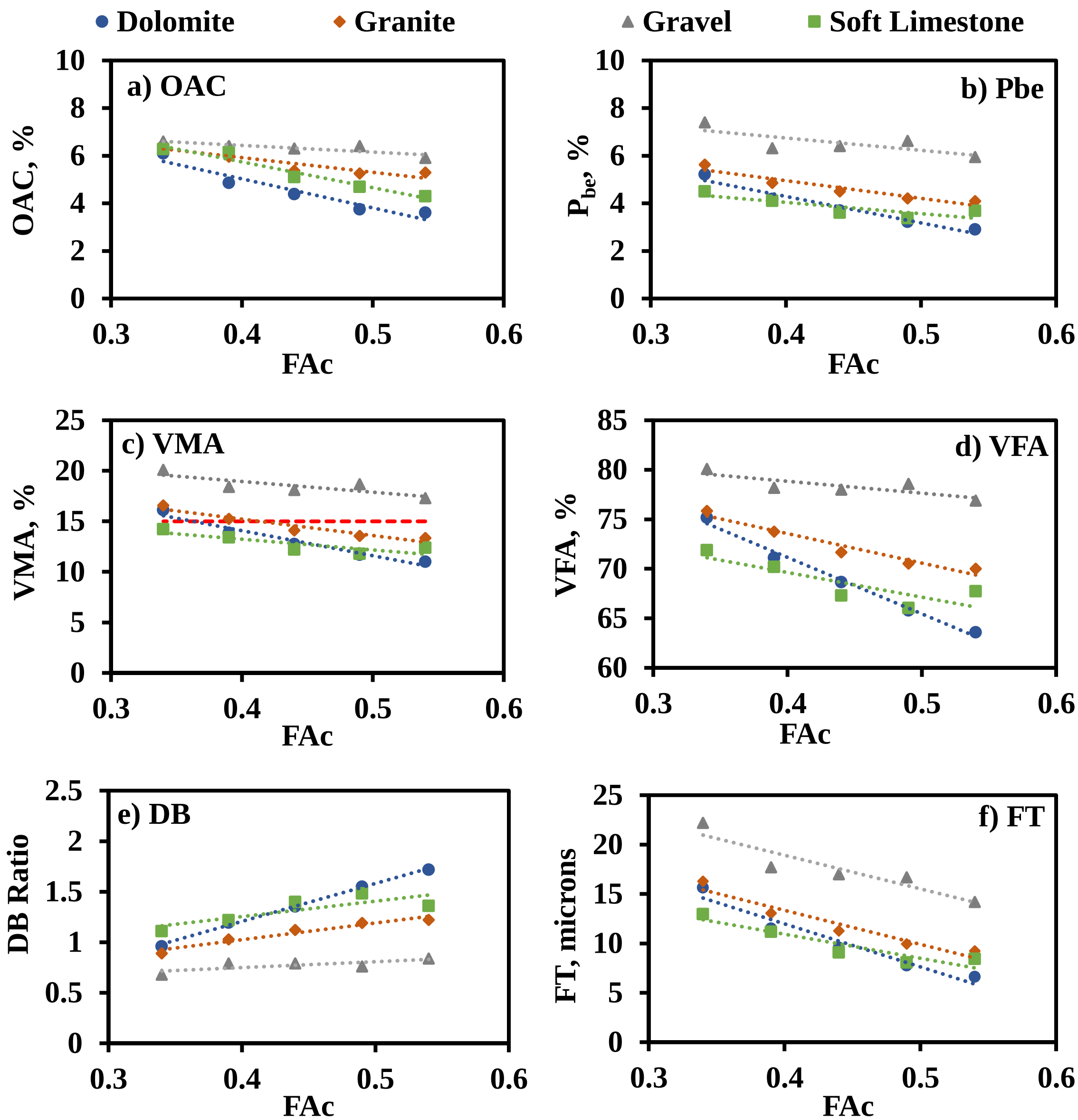


Figure 5.9 - Influence of FA_c on Volumetric Properties of Mixtures

<u>Influence of Fine Aggregate Fine Fraction</u>

FA_f controls the dust content (materials passing sieve No. 200, P200) in the overall aggregate gradation. Figure 5.4d presents the five gradations formulated to evaluate the influence of FA_f on the volumetric properties of the mixtures with the four aggregate types. FA_f was varied from 0.55 to 0.35, while the PCS, CAR and FA_c parameters were maintained at 37.5%, 0.61 and 0.44, respectively. As shown in Figure 5.11 and Table 5.5, all volumetric properties are correlated with FA_f except those from the mixtures with gravel aggregates. The mixtures with gravel aggregates showed less sensitivity to the change in FA_f, which may be due to the low absorptive properties of this aggregate type.

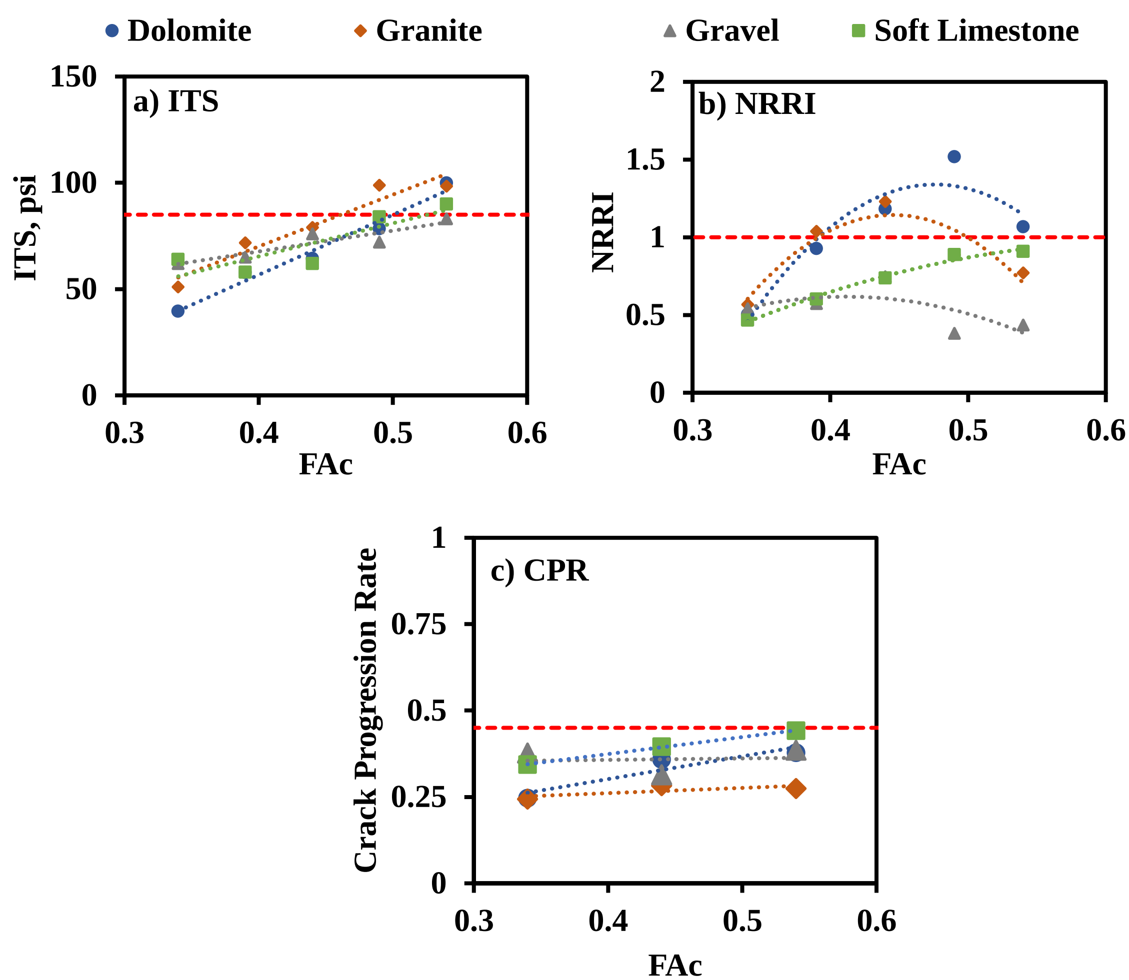


Figure 5.10 - Influence of FA_c on Mechanical Performance of Mixtures

Table 5.4 - Correlations of Volumetric and Mechanical Properties of Mixtures to FA_c

Aggregate	Correlation Coefficient (R)								
	OAC	P_{be}	VMA	VFA	DB	FT	ITS	NRRI	CPR
Dolomite	-0.96	-0.97	-0.97	-0.99	1.00	-0.97	0.99	0.73	0.93
Granite	-0.91	-0.95	-0.96	-0.97	0.97	-0.96	0.96	0.16	0.74
Gravel	-0.86	-0.76	-0.82	-0.82	0.78	-0.92	0.92	-0.45	0.11
Soft Limestone	-0.97	-0.84	-0.84	-0.83	0.81	-0.93	0.86	0.98	1.00

Mixtures yielded marginally acceptable or low VMAs for the selected aggregates, except for mixtures with gravel that resulted on very high VMA values. From Figure 5.11c, the VMA steadily decreases as the FA_f increases. As FA_f increases, the dust content in the aggregate blend increases and occupies the space for asphalt binder. Again, FA_f should be controlled to avoid mixtures with low OAC and VMA.

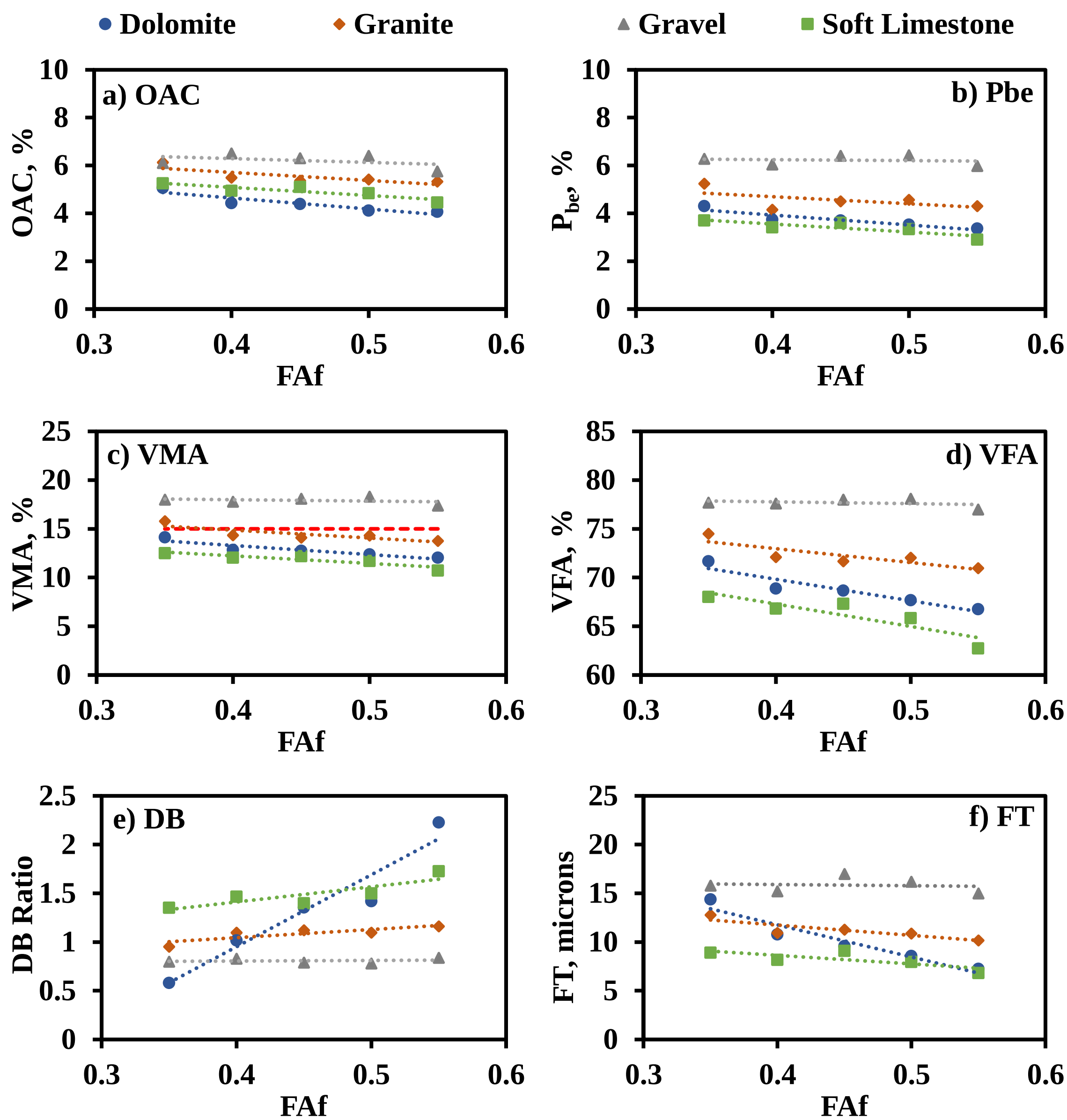


Figure 5.11 - Influence of FA_f on Volumetric Properties of Mixtures

Figure 5.12 presents the variations in the mechanical properties with FA_f. The ITS values were less than the minimum ITS requirement of 85 psi and were very similar among the mixtures containing different aggregate types and FA_f gradations. Figure 5.12b depicts the variations in NRRI with respect to FA_f. The mixtures containing the dolomite yielded higher NRRI. An optimal FA_f ratio can be found between 0.4 and 0.5. From Figure 12.c, the variations in CPR with respect to FAf are presented. Mixtures containing soft limestone aggregates yielded greater CPR values. Only one mixture containing soft limestone failed the CPR acceptance limit of 0.45. The other mixtures exhibited acceptable CPR values.

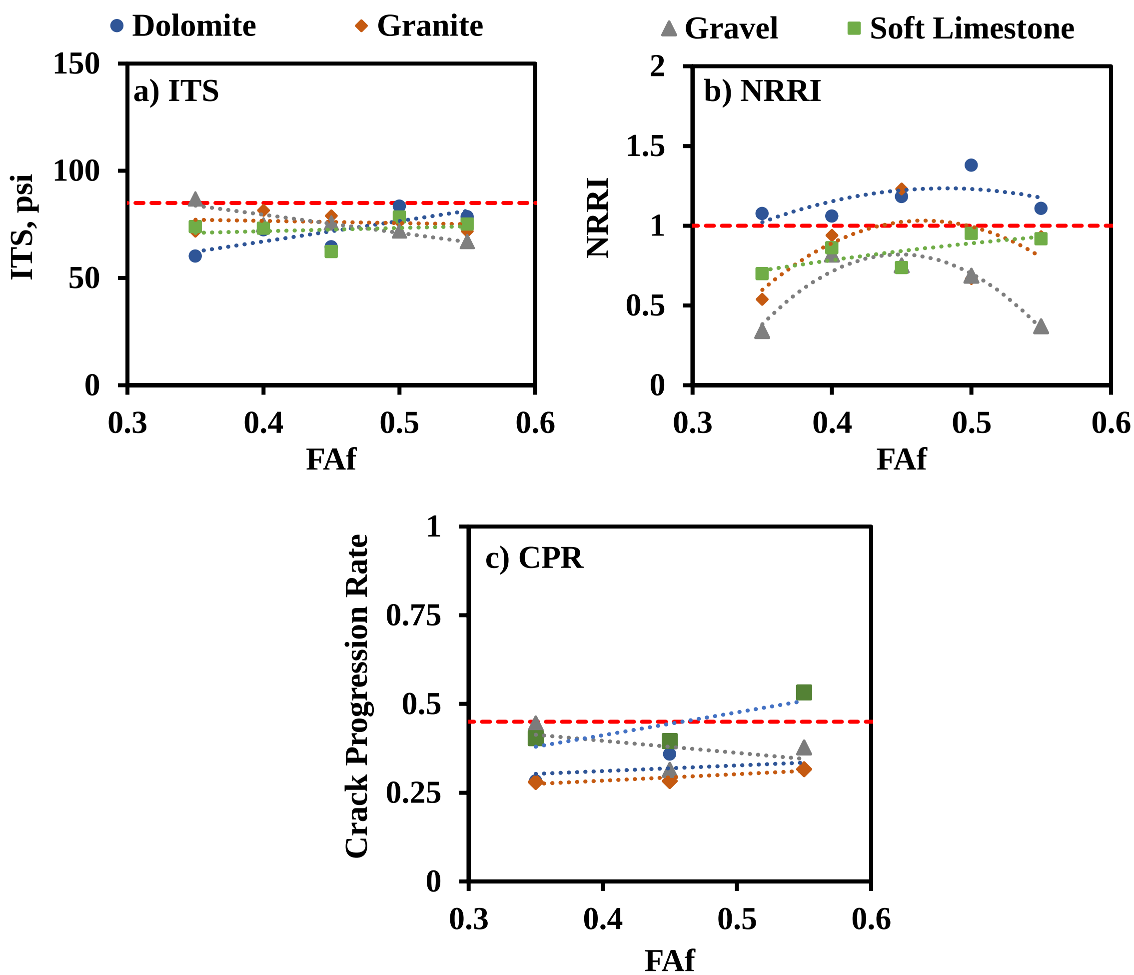


Figure 5.12 - Influence of FA_f on Mechanical Performance of Mixtures

The results from the correlation analysis for FA_f are summarized in Table 5.5. The volumetric properties of mixtures with the four aggregates are impacted by the changed in FA_f, except for the mixtures containing gravel aggregates. ITS did not correlate consistently with FA_f, while the correlation between NRRI and FA_f is not linear resulting on low R values. The NRRI parameter is linearly related when FA_f is less than 0.45. Only mixtures containing granite and soft limestone yielded strong correlation between CPR and FA_c, with R values greater than 0.84.

Table 5.5 - Correlations of Volumetric and Mechanical Properties of Mixtures to FA_f

Aggregate	Correlation Coefficient (R)								
	OAC	P_{be}	VMA	VFA	DB	FT	ITS	NRRI	CPR
Dolomite	-0.92	-0.93	-0.93	-0.94	0.96	-0.96	0.78	0.46	0.41
Granite	-0.80	-0.56	-0.83	-0.85	0.84	-0.87	-0.19	0.30	0.90
Gravel	-0.43	-0.15	-0.32	-0.33	0.18	-0.12	-0.92	-0.05	-0.52
Soft Limestone	-0.88	-0.85	-0.90	-0.88	0.85	-0.77	0.20	0.75	0.84

Key Remarks and Findings

The formulation of the aggregate gradation plays a key role to produce mixtures with acceptable volumetric and mechanical properties. Gradation selection tools, such as the Bailey method, only considers the volumetric properties of the asphalt mixtures. Even though these tools can be used to modify aggregate gradations, further research must be conducted to explore alternative approaches for formulating aggregate gradations that can potentially result on BMD mixtures.

Altering the portions of the gradation curve that represent coarse and fine aggregates resulted on significant changes in volumetric and mechanical properties of the asphalt mixtures regardless of the aggregate type. While the coarse portion of the gradation influenced the rutting resistance of the asphalt mixtures, the fine portion of the gradation impacted the volumetric and cracking properties of the asphalt mixtures. Given that many mix designs exhibit poor cracking resistance, modifying the portion of the gradation curve that represents the intermediate aggregates may help to introduce more asphalt binder into the asphalt mixture aiming to improve cracking properties.

CHAPTER 6 – FORMULATION OF BALANCED MIX DESIGNS

This chapter presents the modification of four TMD mixtures to meet the BMD requirements. The mixtures were balanced by adjusting the aggregate gradation, gyrations levels, binder PG and removing field sand. A volumetric design with performance verifications approach was used to design the BMD mixtures. The key modification to produce BMD mixtures was the formulation of an alternative aggregate gradation. Several volumetric properties including asphalt content, voids in mineral aggregates (VMA), theoretical maximum specific gravity (Gmm), bulk specific gravity (Gmb) and lab-molded density were measured and documented for the TMD and BMD mixtures. For performance testing, the OT, HWT and IDEAL CT tests were performed. OT and HWT tests were used to determine the cracking and rutting potentials of the mixtures, while IDEAL CT test is considered a quality control test for production and placement of the asphalt mixtures.

Alternative Approach to Increase Asphalt Content of Asphalt Mixtures

One feasible way to produce BMD mixtures by coupling the volumetric and performance criteria is by optimizing the selection of aggregate gradation. In that approach, the gradation is optimized to not only provide aggregate interlocking but also provide enough void space to accept more asphalt binder and potentially balance both rutting and cracking potentials. To investigate the role of the aggregate gradation on the volumetric properties of the mixtures, four aggregate gradations were studied by modifying the aggregate gradation of TMD 1 (referred to Control, CNT). As shown in Figure 6.1, the coarse portion of the gradation was modified to produce a high and low coarse aggregate (HCA and LCA) gradations, while the fine portion of the gradation was perturbed to generate a high and low fine aggregate (HFA and LFA) gradations.

The measured volumetric properties of the mixtures are shown in Table 6.1. The coarse portion of the gradation did not influence considerably the volumetric properties of the mixtures. From the change in the fine portion of the gradation, the mix with LFA gradation yielded a greater OAC and VMA than the mix with the CNT gradation. The mix with the LFA gradation exhibited an OAC of 5.3% and a VMA of 16.2%. In comparison with the CNT gradation, the LFA gradation

Table 6.1 - Influence of Aggregate Gradation on Volumetric Properties of Mixtures

Gradation	OAC, %	VMA, %	G_{mm}	G_{mb}	Dust to Binder Ratio
HCA	4.7	15.0	2.474	2.374	1.1
LCA	4.6	14.7	2.477	2.375	1.0
CNT	4.7	15.0	2.470	2.369	1.0
HFA	4.6	14.8	2.478	2.380	1.1
LFA	5.3	16.2	2.459	2.358	0.9

requires less amount of intermediate aggregates (material retained on No. 8, No. 16 and No. 30 sieves), which can create more void space within the mix to accommodate the binder. A gradation similar to the LFA gradation can be used to optimize and balance the volumetric and mechanical properties of the mixture.

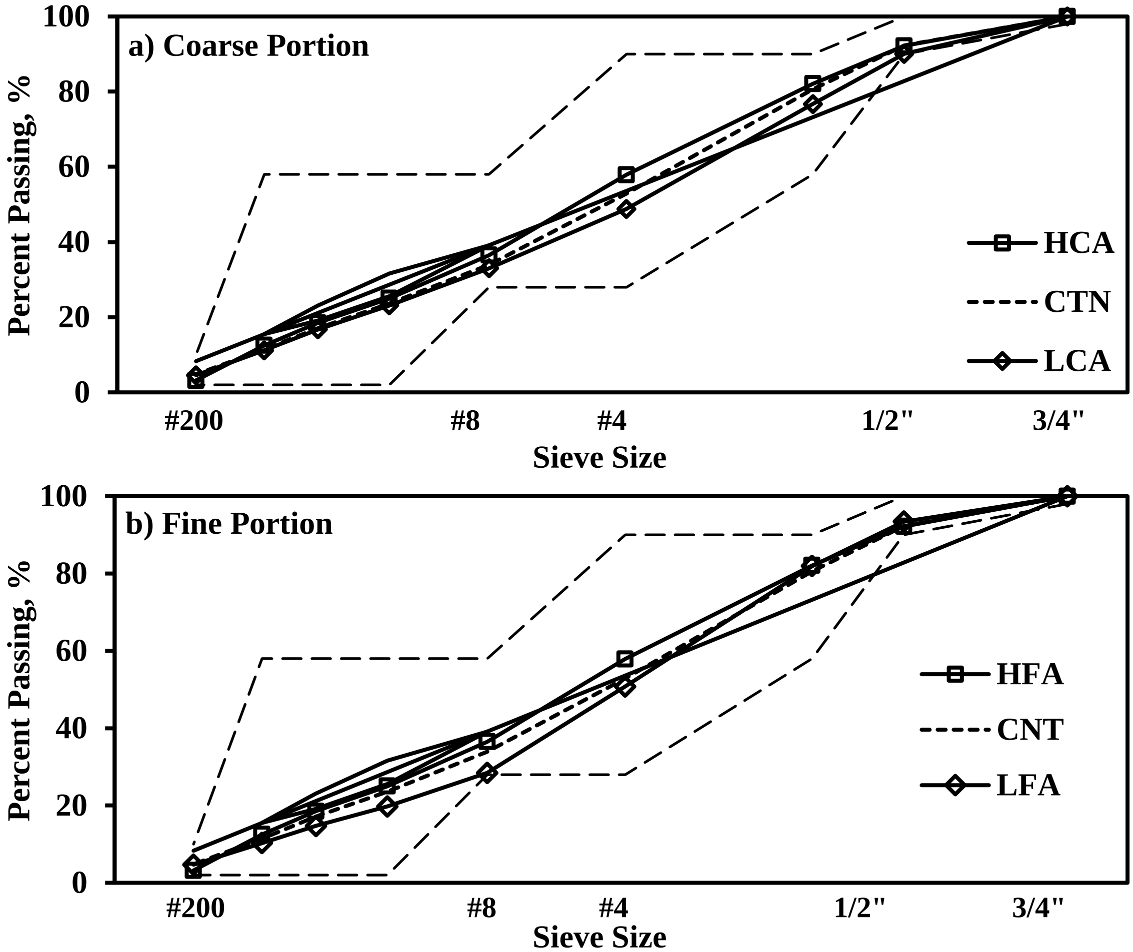


Figure 6.1 - Altered Aggregate Gradations for TMD 1 Mixture

Plant 1 (Crack-Susceptible Mix Design)

The raw materials from Plant 1 were used to produce two mixtures with different gradations. BMD 1 was designed using the same aggregates sources, binder type and RAP source used for TMD 1, as shown in Figure 6.2. As previously described, TMD 1 is considered a crack susceptible mix design. The major difference between the two aggregate gradations is the content of intermediate aggregates. It is surmised that this modification should increase the asphalt content without significantly affecting the rutting resistance of the mixture.

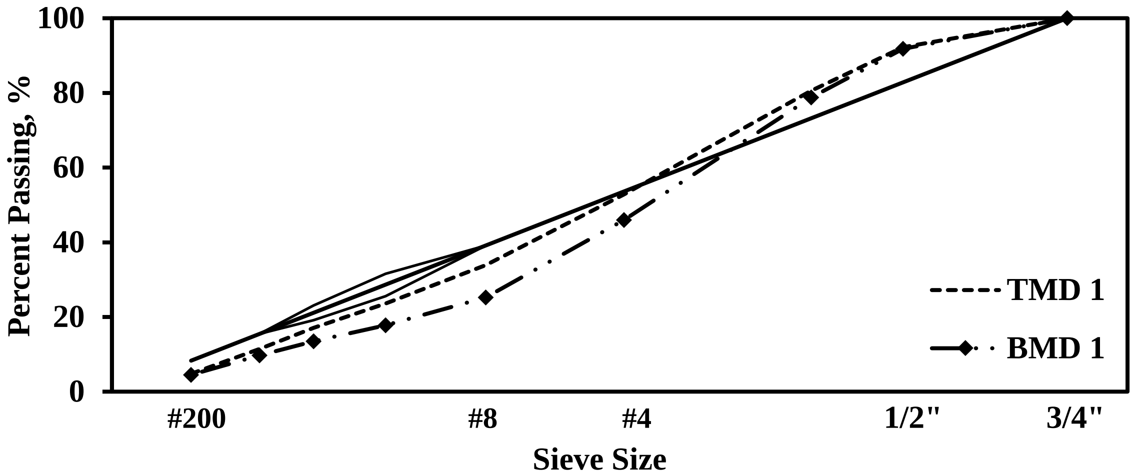


Figure 6.2 - Comparison of Aggregate Gradations for Mixtures from Plant 1

The volumetric properties of TMD 1 and BMD 1 mixes are compared in Table 6.2. The OAC for BMD 1 was determined to be 5.5%, while TMD 1 yielded an OAC of 4.7%. Both TMD 1 and BMD 1 mixes met the minimum VMA requirement of 15%. The mechanical performance of the mixtures is compared in Table 5.2. From the performance space diagram in Figure 6.3, both TMD 1 and BMD 1 yielded acceptable rutting properties based on the NRRI values. The modification to TMD 1 mix gradation to produce BMD 1 mix improved the cracking properties based on the OT and IDEAL CT test results. Furthermore, BMD 1 mix still provides acceptable volumetric properties and lab molded density as required by the current specifications. The modification of the aggregate gradation helped to improve the performance of the mixture, specifically the cracking susceptibility.

Table 6.2 - Volumetric and Performance Properties of Mixtures for Plant 1

Parameters		TMD 1	BMD 1
Volumetric Properties	Optimum Asphalt Content, %	4.7	5.5
	Voids in Mineral Aggregates, %	15.0	16.7
	Bulk Specific Gravity	2.369	2.353
	Maximum Specific Gravity	2.470	2.450
Mechanical Properties	OT Crack Progression Rate	0.57	0.35
	Rut Depth, mm	6.6	9.2
	Number of Passes	20,000	20,000
	Normalized Rutting Resistance Index	1.9	2.0
	CT Index	65	103

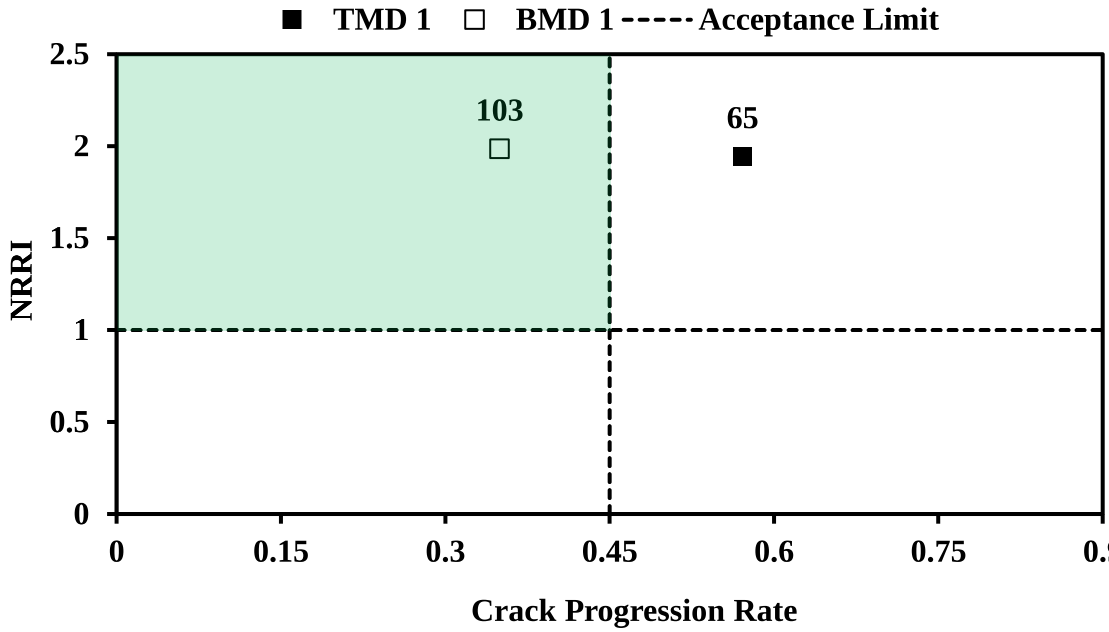


Figure 6.3 - Performance Space Diagram for Mixtures from Plant 1

Plant 2 (Unbalanced Mix Design)

TMD 2 and BMD 2 mixes were produced using the pavement raw materials from Plant 2. The aggregate gradation proposed for BMD 2 mix is compared with that of TMD 2 mix in Figure 6.4. Since the aggregates used in TMD 2 mix are very absorptive and considered very soft, BMD 2 mix was designed with 35 gyrations instead of 50 gyrations to increase the asphalt content of the mixture, specifically the effective binder content.

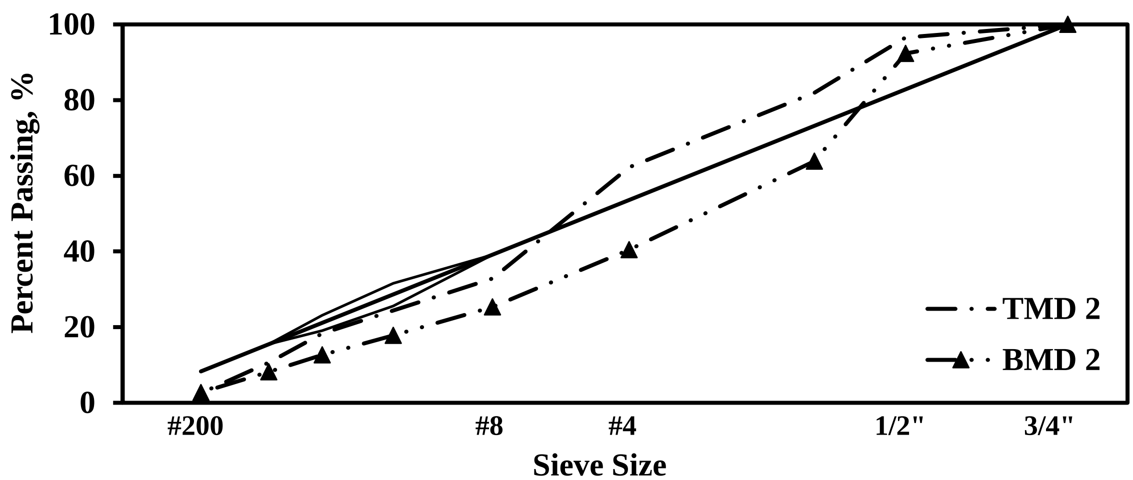


Figure 6.4 - Comparison of Aggregate Gradations for Mixtures from Plant 2

The volumetric and mechanical properties of TMD 2 and BMD 2 mixes are summarized in Table 6.3. BMD 2 mix yielded an OAC of 5.4%, while TMD 2 mix had an OAC of 4.6%. BMD 2 mix yielded a VMA of 16.3% which satisfactorily meets the minimum VMA requirement. The mechanical performance of the mixes is compared in the performance diagram shown in Figure 6.5. The cracking and rutting resistance of BMD 2 mix satisfactorily passed the performance acceptance criteria as judged by its CPR and NRRI. The modification to the TMD 2 mix gradation and lowering the N_{design} to produce BMD 2 mix improved the cracking and rutting properties based on the OT, IDEAL CT and HWT test results. Unlike TMD 2 mix, BMD 2 mix satisfied all the performance requirements while providing acceptable VMA and target lab molded density as required under the current specifications.

Table 6.3 - Volumetric and Performance Properties of Mixtures for Plant 2

Parameters		TMD 2	BMD 2
Volumetric Properties	Optimum Asphalt Content, %	4.6	5.4
	Voids in Mineral Aggregates, %	14.7	16.3
	Bulk Specific Gravity	2.379	2.345
	Maximum Specific Gravity	2.486	2.445
Mechanical Properties	OT Crack Progression Rate	0.49	0.41
	Rut Depth, mm	12.9	6.2
	Number of Passes	11,110	20,000
	Normalized Rutting Resistance Index	0.7	1.6
	CT Index	18	85

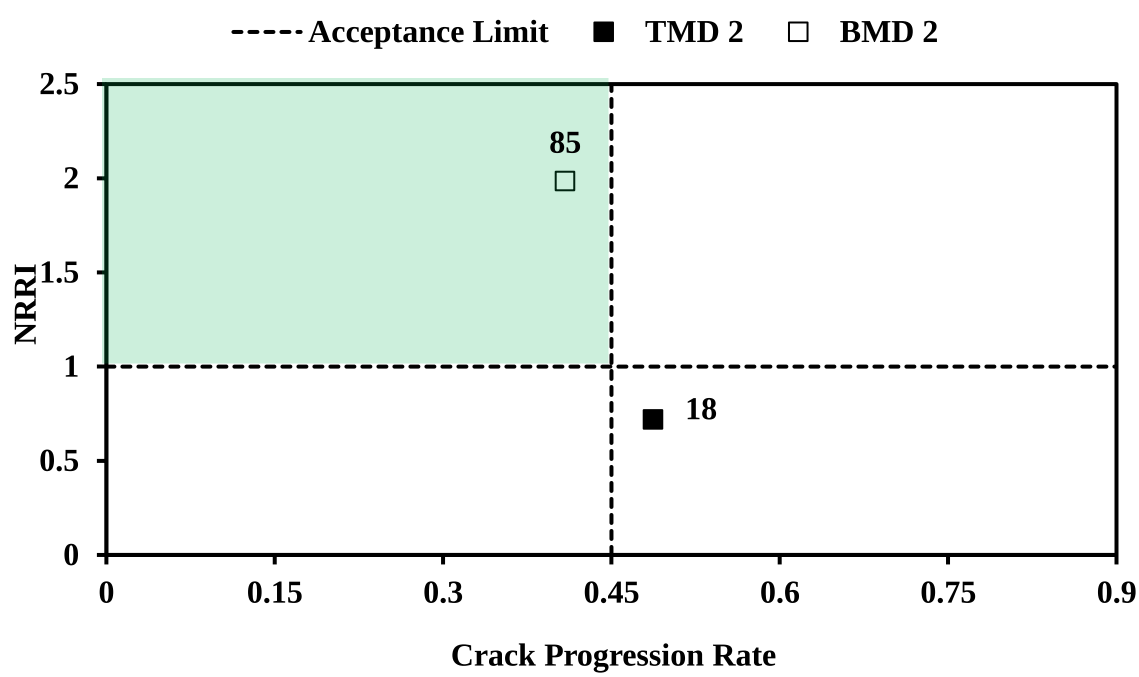


Figure 6.5 - Performance Space Diagram for Mixtures from Plant 2

Plant 3 (Crack-susceptible Mix Design)

The pavement raw materials from Plant 3 were used to produce a TMD and a BMD mixture. The aggregate gradations for TMD 3 and BMD 3 mixes are presented in Figure 6.6. Apart from the aggregate gradation modification, another difference between TMD 3 and BMD 3 mixes is the PG of the binder. While TMD 3 mix was initially designed with a PG 64-22 binder, BMD 3 mix used a PG 70-22 binder.

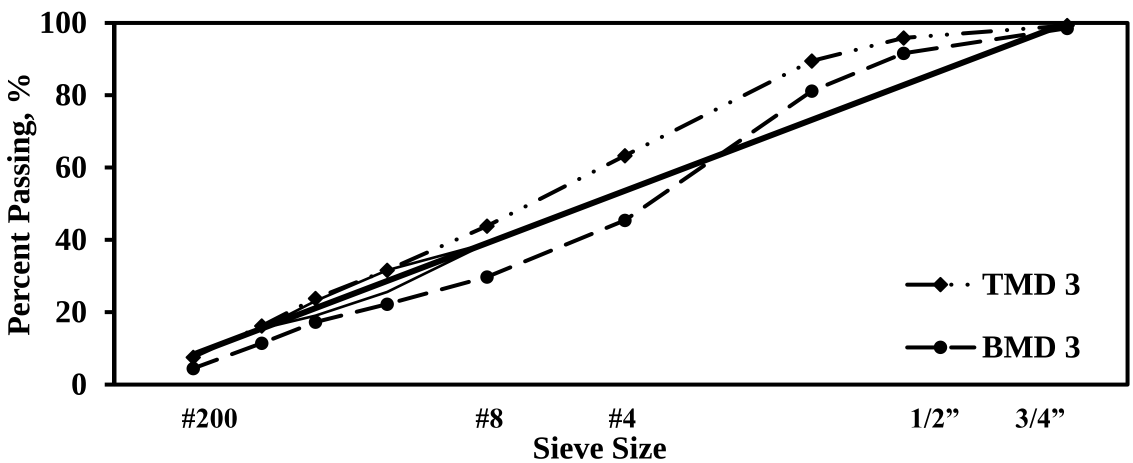


Figure 6.6 - Comparison of Aggregate Gradations for Mixtures from Plant 3

The volumetric and mechanical properties of TMD 3 and BMD 3 mixes are summarized in Table 6.4. BMD 3 mix yielded an OAC of 5.7%, while TMD 3 mix exhibited an OAC of 4.6%. TMD 3 mix yielded a VMA of 14.8% and BMD 3 mix yielded a VMA of 17.1%. The mechanical performance of the mixtures is compared in the performance space diagram shown in Figure 6.7. Both TMD 3 and BMD 3 mixes yielded acceptable NRRI values. TMD 3 and BMD 3 mixes exhibited CPR values of 0.55 and 0.35, respectively. Apart from satisfying the performance requirements of OT, IDEAL CT and HWT tests, BMD 3 mix yielded acceptable VMA and lab molded density.

Table 6.4 - Volumetric and Performance Properties of Mixtures from Plant 3

Parameters		TMD 3	BMD 3
Volumetric Properties	Optimum Asphalt Content, %	4.6	5.7
	Voids in Mineral Aggregates, %	14.8	17.1
	Bulk Specific Gravity	2.399	2.345
	Maximum Specific Gravity	2.504	2.445
Mechanical Properties	OT Crack Progression Rate	0.55	0.35
	Rut Depth, mm	12.4	4.3
	Number of Passes	20,000	20,000
	Normalized Rutting Resistance Index	1.3	2.2
	CT Index	37	178

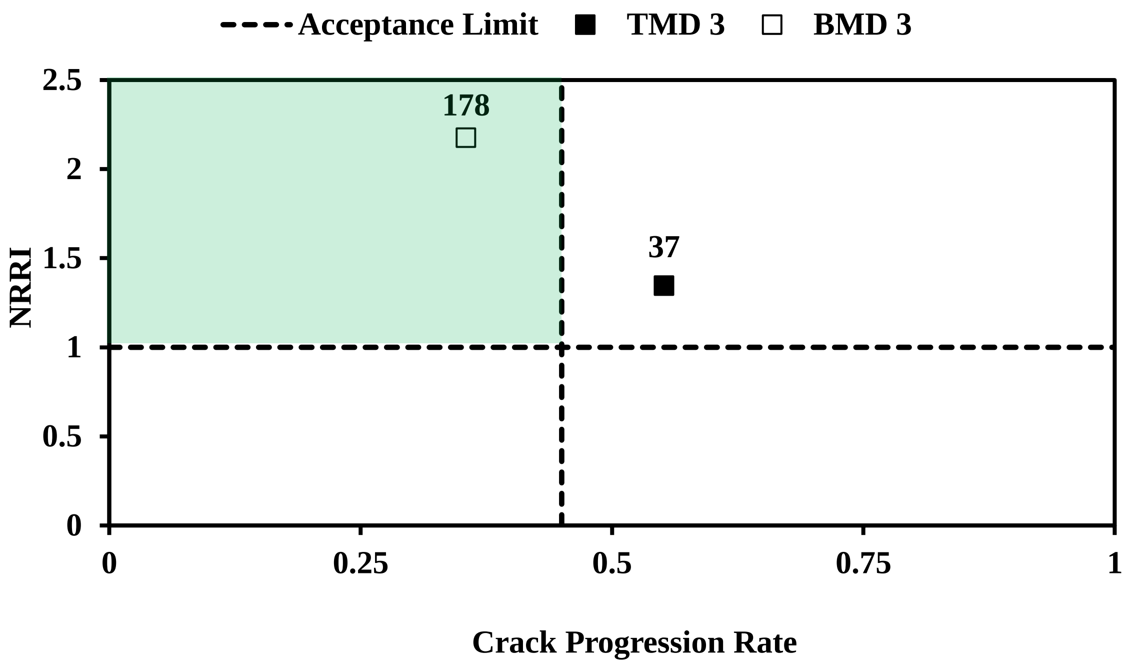


Figure 6.7 - Performance Space Diagram for Mixtures from Plant 3

Plant 4 (Rut-susceptible Mix Design)

The raw materials from Plant 4 were used to produce TMD 4 and BMD 4 mixes. To produce BMD 4 mix, the same pavement raw materials were used except for the substitution of the asphalt binder with a PG 70-28 binder and the removal of the field sand. The aggregate gradation proposed for BMD 4 mix is compared with that of TMD 4 mix in Figure 6.8. It was surmised that removing the field sand would create more space for asphalt binder, while increasing the high-temperature grade of the binder would improve the rutting resistance and tensile strength of the mixture.

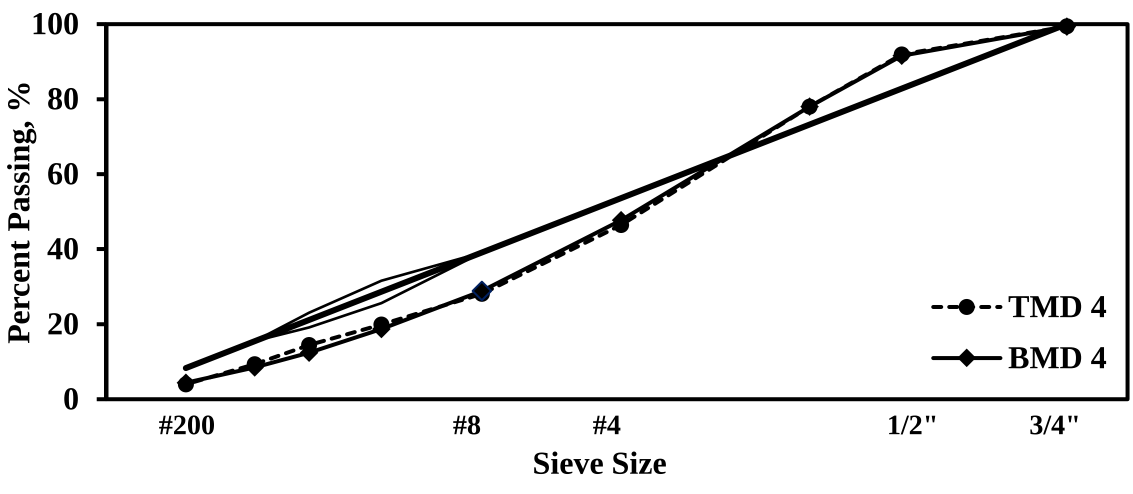


Figure 6.8 - Comparison of Gradations for Mixtures from Plant 4

The volumetric and mechanical properties of TMD 4 and BMD 4 mixes are summarized in Table 6.5. BMD 4 mix yielded an OAC of 5.2%, while TMD 2 mix exhibited an OAC of 4.8%. TMD 4 and BMD 4 mixes yielded VMAs of 15.1 and 15.9%, respectively, which satisfactorily meet the minimum VMA requirement. The mechanical performance of the mixes is compared in the performance diagram shown in Figure 6.9. Both TMD 4 and BMD 4 mixes yielded acceptable CPR values. The increase in the high-temperature grade of the binder improved the rutting resistance and the stiffness properties as determined with the HWT tests. Unlike TMD 4, BMD 4 yielded acceptable NRRI, CT Index and CPR values while providing acceptable VMA and lab molded density as required under the current specifications.

Table 6.5 - Volumetric and Performance Properties of Mixtures from Plant 4

Parameters		TMD 4	BMD 4
Volumetric Properties	Optimum Asphalt Content, %	4.8	5.2
	Voids in Mineral Aggregates, %	15.1	15.9
	Bulk Specific Gravity	2.370	2.362
	Maximum Specific Gravity	2.468	2.461
Mechanical Properties	OT Crack Progression Rate	0.31	0.40
	Rut Depth, mm	12.5	4.95
	Number of Passes	13690	20,000
	Normalized Rutting Resistance Index	0.9	2.1
	CT Index	101	66

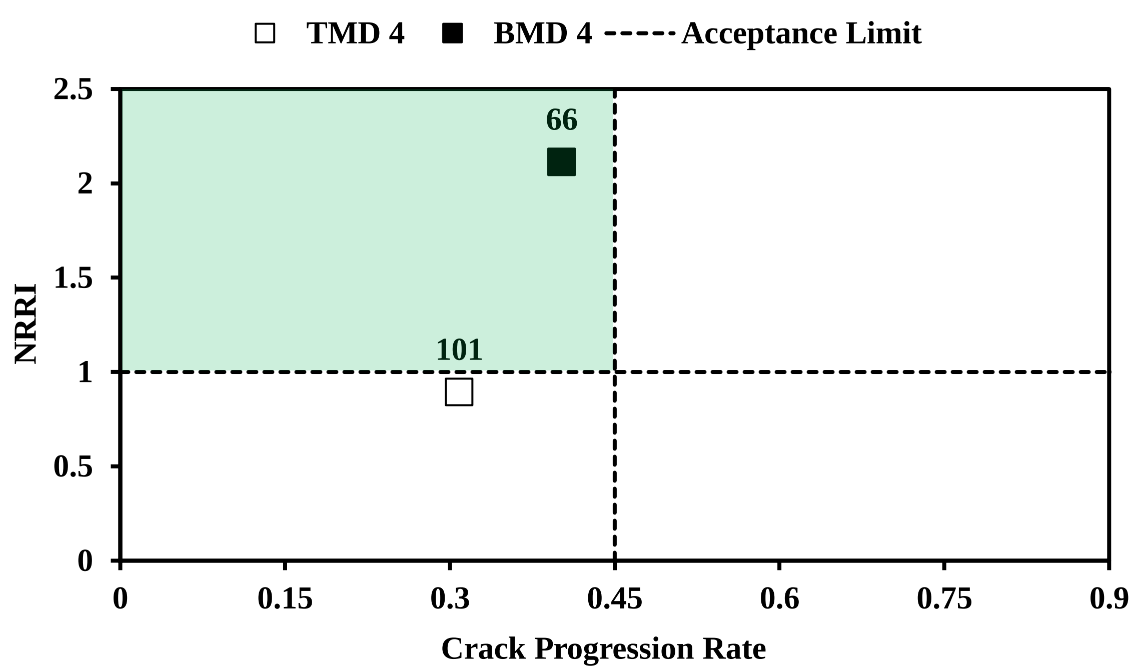


Figure 6.9 - Performance Space Diagram for Mixtures from Plant 4

Key Remarks and Findings

The implementation of a *volumetric design with performance verification* approach was tied to the selection of the aggregate gradation to produce BMD mixtures. The selection of the aggregate gradation is a very important step during the mix design process, especially for formulating BMD mixtures. In addition, the selection of the aggregate gradation can significantly help to produce an aggregate skeleton that yields stone-to-stone contact as well as enough void space for effective binder. The incorporation of performance tests and requirements such as the OT and HWT tests was key to discriminate the properties of mixtures and delineate BMD mixtures. As a result, asphalt mixtures with optimized aggregate gradations can potentially exhibit acceptable durability and stability based on the evaluated performance test methods.

TMD mixture from Plant 1, considered a crack susceptible mixture, was balanced by adjusting the aggregate gradation and allowing more binder to get into the mixture. The rutting resistance of the BMD mixtures was not significantly impacted by this modification.

TMD mixture from Plant 2, considered a crack and rut susceptible mixtures, was balanced by adjusting the aggregate gradation and decreasing the compaction effort based on the number of gyrations. For aggregate sources with a high absorption property, the asphalt content must be increased to account for absorption. Lowering N_{design} can also enable higher total asphalt content, and consequently higher effective binder content. In this case, both cracking and rutting properties were improved to make the mixture satisfactorily meet the performance requirements.

TMD mixture from Plant 3, considered a crack susceptible mixture, was balanced by adjusting the aggregate gradation and replacing the asphalt binder with a PG 70-22 binder. For this mix design, cracking and rutting resistance were significantly improved.

TMD mixture from Plant 4, considered a rut susceptible mixture, was balanced by replacing the original binder grade with a PG 70-28 binder. The rutting resistance of the asphalt mixture was improved without sacrificing the cracking resistance.

CHAPTER 7 – INFLUENCE OF ESSENTIAL MIX DESIGN VARIABLES

With the introduction of BMD mixtures, the influence of essential design variables such as binder source, PG binder, recycled material content and long-term aging must be documented to develop thorough specifications and guidelines. A comparison of the sensitivity of TMD and BMD mixtures to changes in the mix design was carried out. The results from this evaluation are discussed next.

Influence of Asphalt Binder Source

The influence of the asphalt binder source was investigated using the raw materials from Plant 2. PG 70-22 binders from five different producers were collected and evaluated in this section. Figure 7.1 depicts the CPR values from OT tests for TMD 2 and BMD 2 mixtures. The data labels reflect the COVs, which were less than 40% for CPR parameter. In general, all BMD 2 mixtures exhibited acceptable cracking resistance as judged by CPR. In the contrary to the BMD 2 mixtures, only TMD 2 mixture designed with Source B binder yielded an acceptable CPR of 0.44. In addition, TMD 2 mixtures were more sensitive to the change in binder source as observed by the wide range of CPR values ranging from 0.40 to 0.75. BMD mixtures yielded similar CPR values except for mixture designed with Source B binder that exhibited a CPR of 0.26.

The HWT test results are presented in Figure 7.2. NRRI is shown as a data label. TMD 2 mixtures with different binders yielded RRI values that ranged from 5481 to 8533. For BMD 2 mixtures with different binders the values ranged from 9561 to 17236. Based on NRRI, only three out of five TMD mixtures passed the HWT test requirements, while the five BMD mixtures satisfactorily passed the HWT test requirements. Regardless of the binder source, passing the HWT test requirements would be easier with BMD mixtures.

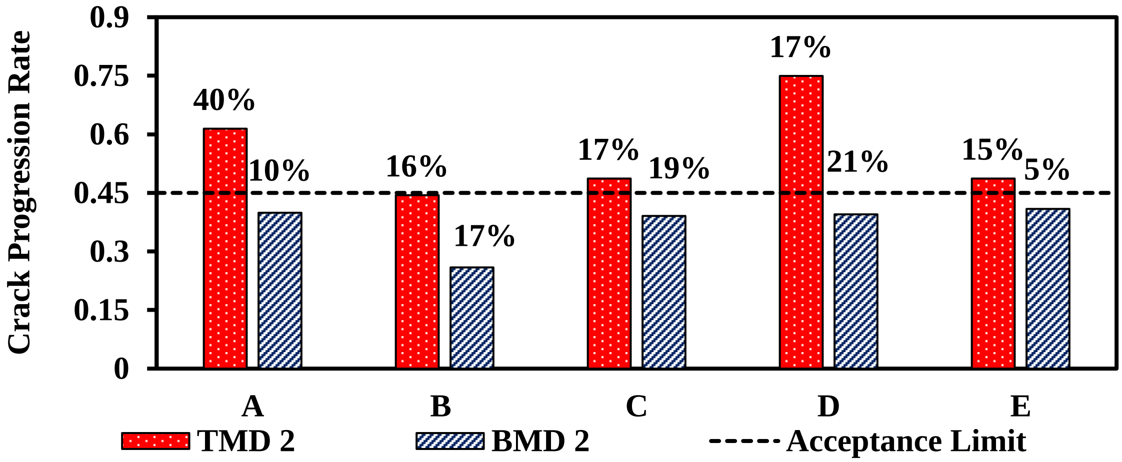


Figure 7.1 - OT Test Results: Influence of Binder Source

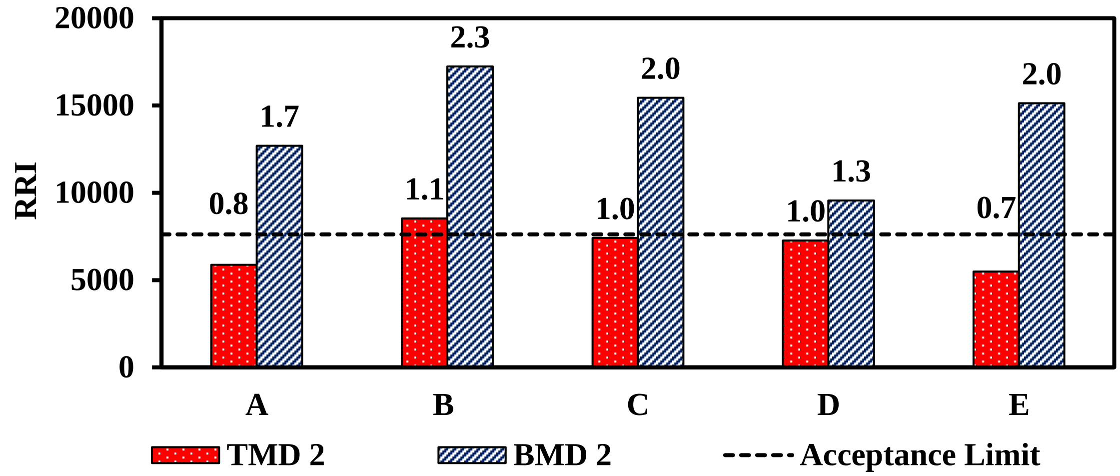


Figure 7.2 - HWT Test Results: Influence of Binder Source

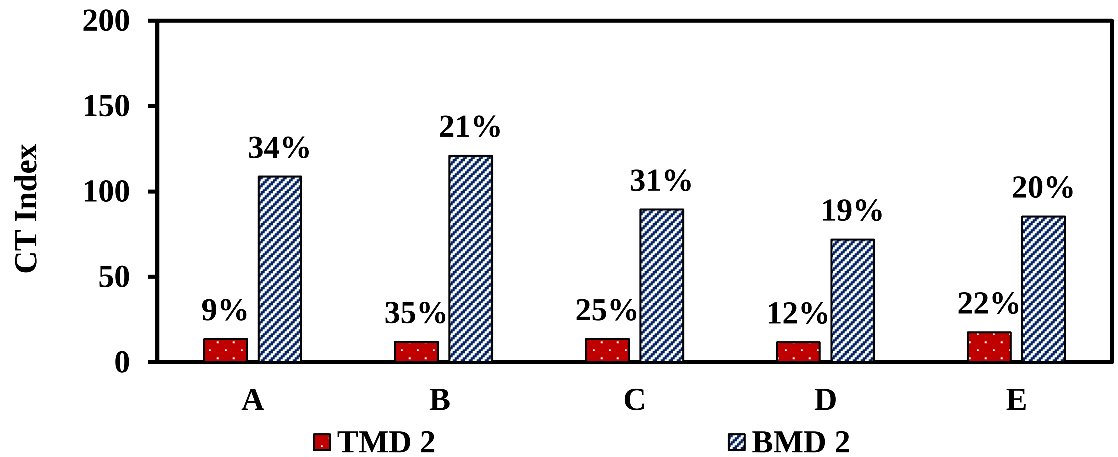


Figure 7.3 - IDT Test Results: Influence of Binder Source

The CT index for TMD 2 and BMD 2 mixtures are presented in Figure 7.3. The COVs shown as data labels varied from 9% up to 35%. The CT index values from TMD mixtures were considerably low ranging from 12 to 22. However, BMD mixtures yielded values that ranged from 72 to 171. BMD mixtures were more sensitive to change in binder source than TMD mixtures in terms of CT index.

The OT, HWT and IDEAL CT performance indicators are plotted on the performance space diagrams shown in Figure 7.4. BMD 2 mixtures from all five binder sources performed well in cracking and rutting resistance. On the other hand, only TMD 2 mixture designed with Source B binder meet the cracking and rutting requirements. BMD mixtures, as anticipated, meet mechanical performance easier.

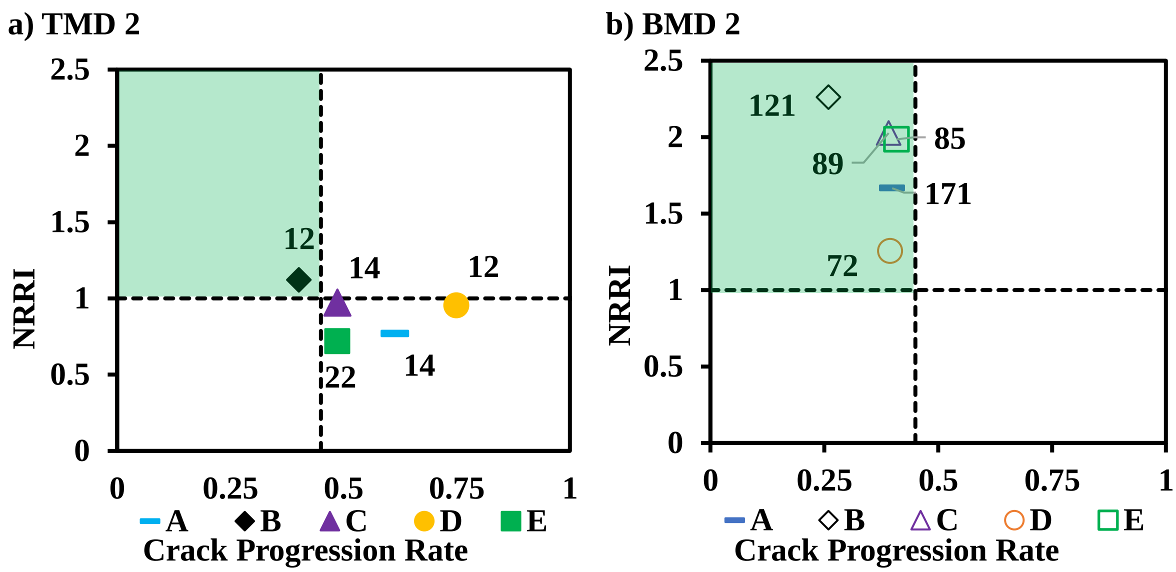


Figure 7.4 - Performance Space Diagram: Influence of Binder Source

Influence of Performance Grade of Asphalt Binder

The influence of the performance grade of asphalt binder was investigated using the mixtures from Plant 1. Binders from the same source but different PG (incl., PG 64-22, PG 70-22 and PG 76-22) were used to produce the TMD and BMD mixtures.

Figure 7.5 depicts the CPR values from OT tests for TMD 1 and BMD 1 mixtures. The data label reflects the COVs. The COV values were less than 22% for CPR. The increase in high-temperature grade of the binder did not impact the CPR for TMD 1 and BMD 1 mixtures.

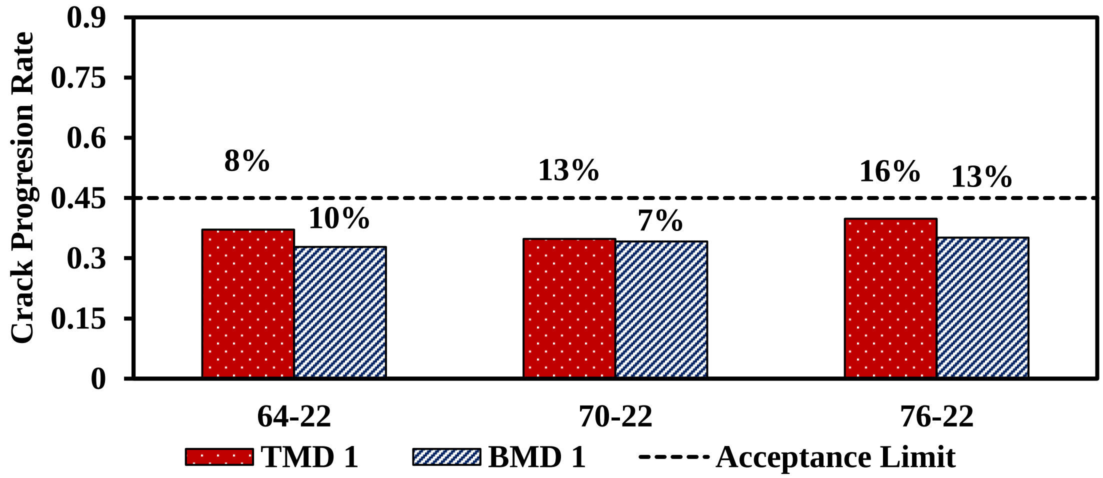


Figure 7.5 - OT Test Results: Influence of PG Binder

The HWT test results are presented in Figure 7.6. NRRI is reflected as a label above each bar. TMD 1 mixtures with different performance grade of binders yielded RRI values that ranged from 6750 to 16669. For BMD 1 mixtures with different performance grade of binders the values ranged from 14543 to 16031. For TMD 1 The increase in the high-temperature grade of the asphalt binder resulted in mixtures with better rutting resistance. Based on NRRI, all AC mixtures exhibited acceptable rutting resistance regardless of their asphalt binder PG.

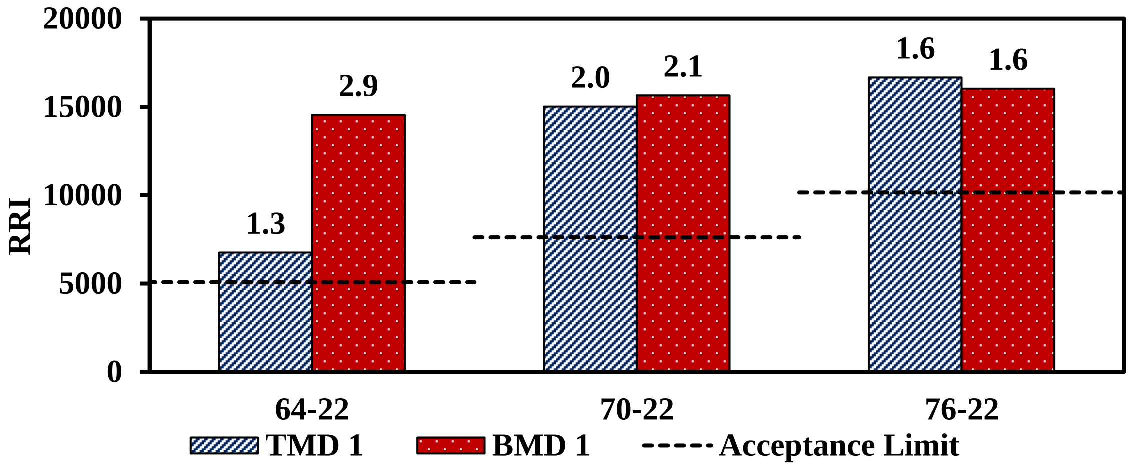


Figure 7.6 - HWT Test Results: Influence of PG Binder

The average CT Index from TMD 1 and BMD 1 mixtures are presented in Figure 7.7. The COVs that are shown as data labels were less than 34%. TMD 1 mixtures yielded CT Index values that ranged from 40 to 96. BMD 1 mixtures yielded higher CT Index values than TMD 1 mixtures.

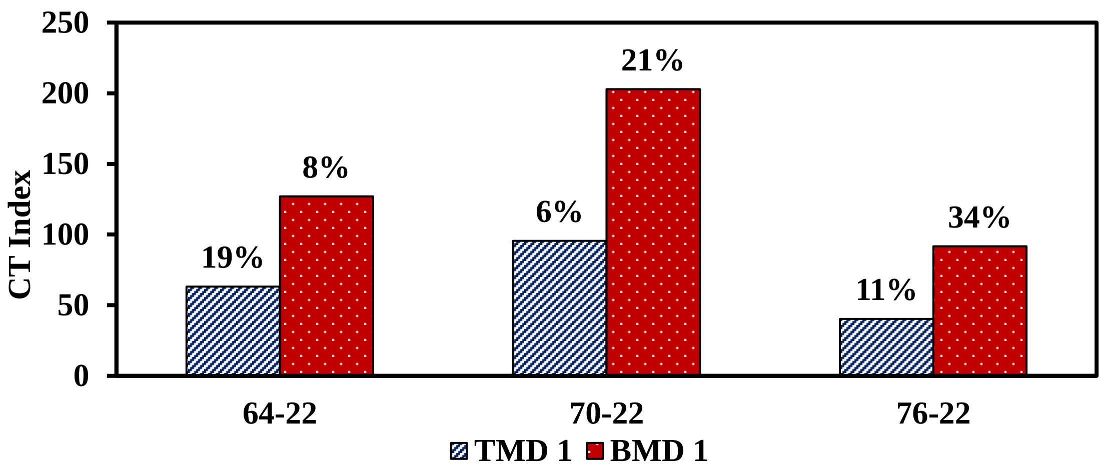


Figure 7.7 - IDT Test Results: Influence of PG Binder

The OT, HWT and IDEAL CT performance indicators are superimposed on the performance space diagram shown in Figure 7.8. Both TMD 1 and BMD 1 mixtures performed well in cracking and rutting resistance. However, TMD 1 mixtures with PG 64-22 showed the lowest NRRI. All AC mixtures can be categorized as balanced, but the increase in high-temperature grade of the binder increased the rutting resistance for TMD 1 mixture.

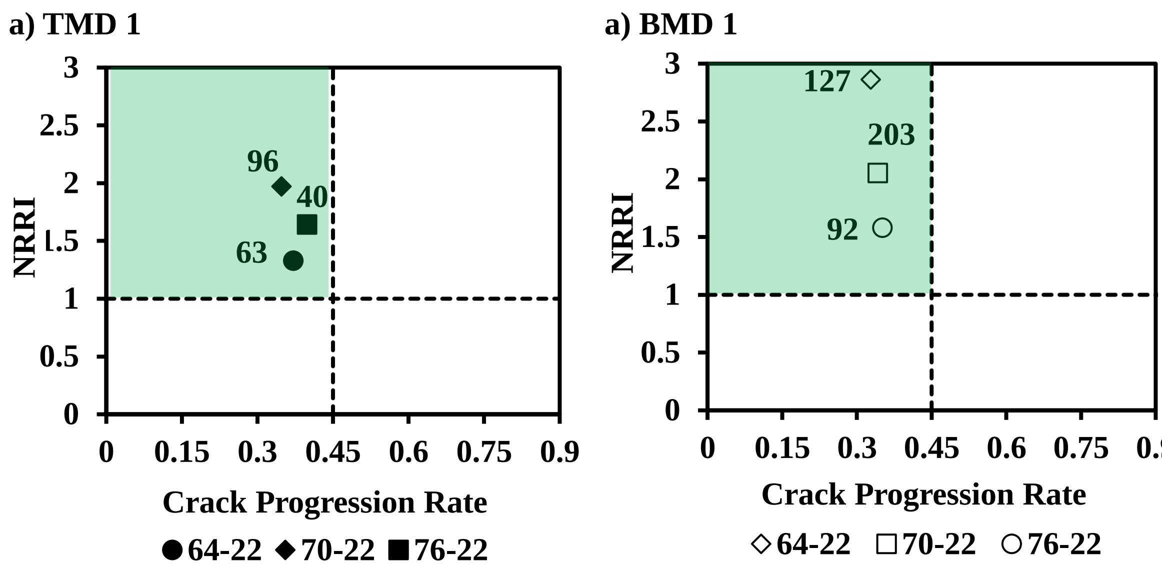


Figure 7.8 - Performance Space Diagram: Influence of Binder PG

Influence of Recycled Material Content

To investigate the influence of recycled material content on mixture's performance, two mixtures were designed using two recycled materials: reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS). BMD 1 mix was designed with three different RAP contents of 18%, 26% and 38%. BMD 4 mixture was designed with three RAS contents of 3%, 6% and 9%.

Influence of Reclaimed Asphalt Pavement for Plant 1

The volumetric properties of the AC mixes are summarized in Table 7.1. The OAC for BMD 1 mix with 18% RAP was determined to be 5.5%, while BMD 1 mix containing 26 % RAP yielded an OAC of 6.0% and for BMD 1 mix with 38% RAP an OAC of 5.7% was obtained. All AC mixtures met the minimum 15% VMA requirement for SP C mixes.

Table 7.1 - Volumetric and Performance Properties of Mixtures

BMD 1		18%	26%	38%
Volumetric Properties	Optimum Asphalt Content, %	5.5	6.0	5.7
	Voids in Mineral Aggregates, %	16.7	17.6	15.9
	Bulk Specific Gravity	2.353	2.327	2.324
	Maximum Specific Gravity	2.450	2.424	2.422

Figure 7.9 depicts the OT test results in terms of CPR for BMD 1 mixtures with different RAP contents. The data label reflects the COV. The COV values were less than 11% for CPR. All mixtures exhibited acceptable cracking resistance as judged by CPR. The good cracking resistance of mixture containing 26% RAP can be explained by the higher OAC obtained during the mix design process.

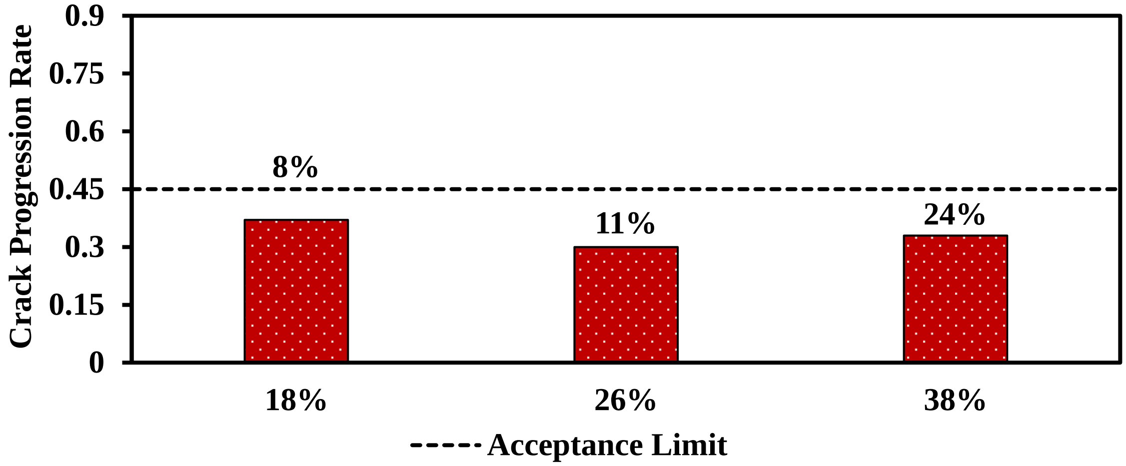


Figure 7.9 - OT Test Results: Influence of RAP

The HWT test results are presented in Figure 7.10. NRRI is reflected as a label above each bar. TMD 1 mixtures with different performance grade of binders yielded RRI values that ranged from 13906 to 15323. The range of NRRI values for BMD 1 mixtures with different RAP content did not change significantly, and all AC mixtures exhibited acceptable rutting resistance.

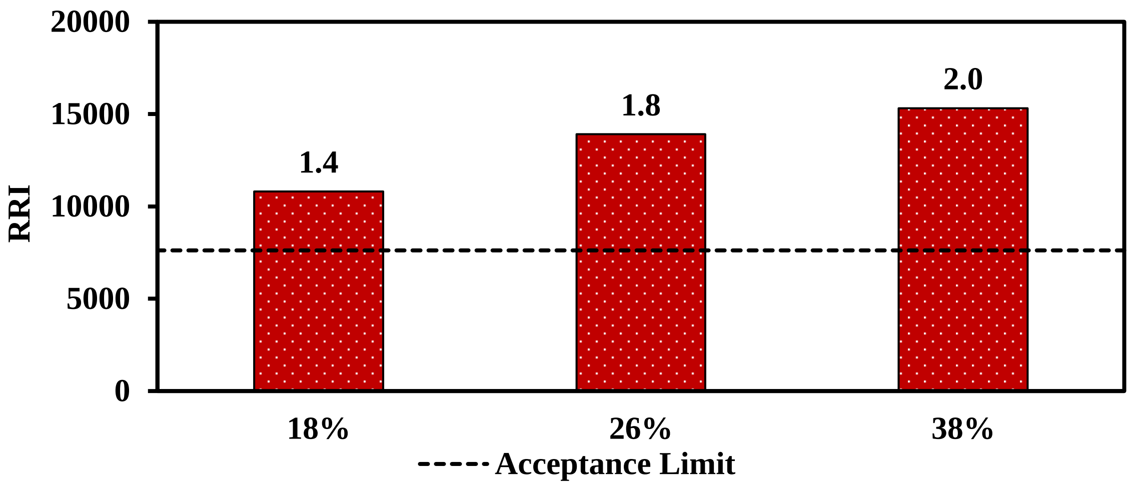


Figure 7.10 - HWT Test Results: Influence of RAP

The average CT Index values are presented in Figure 7.11. COVs are presented as data labels and were less than 33%. BMD 1 mixture with 38 % RAP yielded the lowest CT Index value of 70. The CT Index for mix with 26% RAP was greater than that with 18% RAP and 38% RAP, due to a higher OAC obtained during the design process.

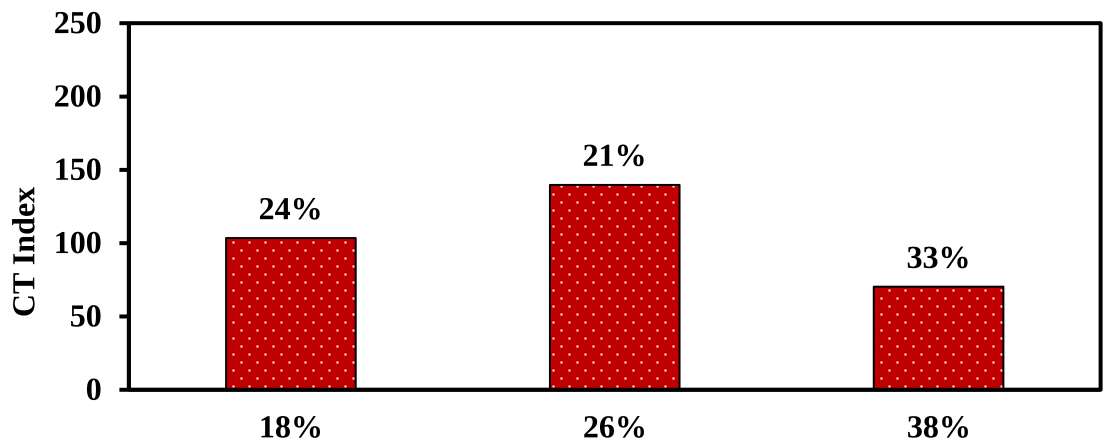


Figure 7.11 - IDT Test Results: Influence of RAP

The OT, HWT and IDEAL CT performance indicators are superimposed on the performance space diagram shown in Figure 7.12. All BMD 1 mixtures with different RAP contents performed well in cracking and rutting resistance. However, the mixtures containing 26 % RAP yielded the lowest CPR due to the higher OAC obtained during the mix design. All BMD 1 mixtures with different RAP content were within the acceptable zone and can be categorized as balanced.

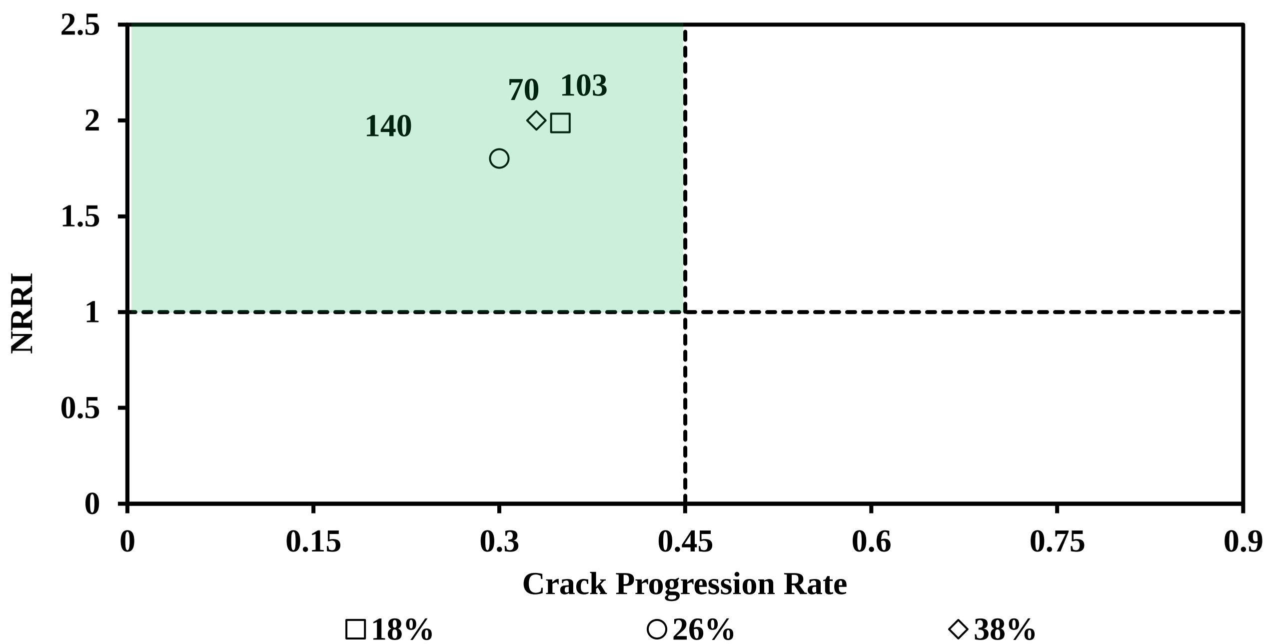


Figure 7.12 - Performance Space Diagram: Influence of RAP

Influence of Recycled Asphalt Shingles for Plant 4

The influence of the RAS was investigated by designing BMD 4 mixture with three RAS contents of 3%, 6% and 9%. The volumetric properties, such as OAC, VMA, Gmm and Gmb did not change for different RAS contents. However, the change of performance grade of asphalt binder changed significantly the mechanical properties.

Figure 7.13 depicts the CPR values from OT tests of for BMD 4 mixtures with different RAS contents. The COV values were less than 33% for CPR. Only BMD 4 mix with 3 % RAS mixtures exhibited acceptable cracking resistance as judged by the CPR. The cracking susceptibility of BMD 4 mixtures containing 6% and 9% RAS can be explained by the increase in RAS content.

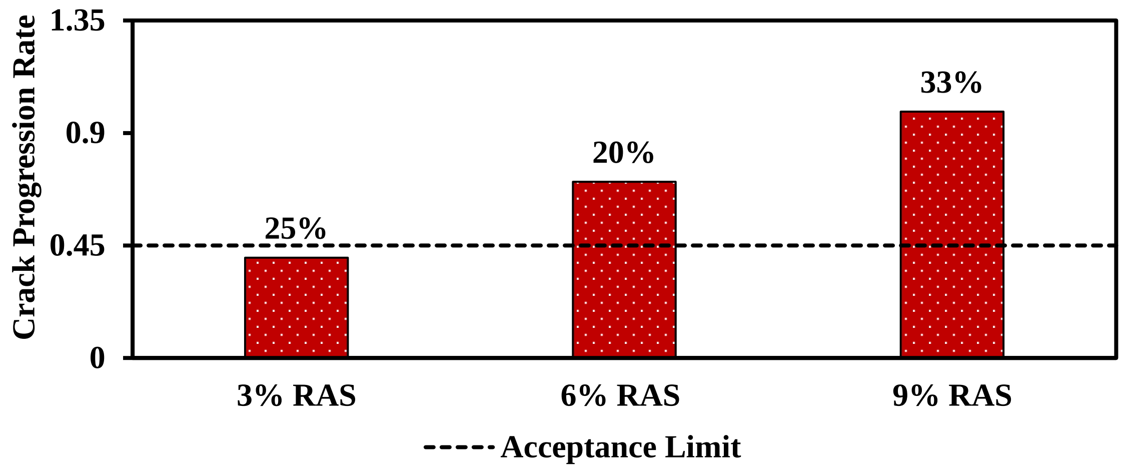


Figure 7.13 - OT Test Results: Influence of RAS

The HWT test results are presented in Figure 7.14. NRRI is reflected as a label above each bar. The increase in RAS content resulted in AC mixtures with slightly better rutting resistance. The range of NRRI values for BMD 4 mixtures with different RAS content did not change significantly, and all mixtures exhibited acceptable rutting resistance.

The average CT Index values are presented in Figure 7.15. COVs are presented as data labels and were less than 24%. BMD 4 mix with 9% RAS yielded the lowest CT Index. The increase in the RAS content reduced the CT Index values.

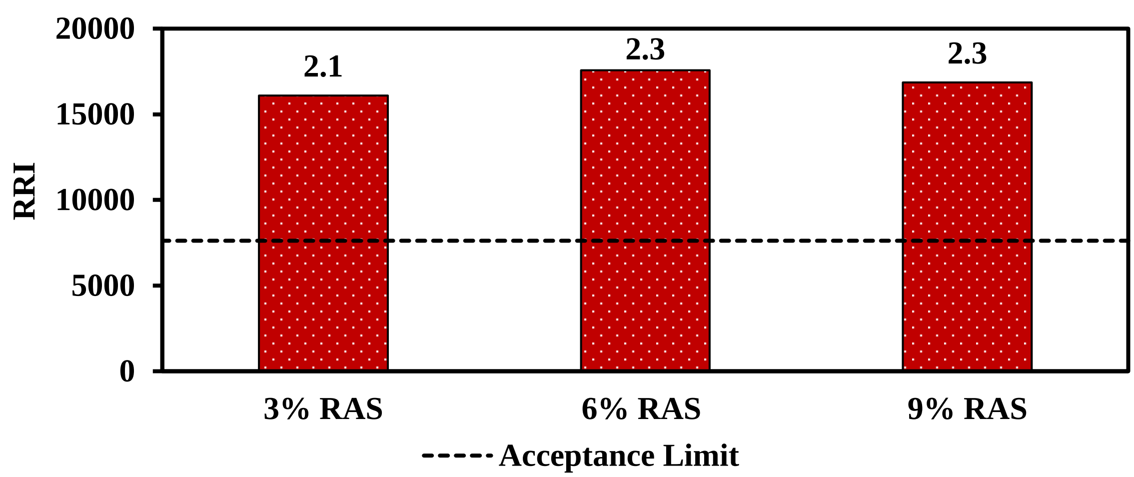


Figure 7.14 - HWT Test Results: Influence of RAS

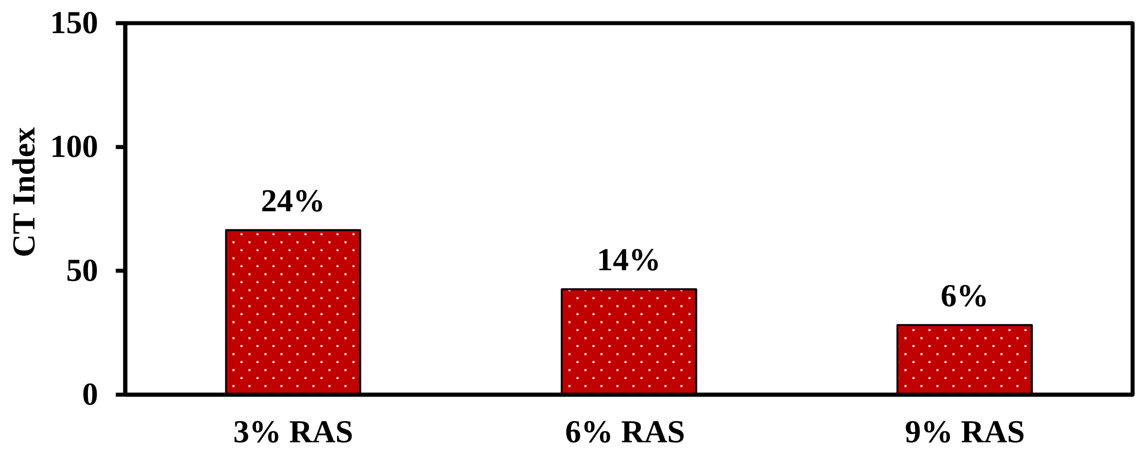


Figure 7.15 - IDT Test Results: Influence of RAS

The OT, HWT and IDEAL CT performance indicators are superimposed on the performance space diagram shown in Figure 7.16. Only BMD 2 mix with 3 % RAS met the acceptable CPR and NRRI parameters and can be classified as balanced. The increase in RAS content increased the mixture's cracking potential.

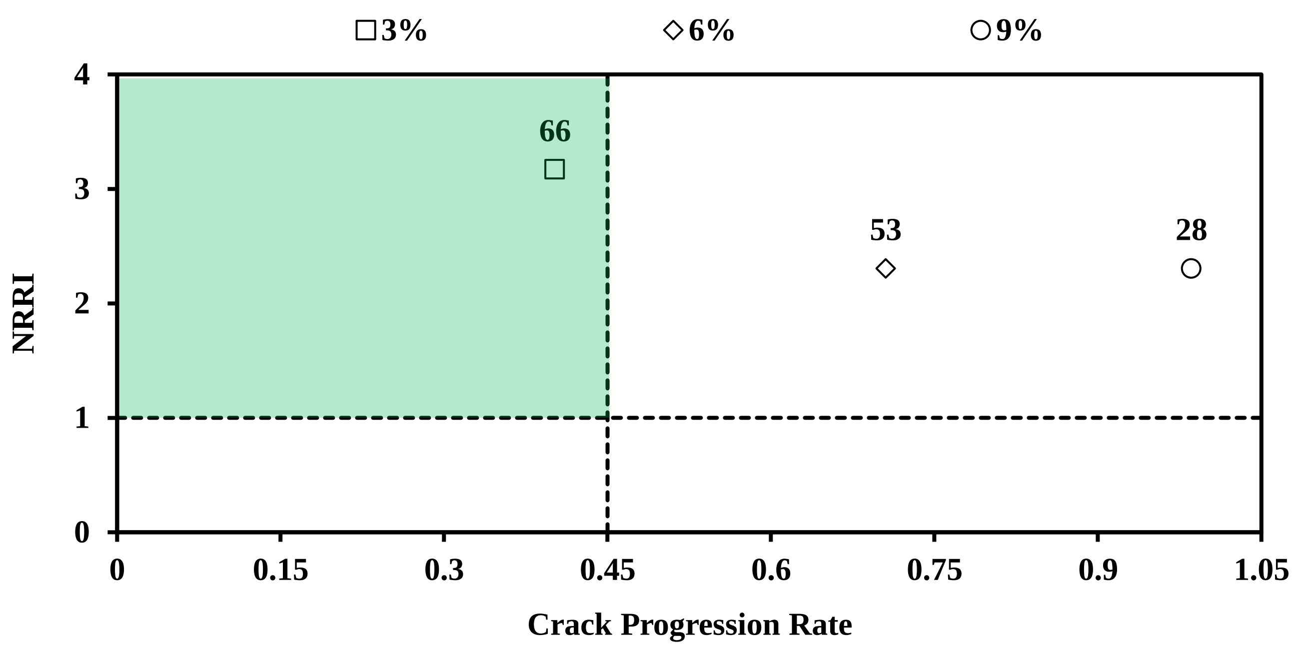


Figure 7.16 - Performance Space Diagram: Influence of RAS

Key Remarks and Findings

Several mix design variables including aggregate type, binder type and source, recycled material type and content, and additives must be considered to produce asphalt mixtures. The role of these variables must be well understood to facilitate the design of BMD mixtures. The following guidelines must be considered to formulate BMD mixtures:

- The mechanical properties of asphalt mixtures are very sensitive to the source of the binder, especially for modified binders. Between TMD and BMD mixtures, BMD mixtures will tend to be less sensitive to the change in binder PG. Even though the binders may be graded with the same PG, the designer must expect a considerable variation in the mechanical properties of the asphalt mixtures.
- Changing the PG of the binder mainly influenced the stiffness and stability of the asphalt mixtures. Modifying this mix design variable is an option when asphalt mixtures present poor rutting performance. Both TMD and BMD mixtures responded similarly to the change in binder PG.
- The inclusion of recycled materials, either RAP or RAS, must be limited to avoid crack-susceptible asphalt mixtures. Given that the current mix design assumes 100% binder availability from the recycled material, the OAC of an asphalt mixture containing high contents of recycled material must be adjusted to account for the needed extra asphalt binder to minimize cracking.

CHAPTER 8 – FRAMEWORK OF BMD SPECIFICATIONS

Summary of Activities

This study started with a comprehensive review of national and international state of practice in mix design and evaluation of asphalt mixtures as well as initiatives to implement the concept of BMD. In collaboration with the project advisory committee (PAC), the research team carried out an extensive experimental evaluation to incorporate the concept of BMD in the current specifications.

The actual work phases in this study consisted of investigating the mix design and evaluation processes for asphalt mixtures using lab-mixed lab-compacted specimens to document the challenges and opportunities to implement the BMD concept into current practices. The raw materials and design information of four commonly used asphalt mixtures were collected to document the mix design and evaluation processes. The OT and HWT tests were the cracking and rutting tests used to evaluate that the asphalt mixtures comply with the BMD concept. Given the underperformance of the typical mix designs (TMDs), the mix design variables of the TMDs specifically the aggregate gradation, were re-formulated in an effort to produce BMD mixtures. In this study, BMD mixtures yielded acceptable volumetric and mechanical properties as judged by the VMA, target lab-molded density as well as the CPR and RRI from the OT and HWT tests, respectively. A draft specification for design and evaluation of BMD mixtures was proposed in special specifications (SS) 3074 "Superpave Mixtures – Balanced Mix Design."

Major Components of New BMD Specifications

This study provides new specifications, SS 3074 "Superpave Mixtures – Balanced Mix Design," that can be used to produce BMD mixtures utilizing locally-available pavement materials. The SS 3074 BMD specifications are presented in ***Appendix B***. The specifications address the following major items:

1. Selection of pavement materials for mix designs
2. Formulation of aggregate gradation
3. Determination of optimum asphalt content
4. Performance evaluation of asphalt mixtures

Recommendations Related to New BMD Specifications

The BMD specifications contain suggestions about the areas that DOTs should modify to properly produce BMD mixtures with a *volumetric analysis with performance verification* design approach. Some guidance in applying the BMD specifications is given for the following sections:

Selection of Pavement Materials

Asphalt mixtures with low asphalt content have shown poor performance in terms of cracking resistance. Field sand or other uncrushed fine aggregate source should be limited to 15% of the total aggregates. The use of field sand increases the packing density of the aggregate blend reducing the void space for effective asphalt binder to be introduced into the asphalt mixture. To produce BMD mixtures, minimizing the use of field sand can be a key to optimize the mechanical properties of the asphalt mixture.

Asphalt binders are always characterized with the performance grading system to assess the high and low temperature grades. The characterization of the asphalt binders should be supplemented by incorporating parameters such as ΔT_c. Parameter ΔT_c, which is the difference between the low temperature grades based on creep stiffness ($T_{c,s}$) and m-value ($T_{c,m}$), must meet a minimum acceptance limit of 6.0 °C.

In terms of specifying additives to produce BMD mixtures, the following items should be considered:

- A chemical warm mix additive that is used to produce an asphalt mixture at a discharge temperature greater than 275 °F must be considered a compaction aid. If the discharge temperature is maintained at or lower than 275 °F, the additive is considered a warm mix additive.
- The use of rejuvenators approved by the TxDOT Materials and Tests Division is allowed if specified or shown on the plans.

The use of recycled materials such as RAP and RAS is allowed in BMD mixtures. A maximum amount of 35% of recycled materials is allowed as long as the mixture meets the performance requirements. In addition, BMD mixtures with RAP must also meet the recycled binder ratio of 30. Up to 5% RAS is allowed., the substitution of PG binders in the presence of recycled materials is limited to only PG 76-22 and PG 76-28 binders. The other binders must be used as originally specified in the plans

Formulation of Aggregate Gradation

The formulation of the aggregate gradation is a key step in the proper BMD mix design process. The use of the master gradation limits is proposed to formulate the gradation of asphalt mixtures. To facilitate the formulation of the aggregate gradation for BMD mixtures, the master gradations limits, specifically the maximum percent passing s for #8, #16, #30 and #50 sieves, were refined. This change is proposed to optimize the binder content of the asphalt mixture.

Determination of Optimum Asphalt Content

The optimum asphalt content for a BMD mixture is still determined by compacting the mixtures at different asphalt contents and aiming to match a pre-defined target lab-molded density. The number of gyrations during compaction can be adjusted to facilitate a BMD. The number of gyrations, which can range between 35 and 100, is proposed to indirectly control the amount of asphalt binder required to produce a BMD mixture. In addition, the dust to asphalt binder ratio is proposed to range from 0.6 to 1.4 to increase the amount of effective asphalt binder in the BMD mixture.

Performance Evaluation of Asphalt Mixtures

After selecting the OAC following the volumetric analysis design process, the asphalt mixture must be evaluated with a cracking and a rutting test. The OT test is proposed as the cracking test, while the HWT test is used as the rutting test. BMD mixtures must exhibit a maximum CPR value of 0.45 for the OT test. The already established acceptance thresholds for the HWT test in terms of the number of passes and rut depth should be used. Parameter RRI is proposed as an alternative rutting performance parameter (See Table 3.3).

Dissemination of Information

The key findings of this study should be disseminated in a balanced way to the pavement community (i.e., DOTs, asphalt producers and pavement designers). Technical presentation should not only emphasize on the key findings from the research work but also on the benefits of implementing the BMD specifications in other sections such as economy and sustainability. Training workshops on BMD specifications must also enumerate the expected changes in day-to-day operations of DOTs and asphalt contractors and means of adapting them in a gradual manner.

Application of Balanced Mix Design

The following activities are recommended to properly adapt BMD concept into current practices:

- Apply BMD specifications to evaluate a wider range of mix design variables such as the aggregate type and gradation, asphalt binder type and source, recycled material content and source, and additives.
- Document the cost-benefit of new BMD specifications in comparison with other mix design specification such as Superpave, traditional dense-graded and SMA mixtures.
- Evaluate the production process for BMD mixtures including design process, trial batch verification, and plant-produced material.
- Document the use of volumetric and/or mechanical parameters for quality control and acceptance process for BMD mixtures.
- Implement BMD specifications to build pavement field test sections for laboratory-field verification of BMD mixture performance through a pilot field study (See ***Appendix C***)

This study demonstrates the technical benefits and the challenges that are related to the implementation of the BMD specifications. Even though all aspects of the development of the BMD specifications, testing protocols and guidelines are thoroughly and comprehensively discussed, the number of mix designs and variables is limited to leverage a full implementation of the proposed solutions.

However, around the start of the efforts to carry out limited implementation, an Inter-Agency Contract (IAC) was initiated by TxDOT that involved three universities: a) Texas A&M through Texas Transportation Institute (TTI), UT through Center for Transportation Research (CTR), and UTEP through Center for Transportation Infrastructure Systems(CTIS). The contract's main goal was to place BMD sections throughout the state.

In conjunction with IAC 10 to 12 construction project were identified as field demonstration sites. The goal was to try to have alternative mixes to be placed on four sections of the project. The preference can be given to projects that may be willing to experiment with the surface mixes. Since UTEP was to carry out most of the laboratory verification efforts, TTI was handling all the logistics of material gathering and field coring. The goal was to core right after construction and revisit yearly for additional monitoring and coring. In addition, due to having such a large number of field testing sections, it was crucial to be consistent in all aspects of data gathering so that the laboratory performance can deliver the performance results to the contractors in a timely manner. Appendix D has the application of the of balanced mix design efforts.

Each of the research groups created and maintained a data depository to safely store the laboratory and field performance data and facilitate access for future use, reference and analysis. With respect to the work done under research project 0-6923 all the mix design support was carried out by using the online gradation design tool developed under this research. Appendix E provides the development of the online gradation tool. In addition, since UTEP was to perform the OT testing for all aspects of the project, the online OT tool that was developed under 0-6923 was used for the data reduction.

CHAPTER 9 – CONCLUSIONS AND RECOMMENDATIONS

Possible mix design modifications that can be carried out to improve the volumetric and mechanical properties of asphalt mixtures, specifically their cracking resistance were documented. Four typical Superpave mixtures that exhibited poor mechanical performance were selected and evaluated. A *volumetric based design with performance verification* was implemented to produce BMD mixtures using the OT and HWT tests as the cracking and rutting tests, respectively. The volumetric and mechanical properties of the Superpave mixes were improved by formulating an alternative aggregate gradation. The BMD mixtures developed meet the volumetric and performance requirements for Superpave mixtures. The influence of essential mix design variables was also documented by evaluating TMD and BMD mixtures with varying binder sources, binder PGs and recycled material contents.

Conclusions

From this study, the following conclusions can be drawn:

1. Current Superpave mixtures are designed to optimize the content of asphalt binder and volumetric properties without strictly considering the use of performance requirements. Due to the low binder content, Superpave mixtures exhibit poor cracking resistance. With the inclusion of recycled materials, the cracking resistance of these Superpave mixtures is further aggravated. Increasing the amount of asphalt content is the answer to improve the mechanical performance of mixtures.
2. Based on the *performance-based approach*, the change in asphalt content can improve the cracking resistance of a crack-susceptible mix. However, the volumetric properties (e.g. laboratory molded density) of the mixture may fall outside the current operational tolerance limits. If improving the mechanical performance of mixtures by adjusting only the asphalt content of a mix is the approach to be implemented, the volumetric requirements for mixtures will need to be relaxed and refined, specifically the lab-molded density.
3. Regardless of the mix design approach, the selection of an aggregate gradation is key to produce a BMD mixture. By optimizing the gradation, the durability of the mixture can be improved by increasing the asphalt content and the stability of the mixture can be controlled by providing stone-to-stone contact through the aggregate skeleton.
4. The coarse portion of the gradation did not change the volumetric properties of the mix. Volumetric properties were more sensitive to the change of the intermediate portion of the gradation. Decreasing the percent passing of the intermediate portion of the gradation resulted in an increase in the volumetric properties (e.g. greater VMA and OAC).
5. Within the ranges tested the optimization of the aggregate gradation is a promising approach that can potentially improve and balance the volumetric and mechanical properties of a mix design. As demonstrated with the selected mix designs, the portion of the gradation that represents the intermediate aggregate size can be adjusted to produce BMD mixtures with acceptable volumetric properties. While the aggregate gradation can positively impact the stability of the mixture (as judge by the HWT test), adjusting the

aggregate gradation can also create space for asphalt binder within the aggregate skeleton to improve the durability of the mixture (as judged by the OT test).

6. The influence of binder source was different for TMD and BMD mixtures. BMD mixtures with binders from five sources exhibited similar and acceptable cracking performance. On the other hand, the change of binder source for TMD mixtures yielded high variation in the CPRs and did not help to pass the cracking requirements.
7. The change in high-temperature grade of the binder improved the rutting resistance of TMD and BMD mixtures as determined with the HWT test. The change in binder PG did not impact the cracking resistance of TMD and BMD mixtures based on the OT test.
8. The change in RAP content while keeping the gradation constant only increased the rutting resistance of BMD mixtures without impacting their cracking resistance.
9. The increase in RAS content negatively affected the cracking properties of the BMD mixtures. The increase in RAS resulted in an increase of rutting resistance for BMDs.

Recommendations

The following recommendations are provided to continue implementing the BMD concept:

1. Laboratory standard for aging mixtures during mix design should be investigated to ensure an adequate level of aging. Practical guidelines and acceptance limits also should be investigated under the long-term aging testing procedure of the asphalt mixture.
2. The implementation of a *performance-based design* approach sounds ideal to consider directly the cracking and rutting resistance of an asphalt mixture for selecting an optimum asphalt content during the design process. However, implementing a *performance-based design* approach requires several modifications to current design, production and placement processes for asphalt mixtures. Further research is required to fully implement a *performance-based design* and corresponding design and construction specifications.
3. Regardless of the mix design approach, a procedure for introducing cracking tests into QC/QA should be worked out.
4. Even though the variability of the tests was reasonable, more attention can be paid to mitigating as much variability as possible for the sake of accuracy and bias.

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APPENDIX A – VOLUMETRIC ANALYSIS OF ASPHALT MIXTURES

Calculate the design VMA:

$$VMA = \left\{100 - \left[\left(\frac{G_{mb}}{G_{mm}}\right) * 100\right]\right\} + [\frac{G_{mb} * A_s}{G_s}]$$

Where:
VMA = voids in mineral aggregates

Calculate VFA:

$$VFA = 100 * \frac{VMA - V_a}{VMA}$$

Where:
VFA = voids filled with asphalt
VMA = voids in the material aggregate, percent bulk volume
Va = air voids in compacted mixture, percent of total volume

Calculate Dust-to-Binder Ratio (DB ratio)

$$DB\ Ratio = P_{200}/P_{be}$$

Where:
P_{200}= mass of particles retained on No. 200 sieve
P_{be}= effective binder content = the total asphalt binder content of a paving mixture less the portion of asphalt binder that is lost by absorption into the aggregate particles.

Calculate FT:

$$FT = \frac{\left(\frac{\frac{P_{be}}{100}}{1 - \frac{P_{be}}{100}}\right)}{SA * G_s * 1000} * 10^6$$

$$P_{ba} = 100 * G_s\left(\frac{G_s - G_{sb}}{G_{sb} * G_e}\right)$$

$$P_{be} = A_s - P_{ba}(\frac{100 - A_s}{100})$$

Where:
F_T = film thickness of asphalt binder in mixture, microns
$P_{ba=}$ absorbed asphalt in mixture, %
G_{sb}= bulk specific gravity of combined aggregates
P_{be} = effective asphalt in mixture, %

Calculate the VCA_{Mix}

$$VCA_{Mix} = 100 - \left[\left(\frac{G_{mb}}{G_{CA}}\right)\right] * P_{CA}]$$

Where:
VCA_{Mix}= voids in coarse aggregate for the compacted mixture
P_{CA} = percentage coarse aggregate in the total mix.

APPENDIX B – PROPOSED BMD SPECIFICATIONS

Special Specification 3074

Superpave Mixtures – Balanced Mix Design

1. DESCRIPTION

Construct a hot-mix asphalt (HMA) surface pavement layer composed of a compacted, Superpave (SP) mixture of aggregate and asphalt binder mixed hot in a mixing plant utilizing a Balanced Mix Design (BMD) approach. Payment adjustments will apply to HMA placed under this specification unless the HMA is deemed exempt in accordance with Section 344.4.9.4., "Exempt Production."

2. MATERIALS

Furnish uncontaminated materials of uniform quality that meet the requirements of the plans and specifications.

Notify the Engineer of all material sources and before changing any material source or formulation. The Engineer will verify that the specification requirements are met when the Contractor makes a source or formulation change and may require a new laboratory mixture design, trial batch, or both. The Engineer may sample and test project materials at any time during the project to verify specification compliance in accordance with Item 6, "Control of Materials."

2.1. **Aggregate**. Furnish aggregates from sources that conform to the requirements shown in Table 1 and as specified in this Section. Aggregate requirements in this Section, including those shown in Table 1, may be modified or eliminated when shown on the plans. Additional aggregate requirements may be specified when shown on the plans. Provide aggregate stockpiles that meet the definitions in this Section for coarse, intermediate, or fine aggregate. Aggregate from reclaimed asphalt pavement (RAP) is not required to meet Table 1 requirements unless otherwise shown on the plans. Supply aggregates that meet the definitions in Tex-100-E for crushed gravel or crushed stone. The Engineer will designate the plant or the quarry as the sampling location. Provide samples from materials produced for the project. The Engineer will establish the Surface Aggregate Classification (SAC) and perform Los Angeles abrasion, magnesium sulfate soundness, and Micro-Deval tests. Perform all other aggregate quality tests listed in Table 1. Document all test results on the mixture design report. The Engineer may perform tests on independent or split samples to verify Contractor test results. Stockpile aggregates for each source and type separately. Determine aggregate gradations for mixture design and production testing based on the washed sieve analysis given in Tex-200-F, Part II.

2.1.1. **Coarse Aggregate**. Coarse aggregate stockpiles must have no more than 20% material passing the No. 8 sieve. Aggregates from sources listed in the Department's *Bituminous Rated Source Quality Catalog* (BRSQC) are preapproved for use. Use only the rated values for hot-mix listed in the BRSQC. Rated values for surface treatment (ST) do not apply to coarse aggregate sources used in hot-mix asphalt.

For sources not listed on the Department's BRSQC:

- build an individual stockpile for each material;
- request the Department test the stockpile for specification compliance; and
- once approved, do not add material to the stockpile unless otherwise approved.

Provide aggregate from non-listed sources only when tested by the Engineer and approved before use. Allow 30 calendar days for the Engineer to sample, test, and report results for non-listed sources.

Provide coarse aggregate with at least the minimum SAC shown on the plans. SAC requirements only apply to aggregates used on the surface of travel lanes. SAC requirements apply to aggregates used on surfaces other than travel lanes when shown on the plans. The SAC for sources on the Department's *Aggregate Quality Monitoring Program* (AQMP) (Tex-499-A) is listed in the BRSQC.

2.1.1.1. **Blending Class A and Class B Aggregates**. Class B aggregate meeting all other requirements in Table 1 may be blended with a Class A aggregate to meet requirements for Class A materials, unless otherwise shown on the plans. Ensure that at least 50% by weight, or volume if required, of the material retained on the No. 4 sieve comes from the Class A aggregate source when blending Class A and B aggregates to meet a Class A requirement unless otherwise shown on the plans. Blend by volume if the bulk specific gravities of the Class A and B aggregates differ by more than 0.300. Coarse aggregate from RAP and Recycled Asphalt Shingles (RAS) will be considered as Class B aggregate for blending purposes.

The Engineer may perform tests at any time during production, when the Contractor blends Class A and B aggregates to meet a Class A requirement, to ensure that at least 50% by weight, or volume if required, of the material retained on the No. 4 sieve comes from the Class A aggregate source. The Engineer will use the Department's mix design template, when electing to verify conformance, to calculate the percent of Class A aggregate retained on the No. 4 sieve by inputting the bin percentages shown from readouts in the control room at the time of production and stockpile gradations measured at the time of production. The Engineer may determine the gradations based on either washed or dry sieve analysis from samples obtained from individual aggregate cold feed bins or aggregate stockpiles. The Engineer may perform spot checks using the gradations supplied by the Contractor on the mixture design report as an input for the template; however, a failing spot check will require confirmation with a stockpile gradation determined by the Engineer.

2.1.1.2. **Micro-Deval Abrasion**. The Engineer will perform a minimum of one Micro-Deval abrasion test in accordance with Tex-461-A for each coarse aggregate source used in the mixture design that has a Rated Source Soundness Magnesium (RSSM) loss value greater than 15 as listed in the BRSQC. The Engineer will perform testing before the start of production and may perform additional testing at any time during production. The Engineer may obtain the coarse aggregate samples from each coarse aggregate source or may require the Contractor to obtain the samples. The Engineer may waive all Micro-Deval testing based on a satisfactory test history of the same aggregate source.

The Engineer will estimate the magnesium sulfate soundness loss for each coarse aggregate source, when tested, using the following formula:

$$Mg_{est.} = (RSSM)(MD_{act.}/RSMD)$$

where:
$Mg_{est.}$ = magnesium sulfate soundness loss
$MD_{act.}$ = actual Micro-Deval percent loss
RSMD = Rated Source Micro-Deval

When the estimated magnesium sulfate soundness loss is greater than the maximum magnesium sulfate soundness loss specified, the coarse aggregate source will not be allowed for use unless otherwise approved. The Engineer will consult the Soils and Aggregates Section of the Materials and Tests Division, and additional testing may be required before granting approval.

2.1.2. **Intermediate Aggregate**. Aggregates not meeting the definition of coarse or fine aggregate will be defined as intermediate aggregate. Supply intermediate aggregates, when used that are free from organic impurities. The Engineer may test the intermediate aggregate in accordance with Tex-408-A to verify the material is free from organic impurities. Supply intermediate aggregate from coarse aggregate sources, when used that meet the requirements shown in Table 1 unless otherwise approved.

Test the stockpile if 10% or more of the stockpile is retained on the No. 4 sieve, and verify that it meets the requirements in Table 1 for crushed face count (Tex-460-A) and flat and elongated particles (Tex-280-F).

2.1.3. **Fine Aggregate**. Fine aggregates consist of manufactured sands, screenings, and field sands. Fine aggregate stockpiles must meet the gradation requirements in Table 2. Supply fine aggregates that are free from organic impurities. The Engineer may test the fine aggregate in accordance with Tex-408-A to verify the material is free from organic impurities. No more than 15% of the total aggregate may be field sand or other uncrushed fine aggregate. Use fine aggregate, with the exception of field sand, from coarse aggregate sources that meet the requirements shown in Table 1 unless otherwise approved.

Test the stockpile if 10% or more of the stockpile is retained on the No. 4 sieve and verify that it meets the requirements in Table 1 for crushed face count (Tex-460-A) and flat and elongated particles (Tex-280-F).

Table 1
Aggregate Quality Requirements

Property	Test Method	Requirement
Coarse Aggregate		
SAC	Tex-499-A (AQMP)	As shown on the plans
Deleterious material, %, Max	Tex-217-F, Part I	1.0
Decantation, %, Max	Tex-217-F, Part II	1.5
Micro-Deval abrasion, %	Tex-461-A	Note 1
Los Angeles abrasion, %, Max	Tex-410-A	35
Magnesium sulfate soundness, 5 cycles, %, Max	Tex-411-A	25
Crushed face count,[2] %, Min	Tex-460-A, Part I	85
Flat and elongated particles @ 5:1, %, Max	Tex-280-F	10
Fine Aggregate		
Linear shrinkage, %, Max	Tex-107-E	3
Sand equivalent, %, Min	Tex-203-F	45

1. Used to estimate the magnesium sulfate soundness loss in accordance with Section 344.2.1.1.2., “Micro-Deval Abrasion.”
2. Only applies to crushed gravel.

Table 2
Gradation Requirements for Fine Aggregate

Sieve Size	% Passing by Weight or Volume
3/8"	100
#8	70–100
#200	0–30

2.2. **Mineral Filler**. Mineral filler consists of finely divided mineral matter such as agricultural lime, crusher fines, hydrated lime, or fly ash. Mineral filler is allowed unless otherwise shown on the plans. Use no more than 2% hydrated lime or fly ash unless otherwise shown on the plans. Use no more than 1% hydrated lime if a substitute binder is used unless otherwise shown on the plans or allowed. Test all mineral fillers except hydrated lime and fly ash in accordance with Tex-107-E to ensure specification compliance. The plans may require or disallow specific mineral fillers. Provide mineral filler, when used, that:

- is sufficiently dry, free-flowing, and free from clumps and foreign matter as determined by the Engineer;
- does not exceed 3% linear shrinkage when tested in accordance with Tex-107-E; and
- meets the gradation requirements in Table 3.

Table 3
Gradation Requirements for Mineral Filler

Sieve Size	% Passing by Weight or Volume
#8	95–100
#200	45–100

2.3. **Baghouse Fines**. Fines collected by the baghouse or other dust-collecting equipment may be reintroduced into the mixing drum.

2.4. **Asphalt Binder**. Furnish the type and grade of performance-graded (PG) asphalt specified on the plans. In addition to meeting the requirements in Item 300, “Asphalts, Oils, and Emulsions,” the difference in critical temperatures for low temperature testing (ΔT_c) based on creep stiffness ($T_{c,s}$) and m-value ($T_{c,m}$) must be less than 6.0 °C. The critical temperature is defined as the temperature at which the test parameter is equal to the specification limit.

2.5. **Tack Coat**. Furnish CSS-1H, SS-1H, or a PG binder with a minimum high-temperature grade of PG 58 for tack coat binder in accordance with Item 300, “Asphalts, Oils, and Emulsions.” Specialized tack coat materials listed on the Department’s MPL are allowed or required when shown on the plans. Do not dilute emulsified asphalts at the terminal, in the field, or at any other location before use.

2.6. **Additives**. Use the type and rate of additive specified when shown on the plans. Additives that facilitate mixing, compaction, or improve the quality of the mixture are allowed when approved. Provide the Engineer with documentation such as the bill of lading showing the quantity of additives used in the project unless otherwise directed.

2.6.1. **Lime and Liquid Antistripping Agent**. When lime or a liquid antistripping agent is used, add in accordance with Item 301, “Asphalt Antistripping Agents.” Do not add lime directly into the mixing drum of any plant where lime is removed through the exhaust stream unless the plant has a baghouse or dust collection system that reintroduces the lime into the drum.

2.6.2. **Warm Mix Asphalt (WMA)**. Warm Mix Asphalt (WMA) is defined as HMA that is produced within a target temperature discharge range of 215°F and 275°F using approved WMA additives or processes from the Department’s MPL.

WMA is allowed for use on all projects and is required when shown on the plans. When WMA is required, the maximum placement or target discharge temperature for WMA will be set at a value below 275°F.

Department-approved WMA additives or processes may be used to facilitate mixing and compaction of HMA produced at target discharge temperatures above 275°F; however, such mixtures will not be defined as WMA.

2.6.3. **Compaction Aid.** Compaction Aid is defined as a chemical warm mix additive that is used to produce an asphalt mixture at a discharge temperature greater than 275°F.

Compaction Aid is allowed for use on all projects and is required when shown on the plans.

2.6.4. **Rejuvenators.** Furnish rejuvenators approved by the Materials and Tests Division when specified or shown on the plans.

2.7. **Recycled Materials**. Use of RAP and RAS is permitted unless otherwise shown on the plans. Do not exceed the maximum allowable percentages of RAP and RAS shown in Table 4. The allowable percentages shown in Table 4 may be decreased or increased when shown on the plans. Determine the asphalt binder content and gradation of the RAP and RAS stockpiles for mixture design purposes in accordance with Tex-236-F, Part I. The Engineer may verify the asphalt binder content of the stockpiles at any time during production. Perform other tests on RAP and RAS when shown on the plans. Asphalt binder from RAP and RAS is designated as recycled asphalt binder. Calculate and ensure that the ratio of the recycled asphalt binder to total binder does not exceed the percentages shown in Table 5 during mixture design and HMA production when RAP or RAS is used. Use a separate cold feed bin for each stockpile of RAP and RAS during HMA production.

Surface mixes referenced in Tables 4 and 5 are defined as follows:

- **Surface**. The final HMA lift placed at the top of the pavement structure or placed directly below mixtures produced in accordance with Items 316, 342, 347, or 348.

2.7.1. **RAP**. RAP is salvaged, milled, pulverized, broken, or crushed asphalt pavement. Fractionated RAP is defined as a RAP stockpile that contains RAP material with a minimum of 95.0% passing the 3/8-in. or 1/2-in.

sieve, prior to burning in the ignition oven, unless otherwise approve. The Engineer may allow the Contractor to use an alternate to the 3/8-in. or 1/2-in. screen to fractionate the RAP.

Use of Contractor-owned RAP including HMA plant waste is permitted unless otherwise shown on the plans. Department-owned RAP stockpiles are available for the Contractor's use when the stockpile locations are shown on the plans. If Department-owned RAP is available for the Contractor's use, the Contractor may use Contractor-owned fractionated RAP and replace it with an equal quantity of Department-owned RAP. Department-owned RAP generated through required work on the Contract is available for the Contractor's use when shown on the plans. Perform any necessary tests to ensure Contractor- or Department-owned RAP is appropriate for use. The Department will not perform any tests or assume any liability for the quality of the Department-owned RAP unless otherwise shown on the plans. The Contractor will retain ownership of RAP generated on the project when shown on the plans.

Do not use Department- or Contractor-owned RAP contaminated with dirt or other objectionable materials. Do not use Department- or Contractor-owned RAP if the decantation value exceeds 5% and the plasticity index is greater than 8. Test the stockpiled RAP for decantation in accordance with Tex-406-A, Part I. Determine the plasticity index in accordance with Tex-106-E if the decantation value exceeds 5%. The decantation and plasticity index requirements do not apply to RAP samples with asphalt removed by extraction or ignition.

Do not intermingle Contractor-owned RAP stockpiles with Department-owned RAP stockpiles. Remove unused Contractor-owned RAP material from the project site upon completion of the project. Return unused Department-owned RAP to the designated stockpile location.

Table 4
Maximum Allowable Amounts of RAP[1]

Maximum Allowable Fractionated RAP[2] (%)
Surface
35.0

1. Must also meet the recycled binder to total binder ratio shown in Table 5.
2. Up to 5% RAS may be used separately or as a replacement for fractionated RAP.

2.7.2. **RAS**. Use of post-manufactured RAS or post-consumer RAS (tear-offs) is permitted unless otherwise shown on the plans. Up to 5% RAS may be used separately or as a replacement for fractionated RAP in accordance with Table 4 and Table 5. RAS is defined as processed asphalt shingle material from manufacturing of asphalt roofing shingles or from re-roofing residential structures. Post-manufactured RAS is processed manufacturer's shingle scrap by-product. Post-consumer RAS is processed shingle scrap removed from residential structures. Comply with all regulatory requirements stipulated for RAS by the TCEQ. RAS may be used separately or in conjunction with RAP.

Process the RAS by ambient grinding or granulating such that 98% of the particles pass the 1/4 in. sieve when tested in accordance with Tex-200-F, Part I. Perform a sieve analysis on processed RAS material before extraction (or ignition) of the asphalt binder.

Add sand meeting the requirements of Table 1 and Table 2 or fine RAP to RAS stockpiles if needed to keep the processed material workable. Any stockpile that contains RAS will be considered a RAS stockpile and be limited to no more than 5.0% of the HMA mixture in accordance with Table 4.

Certify compliance of the RAS with DMS-11000, "Evaluating and Using Nonhazardous Recyclable Materials Guidelines." Treat RAS as an established nonhazardous recyclable material if it has not come into contact with any hazardous materials. Use RAS from shingle sources on the Department's MPL. Remove substantially all materials before use that are not part of the shingle, such as wood, paper, metal, plastic, and felt paper. Determine the deleterious content of RAS material for mixture design purposes in accordance with Tex-217-F, Part III. Do not use RAS if deleterious materials are more than 0.5% of the stockpiled RAS unless otherwise approved. Submit a sample for approval before submitting the mixture design. The Department will perform the testing for deleterious material of RAS to determine specification compliance.

2.8. **Substitute Binders**. Unless otherwise shown on the plans, the Contractor may use a substitute PG binder listed in Table 5 instead of the PG binder originally specified if using recycled materials, and if the substitute PG binder and mixture made with the substitute PG binder meet the following:

- the substitute binder meets the specification requirements for the substitute binder grade in accordance with Section 300.2.10., "Performance-Graded Binders;" and
- the mixture meets the cracking and rutting performance requirements shown in Tables 11A and 11B. The mixture must have less than 12.5 mm of rutting on the Hamburg Wheel test (Tex-242-F) after the number of passes required for the originally specified binder.

Table 5
Allowable Substitute PG Binders and Maximum Recycled Binder Ratios

Originally Specified PG Binder	Allowable Substitute PG Binder for Surface Mixes	Maximum Ratio of Recycled Binder[1] to Total Binder (%)
		Surface
76-22[3]	70-22	30.0
70-22[2]	N/A	30.0
64-22[2]	N/A	30.0
76-28[3]	70-28	30.0
70-28[2]	N/A	30.0
64-28[2]	N/A	30.0

1. Combined recycled binder from RAP and RAS.
2. Binder substitution is not allowed for surface mixtures, unless otherwise approved by the Engineer.
3. Use no more than 30.0% recycled binder in surface mixtures when using this originally specified PG binder.

3. EQUIPMENT

Provide required or necessary equipment in accordance with Item 320, "Equipment for Asphalt Concrete Pavement."

4. CONSTRUCTION

Produce, haul, place, and compact the specified paving mixture. In addition to tests required by the specification, Contractors may perform other QC tests as deemed necessary. At any time during the project, the Engineer may perform production and placement tests as deemed necessary in accordance with Item 5, "Control of the Work." Schedule and participate in a mandatory pre-paving meeting with the Engineer on or before the first day of paving unless otherwise shown on the plans.

4.1. **Certification**. Personnel certified by the Department-approved hot-mix asphalt certification program must conduct all mixture designs, sampling, and testing in accordance with Table 6. Supply the Engineer with a list of certified personnel and copies of their current certificates before beginning production and when personnel changes are made. Provide a mixture design developed and signed by a Level 2 certified specialist. Provide Level 1A certified specialists at the plant during production operations. Provide Level 1B certified specialists to conduct placement tests. Provide AGG101 certified specialists for aggregate testing.

Table 6
Test Methods, Test Responsibility, and Minimum Certification Levels

Test Description	Test Method	Contractor	Engineer	Level[1]
1. Aggregate and Recycled Material Testing				
Sampling	Tex-221-F	✓	✓	1A/AGG101
Dry sieve	Tex-200-F, Part I	✓	✓	1A/AGG101
Washed sieve	Tex-200-F, Part II	✓	✓	1A/AGG101
Deleterious material	Tex-217-F, Parts I & III	✓	✓	AGG101
Decantation	Tex-217-F, Part II	✓	✓	AGG101
Los Angeles abrasion	Tex-410-A		✓	TxDOT
Magnesium sulfate soundness	Tex-411-A		✓	TxDOT
Micro-Deval abrasion	Tex-461-A		✓	AGG101
Crushed face count	Tex-460-A	✓	✓	AGG101
Flat and elongated particles	Tex-280-F	✓	✓	AGG101
Linear shrinkage	Tex-107-E	✓	✓	AGG101
Sand equivalent	Tex-203-F	✓	✓	AGG101
Bulk specific gravity	Tex-201-F	✓	✓	AGG101
Unit weight	Tex-404-A	✓	✓	AGG101
Organic impurities	Tex-408-A	✓	✓	AGG101
2. Asphalt Binder & Tack Coat Sampling				
Asphalt binder sampling	Tex-500-C, Part II	✓	✓	1A/1B
Tack coat sampling	Tex-500-C, Part III	✓	✓	1A/1B
3. Mix Design & Verification				
Design and JMF changes	Tex-204-F	✓	✓	2
Mixing	Tex-205-F	✓	✓	2
Molding (SGC)	Tex-241-F	✓	✓	1A
Laboratory-molded density	Tex-207-F, Parts I & VI	✓	✓	1A
Rice gravity	Tex-227-F, Part II	✓	✓	1A
Ignition oven correction factors[2]	Tex-236-F, Part II	✓	✓	2
Indirect tensile strength	Tex-226-F	✓	✓	1A
Hamburg Wheel test	Tex-242-F	✓	✓	1A
Overlay Test	Tex-248-F		✓	TxDOT
IDEAL Cracking Index	Tex-250-F		✓	TxDOT
Boil test	Tex-530-C	✓	✓	1A
4. Production Testing				
Selecting production random numbers	Tex-225-F, Part I		✓	1A
Mixture sampling	Tex-222-F	✓	✓	1A/1B
Molding (SGC)	Tex-241-F	✓	✓	1A
Laboratory-molded density	Tex-207-F, Parts I & VI	✓	✓	1A
Rice gravity	Tex-227-F, Part II	✓	✓	1A
Gradation & asphalt binder content[2]	Tex-236-F, Part I	✓	✓	1A
Control charts	Tex-233-F	✓	✓	1A
Moisture content	Tex-212-F, Part II	✓	✓	1A/AGG101
Hamburg Wheel test	Tex-242-F	✓	✓	1A
Overlay Test	Tex-248-F		✓	TxDOT
IDEAL Cracking Index	Tex-250-F		✓	TxDOT
Micro-Deval abrasion	Tex-461-A		✓	AGG101
Boil test	Tex-530-C	✓	✓	1A
Abson recovery	Tex-211-F		✓	TxDOT
5. Placement Testing				
Selecting placement random numbers	Tex-225-F, Part II		✓	1B
Trimming roadway cores	Tex-251-F, Parts I & II	✓	✓	1A/1B
In-place air voids	Tex-207-F, Parts I & VI	✓	✓	1A
In-place density (nuclear method)	Tex-207-F, Part III	✓		1B
Establish rolling pattern	Tex-207-F, Part IV	✓		1B
Control charts	Tex-233-F	✓	✓	1A
Ride quality measurement	Tex-1001-S	✓	✓	Note 3
Segregation (density profile)	Tex-207-F, Part V	✓	✓	1B
Longitudinal joint density	Tex-207-F, Part VII	✓	✓	1B
Thermal profile	Tex-244-F	✓	✓	1B
Shear Bond Strength Test	Tex-249-F		✓	TxDOT

1. Level 1A, 1B, 2, and AGG101 are certification levels provided by the Hot Mix Asphalt Center certification program.
2. Refer to Section XXX.4.9.2.3., "Production Testing," for exceptions to using an ignition oven.
3. Profiler and operator are required to be certified at the Texas A&M Transportation Institute facility when Surface Test Type B is specified.

4.2. **Reporting and Responsibilities**. Use Department-provided templates to record and calculate all test data, including mixture design, production and placement QC/QA, control charts, thermal profiles, segregation density profiles, and longitudinal joint density. Obtain the current version of the templates at http://www.txdot.gov/inside-txdot/forms-publications/consultants-contractors/forms/site-manager.html or from the Engineer. The Engineer and the Contractor will provide any available test results to the other party when requested. The maximum allowable time for the Contractor and Engineer to exchange test data is as given in Table 7 unless otherwise approved. The Engineer and the Contractor will immediately report to the other party any test result that requires suspension of production or placement, a payment adjustment less than 1.000, or that fails to meet the specification requirements. Record and electronically submit all test results and pertinent information on Department-provided templates.

Subsequent sublots placed after test results are available to the Contractor, which require suspension of operations, may be considered unauthorized work. Unauthorized work will be accepted or rejected at the discretion of the Engineer in accordance with Article 5.3., "Conformity with Plans, Specifications, and Special Provisions."

Table 7
Reporting Schedule

Description	Reported By	Reported To	To Be Reported Within
Production Quality Control			
Gradation[1]	Contractor	Engineer	1 working day of completion of the sublot
Asphalt binder content[1]			
Laboratory-molded density[2]			
Moisture content[3]			
Boil test[3]			
Production Quality Assurance			
Gradation[3]	Engineer	Contractor	1 working day of completion of the sublot
Asphalt binder content[3]			
Laboratory-molded density[1]			
Hamburg Wheel test[4]			
Overlay test[5]			
IDEAL Cracking Index[5]			
Boil test[3]			
Binder tests[4]			
Placement Quality Control			
In-place air voids[2]	Contractor	Engineer	1 working day of completion of the lot
Segregation[1]			
Longitudinal joint density[1]			
Thermal profile[1]			
Placement Quality Assurance			
In-place air voids[1]	Engineer	Contractor	1 working day after receiving the trimmed cores[5]
Segregation[3]			1 working day of completion of the lot
Longitudinal joint density[3]			
Thermal profile[3]			
Aging ratio[4]			
Payment adjustment summary	Engineer	Contractor	2 working days of performing all required tests and receiving Contractor test data

1. These tests are required on every sublot.
2. Optional test. When performed on split samples, report the results as soon as they become available.
3. To be performed at the frequency specified in Table 17 or as shown on the plans.
4. To be reported as soon as results become available.
5. 2 days are allowed if cores cannot be dried to constant weight within 1 day.

The Engineer will use the Department-provided template to calculate all payment adjustment factors for the lot. Sublot samples may be discarded after the Engineer and Contractor sign off on the payment adjustment summary documentation for the lot.

Use the procedures described in Tex-233-F to plot the results of all quality control (QC) and quality assurance (QA) testing. Update the control charts as soon as test results for each sublot become available. Make the control charts readily accessible at the field laboratory. The Engineer may suspend production for failure to update control charts.

4.3. **Quality Control Plan (QCP**). Develop and follow the QCP in detail. Obtain approval for changes to the QCP made during the project. The Engineer may suspend operations if the Contractor fails to comply with the QCP.

Submit a written QCP before the mandatory pre-paving meeting. Receive approval of the QCP before beginning production. Include the following items in the QCP:

4.3.1. **Project Personnel**. For project personnel, include:

- a list of individuals responsible for QC with authority to take corrective action;
- current contact information for each individual listed; and
- current copies of certification documents for individuals performing specified QC functions.

4.3.2. **Material Delivery and Storage**. For material delivery and storage, include:

- the sequence of material processing, delivery, and minimum quantities to assure continuous plant operations;
- aggregate stockpiling procedures to avoid contamination and segregation;
- frequency, type, and timing of aggregate stockpile testing to assure conformance of material requirements before mixture production; and
- procedure for monitoring the quality and variability of asphalt binder.

4.3.3. **Production**. For production, include:

- loader operation procedures to avoid contamination in cold bins;
- procedures for calibrating and controlling cold feeds;
- procedures to eliminate debris or oversized material;
- procedures for adding and verifying rates of each applicable mixture component (e.g., aggregate, asphalt binder, RAP, RAS, lime, liquid antistrip, WMA, rejuvenator);
- procedures for reporting job control test results; and
- procedures to avoid segregation and drain-down in the silo.

4.3.4. **Loading and Transporting**. For loading and transporting, include:

- type and application method for release agents; and
- truck loading procedures to avoid segregation.

4.3.5. **Placement and Compaction**. For placement and compaction, include:

- proposed agenda for mandatory pre-paving meeting, including date and location;
- proposed paving plan (e.g., paving widths, joint offsets, and lift thicknesses);
- type and application method for release agents in the paver and on rollers, shovels, lutes, and other utensils;
- procedures for the transfer of mixture into the paver, while avoiding segregation and preventing material spillage;
- process to balance production, delivery, paving, and compaction to achieve continuous placement operations and good ride quality;
- paver operations (e.g., operation of wings, height of mixture in auger chamber) to avoid physical and thermal segregation and other surface irregularities; and
- procedures to construct quality longitudinal and transverse joints.

4.4. **Mixture Design**.

4.4.1. **Design Requirements**. Use the SP design procedure provided in Tex-204-F, unless otherwise shown on the plans. Design the mixture to meet the requirements listed in Tables 1, 2, 3, 4, 5, 8, 9, 10, 11A and 11B.

Design the mixture at 50 gyrations (Ndesign). Use a target laboratory-molded density of 96.0% to design the mixture; however, adjustments can be made to the Ndesign value as noted in Table 10. The Ndesign level may be reduced to no less than 35 gyrations at the Contractor's discretion.

Use an approved laboratory from the Department's MPL to perform the Hamburg Wheel test and provide results with the mixture design, or provide the laboratory mixture and request that the Department perform the Hamburg Wheel test. Provide the laboratory mixture and request that the Department or Department designated laboratory perform the Overlay test. The Engineer will be allowed 10 working days to provide the Contractor with Hamburg Wheel, and Overlay test results on the laboratory mixture design.

The Engineer will provide the mixture design when shown on the plans. The Contractor may submit a new mixture design at any time during the project. The Engineer will verify and approve all mixture designs (JMF1) before the Contractor can begin production.

The aggregate gradation may pass below or through the reference zone shown in Table 9 unless otherwise shown on the plans. Design a mixture with a gradation that has stone-on-stone contact and passes below the reference zone shown in Table 9 when shown on the plans. Verify stone-on-stone contact using the method given in the SP design procedure in Tex-204-F, Part IV.

Provide the Engineer with a mixture design report using the Department-provided template. Include the following items in the report:

- the combined aggregate gradation, source, specific gravity, and percent of each material used;
- asphalt binder content and aggregate gradation of RAP and RAS stockpiles;
- the Ndesign level used;
- results of all applicable tests;
- the mixing and molding temperatures;
- the signature of the Level 2 person or persons that performed the design;
- the date the mixture design was performed; and
- a unique identification number for the mixture design.

Table 8
Master Gradation Limits (% Passing by Weight or Volume) and VMA Requirements

Sieve Size	SP-C Surface	SP-D Fine Mixture
2"	–	–
1-1/2"	–	–
1"	100.0[1]	–
3/4"	98.0–100.0	100.0[1]
1/2"	90.0–100.0	98.0–100.0
3/8"	Note[2]	90.0–100.0
#4	28.0–90.0	32.0–90.0
#8	28.0–35.0	32.0–39.0
#16	2.0–31.6	2.0–37.6
#30	2.0–23.1	2.0–27.5
#50	2.0–15.5	2.0–18.7
#200	2.0–10.0	2.0–10.0
Design VMA, % Minimum		
-	15.0	16.0
Production (Plant-Produced) VMA, % Minimum		
-	14.5	15.5

1. Defined as maximum sieve size. No tolerance allowed.

2. Must retain at least 10% cumulative.

Table 9
Reference Zones (% Passing by Weight or Volume)

Sieve Size	SP-C Surface	SP-D Fine Mixture
2"	–	–
1-1/2"	–	–
1"	–	–
3/4"	–	–
1/2"	–	–
3/8"	–	–
#4	–	–
#8	39.1–39.1	47.2–47.2
#16	25.6–31.6	31.6–37.6
#30	19.1–23.1	23.5–27.5
#50	15.5–15.5	18.7–18.7
#200	–	–

Table 10
Laboratory Mixture Design Properties

Mixture Property	Test Method	Requirement
Target laboratory-molded density, %	Tex-207-F	96.0
Design gyrations (Ndesign)	Tex-241-F	50[1]
Indirect tensile strength (dry), psi	Tex-226-F	85–200[2]
Dust/asphalt binder ratio[3]	–	0.6–1.4
Boil test[4]	Tex-530-C	–

1. Adjust within a range of 35–100 gyrations when shown on the plans or specification or mutually agreed between the Engineer and Contractor.
2. The Engineer may allow the IDT strength to exceed 200 psi if the corresponding Hamburg Wheel rut depth is greater than 3.0 mm and less than 12.5 mm.
3. Defined as % passing #200 sieve divided by asphalt binder content.
4. Used to establish baseline for comparison to production results. May be waived when approved.

Table 11A
Hamburg Wheel Test Requirements

High-Temperature Binder Grade	Test Method	Minimum # of Passes @ 12.5 mm[1] Rut Depth, Tested @ 50°C
PG 64 or lower	Tex-242-F	10,000[2]
PG 70		15,000[3]
PG 76 or higher		20,000

1. When the rut depth at the required minimum number of passes is less than 3 mm, the Engineer may require the Contractor to lower the Ndesign level to no less than 35 gyrations.
2. May be decreased to no less than 5,000 passes when shown on the plans.
3. May be decreased to no less than 10,000 passes when shown on the plans.

Table 11B
Overlay Test Requirements

Mixture Property	Test Method	Surface Mixtures
Critical Fracture Energy (CFE), in.-lb/in.^{2}, Min	Tex-248-F[1]	1.0
Crack Progression Rate (CPR), Max		0.45

1. For JMF 2 and greater, Tex-250-F and the IDEAL CT correlation developed during the trial batch may be used to monitor cracking performance. If at any time the minimum correlation limit is not met, use Tex-248-F and the limits above to determine specification compliance.

4.4.2. **Job-Mix Formula Approval.** The job-mix formula (JMF) is the combined aggregate gradation, Ndesign level, and target asphalt percentage used to establish target values for hot-mix production. JMF1 is the original laboratory mixture design used to produce the trial batch. When WMA is used, JMF1 may be designed and submitted to the Engineer without including the WMA additive. When WMA is used, document the additive or process used and recommended rate on the JMF1 submittal. The Engineer and the Contractor will verify JMF1 based on plant-produced mixture from the trial batch unless otherwise approved. The Department may require the Contractor to reimburse the Department for verification tests if more than 2 trial batches per design are required.

4.4.2.1. **Contractor's Responsibilities**.

4.4.2.1.1. **Providing Superpave Gyratory Compactor (SGC)**. Furnish an SGC calibrated in accordance with Tex-241-F for molding production samples. Locate the SGC at the Engineer's field laboratory and make the SGC available to the Engineer for use in molding production samples.

4.4.2.1.2. **Gyratory Compactor Correlation Factors**. Use Tex-206-F, Part II, to perform a gyratory compactor correlation when the Engineer uses a different SGC. Apply the correlation factor to all subsequent production test results.

4.4.2.1.3. **Submitting JMF1**. Furnish a mix design report (JMF1) with representative samples of all component materials and request approval to produce the trial batch.

Provide approximately 10,000 g of the design mixture if opting to have the Department perform the Hamburg Wheel test on the laboratory mixture, and request that the Department perform the test.

Provide approximately 25,000 g of the laboratory mixture to have the Department or Department designated laboratory perform the Overlay test on the laboratory mixture, and request the Department perform the test.

If the Hamburg Wheel test and Overlay test meets the requirements in Table 11A and Table 11B, a correlation between the Overlay test and IDEAL CT test will need to be established. If JMF1 does not meet the testing requirements in Table 11A and Table 11B, redesign JMF1 until the requirements are met.

To perform a correlation between the Overlay test and the IDEAL CT test, approximately 40,000 g of the laboratory mixture is needed at the optimum asphalt content (OAC) submitted for JMF1 and at asphalt contents 0.5% above and below the OAC. Provide approximately 40,000 g of each laboratory mixture at the varying asphalt contents and request that the Department or Department designated laboratory perform the IDEAL CT test and develop a correlation with the Overlay test. This will establish an acceptable limit using the IDEAL CT test.

4.4.2.1.4. **Supplying Aggregates**. Provide approximately 40 lb. of each aggregate stockpile unless otherwise directed.

4.4.2.1.5. **Supplying Asphalt**. Provide at least 1 gal. of the asphalt material and sufficient quantities of any additives proposed for use.

4.4.2.1.6. **Ignition Oven Correction Factors**. Determine the aggregate and asphalt correction factors from the ignition oven in accordance with Tex-236-F, Part II. Provide correction factors that are not more than 12 months old. Provide the Engineer with split samples of the mixtures before the trial batch production, including all additives (except water), and blank samples used to determine the correction factors for the ignition oven used for QA testing during production. Correction factors established from a previously approved mixture design may be used for the current mixture design if the mixture design and ignition oven are the same as previously used, unless otherwise directed.

4.4.2.1.7. **Boil Test**. Perform the test and retain the tested sample from Tex-530-C until completion of the project or as directed. Use this sample for comparison purposes during production. The Engineer may waive the requirement for the boil test.

4.4.2.1.8. **Trial Batch Production**. Provide a plant-produced trial batch upon receiving conditional approval of JMF1 and authorization to produce a trial batch, including the WMA additive or process if applicable, for verification testing of JMF1 and development of JMF2. Produce a trial batch mixture that meets the requirements in Table 4, Table 5, and Table 12.

4.4.2.1.9. **Trial Batch Production Equipment**. Use only equipment and materials proposed for use on the project to produce the trial batch.

4.4.2.1.10. **Trial Batch Quantity**. Produce enough quantity of the trial batch to ensure that the mixture meets the specification requirements.

4.4.2.1.11. **Number of Trial Batches**. Produce trial batches as necessary to obtain a mixture that meets the specification requirements.

4.4.2.1.12. **Trial Batch Sampling**. Obtain a representative sample of the trial batch and split it into 3 equal portions in accordance with Tex-222-F. Label these portions as "Contractor," "Engineer," and "Referee." Deliver samples to the appropriate laboratory as directed.

4.4.2.1.13. **Trial Batch Testing**. Test the trial batch to ensure the mixture produced using the proposed JMF1 meets the mixture requirements in Table 12. Use a Department-approved laboratory to perform the Hamburg Wheel test on the trial batch mixture or request that the Department perform the Hamburg Wheel test. Request that the Department or Department designated laboratory perform the Overlay test. Request that the Department or Department designated laboratory perform the IDEAL CT test. Ensure the trial batch meets the Hamburg Wheel test and Overlay test requirements in Table 11A and Table 11B. Validate the correlation between the Overlay and IDEAL CT tests.

The Engineer will be allowed 10 working days to provide the Contractor with Hamburg Wheel test, Overlay test, and IDEAL CT test results on the trial batch. Provide the Engineer with a copy of the trial batch test results.

4.4.2.1.14. **Development of JMF2**. Evaluate the trial batch test results after the Engineer grants full approval of JMF1 and based on results from the trial batch, determine the optimum mixture proportions, and submit as JMF2. Adjust the asphalt binder content or gradation to achieve the specified target laboratory-molded density. The asphalt binder content established for JMF2 is not required to be within any tolerance of the optimum asphalt binder content established for JMF1; however, mixture produced using JMF2 must meet the voids in mineral aggregates (VMA) requirements for production shown in Table 8. If any changes in optimum mixture proportions between the trial batch and JMF2 occur, the Engineer will perform Tex-242-F on Lot 1 to confirm the mixture meets the Hamburg test requirement shown in Table 11A. The Engineer will also perform Tex-250-F to confirm that the mixture meets the IDEAL CT correlation limit determined during JMF1. If the results do not meet the IDEAL CT correlation limit, the Engineer will perform Tex-248-F on Lot 1 to confirm the mixture meets the Overlay test requirement shown in Table 11B. Verify that JMF2 meets the mixture requirements in Table 4 and Table 5.

4.4.2.1.15. **Mixture Production**. Use JMF2 to produce Lot 1 as described in Section XXX.4.9.3.1.1., "Lot 1 Placement," after receiving approval for JMF2 and a passing result from the Department's or a Department-approved laboratory's Hamburg Wheel test and Overlay test on the trial batch. If desired, proceed to Lot 1 production, once JMF2 is approved, at the Contractor's risk without receiving the results from the Department's performance tests on the trial batch. If the results do not meet the IDEAL CT correlation limit, the Engineer will perform Tex-248-F on Lot 1 to confirm the mixture meets the Overlay test requirement shown in Table 11B.

Notify the Engineer if electing to proceed without performance test results from the trial batch. Note that the Engineer may require up to the entire sublot of any mixture failing the Hamburg Wheel test or Overlay test requirements to be removed and replaced at the Contractor's expense.

4.4.2.1.16. **Development of JMF3**. Evaluate the test results from Lot 1, determine the optimum mixture proportions, and submit as JMF3 for use in Lot 2.

4.4.2.1.17. **JMF Adjustments.** If JMF adjustments are necessary to achieve the specified requirements, make the adjustment before beginning a new lot. The adjusted JMF must:

- be provided to the Engineer in writing before the start of a new lot;
- be numbered in sequence to the previous JMF;
- meet the mixture requirements in Table 4 and Table 5;
- meet the performance requirements in Table 10 and Table 11A
- meet the IDEAL CT correlation limit established or the Overlay requirement in Table 11B;
- meet the master gradation limits shown in Table 8; and
- be within the operational tolerances of JMF2 listed in Table 12.

4.4.2.1.18. **Requesting Referee Testing.** Use referee testing, if needed, in accordance with Section XXX.4.9.1., "Referee Testing," to resolve testing differences with the Engineer.

Table 12
Operational Tolerances

Description	Test Method	Allowable Difference Between Trial Batch and JMF1 Target	Allowable Difference from Current JMF Target	Allowable Difference between Contractor and Engineer[1]
Individual % retained for #8 sieve and larger	Tex-200-F or Tex-236-F	Must be Within Master Grading Limits in Table 8	±5.0[2,3]	±5.0
Individual % retained for sieves smaller than #8 and larger than #200			±3.0[2,3]	±3.0
% passing the #200 sieve			±2.0[2,3]	±1.6
Asphalt binder content, %	Tex-236-F	±0.5	±0.3[3]	±0.3
Dust/asphalt binder ratio[4]	–	Note 5	Note 5	N/A
Laboratory-molded density, %	Tex-207-F	±1.0	±1.0	±0.5
In-place air voids, %		N/A	N/A	±1.0
Laboratory-molded bulk specific gravity		N/A	N/A	±0.020
VMA, % min	Tex-204-F	Note 6	Note 6	N/A
Theoretical maximum specific (Rice) gravity	Tex-227-F	N/A	N/A	±0.020

1. Contractor may request referee testing only when values exceed these tolerances.
2. When within these tolerances, mixture production gradations may fall outside the master grading limits; however, the % passing the #200 will be considered out of tolerance when outside the master grading limits.
3. Only applies to mixture produced for Lot 1 and higher.
4. Defined as % passing #200 sieve divided by asphalt binder content.
5. Verify that Table 10 requirement is met.
6. Verify that Table 8 requirements are met.

4.4.2.2. **Engineer's Responsibilities.**

4.4.2.2.1. **Gyratory Compactor.** The Engineer will use a Department SGC, calibrated in accordance with Tex-241-F, to mold samples for laboratory mixture design verification. For molding trial batch and production specimens, the Engineer will use the Contractor-provided SGC at the field laboratory or provide and use a Department SGC at an alternate location. The Engineer will make the Contractor-provided SGC in the Department field laboratory available to the Contractor for molding verification samples.

4.4.2.2.2. **Conditional Approval of JMF1 and Authorizing Trial Batch.** The Engineer will review and verify conformance of the following information within 2 working days of receipt:

- the Contractor's mix design report (JMF1);
- the Contractor-provided Hamburg Wheel test results;
- the Department-provided Overlay test results;
- the established correlation between the Overlay and IDEAL CT tests;
- all required materials including aggregates, asphalt, additives, and recycled materials; and
- the mixture specifications.

The Engineer will grant the Contractor conditional approval of JMF1 if the information provided on the paper copy of JMF1 indicates that the Contractor's mixture design meets specification. The Engineer will be allowed 10 working days to provide the Contractor with Hamburg Wheel test, Overlay test, and IDEAL CT correlation for conditional approval of JMF1. The Engineer will base full approval of JMF1 on the test results on mixture from the trial batch.

Unless waived, the Engineer will determine the Micro-Deval abrasion loss in accordance with Section XXX.2.1.1.2., "Micro-Deval Abrasion." If the Engineer's test results are pending after 2 working days, conditional approval of JMF1 will still be granted within 2 working days of receiving JMF1. When the Engineer's test results become available, they will be used for specification compliance.

After conditionally approving JMF1, including either Contractor- or Department-supplied Hamburg Wheel test results, Department-supplied Overlay test results, and the IDEAL CT correlation, the Contractor is authorized to produce a trial batch.

4.4.2.2.3. **Hamburg Wheel Testing and Overlay Testing of JMF1**. If the Contractor requests the option to have the Department perform the Hamburg Wheel test on the laboratory mixture, the Engineer will mold samples in accordance with Tex-242-F to verify compliance with the Hamburg Wheel test requirement in Table 11A. The Engineer will mold samples in accordance with Tex-248-F to verify compliance with the Overlay test requirements in Table 11B. The Engineer will mold samples in accordance with Tex-250-F to determine the correlation between the Overlay and IDEAL CT tests.

4.4.2.2.4. **Ignition Oven Correction Factors**. The Engineer will use the split samples provided by the Contractor to determine the aggregate and asphalt correction factors for the ignition oven used for QA testing during production in accordance with Tex-236-F. Provide correction factors that are not more than 12 months old.

4.4.2.2.5. **Testing the Trial Batch**. Within 1 full working day, the Engineer will sample and test the trial batch to ensure that the mixture meets the requirements in Table 12. If the Contractor requests the option to have the Department perform the Hamburg Wheel test on the trial batch mixture, the Engineer will mold samples in accordance with Tex-242-F to verify compliance with the Hamburg Wheel test requirement in Table 11A. The Engineer will mold samples in accordance with Tex-248-F to verify compliance with the Overlay test requirement in Table 11B. The Engineer will mold samples in accordance with Tex-250-F to determine the IDEAL CT test results and validate the correlation between the Overlay and IDEAL CT tests.

The Engineer will perform the following tests on the trial batch:

- Tex-226-F, to verify that the indirect tensile strength meets the requirement shown in Table 10;
- Tex-242-F, to confirm the mixture meets the Hamburg test requirements shown in Table 11A;
- Tex-248-F, to confirm the mixture meets the Overlay test requirements shown in Table 11B;
- Tex-250-F, to develop a correlation with the passing Overlay results; and
- Tex-530-C, to retain and use for comparison purposes during production.

4.4.2.2.6. **Full Approval of JMF1**. The Engineer will grant full approval of JMF1 and authorize the Contractor to proceed with developing JMF2 if the Engineer's results for the trial batch meet the requirements in Table 11A, 11B, and 12. The Engineer will notify the Contractor that an additional trial batch is required if the trial batch does not meet these requirements.

4.4.2.2.7. **Approval of JMF2**. The Engineer will approve JMF2 within one working day if the mixture meets the requirements in Table 5, the gradation meets the master grading limits shown in Table 8, and the mixture meets the requirements of Table 11A and Table 11B. The asphalt binder content established for JMF2 is not required to be within any tolerance of the optimum asphalt binder content established for JMF1; however, mixture produced using JMF2 must meet the VMA requirements shown in Table 8. If any changes in optimum mixture proportions between the trial batch and JMF2 occur, the Engineer will perform Tex-242-F on Lot 1 to confirm the mixture meets the Hamburg test requirement shown in Table 11A. The Engineer will also perform Tex-250-F to confirm that the mixture meets the IDEAL CT correlation limit determined during

JMF1. If the results do not meet the IDEAL CT correlation limit, the Engineer will perform Tex-248-F on Lot 1 to confirm the mixture meets the Overlay test requirement shown in Table 11B.

4.4.2.2.8. **Approval of Lot 1 Production**. The Engineer will authorize the Contractor to proceed with Lot 1 production (using JMF2) as soon as a passing result is achieved from the Department's or a Department-approved laboratory's Hamburg Wheel test and a passing Overlay test on the trial batch and the IDEAL CT correlation limit has been established. The Contractor may proceed at their own risk with Lot 1 production without the results from the Hamburg Wheel test and Overlay Test.

If the Department's or Department-approved sample from the trial batch fails the Hamburg Wheel test or if the Department designated laboratory's sample from the trial batch fails the Overlay test, the Engineer will suspend production until further Hamburg Wheel tests and Overlay tests meet the specified values. The Engineer may require up to the entire sublot of any mixture failing the Hamburg Wheel test or Overlay test be removed and replaced at the Contractor's expense.

4.4.2.2.9. **Approval of JMF3 and Subsequent JMF Changes**. JMF3 and subsequent JMF changes are approved if they meet the mixture requirements shown in Table 4, Table 5, Table 11A, the IDEAL CT correlation limit, and the master grading limits shown in Table 8, and are within the operational tolerances of JMF2 shown in Table 12. If the results do not meet the IDEAL CT correlation limit, the Engineer will perform Tex-248-F on Lot 1 to confirm the mixture meets the Overlay test requirement shown in Table 11B.

4.5. **Production Operations**. Perform a new trial batch when the plant or plant location is changed. Take corrective action and receive approval to proceed after any production suspension for noncompliance to the specification. Submit a new mix design and perform a new trial batch when the asphalt binder content of:

- any RAP stockpile used in the mix is more than 0.5% higher than the value shown on the mixture design report; or
- RAS stockpile used in the mix is more than 2.0% higher than the value shown on the mixture design report.

4.5.1. **Storage and Heating of Materials**. Do not heat the asphalt binder above the temperatures specified in Item 300, "Asphalts, Oils, and Emulsions," or outside the manufacturer's recommended values. Provide the Engineer with daily records of asphalt binder and hot-mix asphalt discharge temperatures (in legible and discernible increments) in accordance with Item 320, "Equipment for Asphalt Concrete Pavement," unless otherwise directed. Do not store mixture for a period long enough to affect the quality of the mixture, nor in any case longer than 12 hr. unless otherwise approved.

4.5.2. **Mixing and Discharge of Materials**. Notify the Engineer of the target discharge temperature and produce the mixture within 25°F of the target. Monitor the temperature of the material in the truck before shipping to ensure that it does not exceed the maximum production temperatures listed in Table 13 (or 275°F for WMA) and is not lower than 215°F. The Department will not pay for or allow placement of any mixture produced above the maximum production temperatures listed in Table 13.

Table 13
Maximum Production Temperature

High-Temperature Binder Grade[1]	Maximum Production Temperature
PG 64	325˚F
PG 70	335˚F
PG 76	345˚F

The high-temperature binder grade refers to the high-temperature grade of the virgin asphalt binder used to produce the mixture.

Produce WMA within the target discharge temperature range of 215°F and 275°F when WMA is required. Take corrective action any time the discharge temperature of the WMA exceeds the target discharge range.

The Engineer may suspend production operations if the Contractor's corrective action is not successful at controlling the production temperature within the target discharge range. Note that when WMA is produced, it may be necessary to adjust burners to ensure complete combustion such that no burner fuel residue remains in the mixture.

Control the mixing time and temperature so that substantially all moisture is removed from the mixture before discharging from the plant. Determine the moisture content, if requested, by oven-drying in accordance with Tex-212-F, Part II, and verify that the mixture contains no more than 0.2% of moisture by weight. Obtain the sample immediately after discharging the mixture into the truck, and perform the test promptly.

4.6. **Hauling Operations**. Clean all truck beds before use to ensure that mixture is not contaminated. Use a release agent shown on the Department's MPL to coat the inside bed of the truck when necessary.

Use equipment for hauling as defined in Section XXX.4.7.3.3., "Hauling Equipment." Use other hauling equipment only when allowed.

4.7. **Placement Operations**. Collect haul tickets from each load of mixture delivered to the project and provide the Department's copy to the Engineer approximately every hour or as directed. Use a hand-held thermal camera or infrared thermometer, when a thermal imaging system is not used, to measure and record the internal temperature of the mixture as discharged from the truck or Material Transfer Device (MTD) before or as the mix enters the paver and an approximate station number or GPS coordinates on each ticket. Calculate the daily yield and cumulative yield for the specified lift and provide to the Engineer at the end of paving operations for each day unless otherwise directed. The Engineer may suspend production if the Contractor fails to produce and provide haul tickets and yield calculations by the end of paving operations for each day.

Prepare the surface by removing raised pavement markers and objectionable material such as moisture, dirt, sand, leaves, and other loose impediments from the surface before placing mixture. Remove vegetation from pavement edges. Place the mixture to meet the typical section requirements and produce a smooth, finished surface with a uniform appearance and texture. Offset longitudinal joints of successive courses of hot-mix by at least 6 in. Place mixture so that longitudinal joints on the surface course coincide with lane lines and are not placed in the wheel path, or as directed. Ensure that all finished surfaces will drain properly. Place the mixture at the rate or thickness shown on the plans. The Engineer will use the guidelines in Table 14 to determine the compacted lift thickness of each layer when multiple lifts are required. The thickness determined is based on the rate of 110 lb./sq. yd. for each inch of pavement unless otherwise shown on the plans.

Table 14
Compacted Lift Thickness and Required Core Height

Mixture Type	Compacted Lift Thickness Guidelines		Minimum Untrimmed Core Height (in.) Eligible for Testing
	Minimum (in.)	Maximum (in.)	
SP-C	2.00	3.0	1.25
SP-D	1.25	2.0	1.25

4.7.1. **Weather Conditions**.

4.7.1.1. **When Using a Thermal Imaging System**. Place mixture when the roadway is dry and the roadway surface temperature is at or above the temperatures listed in Table 15A. The Engineer may restrict the Contractor from paving surface mixtures if the ambient temperature is likely to drop below 32°F within 12 hr. of paving. Place mixtures only when weather conditions and moisture conditions of the roadway surface are suitable as determined by the Engineer. Provide output data from the thermal imaging system to demonstrate to the Engineer that no recurring severe thermal segregation exists in accordance with Section XXX.4.7.3.1.2., "Thermal Imaging System."

Table 15A
Minimum Pavement Surface Temperatures

High-Temperature Binder Grade[1]	Minimum Pavement Surface Temperatures (°F)	
	Subsurface Layers or Night Paving Operations	Surface Layers Placed in Daylight Operations
PG 64	35	40
PG 70	45[2]	50[2]
PG 76	45[2]	50[2]

1. The high-temperature binder grade refers to the high-temperature grade of the virgin asphalt binder used to produce the mixture.
2. Contractors may pave at temperatures 10°F lower than these values when a chemical WMA additive is used as a compaction aid in the mixture or when using WMA.

4.7.1.2. **When Not Using a Thermal Imaging System**. When using a thermal camera in lieu of the thermal imaging system, place mixture when the roadway surface temperature is at or above the temperatures listed in Table 15B unless otherwise approved or as shown on the plans. Measure the roadway surface temperature with a hand-held thermal camera or infrared thermometer. The Engineer may allow mixture placement to begin before the roadway surface reaches the required temperature if conditions are such that the roadway surface will reach the required temperature within 2 hr. of beginning placement operations. Place mixtures only when weather conditions and moisture conditions of the roadway surface are suitable as determined by the Engineer. The Engineer may restrict the Contractor from paving if the ambient temperature is likely to drop below 32°F within 12 hr. of paving.

Table 14B
Minimum Pavement Surface Temperatures

High-Temperature Binder Grade[1]	Minimum Pavement Surface Temperatures (°F)	
	Subsurface Layers or Night Paving Operations	Surface Layers Placed in Daylight Operations
PG 64	45	50
PG 70	55[2]	60[2]
PG 76	60[2]	60[2]

1. The high-temperature binder grade refers to the high-temperature grade of the virgin asphalt binder used to produce the mixture.
2. Contractors may pave at temperatures 10°F lower than these values when a chemical WMA additive is used as a compaction aid in the mixture, when using WMA, or utilizing a paving process with equipment that eliminates thermal segregation. In such cases, for each sublot and in the presence of the Engineer, use a hand-held thermal camera operated in accordance with Tex-244-F to demonstrate to the satisfaction of the Engineer that the uncompacted mat has no more than 10°F of thermal segregation.

4.7.2. **Tack Coat**.

4.7.2.1. **Application.** Clean the surface before placing the tack coat. The Engineer will set the rate between 0.04 and 0.10 gal. of residual asphalt per square yard of surface area. Apply a uniform tack coat at the specified rate unless otherwise directed. Apply the tack coat in a uniform manner to avoid streaks and other irregular patterns. Apply the tack coat to all surfaces that will come in contact with the subsequent HMA placement, unless otherwise directed. Allow adequate time for emulsion to break completely before placing any material. Prevent splattering of tack coat when placed adjacent to curb, gutter, and structures. Do not dilute emulsified asphalts at the terminal, in the field, or at any other location before use.

4.7.2.2. **Sampling.** The Engineer will obtain at least one sample of the tack coat binder per project in accordance with Tex-500-C, Part III, and test it to verify compliance with Item 300, "Asphalts, Oils, and Emulsions." The Engineer will notify the Contractor when the sampling will occur and will witness the collection of the sample from the asphalt distributor immediately before use.

For emulsions, the Engineer may test as often as necessary to ensure the residual of the emulsion is greater than or equal to the specification requirement in Item 300, "Asphalts, Oils, and Emulsions."

4.7.3. **Lay-Down Operations**. Use the placement temperatures in Table 16 to establish the minimum placement temperature of mixture delivered to the paver.

Table 16
Minimum Mixture Placement Temperature

High-Temperature Binder Grade[1]	Minimum Placement Temperature (Before Entering Paver)[2,3]
PG 64	260˚F
PG 70	270˚F
PG 76	280˚F

1. The high-temperature binder grade refers to the high-temperature grade of the virgin asphalt binder used to produce the mixture.
2. Minimum placement temperatures may be reduced 10°F if using a chemical WMA additive as a compaction aid.
3. When WMA is required, the minimum placement temperature is 215°

4.7.3.1. **Thermal Profile**. Use a hand-held thermal camera or a thermal imaging system to obtain a continuous thermal profile in accordance with Tex-244-F. Thermal profiles are not applicable in areas described in Section XXX.4.9.3.1.4., "Miscellaneous Areas."

4.7.3.1.1. **Thermal Segregation**.

4.7.3.1.1.1. **Moderate**. Any areas that have a temperature differential greater than 25°F, but not exceeding 50°F, are deemed as having moderate thermal segregation.

4.7.3.1.1.2. **Severe**. Any areas that have a temperature differential greater than 50°F are deemed as having severe thermal segregation.

4.7.3.1.2. **Thermal Imaging System** Review the output results when a thermal imaging system is used, and provide the automated report described in Tex-244-F to the Engineer daily unless otherwise directed. Modify the paving process as necessary to eliminate any recurring (moderate or severe) thermal segregation identified by the thermal imaging system. The Engineer may suspend paving operations if the Contractor cannot successfully modify the paving process to eliminate recurring severe thermal segregation. Density profiles are not required and not applicable when using a thermal imaging system. Provide the Engineer with electronic copies of all daily data files that can be used with the thermal imaging system software to generate temperature profile plots daily or upon completion of the project or as requested by the Engineer.

4.7.3.1.3. **Thermal Camera**. When using a thermal camera in lieu of the thermal imaging system, take immediate corrective action to eliminate recurring moderate thermal segregation when a hand-held thermal camera is used. Evaluate areas with moderate thermal segregation by performing density profiles in accordance with Section XXX.4.9.3.3.2., "Segregation (Density Profile)." Provide the Engineer with the thermal profile of every sublot within one working day of the completion of each lot. When requested by the Engineer, provide the thermal images generated using the thermal camera. Report the results of each thermal profile in accordance with Section XXX.4.2., "Reporting and Responsibilities." The Engineer will use a hand-held thermal camera to obtain a thermal profile at least once per project. No production or placement payment adjustments greater than 1.000 will be paid for any sublot that contains severe thermal segregation. Suspend operations and take immediate corrective action to eliminate severe thermal segregation unless otherwise directed. Resume operations when the Engineer determines that subsequent production will meet the requirements of this Section. Evaluate areas with severe thermal segregation by performing density profiles in accordance with Section XXX.4.9.3.3.2., "Segregation (Density Profile)." Remove and replace the material in any areas that have both severe thermal segregation and a failing result for Segregation (Density Profile) unless otherwise directed. The sublot in question may receive a production and placement payment adjustment greater than 1.000, if applicable, when the defective material is successfully removed and replaced.

4.7.3.2. **Windrow Operations**. Operate windrow pickup equipment so that when hot-mix is placed in windrows, substantially all the mixture deposited on the roadbed is picked up and loaded into the paver.

4.7.3.3. **Hauling Equipment**. Use belly dumps, live bottom, or end dump trucks to haul and transfer mixture; however, with exception of paving miscellaneous areas, end dump trucks are only allowed when used in conjunction with an MTD with remixing capability or when a thermal imaging system is used unless otherwise allowed.

4.7.3.4. **Screed Heaters**. Turn off screed heaters to prevent overheating of the mat if the paver stops for more than 5 min. The Engineer may evaluate the suspect area in accordance with Section XXX.4.9.3.3.4.,"Recovered Asphalt Dynamic Shear Rheometer (DSR)," if the screed heater remains on for more than 5 min. while the paver is stopped.

4.8. **Compaction**. Compact the pavement uniformly to contain between 3.7% and 7.5% in-place air voids. Take immediate corrective action to bring the operation within 3.7% and 7.5% when the in-place air voids exceed the range of these tolerances. The Engineer will allow paving to resume when the proposed corrective action is likely to yield between 3.7% and 7.5% in-place air voids.

Obtain cores in areas placed under Exempt Production, as directed, at locations determined by the Engineer. The Engineer may test these cores and suspend operations or require removal and replacement if the in-place air voids are less than 2.7% or more than 9.0%. Areas defined in Section XXX.4.9.3.1.4., "Miscellaneous Areas," are not subject to in-place air void determination.

Furnish the type, size, and number of rollers required for compaction as approved. Use additional rollers as required to remove any roller marks. Use only water or an approved release agent on rollers, tamps, and other compaction equipment unless otherwise directed.

Use the control strip method shown in Tex-207-F, Part IV, on the first day of production to establish the rolling pattern that will produce the desired in-place air voids unless otherwise directed.

Use tamps to thoroughly compact the edges of the pavement along curbs, headers, and similar structures and in locations that will not allow thorough compaction with rollers. The Engineer may require rolling with a trench roller on widened areas, in trenches, and in other limited areas.

Complete all compaction operations before the pavement temperature drops below 160°F unless otherwise allowed. The Engineer may allow compaction with a light finish roller operated in static mode for pavement temperatures below 160°F.

Allow the compacted pavement to cool to 160°F or lower before opening to traffic unless otherwise directed. Sprinkle the finished mat with water or limewater, when directed, to expedite opening the roadway to traffic.

4.9. **Acceptance Plan**. Payment adjustments for the material will be in accordance with Article XXX.6., "Payment."

Sample and test the hot-mix on a lot and sublot basis. Suspend production until test results or other information indicates to the satisfaction of the Engineer that the next material produced or placed will result in pay factors of at least 1.000 if the production pay factor given in Section XXX.6.1., "Production Payment Adjustment Factors," for 2 consecutive lots or the placement pay factor given in Section XXX.6.2., "Placement Payment Adjustment Factors," for 2 consecutive lots is below 1.000.

4.9.1. **Referee Testing**. The Materials and Tests Division is the referee laboratory. The Contractor may request referee testing if a "remove and replace" condition is determined based on the Engineer's test results, or if the differences between Contractor and Engineer test results exceed the maximum allowable difference shown in Table 12 and the differences cannot be resolved. The Contractor may also request referee testing if the Engineer's test results require suspension of production and the Contractor's test results are within specification limits. Make the request within 5 working days after receiving test results and cores from the Engineer. Referee tests will be performed only on the sublot in question and only for the particular tests in question. Allow 10 working days from the time the referee laboratory receives the samples for test results to be reported. The Department may require the Contractor to reimburse the Department for referee tests if more than 3 referee tests per project are required and the Engineer's test results are closer to the referee test results than the Contractor's test results.

The Materials and Tests Division will determine the laboratory-molded density based on the molded specific gravity and the maximum theoretical specific gravity of the referee sample. The in-place air voids will be determined based on the bulk specific gravity of the cores, as determined by the referee laboratory and the Engineer's average maximum theoretical specific gravity for the lot. With the exception of "remove and replace" conditions, referee test results are final and will establish payment adjustment factors for the sublot in question. The Contractor may decline referee testing and accept the Engineer's test results when the placement payment adjustment factor for any sublot results in a "remove and replace" condition. Placement sublots subject to be removed and replaced will be further evaluated in accordance with Section XXX.6.2.2., "Placement Sublots Subject to Removal and Replacement."

4.9.2. **Production Acceptance**.

4.9.2.1. **Production Lot**. A production lot consists of 4 equal sublots. The default quantity for Lot 1 is 1,000 tons; however, when requested by the Contractor, the Engineer may increase the quantity for Lot 1 to no more than 4,000 tons. The Engineer will select subsequent lot sizes based on the anticipated daily production such that approximately 3 to 4 sublots are produced each day. The lot size will be between 1,000 tons and 4,000 tons. The Engineer may change the lot size before the Contractor begins any lot.

If any changes in optimum mixture proportions between the trial batch and JMF2 occur, the Engineer will perform Tex-242-F to confirm the mixture meets the Hamburg test requirement shown in Table 11A. The Engineer will perform Tex-250-F and confirm the mixture meets the minimum correlation limit established during the trial batch. If the mixture does not meet this requirement, the Engineer will perform Tex-248-F to confirm the mixture meets the Overlay test requirement shown in Table 11B. Take corrective action to bring the mixture within specification compliance if the Hamburg or Overlay test results do not meet the requirements shown in Table 11A and 11B.

4.9.2.1.1. **Incomplete Production Lots**. If a lot is begun but cannot be completed, such as on the last day of production or in other circumstances deemed appropriate, the Engineer may close the lot. Adjust the payment for the incomplete lot in accordance with Section XXX.6.1., "Production Payment Adjustment Factors." Close all lots within 5 working days unless otherwise allowed.

4.9.2.2. **Production Sampling**.

4.9.2.2.1. **Mixture Sampling**. Obtain hot-mix samples from trucks at the plant in accordance with Tex-222-F. The sampler will split each sample into 3 equal portions in accordance with Tex-200-F and label these portions as "Contractor," "Engineer," and "Referee." The Engineer will perform or witness the sample splitting and take immediate possession of the samples labeled "Engineer" and "Referee." The Engineer will maintain the custody of the samples labeled "Engineer" and "Referee" until the Department's testing is completed.

4.9.2.2.1.1. **Random Sample**. At the beginning of the project, the Engineer will select random numbers for all production sublots. Determine sample locations in accordance with Tex-225-F. Take one sample for each sublot at the randomly selected location. The Engineer will perform or witness the sampling of production sublots.

4.9.2.2.1.2. **Blind Sample**. For one sublot per lot, the Engineer will obtain and test a "blind" sample instead of the random sample collected by the Contractor. Test either the "blind" or the random sample; however, referee testing (if applicable) will be based on a comparison of results from the "blind" sample. The location of the Engineer's "blind" sample will not be disclosed to the Contractor. The Engineer's "blind" sample may be randomly selected in accordance with Tex-225-F for any sublot or selected at the discretion of the Engineer. The Engineer will use the Contractor's split sample for sublots not sampled by the Engineer.

4.9.2.2.2. **Informational Shear Bond Strength Testing.** Select one random sublot from Lot 2 or higher for shear bond strength testing. Obtain full depth cores in accordance with Tex-249-F. Label the cores with the Control Section Job (CSJ), producer of the tack coat, mix type, shot rate, lot, and sublot number and provide to the Engineer. The Engineer will ship the cores to the Materials and Tests Division or district laboratory for shear bond strength testing. Results from these tests will not be used for specification compliance.

4.9.2.2.3. **Asphalt Binder Sampling**. Obtain a 1-qt. sample of the asphalt binder witnessed by the Engineer for each lot of mixture produced. The Contractor will notify the Engineer when sampling will occur. Obtain the sample at approximately the same time the mixture random sample is obtained. Sample from a port located immediately upstream from the mixing drum or pug mill in accordance with Tex-500-C, Part II. Label the can with the corresponding lot and sublot numbers, producer, producer facility location, grade, district, date sampled, and project information including highway and CSJ. The Engineer will retain these samples for one year. The Engineer may also obtain independent samples. If obtaining an independent asphalt binder sample and upon request of the Contractor, the Engineer will split a sample of the asphalt binder with the Contractor.

At least once per project, the Engineer will collect split samples of each binder grade and source used. The Engineer will submit one split sample to MTD to verify compliance with Item 300, "Asphalts, Oils, and Emulsions" and will retain the other split sample.

4.9.2.3. **Production Testing**. The Contractor and Engineer must perform production tests in accordance with Table 17. The Contractor has the option to verify the Engineer's test results on split samples provided by the Engineer. Determine compliance with operational tolerances listed in Table 12 for all sublots.

Take immediate corrective action if the Engineer's laboratory-molded density on any sublot is less than 95.0% or greater than 98.0% to bring the mixture within these tolerances. The Engineer may suspend operations if the Contractor's corrective actions do not produce acceptable results. The Engineer will allow production to resume when the proposed corrective action is likely to yield acceptable results.

The Engineer may allow alternate methods for determining the asphalt binder content and aggregate gradation if the aggregate mineralogy is such that Tex-236-F does not yield reliable results. Provide evidence that results from Tex-236-F are not reliable before requesting permission to use an alternate method unless otherwise directed. Use the applicable test procedure as directed if an alternate test method is allowed.

Table 17
Production and Placement Testing Frequency

Description	Test Method	Minimum Contractor Testing Frequency	Minimum Engineer Testing Frequency
Individual % retained for #8 sieve and larger	Tex-200-F or Tex-236-F	1 per sublot	1 per 12 sublots[1]
Individual % retained for sieves smaller than #8 and larger than #200			
% passing the #200 sieve			
Laboratory-molded density	Tex-207-F	N/A	1 per sublot[1]
Laboratory-molded bulk specific gravity			
In-place air voids			
VMA	Tex-204-F		
Segregation (density profile)	Tex-207-F, Part V	1 per sublot[2]	1 per project
Longitudinal joint density	Tex-207-F, Part VII		
Moisture content	Tex-212-F, Part II	When directed	
Theoretical maximum specific (Rice) gravity	Tex-227-F	N/A	1 per sublot[1]
Asphalt binder content	Tex-236-F	1 per sublot	1 per lot[1]
Hamburg Wheel test[3]	Tex-242-F	N/A	1 per project
Overlay test[3]	Tex-248-F	N/A	
Recycled Asphalt Shingles (RAS)[3]	Tex-217-F, Part III	N/A	
Thermal profile	Tex-244-F	1 per sublot[2]	
Asphalt binder sampling and testing	Tex-500-C, Part II	1 per lot (sample only)[4]	
Tack coat sampling and testing	Tex-500-C, Part III	N/A	
Boil test[5]	Tex-530-C	1 per lot	
Shear Bond Strength Test[6]	Tex-249-F	1 per project (sample only)	
IDEAL CT test[3]	Tex-250-F	N/A	1 per sublot[1]

1. For production defined in Section XXX.4.9.4., "Exempt Production," the Engineer will test one per day if 100 tons or more are produced. For Exempt Production, no testing is required when less than 100 tons are produced.
2. To be performed in the presence of the Engineer, unless otherwise approved. Not required when a thermal imaging system is used.
3. Testing performed by the Materials and Tests Division or designated laboratory.
4. Obtain samples witnessed by the Engineer. The Engineer will retain these samples.
5. The Engineer may reduce or waive the sampling and testing requirements based on a satisfactory test history.
6. Testing performed by the Materials and Tests Division or District for informational purposes only.

4.9.2.4. **Operational Tolerances**. Control the production process within the operational tolerances listed in Table 12. When production is suspended, the Engineer will allow production to resume when test results or other information indicates the next mixture produced will be within the operational tolerances.

4.9.2.4.1. **Gradation**. Suspend operation and take corrective action if any aggregate is retained on the maximum sieve size shown in Table 8. A sublot is defined as out of tolerance if either the Engineer's or the Contractor's test results are out of operational tolerance. Suspend production when test results for gradation exceed the operational tolerances in Table 12 for 3 consecutive sublots on the same sieve or 4 consecutive sublots on any sieve unless otherwise directed. The consecutive sublots may be from more than one lot.

4.9.2.4.2. **Asphalt Binder Content**. A sublot is defined as out of operational tolerance if either the Engineer's or the Contractor's test results exceed the values listed in Table 12. No production or placement payment adjustments greater than 1.000 will be paid for any sublot that is out of operational tolerance for asphalt binder content. Suspend production and shipment of the mixture if the Engineer's or the Contractor's asphalt binder content deviates from the current JMF by more than 0.3% for any sublot. If any changes in optimum mixture proportions between the trial batch and JMF2 occur, the Engineer will perform Tex-242-F to confirm the mixture meets the Hamburg test requirement shown in Table 11A. The Engineer will also perform Tex-250-F and confirm that the correlation limit established during the trial batch is met. If the material does not meet this requirement, the Engineer will perform Tex-248-F to confirm the mixture meets the Overlay test requirement shown in Table 11B. Take corrective action to bring the mixture within specification compliance if the Hamburg or Overlay test results do not meet the requirements shown in Table 11A and 11B.

4.9.2.4.3. **Voids in Mineral Aggregates (VMA)**. The Engineer will determine the VMA for every sublot. For sublots when the Engineer does not determine asphalt binder content, the Engineer will use the asphalt binder content results from QC testing performed by the Contractor to determine VMA.

Take immediate corrective action if the VMA value for any sublot is less than the minimum VMA requirement for production listed in Table 8. Suspend production and shipment of the mixture if the Engineer's VMA results on 2 consecutive sublots are below the minimum VMA requirement for production listed in Table 8. No production or placement payment adjustments greater than 1.000 will be paid for any sublot that does not meet the minimum VMA requirement for production listed in Table 8 based on the Engineer's VMA determination.

Suspend production and shipment of the mixture if the Engineer's VMA result is more than 0.5% below the minimum VMA requirement for production listed in Table 8. In addition to suspending production, the Engineer may require removal and replacement or may allow the sublot to be left in place without payment.

4.9.2.4.4. **Hamburg Wheel Test and Overlay Test**. The Engineer may perform a Hamburg Wheel test or Overlay test at any time during production. In addition to testing production samples, the Engineer may obtain cores and perform Hamburg Wheel tests on any areas of the roadway where rutting is observed. Suspend production until further Hamburg Wheel tests or Overlay tests production samples meet the specified values in Table 11A and Table 11B. In addition, suspend production until further Hamburg Wheel tests meet the specified values when the core samples fail the test criteria in Table 11A. Core samples, if taken, will be obtained from the center of the finished mat or other areas excluding the vehicle wheel paths. The Engineer may require up to the entire sublot of any mixture failing the Hamburg Wheel test to be removed and replaced at the Contractor's expense.

If the Department's or Department approved laboratory's Hamburg Wheel test results in a "remove and replace" condition, the Contractor may request that the Department confirm the results by re-testing the failing material. The Materials and Tests Division will perform the Hamburg Wheel tests or Overlay tests and determine the final disposition of the material in question based on the Department's test results.

4.9.2.5. **Individual Loads of Hot-Mix**. The Engineer can reject individual truckloads of hot-mix. When a load of hot-mix is rejected for reasons other than temperature, contamination, or excessive uncoated particles, the Contractor may request that the rejected load be tested. Make this request within 4 hr. of rejection. The Engineer will sample and test the mixture. If test results are within the operational tolerances shown in Table 12, payment will be made for the load. If test results are not within operational tolerances, no payment will be made for the load.

4.9.3. **Placement Acceptance**.

4.9.3.1. **Placement Lot**. A placement lot consists of 4 placement sublots. A placement sublot consists of the area placed during a production sublot.

4.9.3.1.1. **Lot 1 Placement**. Placement payment adjustments greater than 1.000 for Lot 1 will be in accordance with Section XXX.6.2., "Placement Payment Adjustment Factors;" however, no placement adjustment less than 1.000 will be assessed for any sublot placed in Lot 1 when the in-place air voids are greater than or equal to 2.7% and less than or equal to 9.0%. Remove and replace any sublot with in-place air voids less than 2.7% or greater than 9.0%.

4.9.3.1.2. **Incomplete Placement Lots**. An incomplete placement lot consists of the area placed as described in Section XXX.4.9.2.1.1., "Incomplete Production Lot," excluding areas defined in Section XXX.4.9.3.1.4., "Miscellaneous Areas." Placement sampling is required if the random sample plan for production resulted in a sample being obtained from an incomplete production sublot.

4.9.3.1.3. **Shoulders, Ramps, Etc.** Shoulders, ramps, intersections, acceleration lanes, deceleration lanes, and turn lanes are subject to in-place air void determination and payment adjustments unless designated on the plans as not eligible for in-place air void determination. Intersections may be considered miscellaneous areas when determined by the Engineer.

4.9.3.1.4. **Miscellaneous Areas**. Miscellaneous areas include areas that typically involve significant handwork or discontinuous paving operations, such as temporary detours, driveways, mailbox turnouts, crossovers, gores, spot level-up areas, and other similar areas. Temporary detours are subject to in-place air void determination when shown on the plans. Miscellaneous areas also include level-ups and thin overlays when the layer thickness specified on the plans is less than the minimum untrimmed core height eligible for testing shown in Table 14. The specified layer thickness is based on the rate of 110 lb./sq. yd. for each inch of pavement unless another rate is shown on the plans. When "level up" is listed as part of the item bid description code, a payment adjustment factor of 1.000 will be assigned for all placement sublots as described in Article XXX.6, "Payment." Miscellaneous areas are not eligible for random placement sampling locations. Compact miscellaneous areas in accordance with Section XXX.4.8., "Compaction." Miscellaneous areas are not subject to in-place air void determination, thermal profiles testing, segregation (density profiles), or longitudinal joint density evaluations.

4.9.3.2. **Placement Sampling**. The Engineer will select random numbers for all placement sublots at the beginning of the project. The Engineer will provide the Contractor with the placement random numbers immediately after the sublot is completed. Mark the roadway location at the completion of each sublot and record the station number. Determine one random sample location for each placement sublot in accordance with Tex-225-F. Adjust the random sample location by no more than necessary to achieve a 2-ft. clearance if the location is within 2 ft. of a joint or pavement edge.

Shoulders, ramps, intersections, acceleration lanes, deceleration lanes, and turn lanes are always eligible for selection as a random sample location; however, if a random sample location falls on one of these areas and the area is designated on the plans as not subject to in-place air void determination, cores will not be taken for the sublot and a 1.000 pay factor will be assigned to that sublot.

Provide the equipment and means to obtain and trim roadway cores on-site. On-site is defined as in close proximity to where the cores are taken. Obtain the cores within one working day of the time the placement sublot is completed unless otherwise approved. Obtain two 6-in. diameter cores side-by-side from within 1 ft. of the random location provided for the placement sublot. For SP-C and SP-D mixtures, 4-in. diameter cores are allowed. Mark the cores for identification, measure and record the untrimmed core height, and provide the information to the Engineer. The Engineer will witness the coring operation and measurement of the core thickness. Visually inspect each core and verify that the current paving layer is bonded to the underlying layer. Take corrective action if an adequate bond does not exist between the current and underlying layer to ensure that an adequate bond will be achieved during subsequent placement operations.

Trim the cores immediately after obtaining the cores from the roadway in accordance with Tex-251-F if the core heights meet the minimum untrimmed value listed in Table 14. Trim the cores on-site in the presence of the Engineer. Use a permanent marker or paint pen to record the lot and sublot numbers on each core as well as the designation as Core A or B. The Engineer may require additional information to be marked on the core and may choose to sign or initial the core. The Engineer will take custody of the cores immediately after witnessing the trimming of the cores and will retain custody of the cores until the Department's testing is completed. Before turning the trimmed cores over to the Engineer, the Contractor may wrap the trimmed cores or secure them in a manner that will reduce the risk of possible damage occurring during transport by the Engineer. After testing, the Engineer will return the cores to the Contractor.

The Engineer may have the cores transported back to the Department's laboratory at the HMA plant via the Contractor's haul truck or other designated vehicle. In such cases where the cores will be out of the Engineer's possession during transport, the Engineer will use Department-provided security bags and the Roadway Core Custody protocol located at http://www.txdot.gov/business/specifications.htm to provide a secure means and process that protects the integrity of the cores during transport.

Decide whether to include the pair of cores in the air void determination for that sublot if the core height before trimming is less than the minimum untrimmed value shown in Table 14. Trim the cores as described above before delivering to the Engineer if electing to have the cores included in the air void determination. Deliver untrimmed cores to the Engineer and inform the Engineer of the decision to not have the cores included in air void determination if electing to not have the cores included in air void determination. The placement pay factor for the sublot will be 1.000 if cores will not be included in air void determination.

Instead of the Contractor trimming the cores on-site immediately after coring, the Engineer and the Contractor may mutually agree to have the trimming operations performed at an alternate location such as a field laboratory or other similar location. In such cases, the Engineer will take possession of the cores immediately after they are obtained from the roadway and will retain custody of the cores until testing is completed. Either the Department or Contractor representative may perform trimming of the cores. The Engineer will witness all trimming operations in cases where the Contractor representative performs the trimming operation.

Dry the core holes and tack the sides and bottom immediately after obtaining the cores. Fill the hole with the same type of mixture and properly compact the mixture. Repair core holes with other methods when approved.

4.9.3.3. **Placement Testing**. Perform placement tests in accordance with Table 17. After the Engineer returns the cores, the Contractor may test the cores to verify the Engineer's test results for in-place air voids. The allowable differences between the Contractor's and Engineer's test results are listed in Table 12.

4.9.3.3.1. **In-Place Air Voids**. The Engineer will measure in-place air voids in accordance with Tex-207-F and Tex-227-F. Before drying to a constant weight, cores may be pre-dried using a CoreDry or similar vacuum device to remove excess moisture. The Engineer will average the values obtained for all sublots in the production lot to determine the theoretical maximum specific gravity. The Engineer will use the average air void content for in-place air voids.

The Engineer will use the vacuum method to seal the core if required by Tex-207-F. The Engineer will use the test results from the unsealed core to determine the placement payment adjustment factor if the sealed core yields a higher specific gravity than the unsealed core. After determining the in-place air void content, the Engineer will return the cores and provide test results to the Contractor.

4.9.3.3.2. **Segregation (Density Profile)**. Test for segregation using density profiles in accordance with Tex-207-F, Part V when using a thermal camera in lieu of the thermal imaging system. Density profiles are not required and are not applicable when using a thermal imaging system. Density profiles are not applicable in areas described in Section XXX.4.9.3.1.4., "Miscellaneous Areas."

Perform a minimum of one density profile per sublot. Perform additional density profiles when any of the following conditions occur, unless otherwise approved:

- the paver stops due to lack of material being delivered to the paving operations and the temperature of the uncompacted mat before the initial break down rolling is less than the temperatures shown in Table 18;
- areas that are identified by either the Contractor or the Engineer as having thermal segregation;
- any visibly segregated areas that exist.

Table 18
Minimum Uncompacted Mat Temperature Requiring a Segregation Profile

High-Temperature Binder Grade[1]	Minimum Temperature of the Uncompacted Mat Allowed Before Initial Break Down Rolling[2,3,4]
PG 64	<250˚F
PG 70	<260˚F
PG 76	<270˚F

1. The high-temperature binder grade refers to the high-temperature grade of the virgin asphalt binder used to produce the mixture.
2. Segregation profiles are required in areas with moderate and severe thermal segregation as described in Section 4.7.3.1.3.
3. Minimum uncompacted mat temperature requiring a segregation profile may be reduced 10°F if using a chemical WMA additive as a compaction aid.
4. When WMA is required, the minimum uncompacted mat temperature requiring a segregation profile is 215°F.

Provide the Engineer with the density profile of every sublot in the lot within one working day of the completion of each lot. Report the results of each density profile in accordance with Section XXX.4.2., "Reporting and Responsibilities."

The density profile is considered failing if it exceeds the tolerances in Table 19. No production or placement payment adjustments greater than 1.000 will be paid for any sublot that contains a failing density profile. When a hand-held thermal camera is used instead of a thermal imaging system, the Engineer will measure the density profile at least once per project. The Engineer's density profile results will be used when available. The Engineer may require the Contractor to remove and replace the area in question if the area fails the density profile and has surface irregularities as defined in Section XXX.4.9.3.3.5., "Irregularities." The sublot in question may receive a production and placement payment adjustment greater than 1.000, if applicable, when the defective material is successfully removed and replaced.

Investigate density profile failures and take corrective actions during production and placement to eliminate the segregation. Suspend production if 2 consecutive density profiles fail unless otherwise approved. Resume production after the Engineer approves changes to production or placement methods.

Table 19
Segregation (Density Profile) Acceptance Criteria

Mixture Type	Maximum Allowable Density Range (Highest to Lowest)	Maximum Allowable Density Range (Average to Lowest)
SP-C & SP-D	6.0 pcf	3.0 pcf

4.9.3.3.3. **Longitudinal Joint Density**.

4.9.3.3.3.1. **Informational Tests**. Perform joint density evaluations while establishing the rolling pattern and verify that the joint density is no more than 3.0 pcf below the density taken at or near the center of the mat. Adjust the rolling pattern, if needed, to achieve the desired joint density. Perform additional joint density evaluations at least once per sublot unless otherwise directed.

4.9.3.3.3.2. **Record Tests**. Perform a joint density evaluation for each sublot at each pavement edge that is or will become a longitudinal joint. Joint density evaluations are not applicable in areas described in Section XXX.4.9.3.1.4., "Miscellaneous Areas." Determine the joint density in accordance with Tex-207-F, Part VII. Record the joint density information and submit results on Department forms to the Engineer. The evaluation is considered failing if the joint density is more than 3.0 pcf below the density taken at the core random sample location and the correlated joint density is less than 90.0%. The Engineer will make independent joint density verification at least once per project and may make independent joint density verifications at the random sample locations. The Engineer's joint density test results will be used when available.

Provide the Engineer with the joint density of every sublot in the lot within one working day of the completion of each lot. Report the results of each joint density in accordance with Section XXX.4.2., "Reporting and Responsibilities."

Investigate joint density failures and take corrective actions during production and placement to improve the joint density. Suspend production if the evaluations on 2 consecutive sublots fail unless otherwise approved. Resume production after the Engineer approves changes to production or placement methods.

4.9.3.3.4. **Recovered Asphalt Dynamic Shear Rheometer (DSR)**. The Engineer may take production samples or cores from suspect areas of the project to determine recovered asphalt properties. Asphalt binders with an aging ratio greater than 3.5 do not meet the requirements for recovered asphalt properties and may be deemed defective when tested and evaluated by the Materials and Tests Division. The aging ratio is the DSR value of the extracted binder divided by the DSR value of the original unaged binder. Obtain DSR values in accordance with AASHTO T 315 at the specified high temperature performance grade of the asphalt. The Engineer may require removal and replacement of the defective material at the Contractor's expense. The asphalt binder will be recovered for testing from production samples or cores in accordance with Tex-211-F.

4.9.3.3.5. **Irregularities**. Identify and correct irregularities including segregation, rutting, raveling, flushing, fat spots, mat slippage, irregular color, irregular texture, roller marks, tears, gouges, streaks, uncoated aggregate particles, or broken aggregate particles. The Engineer may also identify irregularities, and in such cases, the Engineer will promptly notify the Contractor. If the Engineer determines that the irregularity will adversely affect pavement performance, the Engineer may require the Contractor to remove and replace (at the Contractor's expense) areas of the pavement that contain irregularities. The Engineer may also require the Contractor to remove and replace (at the Contractor's expense) areas where the mixture does not bond to the existing pavement.

If irregularities are detected, the Engineer may require the Contractor to immediately suspend operations or may allow the Contractor to continue operations for no more than one day while the Contractor is taking appropriate corrective action.

4.9.4. **Exempt Production**. The Engineer may deem the mixture as exempt production for the following conditions:

- anticipated daily production is less than 500 tons;
- total production for the project is less than 5,000 tons;
- when mutually agreed between the Engineer and the Contractor; or
- when shown on the plans.

For exempt production, the Contractor is relieved of all production and placement QC/QA sampling and testing requirements, except for coring operations when required by the Engineer. The production and placement pay factors are 1.000 if the specification requirements listed below are met, all other specification requirements are met, and the Engineer performs acceptance tests for production and placement listed in Table 16 when 100 tons or more per day are produced*:*

- produce, haul, place, and compact the mixture in compliance with the specification and as directed;
- control mixture production to yield a laboratory-molded density that is within ±1.0% of the target laboratory-molded density as tested by the Engineer;
- compact the mixture in accordance with Section XXX.4.8., "Compaction"; and
- when a thermal imaging system is not used, the Engineer may perform segregation (density profiles) and thermal profiles in accordance with the specification.

4.9.5. **Ride Quality**. Measure ride quality in accordance with Item 585, "Ride Quality for Pavement Surfaces," unless otherwise shown on the plans.

5. MEASUREMENT

5.1. **Superpave Mixtures.** Hot mix will be measured by the ton of composite hot-mix, which includes asphalt, aggregate, and additives. Measure the weight on scales in accordance with Item 520, "Weighing and Measuring Equipment."

5.2. **Tack Coat.** Tack coat will be measured at the applied temperature by strapping the tank before and after road application and determining the net volume in gallons from the calibrated distributor. The Engineer will witness all strapping operations for volume determination. All tack, including emulsions, will be measure by the gallon applied.

The Engineer may allow the use of a metering device to determine the asphalt volume used and application rate if the device is accurate within 1.5% of the strapped volume.

6. PAYMENT

The work performed and materials furnished in accordance with this Item and measured as provided under Article XXX.5.1, "Measurement," will be paid for at the unit bid price for "Superpave Mixtures" of the mixture type, SAC, and binder specified. These prices are full compensation for surface preparation, materials, placement, equipment, labor, tools, and incidentals.

The work performed and materials furnished in accordance with this Item and measured as provided under Article XXX.5.2, "Measurement," will be paid for at the unit bid price for "Tack Coat" of the tack coat provided. These prices are full compensation for materials, placement, equipment, labor, tools, and incidentals.

Payment adjustments will be applied as determined in this Item; however, a payment adjustment factor of 1.000 will be assigned for all placement sublots for "level ups" only when "level up" is listed as part of the item bid description code. A payment adjustment factor of 1.000 will be assigned to all production and placement sublots when "exempt" is listed as part of the item bid description code, and all testing requirements are met.

Payment for each sublot, including applicable payment adjustments greater than 1.000, will only be paid for sublots when the Contractor supplies the Engineer with the required documentation for production and placement QC/QA, thermal profiles, segregation density profiles, and longitudinal joint densities in accordance with Section XXX.4.2., "Reporting and Responsibilities." When a thermal imaging system is used, documentation is not required for thermal profiles or segregation density profiles on individual sublots; however, the thermal imaging system automated reports described in Tex-244-F are required.

Trial batches will not be paid for unless they are included in pavement work approved by the Department.

Payment adjustment for ride quality will be determined in accordance with Item 585, "Ride Quality for Pavement Surfaces."

6.1. **Production Payment Adjustment Factors**. The production payment adjustment factor is based on the laboratory-molded density using the Engineer's test results. The bulk specific gravities of the samples from each sublot will be divided by the Engineer's maximum theoretical specific gravity for the sublot. The individual sample densities for the sublot will be averaged to determine the production payment adjustment factor in accordance with Table 20 for each sublot using the deviation from the target laboratory-molded density defined in Table 10. The production payment adjustment factor for completed lots will be the average of the payment adjustment factors for the 4 sublots sampled within that lot.

Table 20
Production Payment Adjustment Factors for Laboratory-Molded Density[1]

Absolute Deviation from Target Laboratory-Molded Density	Production Payment Adjustment Factor (Target Laboratory-Molded Density)
0.0	1.075
0.1	1.075
0.2	1.075
0.3	1.066
0.4	1.057
0.5	1.047
0.6	1.038
0.7	1.029
0.8	1.019
0.9	1.010
1.0	1.000
1.1	0.900
1.2	0.800
1.3	0.700
> 1.3	Remove and replace

1. If the Engineer's laboratory-molded density on any sublot is less than 95.0% or greater than 97.0%, take immediate corrective action to bring the mixture within these tolerances. The Engineer may suspend operations if the Contractor's corrective actions do not produce acceptable results. The Engineer will allow production to resume when the proposed corrective action is likely to yield acceptable results.

6.1.1. **Payment for Incomplete Production Lots**. Production payment adjustments for incomplete lots, described under Section XXX.4.9.2.1.1., "Incomplete Production Lots," will be calculated using the average production pay factors from all sublots sampled.

A production payment factor of 1.000 will be assigned to any lot when the random sampling plan did not result in collection of any samples within the first sublot.

6.1.2. **Production Sublots Subject to Removal and Replacement**. If after referee testing, the laboratory-molded density for any sublot results in a "remove and replace" condition as listed in Table 20, the Engineer may require removal and replacement or may allow the sublot to be left in place without payment. The Engineer may also accept the sublot in accordance with Section 5.3.1., "Acceptance of Defective or Unauthorized Work." Replacement material meeting the requirements of this Item will be paid for in accordance with this Section.

6.2. **Placement Payment Adjustment Factors**. The placement payment adjustment factor is based on in-place air voids using the Engineer's test results. The bulk specific gravities of the cores from each sublot will be divided by the Engineer's average maximum theoretical specific gravity for the lot. The individual core densities for the sublot will be averaged to determine the placement payment adjustment factor in accordance with Table 21 for each sublot that requires in-place air void measurement. A placement payment adjustment factor of 1.000 will be assigned to the entire sublot when the random sample location falls in an area designated on the plans as not subject to in-place air void determination. A placement payment adjustment factor of 1.000 will be assigned to quantities placed in areas described in Section XXX.4.9.3.1.4., "Miscellaneous Areas." The placement payment adjustment factor for completed lots will be the average of the placement payment adjustment factors for up to 4 sublots within that lot.

Table 21
Placement Payment Adjustment Factors for In-Place Air Voids

In-Place Air Voids	Placement Payment Adjustment Factor	In-Place Air Voids	Placement Payment Adjustment Factor
< 2.7	Remove and Replace	5.9	1.048
2.7	0.710	6.0	1.045
2.8	0.740	6.1	1.042
2.9	0.770	6.2	1.039
3.0	0.800	6.3	1.036
3.1	0.830	6.4	1.033
3.2	0.860	6.5	1.030
3.3	0.890	6.6	1.027
3.4	0.920	6.7	1.024
3.5	0.950	6.8	1.021
3.6	0.980	6.9	1.018
3.7	1.000	7.0	1.015
3.8	1.015	7.1	1.012
3.9	1.030	7.2	1.009
4.0	1.045	7.3	1.006
4.1	1.060	7.4	1.003
4.2	1.075	7.5	1.000
4.3	1.075	7.6	0.980
4.4	1.075	7.7	0.960
4.5	1.075	7.8	0.940
4.6	1.075	7.9	0.920
4.7	1.075	8.0	0.900
4.8	1.075	8.1	0.880
4.9	1.075	8.2	0.860
5.0	1.075	8.3	0.840
5.1	1.072	8.4	0.820
5.2	1.069	8.5	0.800
5.3	1.066	8.6	0.780
5.4	1.063	8.7	0.760
5.5	1.060	8.8	0.740
5.6	1.057	8.9	0.720
5.7	1.054	9.0	0.700
5.8	1.051	> 9.0	Remove and Replace

6.2.1. **Payment for Incomplete Placement Lots**. Payment adjustments for incomplete placement lots described under Section XXX.4.9.3.1.2., “Incomplete Placement Lots,” will be calculated using the average of the placement pay factors from all sublots sampled and sublots where the random location falls in an area designated on the plans as not eligible for in-place air void determination.

If the random sampling plan results in production samples, but not in placement samples, the random core location and placement adjustment factor for the sublot will be determined by applying the placement random number to the length of the sublot placed.

If the random sampling plan results in placement samples, but not in production samples, no placement adjustment factor will apply for that sublot placed.

A placement payment adjustment factor of 1.000 will be assigned to any lot when the random sampling plan did not result in collection of any production samples.

6.2.2. **Placement Sublots Subject to Removal and Replacement**. If after referee testing, the placement payment adjustment factor for any sublot results in a “remove and replace” condition as listed in Table 21, the Engineer will choose the location of 2 cores to be taken within 3 ft. of the original failing core location. The Contractor will obtain the cores in the presence of the Engineer. The Engineer will take immediate possession of the untrimmed cores and submit the untrimmed cores to the Materials and Tests Division, where they will be trimmed, if necessary, and tested for bulk specific gravity within 10 working days of receipt.

The bulk specific gravity of the cores from each sublot will be divided by the Engineer's average maximum theoretical specific gravity for the lot. The individual core densities for the sublot will be averaged to determine the new payment adjustment factor of the sublot in question. If the new payment adjustment factor is 0.700 or greater, the new payment adjustment factor will apply to that sublot. If the new payment adjustment factor is less than 0.700, no payment will be made for the sublot. Remove and replace the failing sublot, or the Engineer may allow the sublot to be left in place without payment. The Engineer may also accept the sublot in accordance with Section 5.3.1., "Acceptance of Defective or Unauthorized Work." Replacement material meeting the requirements of this Item will be paid for in accordance with this Section.

6.3. **Total Adjusted Pay Calculation.** Total adjusted pay (TAP) will be based on the applicable payment adjustment factors for production and placement for each lot.

TAP = (A+B)/2

where:
A = Bid price × production lot quantity × average payment adjustment factor for the production lot
B = Bid price × placement lot quantity × average payment adjustment factor for the placement lot + (bid price × quantity placed in miscellaneous areas × 1.000)

Production lot quantity = Quantity actually placed - quantity left in place without payment

Placement lot quantity = Quantity actually placed - quantity left in place without payment - quantity placed in miscellaneous areas

APPENDIX C – PILOT STUDY FOR PAVEMENT FIELD TEST SECTIONS

Recommendation for Implementation and Pilot Study

To accomplish successfully the main goal of this project, the research team has developed an implementation plan and a pilot study to validate the balanced mix design (BMD) concept. The results from Phase I (Feasibility) and Phase II (Development) were used for that purpose. Several pavement test sections were selected to investigate the field performance of BMD mixes containing RAP, RAS and additives as well as the influence of many external factors including traffic, climate, and existing pavement structural and design conditions. The implementation and pilot study consist of five different activities:

1. Selection of Mix Designs and Key Variables for Pavement Test Sections
2. Development of Job Mix Formula for Selected Mix Designs
3. Performance Evaluation of Plant Produced Mixtures
4. Field Performance Monitoring of Pavement Test Sections
5. Reporting Project Progress and Disseminating Research Findings

For the benefit of TxDOT and industry, the research team recommends the involvement of these entities during the mix design, production and construction phases for the selected test sections.

Selection of Mix Designs and Key Variables for Pavement Test Sections

Several pavement test sections should be placed as part on a follow-on implementation project to continue investigating and to finalize implementing of the BMD concept into current mix design practices. Each pavement test section may have five subsections with an approximate length of 2,000 ft and a lane-wide width. Figure 1 depicts an example of a pavement section with three variations of the BMD mix. The first subsection will be the control subsection which will be paved with the traditional mix design (designated as TMD) currently used by the contractor for the selected pavement construction project. The second subsection should be constructed with the BMD mix following the specifications and guidelines developed under Task 5. The other three subsections should be used to research the influence that key variables have on the performance of BMD mixes.

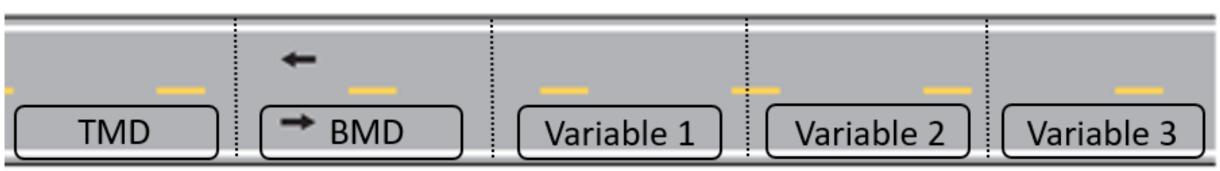


Figure 1 – Pavement Test Section Layout for BMD

The distribution of the pavement section, key variables and number of subsections per test section is presented in Table 1. The selection of TMD mixes should be done based on the variety of mix design variables. The mixes for the test sections should be directed to investigate the impact of the following key variables on the BMD mixes:

1. Aggregate gradation (coarse and fine graded mixtures as well as adjustment to gradations that will allow additional asphalt binder
2. Asphalt content and lab density (sensitivity of the mixture design method to asphalt binder content)
3. Asphalt source (look at extremes in asphalt physical and chemical properties)
4. RAP content and recycling agents (design method for mixtures containing RAP)

Table 1 – Pavement Test Sections, Key Variables and Location Conditions

Placement Year	Test Project Key Variables	Geographic Locations	Number of Test Sections per Test Project
2019	RAP/Recycling Agents	2	5
	Gradation	2	5
	Asphalt Binder Content	2	5
	Asphalt Binder Source	1	5
2020	RAP/Recycling Agents	2	5
	Gradation	2	5
	Asphalt Binder Content	2	5
	Asphalt Binder Source	1	5

Several mixes that were investigated and evaluated in Task 6 can be identified as potential TMD mixes for this experiment research plan.

Development of Job Mix Formula for Selected Mixes

The mixes should be prepared by TxDOT and contractors as a means of smooth transition to the BMD specifications during the design process, production and placement of actual pavement sections. The research team proposes to actively support contractors and TxDOT during the mix design process to produce the selected mixes. With the consent of TxDOT, the research team will participate in the mix design process for at least the TMD and BMD sections through communication with the contractor that will champion each test section. The research team will visit the contractor to assist during the mix design process as well as to collect raw materials to develop complementary information and performance data that can be helpful to the contractor and TxDOT.

During the design process for the selected mixtures, the research team will conduct the following three performance tests:

- Tex-248-F – Overlay Tester (OT) Test
- Tex-242-F – Hamburg Wheel Tracking (HWT) Test
- Tex-226-F – Indirect Tensile Strength (IDT) Test

The OT and HWT tests will be used as performance qualifiers to determine whether a mix meets the performance requirements associated with cracking and rutting. The IDT test is a surrogate test that has been recommended to tie the existing mix design process with the proposed BMD mix design. The tests will be conducted on specimens prepared by the contractors during the process.

Lab-mixed lab-compacted (LMLC) samples will be required to reproduce a mix design in the laboratory using raw material (e.g. mineral aggregates, recycled materials and neat binder). The amount of the raw materials needed depends on the material types specified in the mix design sheet. Upon access to the specific mix design, the research team will provide the amount of material required to carry out the needed mix design and to conduct associated index and performance tests.

Performance Evaluation of Plant Produced Mixtures

Figure 2 depicts the test methods, performance parameters, amount of plant-produced material and the number of samples proposed by the research team for routine evaluation of each mix during this project. At least 100 lbs of plant-produced material per subsection is needed.

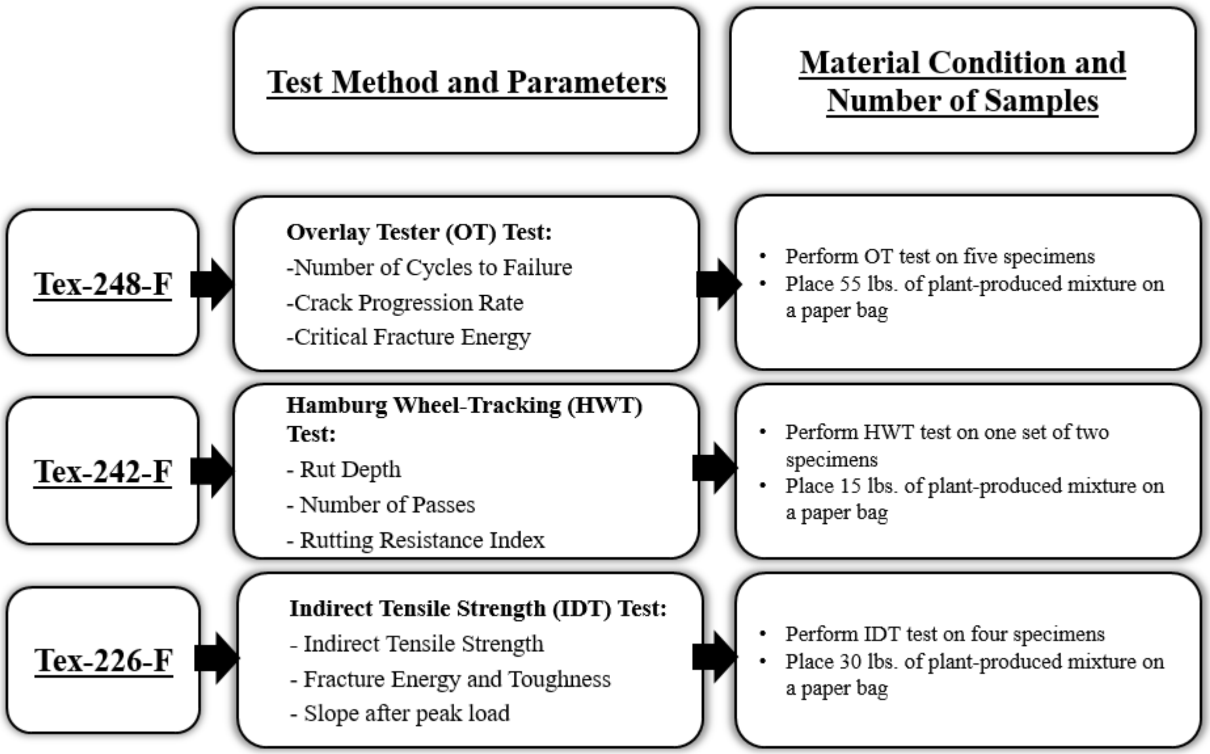


Figure 2 – Performance Test Methods for BMD Specifications

The main performance parameters will be the crack progression rate (CPR) from the OT test, normalized rutting resistance index (NRRI) from the HWT test, and indirect tensile strength (ITS) from the IDT test. A performance-based analysis will be carried out by plotting the three performance parameters in a performance space diagram as shown in Figure 3. CPR from OT test is plotted on the abscissa with a preliminary acceptance limit of 0.50, while NRRI from HWT test is plotted on the ordinance with an acceptance limit of 1.0. ITS from IDT is also shown as a data label for a more informed analysis.

The mixtures will be classified in one of the following four general categories:

Quadrant 1: Pass both rutting and cracking resistance. Balanced mix designs (BMD), good cracking resistance (flexible) and rutting resistance (rigid), are expected to be in this quadrant.

Quadrant 2: Pass only the rutting resistance requirements. Crack-susceptible mixes with poor cracking resistance (brittle) and good rutting resistance (rigid) are expected to be in this quadrant.

Quadrant 3: Only pass the cracking resistance requirements. Rut-susceptible mixes with acceptable cracking resistance (flexible) but poor rutting resistance (unstable) are expected to be in this quadrant.

Quadrant 4: Fail both rutting and cracking resistance requirements. Unacceptable mixes with significantly poor cracking resistance (brittle) and rutting resistance (unstable) are expected to be in this quadrant.

A BMD mix will be located within the green shaded area in Figure 3 and exhibits a minimum tensile strength of 85 psi.

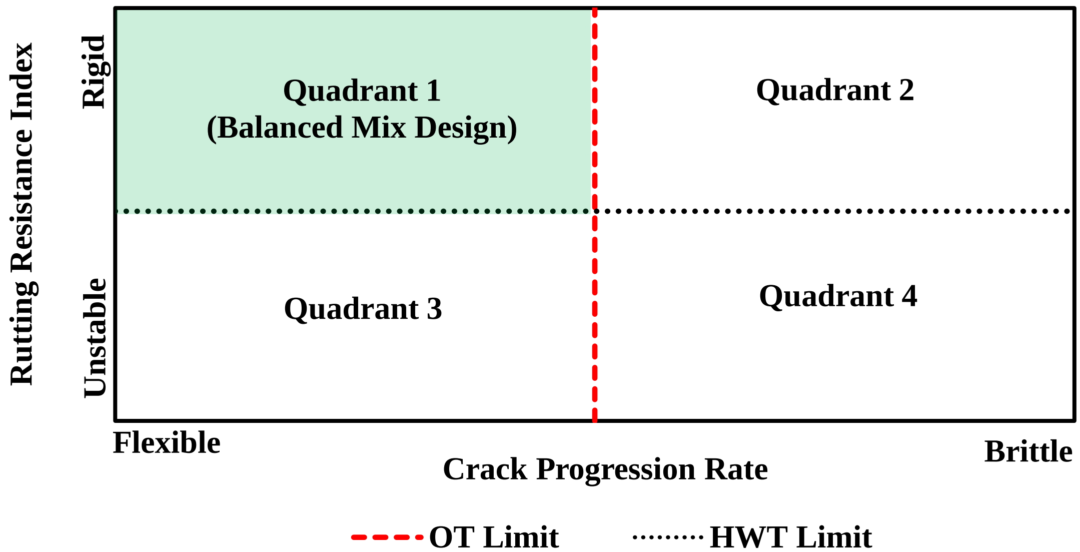


Figure 3 – Performance Space Diagram

Different sample types will be used during this project including LMLC, PMLC, and plant-mixed field-compacted (PMFC) samples. Figure 4 shows the sampling process and curing conditions for each sample type. To consider the aging level of various groups of samples, and provide reproducible and consistent results, representative curing conditions will be implemented to produce the specimens for performance testing. While the mixture will be cured for 2 hours at compaction temperature before molding specimens for rutting performance, the mixture will be cured for 4 hours at compaction temperature before molding specimens for cracking performance.

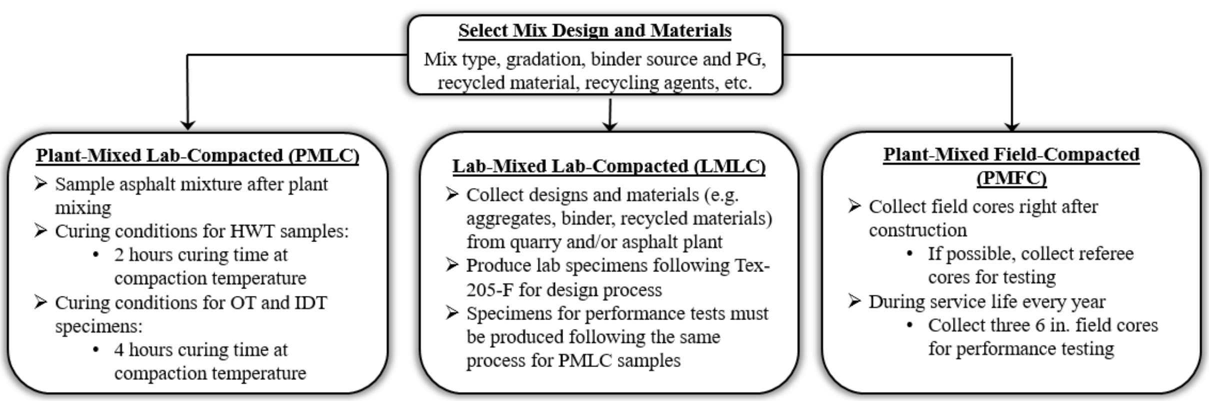


Figure 3 – Material and Curing Conditions for Different Sample Types

Field Performance Monitoring of Pavement Test Sections

The research team will interact with the PMC and districts to identify at least five pavement construction projects as field demonstration sites. If time permits, a clause will be added to the bid packages indicating that alternative mixes will be placed on four sections of the project. The preference can be given to projects that may be willing to experiment with the surface mixes.

The activities summarized in Table 2 will be tentatively carried out at each site. The research team proposes two days of production will be studied (one day for CNT mix and another for the BMD mix). After the completion of the field work, the field cores will be brought to the lab for further evaluation under appropriate test methods. These tests are summarized in Table 3.

The pavement test sections selected will be revisited in six-month intervals. The following activities will be carried out at each site provided major performance problems are not encountered.

i. Conduct a condition survey to map the condition of the pavement (cracking and rutting)
ii. Perform roughness measurement
iii. Conduct PSPA at locations tested during the initial visit
iv. Conduct FWD tests at locations tested during the initial visit
v. Compare results with the previous monitoring activities of the section.

Table 2 – Field Activities during Construction Pavement Test Sections

Timeline from Site Visit	Activity	Outcome
Preconstruction Meeting	Attend Meeting and share with all stake holders the steps to be taken by Research Team	Clarify responsibilities of research team, contractor and TxDOT staff
1 day before	Arrive at site and meet with the contractor and TxDOT personnel	Verify that all parties are aware of their responsibilities
Day of Paving	Sample mix from paver six times	Gradation curve/asphalt content/asphalt viscosity to ensure uniformity of mix
	Measure the temperature of mat at compaction	Compaction temperature
	Operate PQI after completion of compaction	Density of mat
	Observe problems with placement or compaction	
Next Day	Perform PSPA at six locations in vicinity of locations where lose mixes were sampled	Modulus of Mat
	Extract cores as planned	Cores for lab testing
After Construction	Perform FWD	Structural uniformity of sections to be considered during evaluation of performance.

Field cores will be extracted only once a year for three consecutive years. The research team proposes to at least collect four field cores per subsection for laboratory testing and evaluation.

Table 3 – Laboratory Testing Activities on PMLC and PMFC Material

Step	Test Method	Outcome
1a	NCAT Ignition Oven on loose mixes	Variation of binder content and gradation of mix along project
1b	Gradation of loose mixes	
2a	Extraction of binder from loose mixes	Variation of binder viscosity and G* along project
2b	Viscosity and G* of binder	
3a	G_{mm} of Loose mixes	Determine air void contents of specimens
3b	G_{mb} of all cores	
4a	HWT on compacted specimens and select cores	Estimate performance of mix, compare cores and prepared specimens' responses
4b	Overlay Tester on compacted specimens and select cores	
5	IDT strength of cores	Variation in strength along project
6a	NCAT Ignition Oven of all cores	Variation in AC content and gradation along project
6b	Gradation of all cores	

Reporting Project Progress and Disseminating Research Findings

The research team proposes the following activities to document, report and disseminate the progress of the project and research findings:

- ***Quarterly progress memoranda (QPM)*** will be prepared and submitted to TxDOT to document the progress of the project.
- ***Power-point progress presentations (PPP)*** will be developed to discuss the research work and the direction of the project during quarterly progress meetings.
- ***Final project report (FPR)*** will be prepared and submitted to the Receiving Agency to document the research work, key findings and recommendations from this project.

The research team recommends creating and maintaining a data depository to safely store the laboratory and field performance data and facilitate access for future use, reference and analysis.

Appendix D - Application of Balanced Mix Design Efforts

The following table lists the field projects that were selected. Table 1 also provides phases of each activity performed for each of the selected field project. In total, there were eleven projects selected, but 2 of the projects were dropped out due to construction issues (Project Numbers 10 and 11). One of those projects, the mix design support was carried out for the district, however, the project was postponed to a later date and was not feasible in our timeline to participate in the project. Projects 8 and 9 are underway. UTEP has carried out the complete mix design support for both of those projects. Project 8 is in San Angelo with the possibility of 5 test sections. In that project, we are looking at difference in binder as well as SAC A and SAC B aggregate. Project 9 is in San Antonio and consists of looking at impact of rejuvenator with a total of three sections. The efforts and result summary are presented in this technical memorandum. As presented in the table, the different stages of each project were a huge undertaken and most was carried out by UTEP. Looking at the efforts, UTEP provided mix support for over forty plus sections. Only 22 of those mix design sections that were designed and verified in terms of performance testing by UTEP ended up constructed in the field. UTEP performed the mix design using the gradation tool and the laboratory team performed the volumetrics followed by the performance testing. The performance testing was HWT, OT, and Indirect Tensile testing. The results of the sections were approved and presented to the team which is composed members from the three universities, MTD members, contractor and area office folks. In general, an agreement is reach to which of the mix designs are most appropriate to the district and logistically feasible to do within the construction timeframe. The next phase is the trial batch. The mix is sent to the universities, where UTEP carried out the performance tests on the mix for each of the trial batch section. The results of the PMLC samples were then presented to the contractor. In many cases, the contractor decision to proceed was based on the results of the mix performance. There were few cases were the contractor proceeded before the results of the trial batch were completed. The next step was the mix design verification

In the mix design verification, the raw material is delivered to UTEP to perform LMLC samples to verify the mix design. In addition, plant mix is sent to UTEP labs for each sublot for each of the test sections. PMLC samples are produced and tested. The results of both mix design verification and production are presented to the team. The final step in the process is the cores. The section cores that are sent to UTEP are tested and compared to the other phases for each project. That was the test plan for each of the projects. However, as we all are aware of, during paving season not all the steps performed. In some cases, not enough material is collected and sent to the lab for testing. In order cases not enough cores are extracted.

Table 1 – Overall Summary of the Field Projects Across All Stages of Mix Verification

Project No.	NS	MDS	TBV	MDV (LMLC)	PST (PMLC)	Cores (AfC)	Cores (yr 1)
1	3	Carried out by contractor	Carried out by contractor	Completed	Completed (3 Sublots)	Completed	Completed
2	3	Completed	Completed	Completed	Completed (2 Sublots)	Completed	Completed
3	3	Completed	Completed	Completed	Completed (3 Sublots)	Completed	Completed
4	4	Carried out by contractor	Completed	Completed	Completed (4 Sublots)	cores were too thin and not to spec.-	
5	4	Carried out by contractor	Completed	Completed	Completed (4 Sublots)	Completed	Completed
6	4	Completed	Completed	Completed	Completed (1 Sublots)	Completed	Completed
7	3	Completed	Completed	Completed	Completed (2 Sublots)	Completed	Not Started
8*	5	Completed	Not Started	In Progress	Not Started	Not Started	Not Started
9*	4	Completed	Not Started	In Progress	Not Started	Not Started	Not Started
10**	5	Completed	Cancelled	Cancelled	Cancelled	Cancelled	Cancelled
11***	-	Cancelled	Cancelled	Cancelled	Cancelled	Cancelled	Cancelled

NS - Number of Sections, MDS – Mix Design Support, TBV – Trial Batch Verification, MDV – Mix Design Verification, PST - Production Sample Testing, AfC – After Construction

*** - Projects 8 and 9 are on the first phase of construction where the mix design support was competed. Construction is not yet started thus the remaining phases of the mix verification was not carried out.**

**** - Project 10 mix design support was completed by UTEP. However, the project was cancelled.**

***** - Project 11 was cancelled few months after being identified as a possible section for this research.**

Projects' Test Sections & Results

Six of the eleven field projects that were evaluated, are presented in this tech memo. A summary of the mix design and gradation are presented followed by charts that compare the stages of each teat section. The test sections are grouped by their field project. The performance test parameters: NRRI based on the HWT, CPR and CFE based on the OT, and tensile strength based on the IDT are presented comparing each stage of the mix evaluation from mix design support to cores. For all the sections, one sample was tested for HWT, three replicates for OT and four replicates for IDT.

Project No 1 – Atlanta District

This field project was in the Atlanta District. It includes a control mix with 10% RAP and PG 76-22. The two proposed sections: 1) A virgin mix with PG 76-22 binder and 2) a section that contains recycled (combination of RAP & RAS) material similar total to the control section but with a softer binder PG 70-22. Table 2 shows the mix design information for those three sections and Table 3 has the gradation percentages used for each of the sections. As shown in the mix design and gradation, this project has the potential to demonstrate the effect of RAP as well as softer binder on mix design and performance.

Table 2 – Project No 1 Mix Design Summary

Section ID	Spec	Binder Grade	RAP (RBR)	Additive	OAC
Section 1 Control RAP	344	PG 76-22	10% (8.2%)	1% Lime	5.5%
Section 2 Virgin	334	PG 76-22	0%	1% Lime	5.6%
Section 3 RAP/RAS+ softer binder	334	PG70-22	11% / 3% (9.0% / 9.3%)	1% Lime	5.5%

RAP=reclaimed asphalt pavement; RBR=recycled binder ratio; RAS=recycled asphalt shingles; OAC=optimum asphalt content

Table 3 – Gradation Summary for Project No 1

Section ID	Sandstone D-Rock	Gravel D-Rock	Gravel Screening	Field Sand	Sandstone Dry Screening	RAP
Section 1 Control RAP	16%	40%	15%	9%	9%	10%
Section 2 Virgin	17%	45%	16%	9%	12%	
Section 3 High RAP	15%	40%	18%	7.3%	20%	11%

The next three four figures show the results of four performance parameters: a) HWT, CPR, CFE, and IDT. Figure 1 compares the results for all stages of the project for three sections. The results from the HWT for the mix design support of all three sections show higher NRRI compared to the other stages of the project evaluation. In this case the mix design support was carried out by the contractor. The remainging stages show very comparible HWT results. Those results were performed at UTEP. Overall, the NRRI values are larger than 1.5 which suggest that all three section will behave weel in rutting.

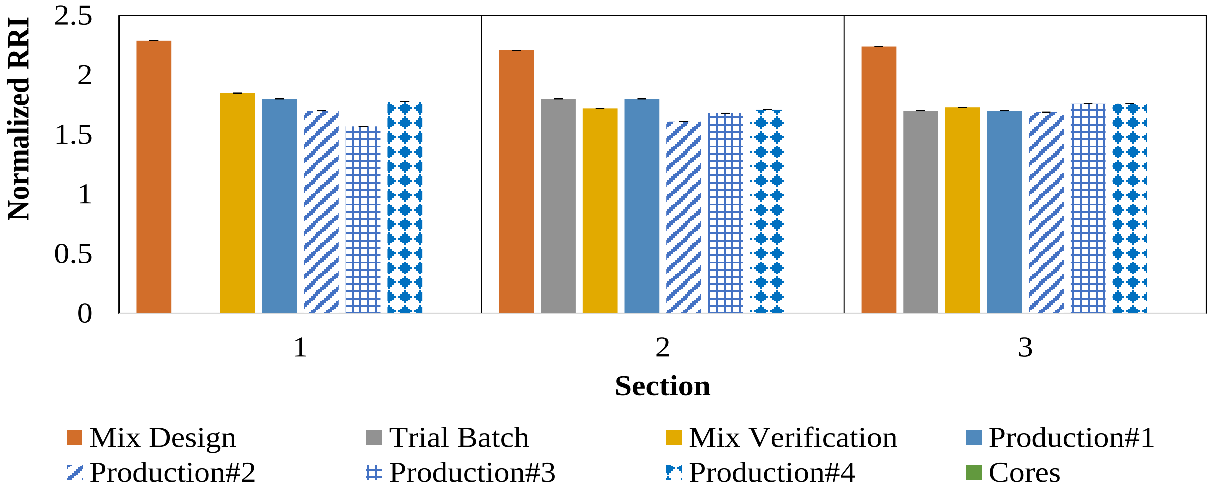


Figure 1 – Summary of NRRI Values for Project No 1

Figures 2 and 3 are the results of the overlay test and the data provided compared the results from mix verification to production to cores. The results of the CPR are very consistent for Section 1 and Section 2 with only one deviant being slightly higher which is the cores from Section 2. Otherwise, the values of the CPR values for both sections were close to 0.3. In Section 3 the results had slightly more variability in the production face. Overall, the CPR values for all three sections were well below the threshold of 0.45.

The CFE results have more spread in values across the stages of the project verification. For Section 1 the mix verification Sublot 1 and 3 of Production and the core are close in values compared to Sublots 2 and 4 where the values are a bit higher. The variability follows a similar trend as the CFE values. Sections 2 and 3 seem to show more consistent results across all stages. One observation is the CFE of the cores is consistently lower for all three sections.

Figure 4 summarizes the data for the indirect tensile strength. The results are consistent throughout the three sections and across all stages of verification. The value of the mix design support was smaller than the rest for all three sections.

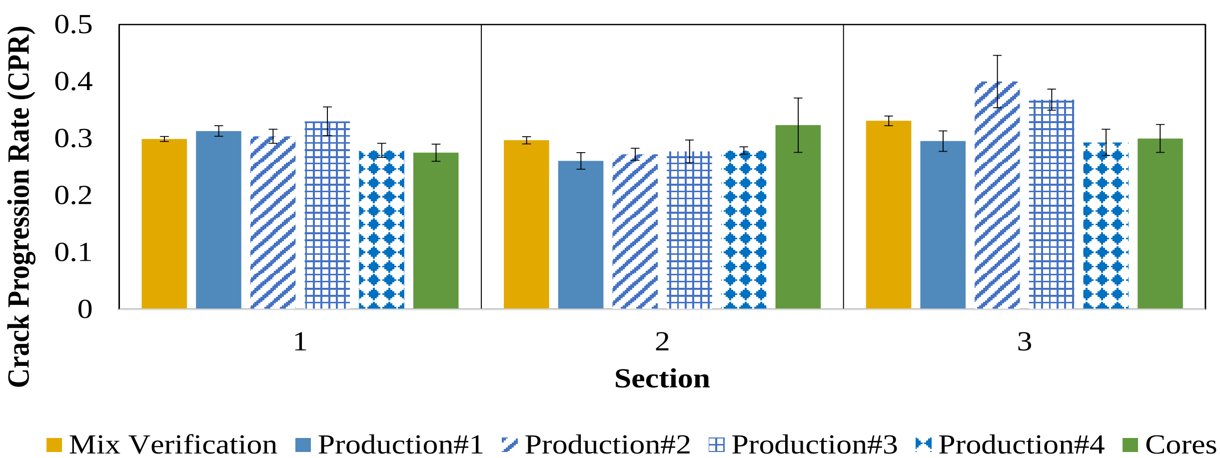


Figure 2 - Summary of CPR Values for Project No 1

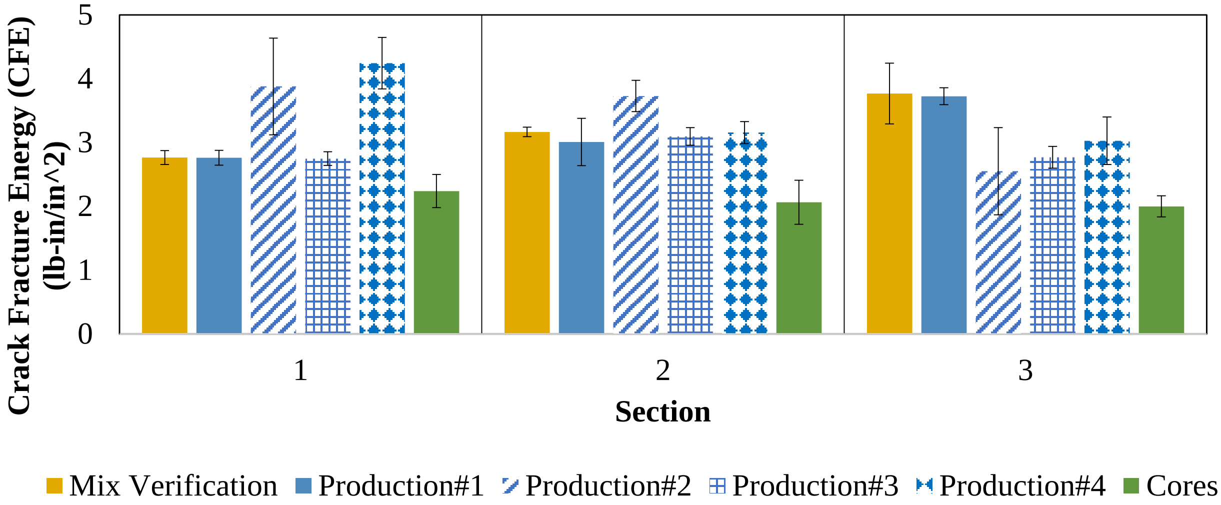


Figure 3 - Summary of CFE Values for Project No 1

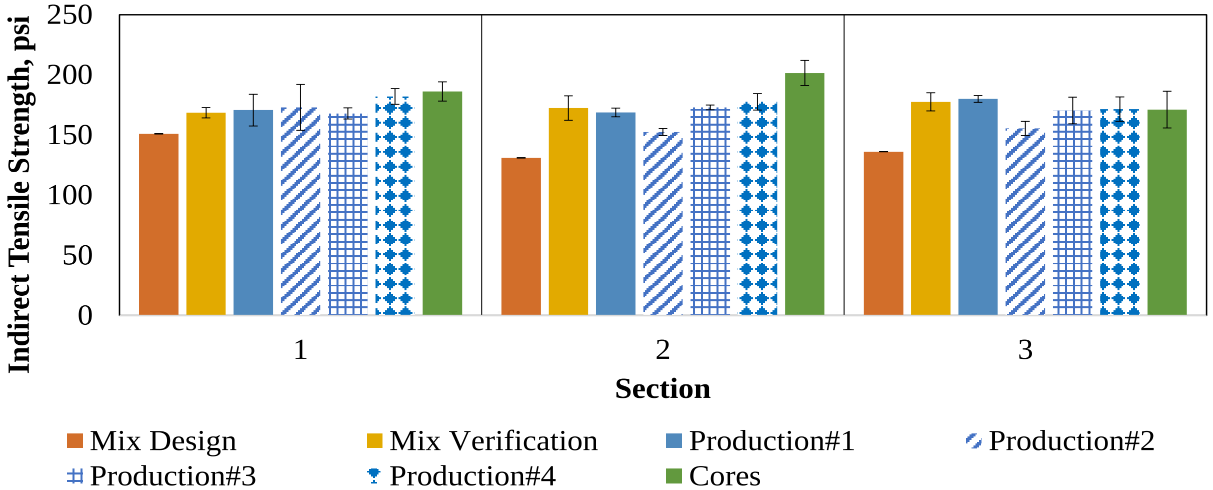


Figure 4 - Summary of Indirect Tensile Strength Values for Project No 1

Figures 5 and 6 provide an alternate view of the data using the interaction plots. The CFE show a bit scatter in the data (Figure 5) compared the NRRI values (Figure 6).

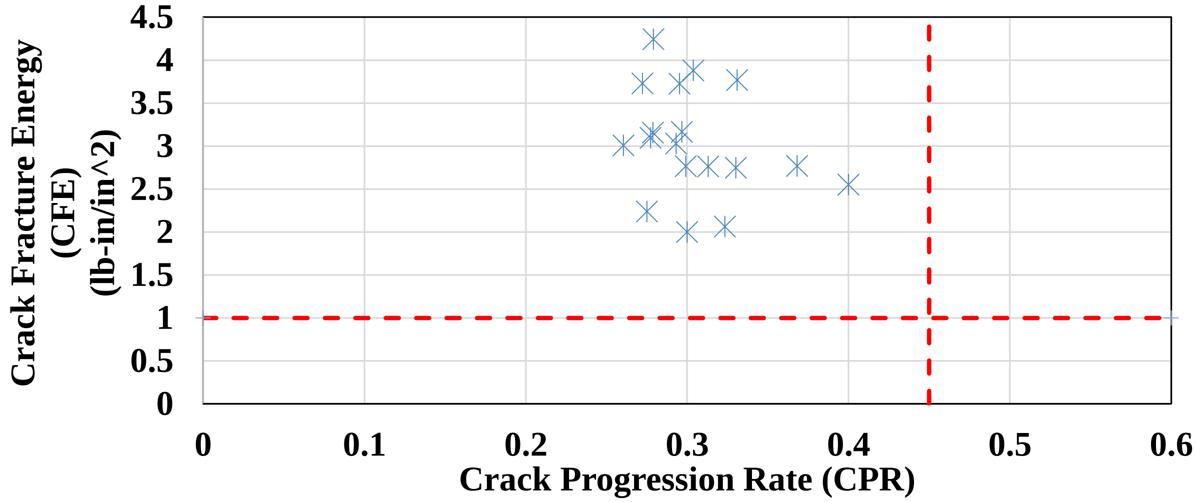


Figure 5 - Summary of OT Interaction Plot for Project No 1

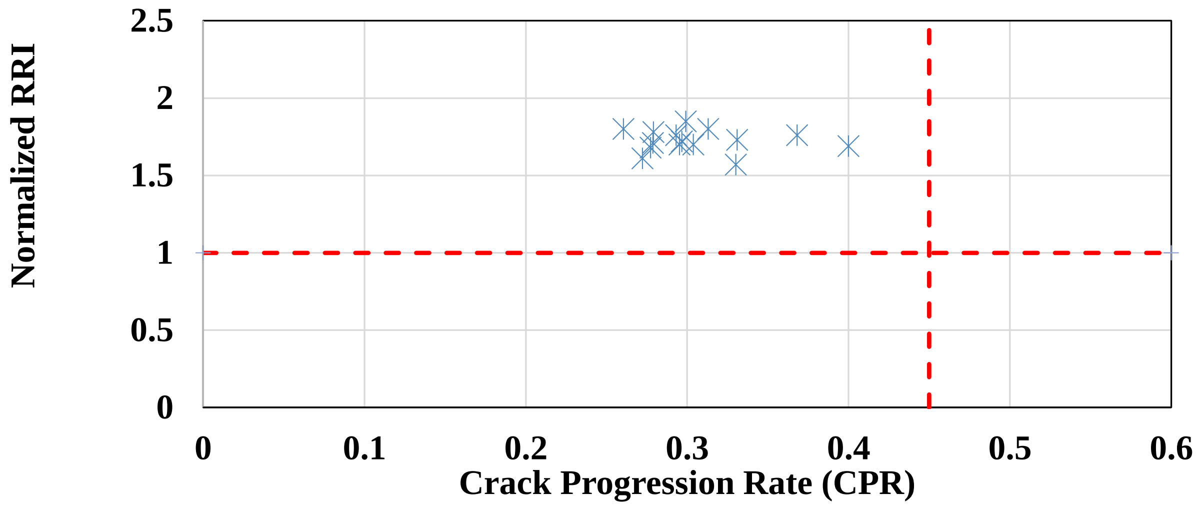


Figure 6 - Summary of Mix Design Interaction Plot for Project No 1

Project No 2 - San Antonio District

The San Antonio field project was constructed in July 2020, and its location is in Comal County. The project included two test sections in addition to the control section. Table 4 provides the summary of the mix design for all three sections.

Table 4 – Project No 2 Mix Design Summary

Section ID	Spec	RAP (RBR)	Additive	OAC
Section 1 Control RAP	3077	15.1% (17.4%)	0.3% Evotherm	5.2%
Section 2 Virgin	3074	0%	-	5.7%
Section 3 High RAP	3074	25.2% (28.0%)	0.6% Evotherm	5.4%

RAP=reclaimed asphalt pavement; RBR=recycled binder ratio; OAC=optimum asphalt content

Table 5 provides the graduation information for each section. This project focused on looking at the influence of RAP in the mix design.

Table 5 – Project No 2 Gradation Summary

Section ID	Igneous Trap C-Rock	Igneous Trap D-Rock	Limestone D-rock	Limestone F-rock	Limestone Manufactured Sand	Silica Sand	RAP
Section 1 Control RAP	15%	10%	12%	18%	25%	5.4%	14.8%
Section 2 Virgin	15%	12%	20%	19%	25%	9%	-
Section 3 High RAP	15%	13%	12%	15%	20%	-	25.2%

During mix design support, the Virgin section showed slightly higher HWT ruth depth when compared to the SP-C Control RAP section. All sections passed the threshold for rutting with NRRI greater than 1.5. In other words, rutting is less than 12.5 mm rut depth at 15,000 load cycles. And all three sections had the core results greater than the remaining stages of mix verification.

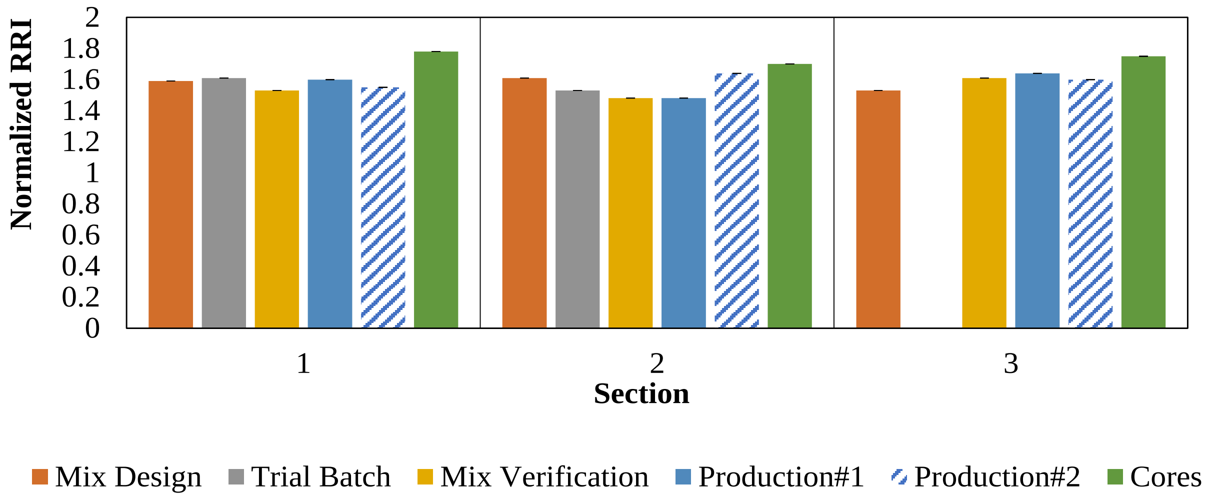


Figure 7 - Summary of NRRI for Project No 2

Figures 8 and 9 present the OT for CPR and CFE respectively. The CPR results indicate that the control section has a CPR value greater than the acceptable threshold of 0.45. The remaining values of the CPR for the Section 1 are well below the threshold. As well as the CPR values for Sections 2 and 3. Section 2, the mix with the virgin binder seem to exhibit the lowest CPR values of all three sections. In Figure 9 the CFE values range between 2 and 3.5 with the trail batch results having the largest values. Like the results of the CPR values, Section 3 seem to have the lowest values of the three sections.

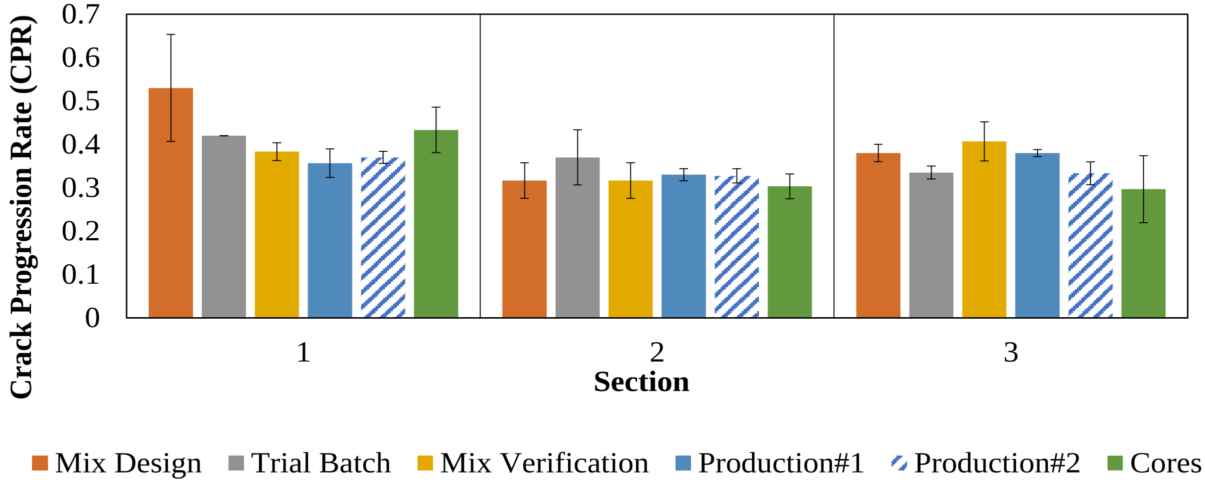


Figure 8 - Summary of CPR value for Project No 2

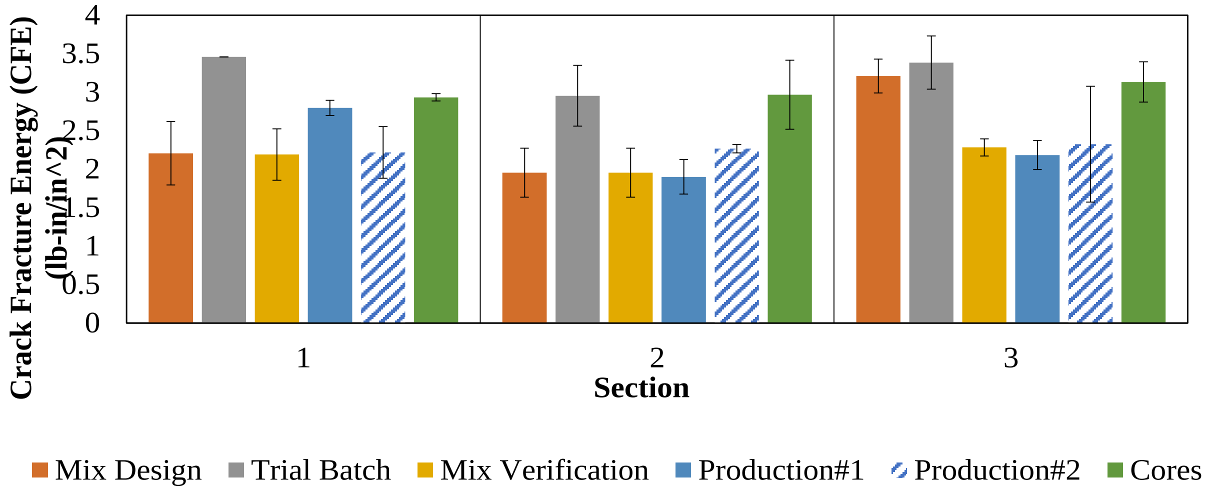


Figure 9 - Summary of CFE for Project No 2

Figure 10 provides the results of IDT with all the values greater than the minimum threshold of 85 psi. Again Section 2 seem to exhibit the lowest values of either of the three sections.

The interaction plot in Figures 11 and 12 both show that most of the sections were balanced except for the Control section in the mix design support, and the virgin section was borderline balanced for both the mix design support and trial batch.

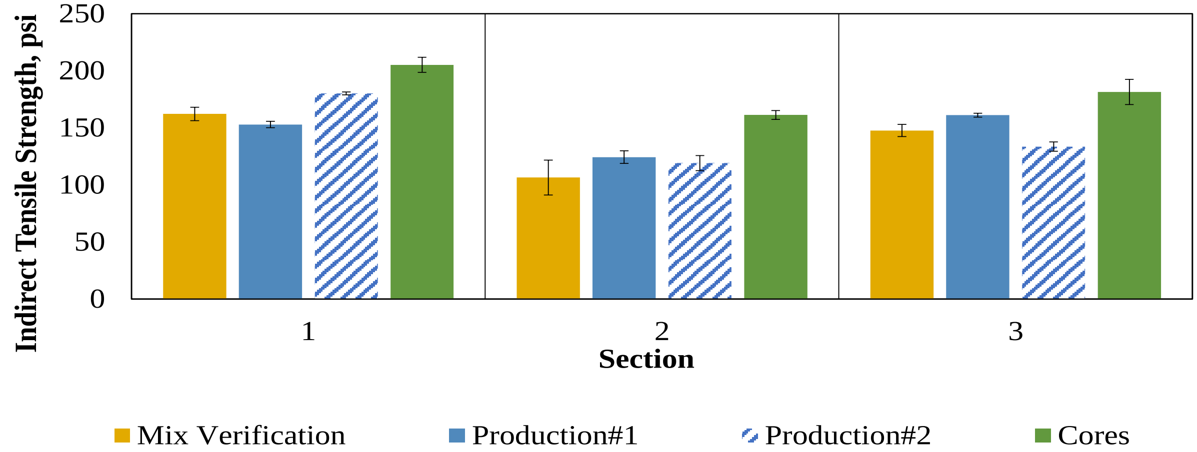


Figure 10 - Summary of Indirect Tensile Strength for Project No 2

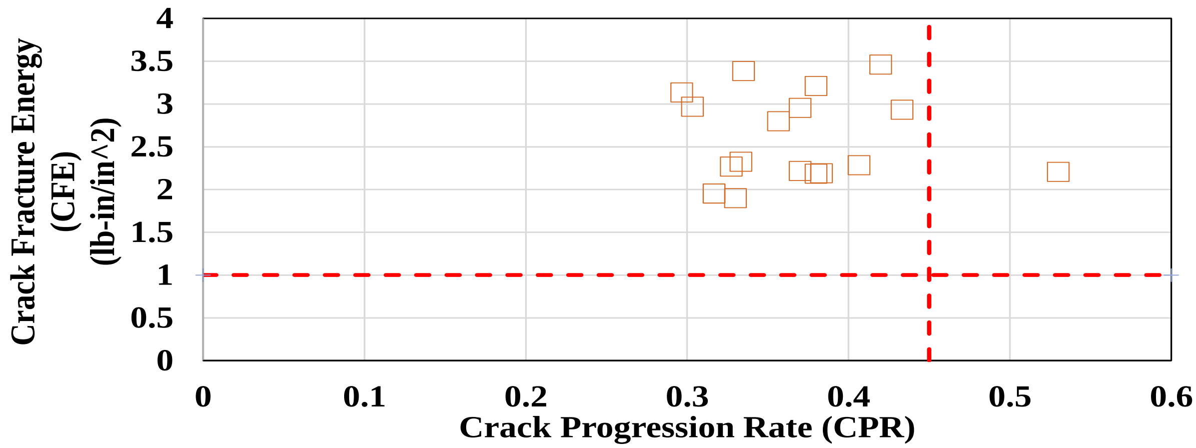


Figure 11 – Overlay Interaction Plot for Project No 2

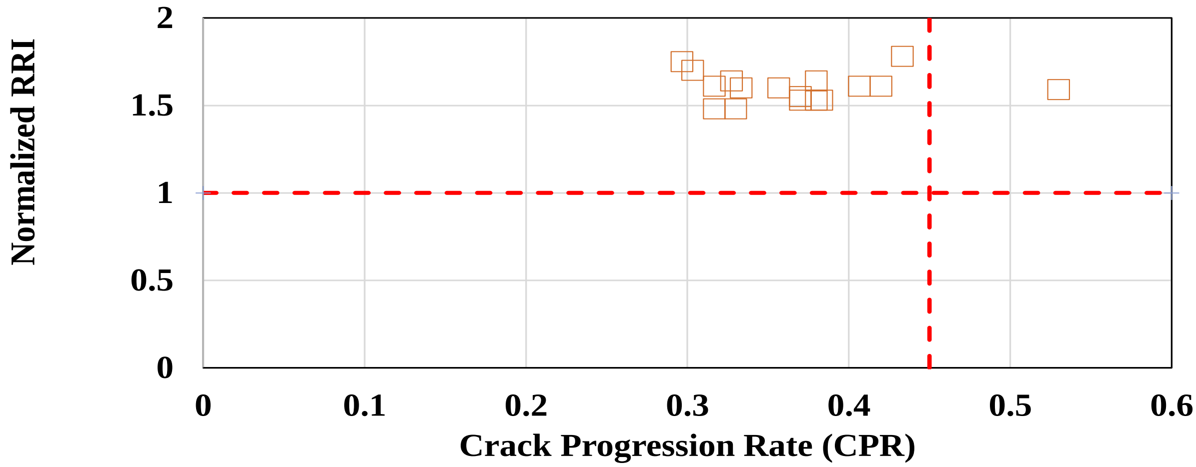


Figure 12 – Mis Design Interaction Plot for Project No 2

Project No 3 - San Antonio District

The second San Antonio field project was constructed in September 2020. It consisted of three sections with different RAP percentages, the first section termed as control section contained the lowest percentage of RAP out of the three sections, the second section was the high RAP mix and used Evoflex as an additive, and the third section contained the highest percentage of RAP. Table 6 summarizes the mix design information for these sections.

Table 6 – Project No 3 Mix Design Summary

Section ID	Spec	RAP/RAS (RBR)	Additive	OAC
1 - Control RAP	344	15%	0.3% EVOTHERM	5.30%
3 – RAP	344	30%	3% EVOFLEX	6.00%
4 - RAP/RAS	344	32%	0.5% EVOTHERM	6.10%

RAP=reclaimed asphalt pavement; RBR=recycled binder ratio; OAC=optimum asphalt content

There were three different mixes used for construction, and they had variations in gradation as can be seen in Table 7.

Table 7 – Project No 3 Mix Design Gradation

Section ID	Limestone Gr. 4	Limestone D/F Blend	Limestone Man sand	Silica	RAP
Section 1 Control RAP	37%	15%	22.9%	10%	15%
Section 3 RAP	29.9%	14%	25.7%	-	30%
Section 4 RAP/RAS	29.9%	14%	25.7%	-	32%

During the mix design support, rutting test was performed by the contractor. The rutting results for trial batch was marginal for Section 3 and Section 4 with Section 4 failing with and NRRI less than 1 as depicted in Figure 13. All sections met the threshold criteria for the CPR and CFE values, displayed in Figures 14 and 15. However, the IDT strength for the RAP section failed to meet the threshold of 85 psi as shown in Figure 18.

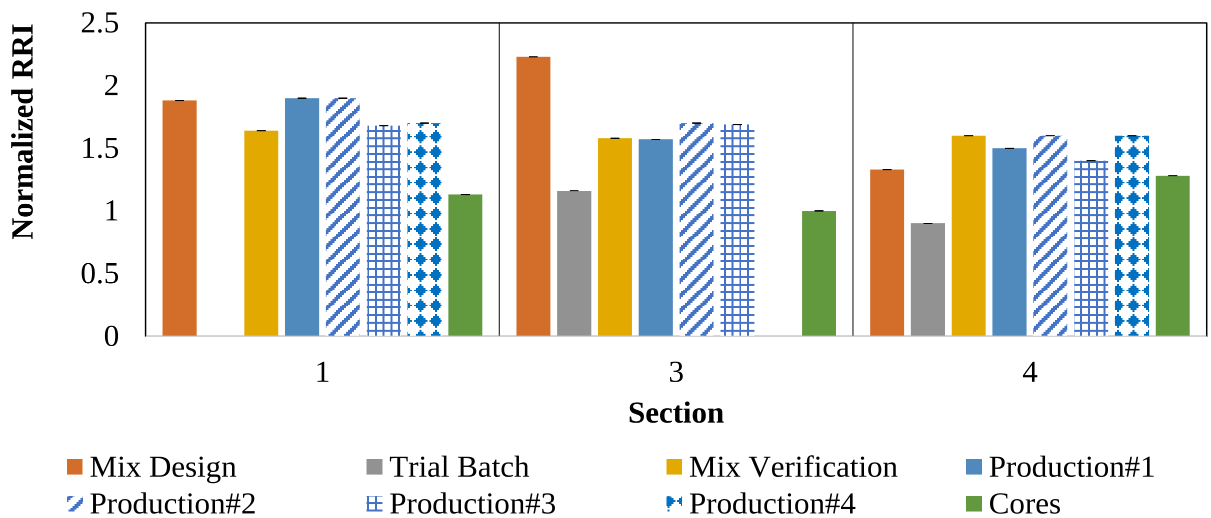


Figure 13 – Summary of NRRI Results for the Mix Verification Stages for Project No 3

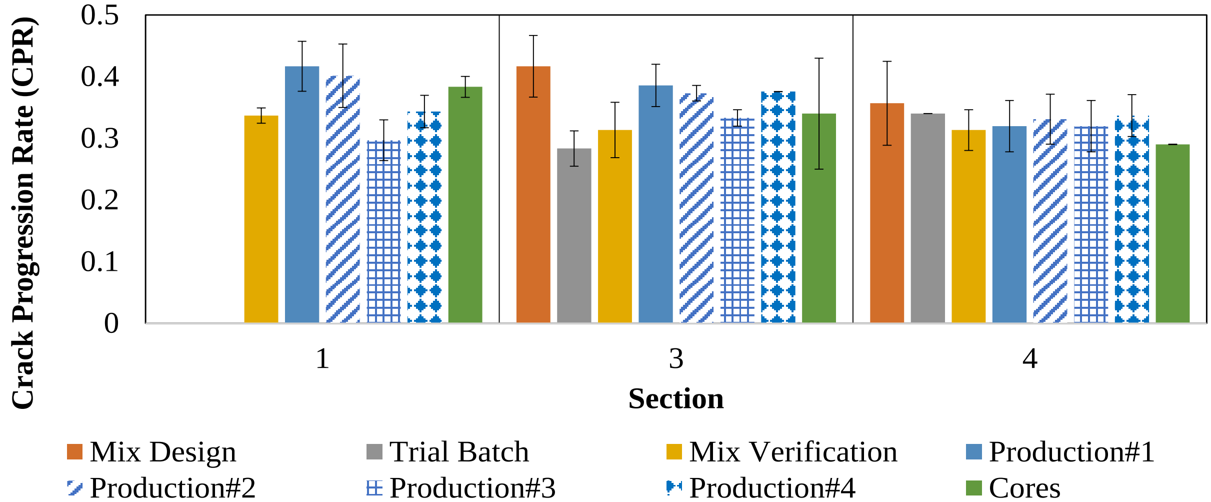


Figure 14 – Summary of CPR Results for the Mix Verification Stages for Project No 3

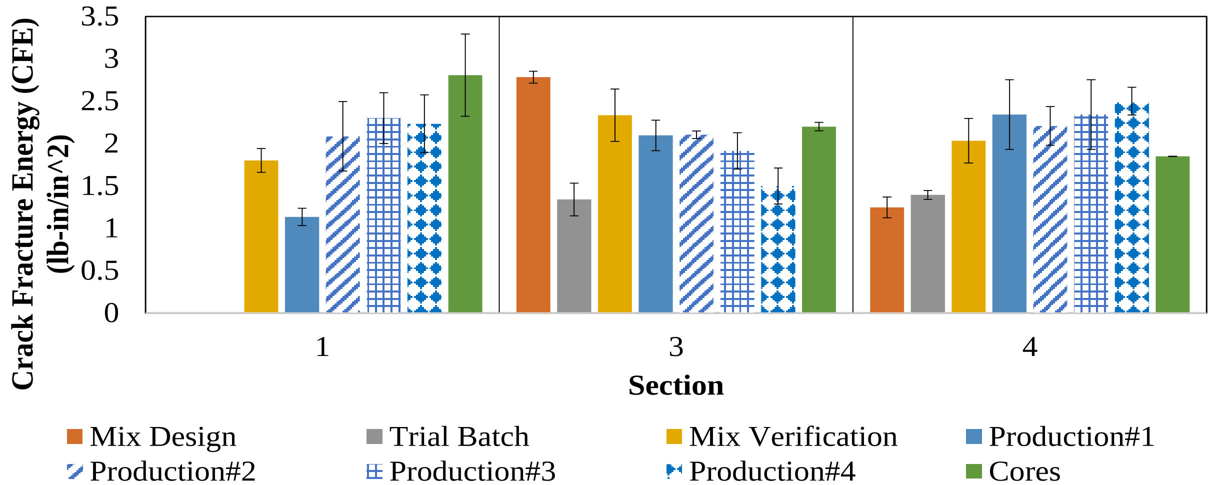


Figure 15 – Summary of CFE Results for the Mix Verification Stages for Project No 3

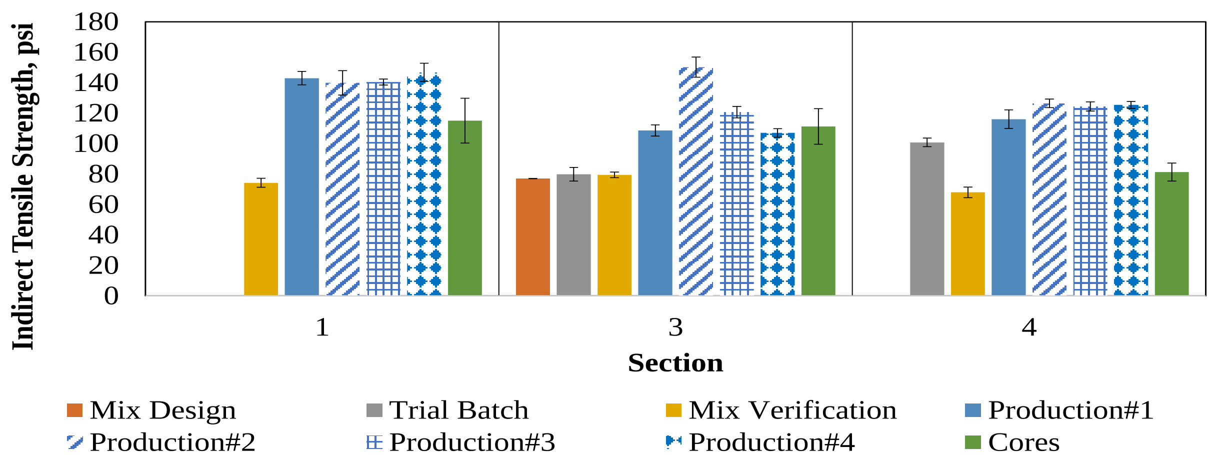


Figure 16 – Summary of Indirect Tensile Strength Results for the Mix Verification Stages for Project No 3

The overlay interaction plot in Figure 17 shows that the mix designs for all sections are passing the OT with few points close to the marginal line of 0.45 as well as one data point close to the lower bound of one for the CFE parameter. Figure 18 shows mix design interaction plot. The plot shows that all the sections are balanced except for the one point that failed in rutting. That as mentioned earlier is for the trail batch. As for the lab mix and production evaluations, all values were balanced.

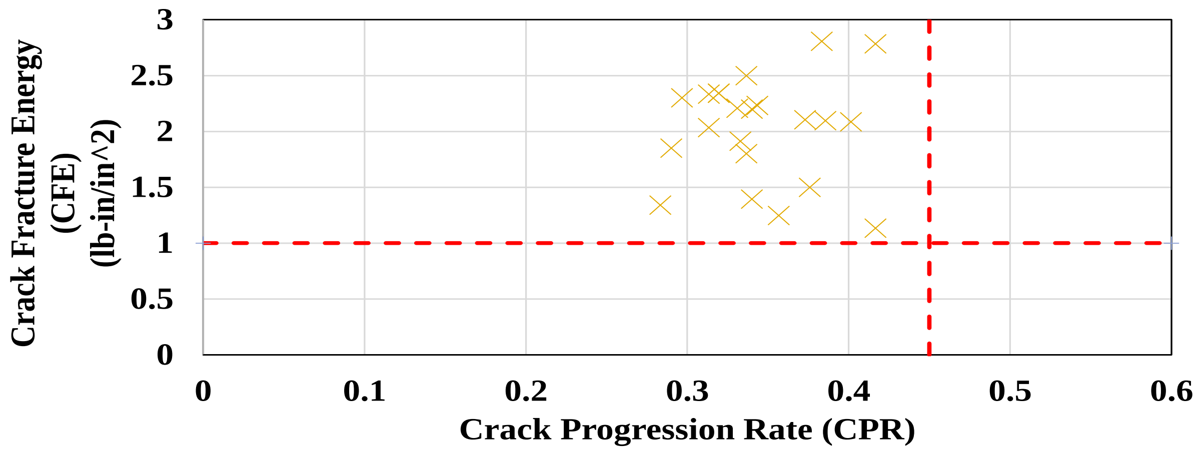


Figure 17 – Summary of OT Interaction Plot for Mix Verification Stages for Project No 3

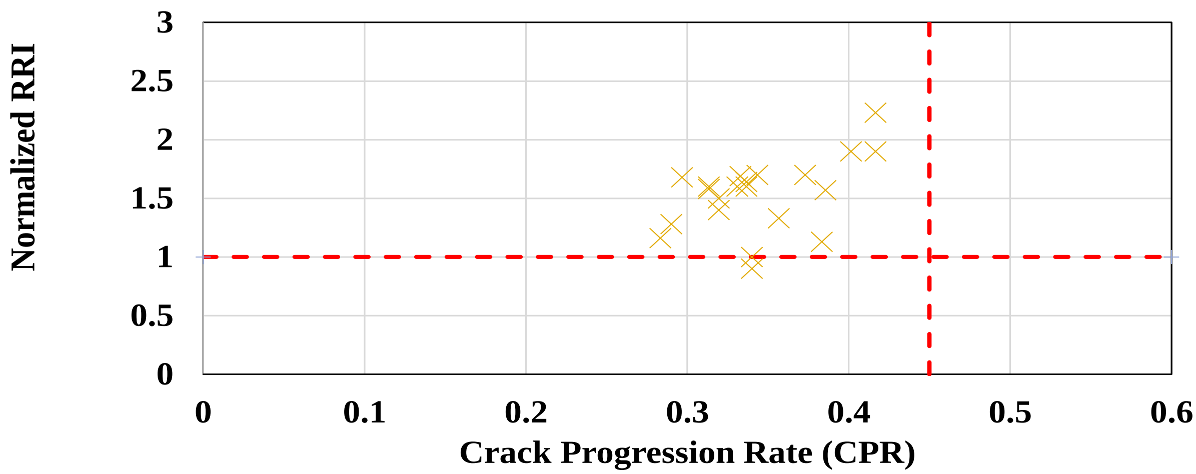


Figure 18 – Summary of Mix Design Interaction Plot for the Mix Verification Stages for Project No 3

Project No 4 - Yoakum District

The Yoakum field project was constructed in September 2020, and it included 4 sections with different percentages of RAP. The control section contained no RAP and is a TOM mixture. The second section was the low RAP mix with Dense Graded mix. The third section contained higher RAP and Superpave mix. And the fourth section contained higher RAP. Table 8 summarizes the mix design information for all the sections.

Table 8 – Project No 4 Mix Design Summary

Section ID	Spec	RAP/RAS (RBR)	Additive	OAC
1 - Control TOM	347	0%	0.3% Evotherm + 1% Lime	6.50%
2 - DG-D 10% RAP	341	10%	0.35% Evotherm + 1% Lime	5.30%
3 - SP-D 20% RAP	344	20%	0.5% Evotherm + 0.5 % Lime	6.10%
4 - SP-D High RAP	344	30%	0.5% Evotherm + 1 % Lime	5.90%

The variations in gradation are summarized in Table 9.

Table 9 – Project No 4 Mix Design Gradation

Section ID	Gravel Gr. 5	Igneous Gr. 6	Limestone Screenings	Hydrated Lime	Limestone Man sand	RAP
Section 1 - Control TOM	35%	40%	14%	1%	10%	-
Section 2 - DG-D 10% RAP	22%	33%	25%	10%	-	10%
Section 3 - SP-D, 20% RAP	21.9%	30.8%	21.9%	4.9%	0.5%	19.9%
Section 4 - SP-D, High RAP	29.7%	22.7%	11.7%	4.9%	1%	29.9%

During the mix design support stage, the only test performed was the HWT to obtain the rut depth. Both sections 1 and 2 passed the minimum criteria for rutting, as Figure 19 depicts. The control section CPR values are all well below the 0.45 limit as presented in Figure 20. However, Section 2 shows that the production results from the sublots are over the threshold value. The core values were too thin to test for cracking. Figure 21 shows that the CFE values were reasonable across all stages of the mix verification. In the case of the indirect tensile strength section 1 had low values for mix design verification compared to the production stage (See Figure 22). The results of the overlay interaction plot and the mix design interaction plot both show the stages that do not pass or marginal in terms of the CPR (See Figures 23 and 24).

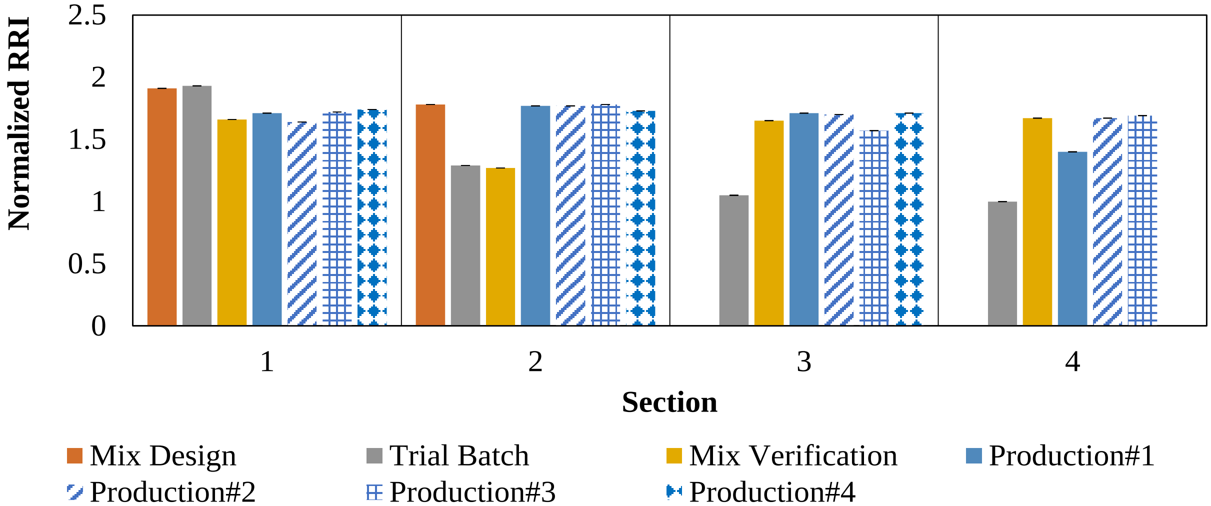


Figure 19 – Summary of HWT Results for the Mix Verification Stages for Project No 4

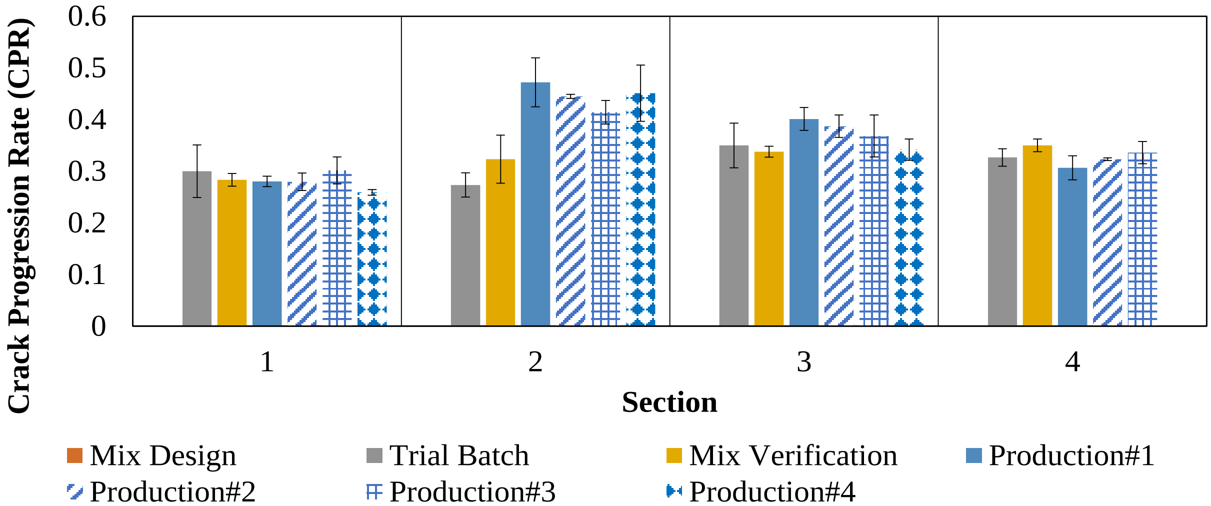


Figure 20 – Summary of CPR Results for the Mix Verification Stages for Project No 4

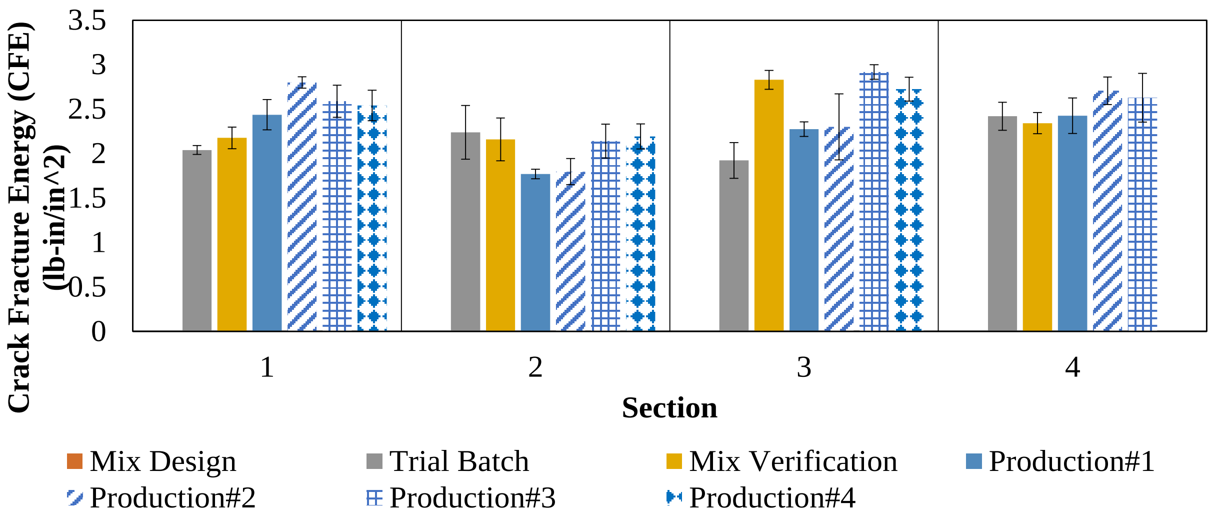


Figure 21 – Summary of CFE Results for the Mix Verification Stages for Project No 4

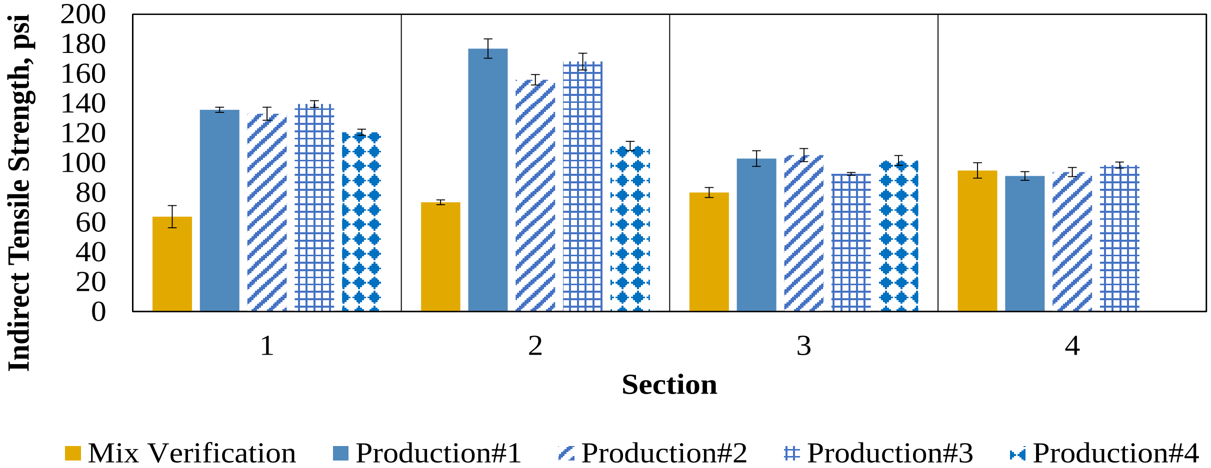


Figure 22 – Summary of Indirect Tensile Strength Results for the Mix Verification Stages for Project No 4

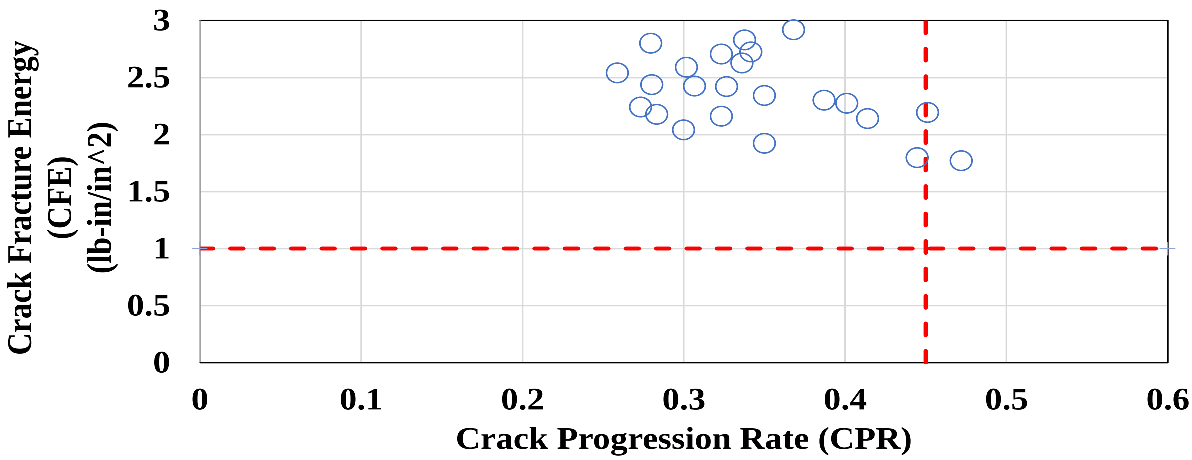


Figure 23 – OT Interaction Plot for the Mix Verification Stages for Project No 4

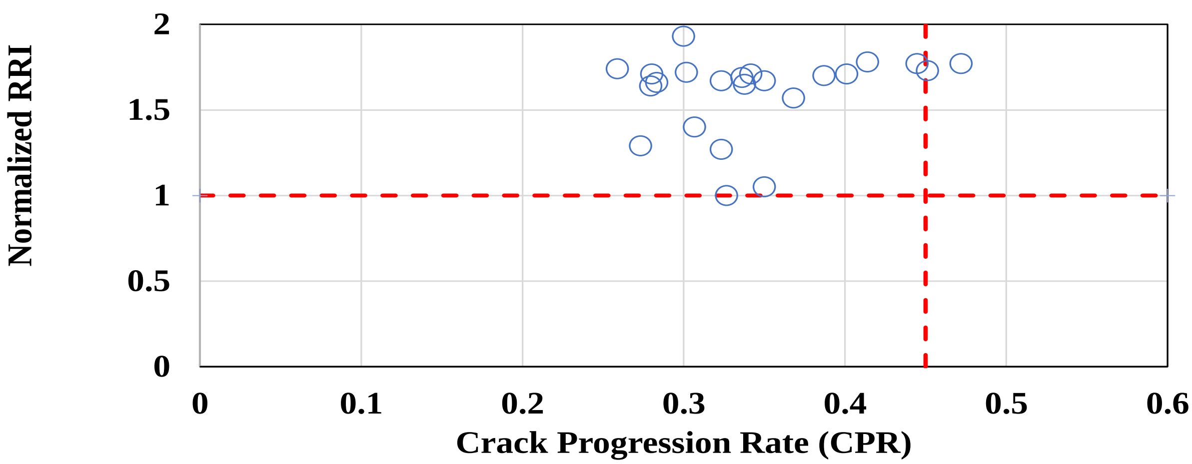


Figure 24 – Mix Design Interaction Plot for the Mix Verification Stages for Project No 4

Project No 5 - Paris District

The Paris field project included four sections with variation in mixes and gradation, Tables 10 and 11 below contain the details for each of the sections.

Table 10 – Project No 5 Mix Design Summary

Section ID	Spec	RAP (RBR)	Additive	OAC
Section 1 Control SP-C	344	20%	0.4% Evotherm	5.3%
Section 2 Coarse Graded SP-C	3074	30%	0.4% Evotherm	5.9%
Section 3 Fine Graded SP-C	3074	20%	0.4% Evotherm	5.4%
Section 4 Dense Graded	344/3076	15%	0.4% Evotherm	4.7%

Table 11 – Project No 5 Mix Design Gradation

Section ID	Sandstone C-rock	Sandstone D-rock	Gravel F-rock	Sandstone Man Sand	Armco Sand	Dry Screenings	RAP
Section 1 Control SP-C	17%	29%	9%	9%	8%	8%	19.8%
Section 2 Coarse Graded SP-C	17%	30%	10%	7%	-	6%	29.6%
Section 3 Fine Graded SP-C	10%	27%	13%	10%	8%	12%	19.8%
Section 4 Dense Graded	20%	30%	10%	-	10%	15%	15%

For Field Project No 5 the rutting results were passing and consistent across the mix verification stages as presented in Figure 25. However, the OT show that several results of the production stage were failing the crack propagation rate (See Figure 26). This was especially the case for Sections 3 and 4. Additionally, the CFE value for Section 2 was much higher than typical and that shows potential brittleness of the mix as shown in Figure 27. Figure 28 shows the indirect tensile strength results. In many cases the results are around 150 psi except for one sublot in each of sections 2, 3 and 4 where the results were marginal. Figures 29 and 30 reflect the results from the previous figures showing how several of the test section will fail in terms of cracking. The is based on the CPR values well exceeding the marginal limit of 0.45.

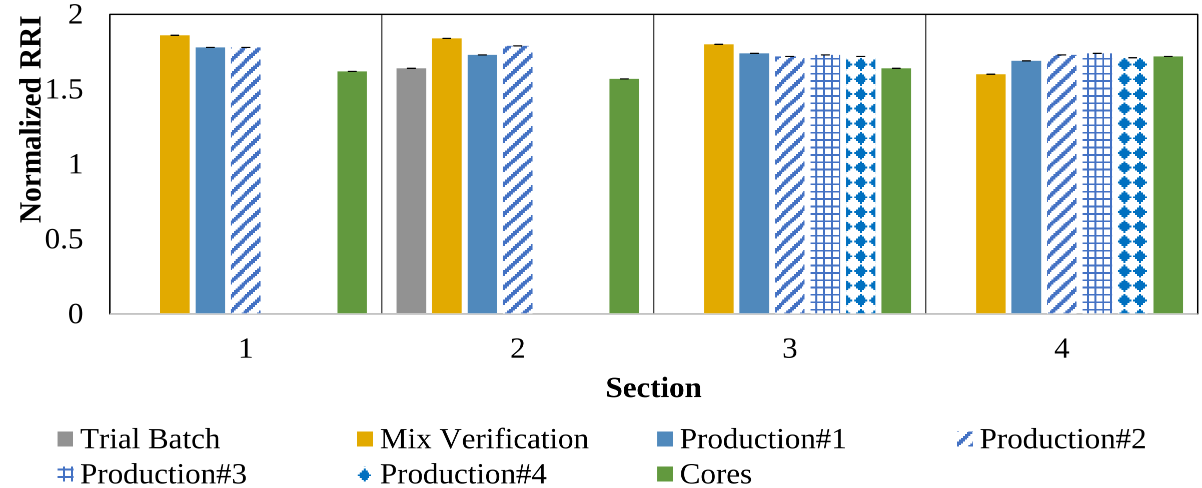


Figure 25 – Summary of NRRI Results for the Mix Verification Stages for Project No 5

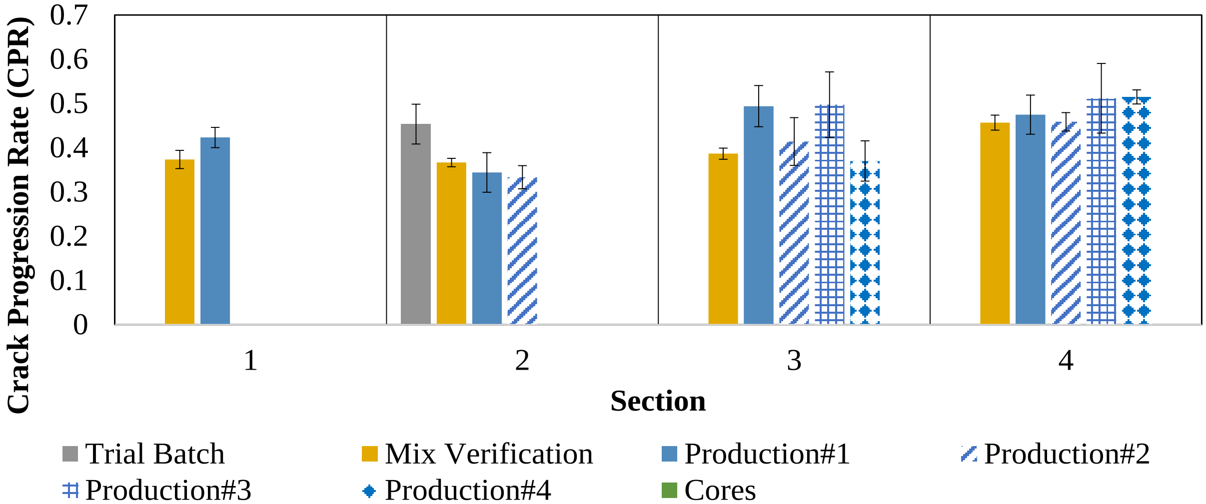


Figure 26 – Summary of CPR Results for the Mix Verification Stages for Project No 5

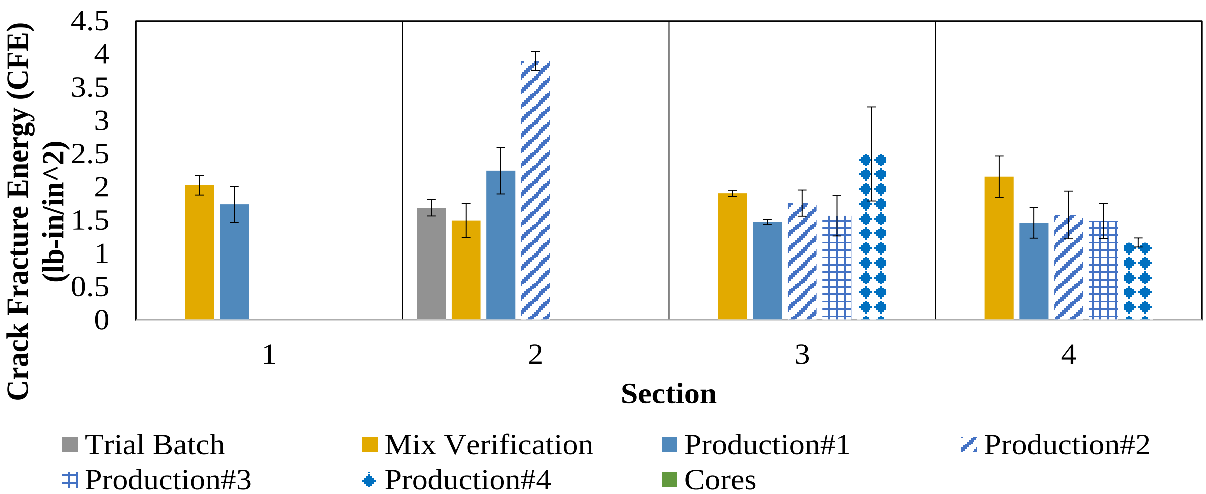


Figure 27 – Summary of CFE Results for the Mix Verification Stages for Project No 5

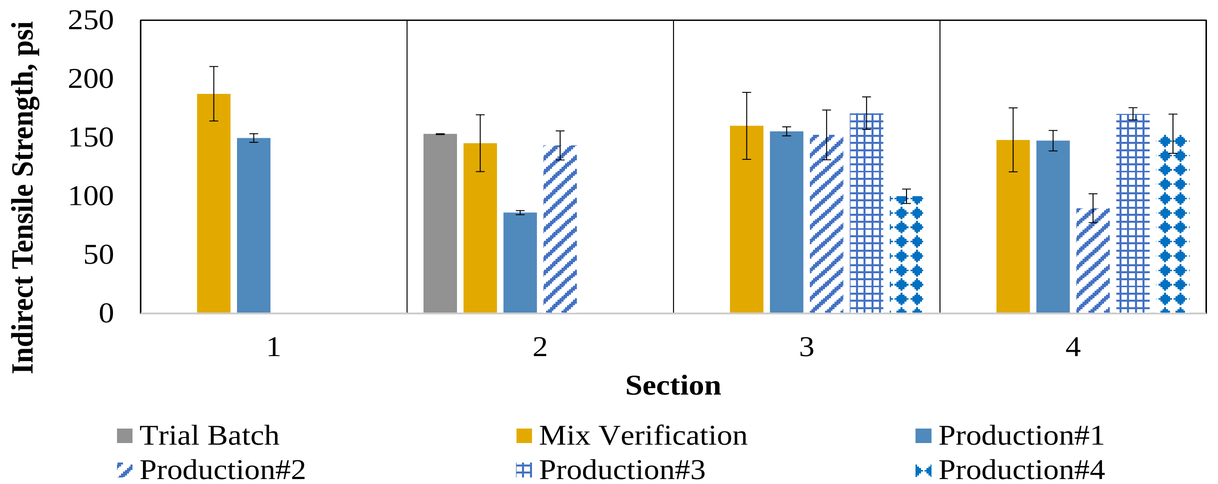


Figure 28 – Summary of Indirect Tensile Strength Results for the Mix Verification Stages for Project No 5

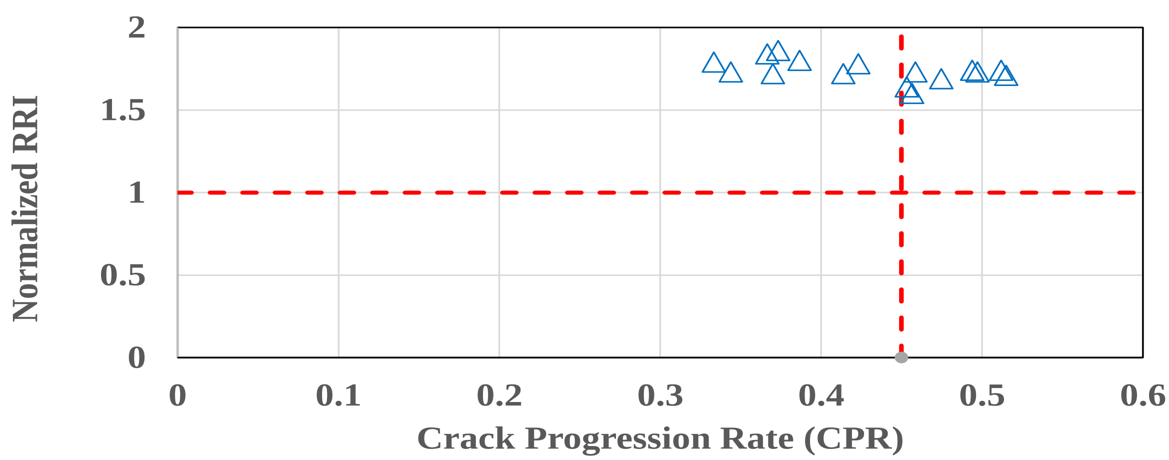


Figure 29 – OT Interaction Plot for the Mix Verification Stages for Project No 5

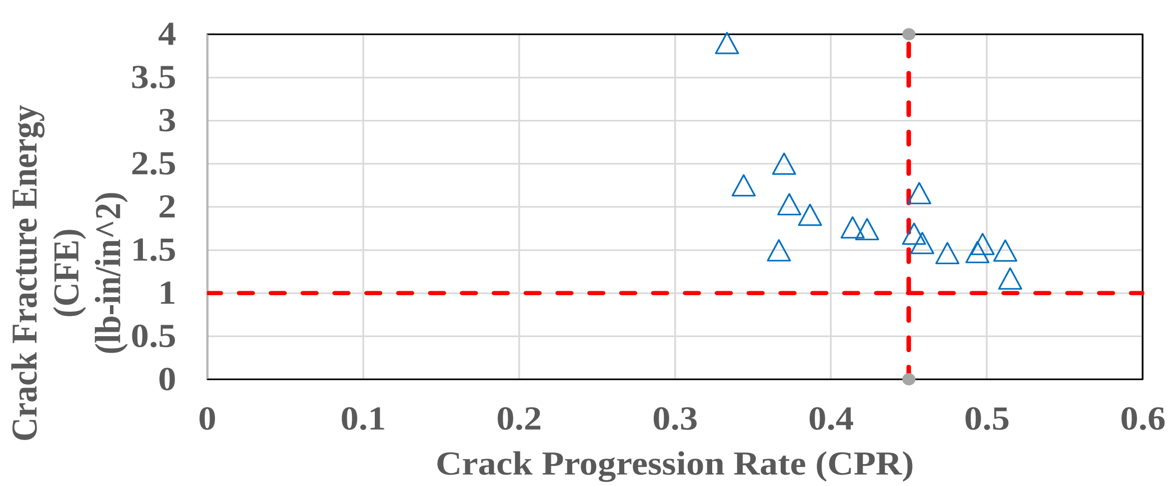


Figure 30 – Mix Design Interaction Plot for the Mix Verification Stages for Project No 5

Project No 6 - Atlanta District

The Atlanta field project was constructed in November 2020. It was composed of four sections with different percentages of RAP, and variation of mix design. The first section was control SMA with no RAP, the second section was BMD SP-C with low RAP, the third section contained higher RAP, and the fourth section contained the highest percentage of RAP. Table 12 summarizes the mix design information for each section, and Table 13 shows the difference in gradation for each of the mixes.

Table 12 – Project No 6 Mix Design Summary

Section ID	**Spec**	**RAP/RAS (RBR)**	**Additive**	**OAC**
1 - Control SMA	346	0%	1% Lime	6.30%
2 - BMD-SP-C	3074	10%		5.40%
3 - BMD-SP-C Lower PG	3074	15%		5.30%
4 - BMD-SP-C High RAP	3074	25%	0.5% Evotherm	5.90%

Table 13 – Project No 6 Mix Design Gradation

Section ID	**Igneous 5/8''**	**Igneous AR1**	**Igneous Screenings**	**Igneous Nepheline Syenite**	**Hydrated Lime**
1 - Control SMA	20%	55%	9%	15%	1%
2 - BMD-SP-C	20%	42%	22%	6%	10%
3 - BMD-SP-C Lower PG	17%	40%	23%	5.1%	15%
4 - BMD-SP-C High RAP	16%	36%	23.1%	-	25%

For Field Project No 6, the rutting results are consistent across all stages of the verification with NRRI values around 1.5. This indicates that all four test sections are not rut susceptible (See Figure 31). Figure 32 presents the results of the CPR with all stages of verifications around 0.35 indicating that the test sections are well behaved in terms of cracking. This is also shown by the CFE values presented in Figure 33. Comparing the test section the CFE values and between 1.5 and 3 with sections 3 and four showing slightly higher CFE values. The indirect tensile strength for all the sections is reasonable as well as presented in Figure 34. The last set of figures for Field Project No 6 recaptures the results in both the OT interaction plot and the mix design interaction plot (See Figures 37 and 38). Both plots show the section are well balanced.

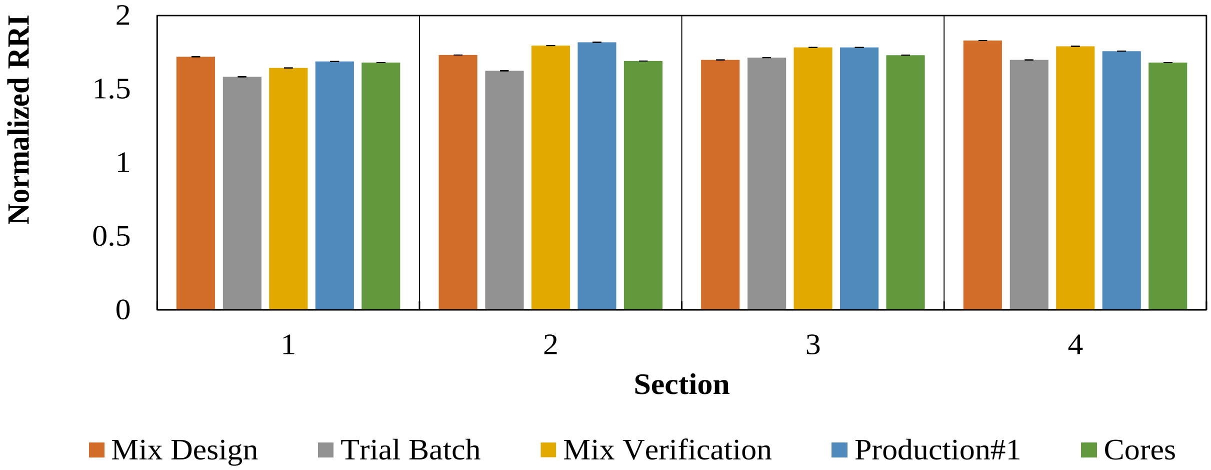


Figure 31 – Summary of NRRI Results for the Mix Verification Stages for Project No 6

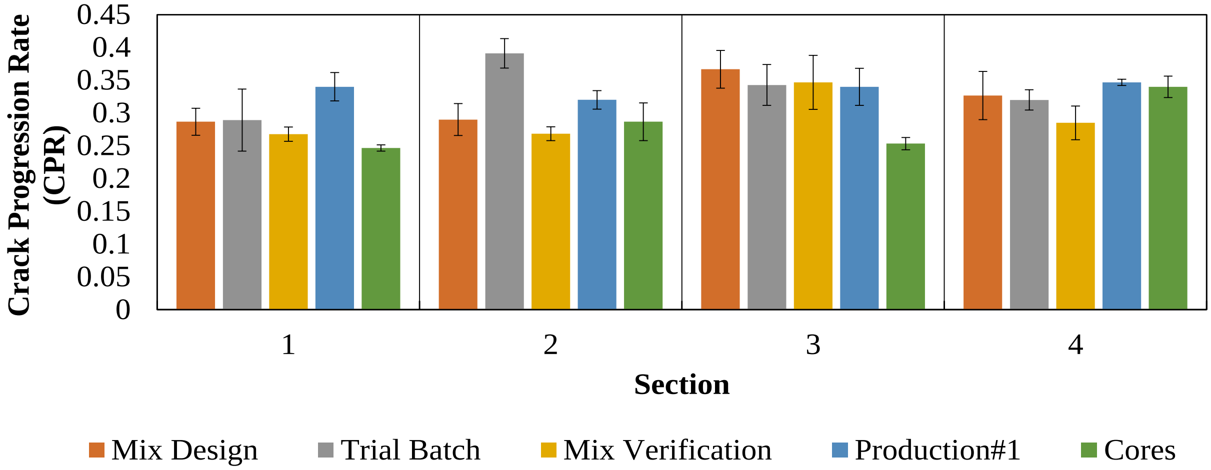


Figure 32 – Summary of CPR Results for the Mix Verification Stages for Project No 6

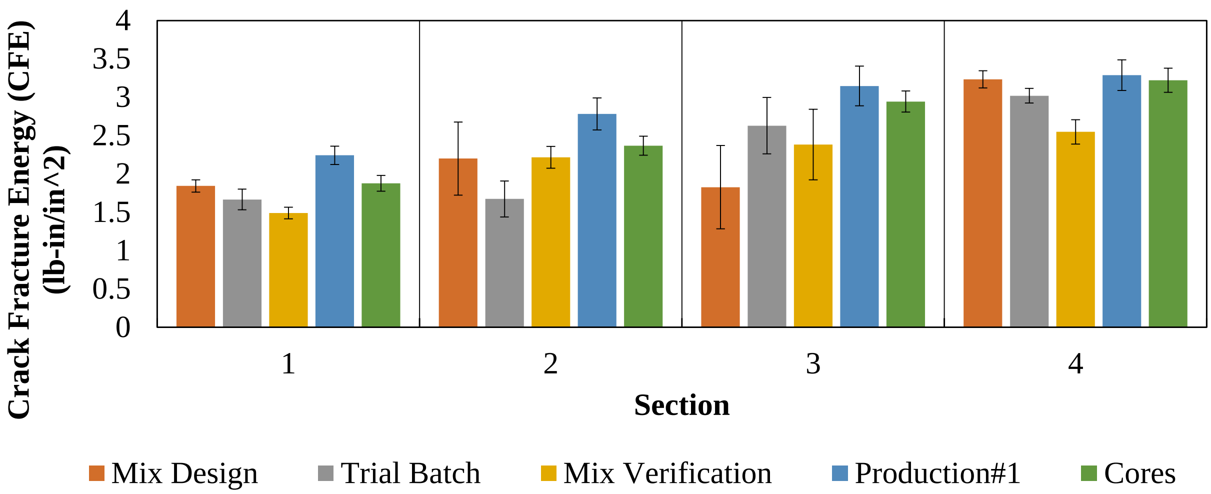


Figure 33 – Summary of CFE Results for the Mix Verification Stages for Project No 6

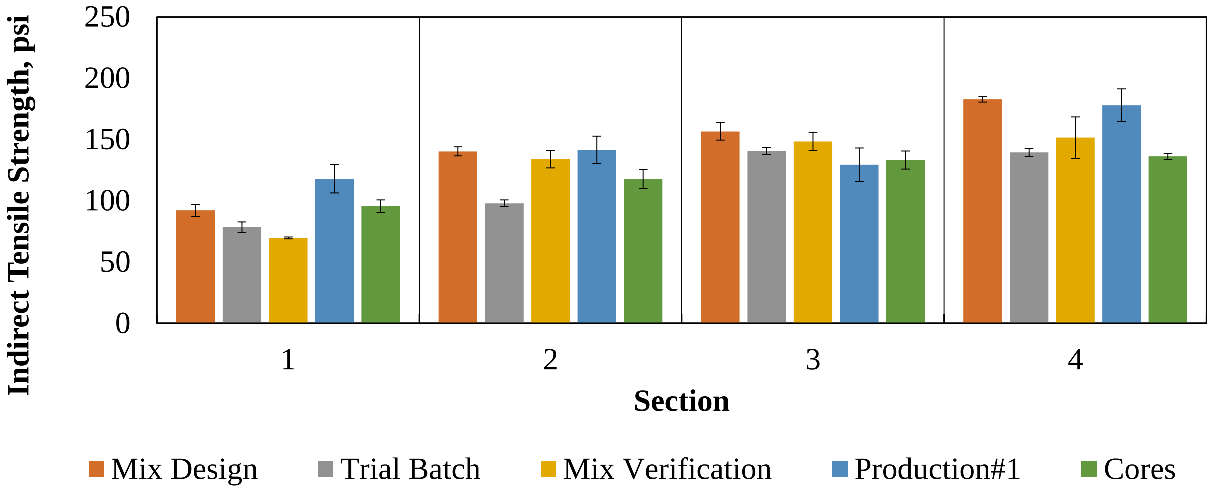


Figure 34 – Summary of Indirect Tensile Strength Results for the Mix Verification Stages for Project No 6

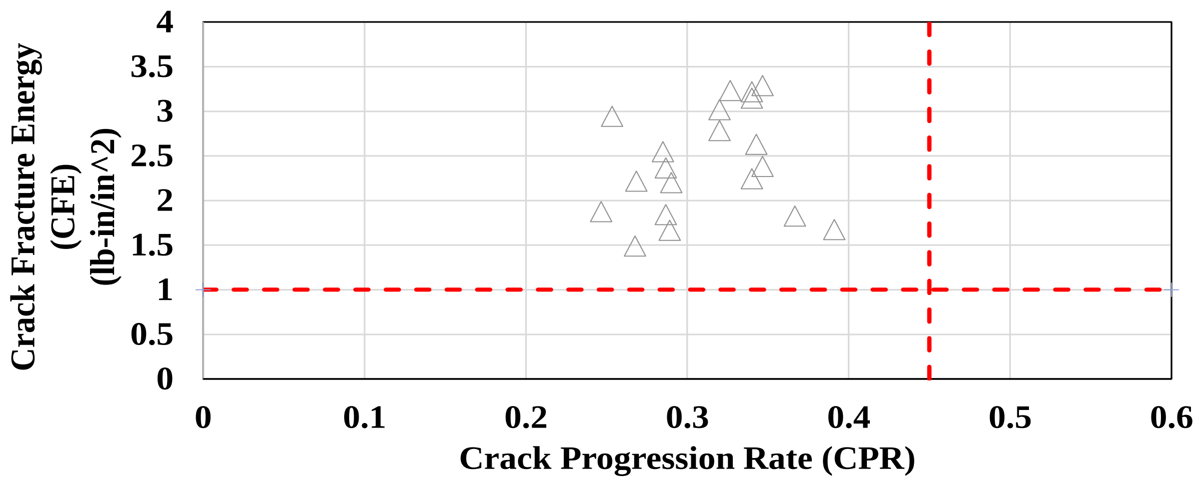


Figure 35 – OT Interaction Plot for the Mix Verification Stages for Project No 6

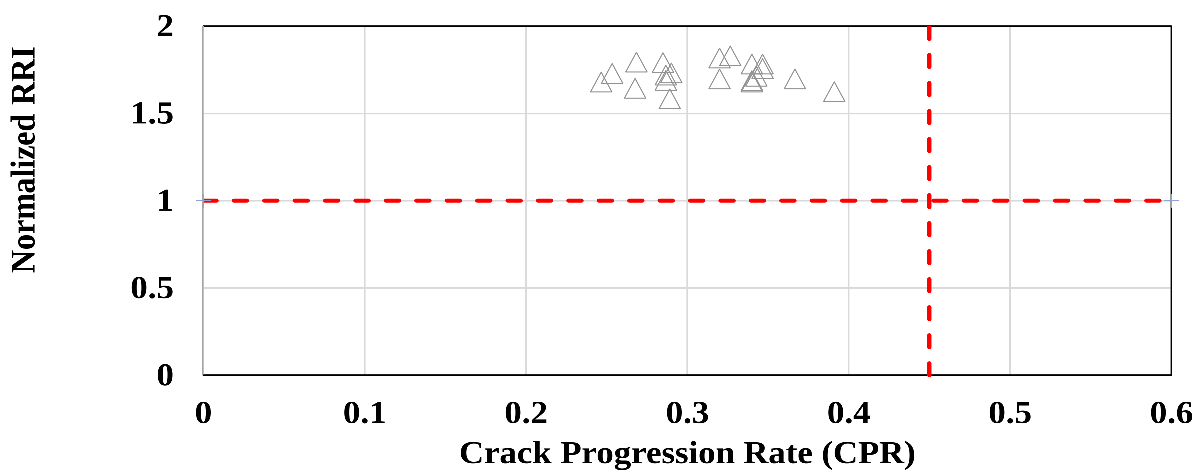


Figure 36 – Mix Design Interaction Plot for the Mix Verification Stages for Project No 6

Project No 7 - Childress District

The Childress field project consisted of three sections with variations in RAP, gradation, and mix designs. Tables 14 and 15 contain the details of all three sections.

Table 14 – Project No 7 Mix Design Summary

Section ID	Spec	RAP (RBR)	Additive	OAC
Section 1 Control DG-D	341	8.5%	0.3% Anti-stripping	5.2%
Section 3 Item 3074-C	3074-C	8.5%	0.3% Anti-stripping	6.1%
Section 7 Item 3074-C	3074	0%	0.3% Anti-stripping	5.6%

Table 15 – Project No 7 Mix Design Gradation

Section ID	Igneous D-rock	Limestone F-rock	Igneous Screenings	Igneous Man sand	SWSS	RAP
Section 1 Control DG-D	31.8%	18%	14.9%	26.2%	1%	8.2%
Section 3 Item 3074-C	35.5%	16.5%	23.5%	10%	6.5%	8%
Section 7 Item 3074-C	38.9%	17.9%	34.4%	2.1%	6.7%	-

During the mix design support, the virgin section showed slightly more rut depth than the RAP sections, as observed in Figure 37. Figures 38 and 39 provide results of the OT. The results in the figures show that all sections met the required CPR criteria of max. 0.45 and the criteria of min. 1.0 for CFE. The Indirect Tensile Strength falls in line with the OT and HWT results. Figure 40 provides the results of the tensile strength. Finally, the interaction plots of OT and mix design are presented in Figures 41 and 42. The figures show all sections for production evaluation, trial batch evaluation, lab mix evaluation, and mix design support were balanced.

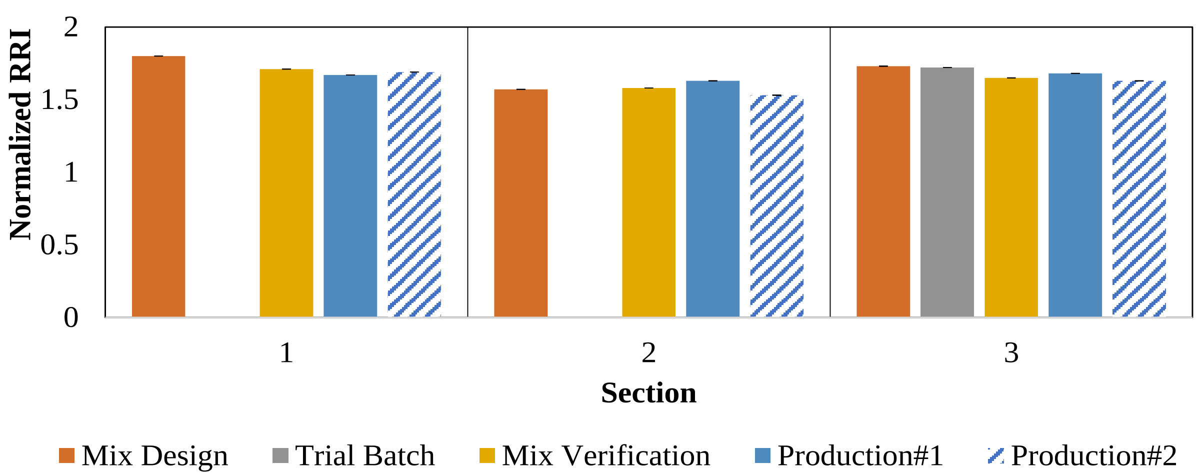


Figure 37 – Summary of NRRI Results for the Mix Verification Stages for Project No 7

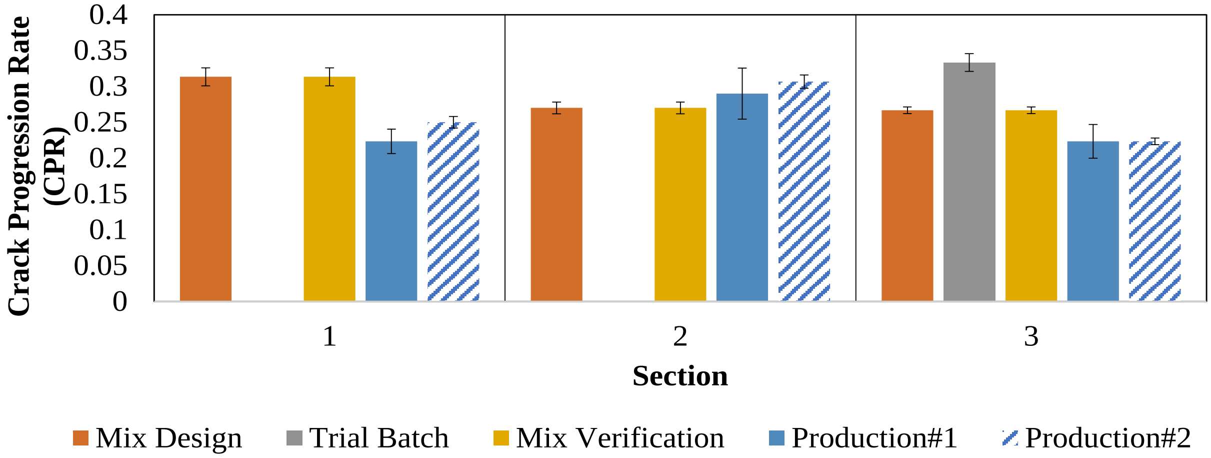


Figure 38 – Summary of CPR Results for the Mix Verification Stages for Project No 7

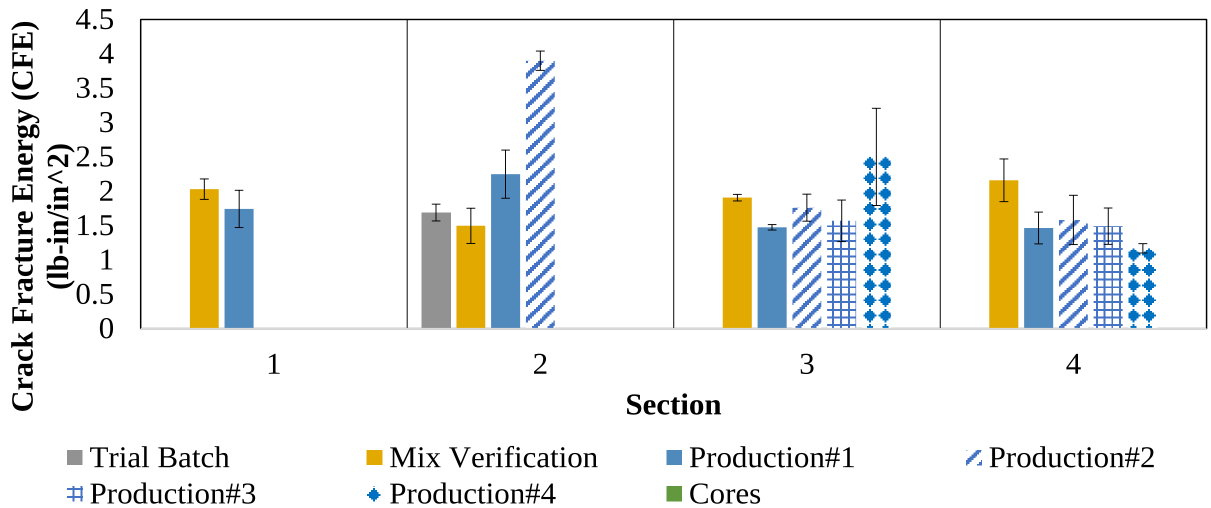


Figure 39 – Summary of CFE Results for the Mix Verification Stages for Project No 7

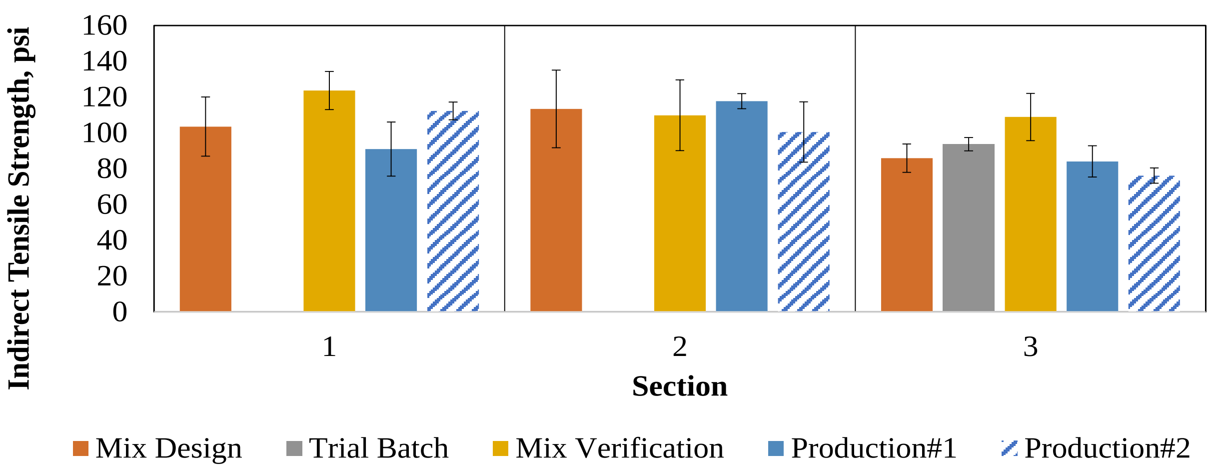


Figure 40 – Summary of Indirect Tensile Strength Results for the Mix Verification Stages for Project No 7

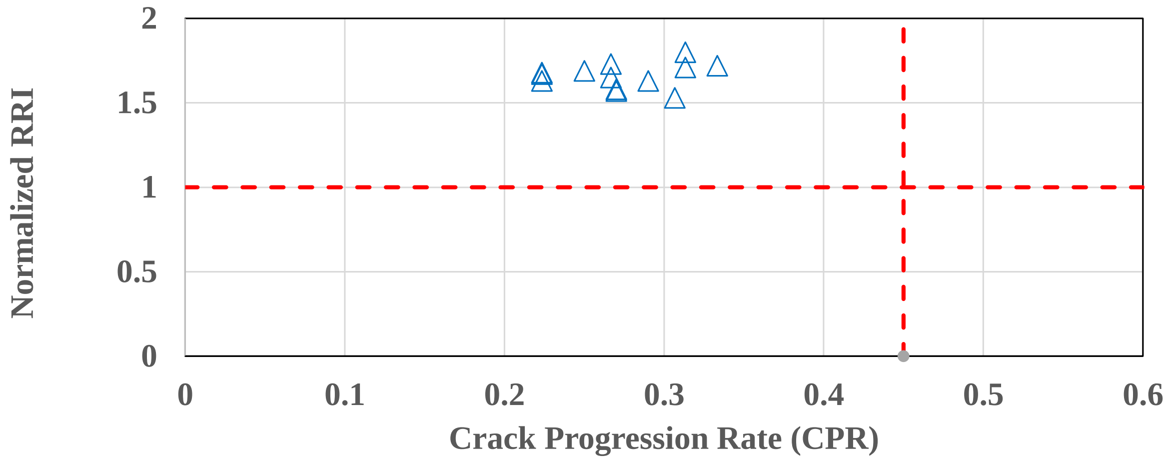


Figure 41 – OT Interaction Plot for the Mix Verification Stages for Project No 7

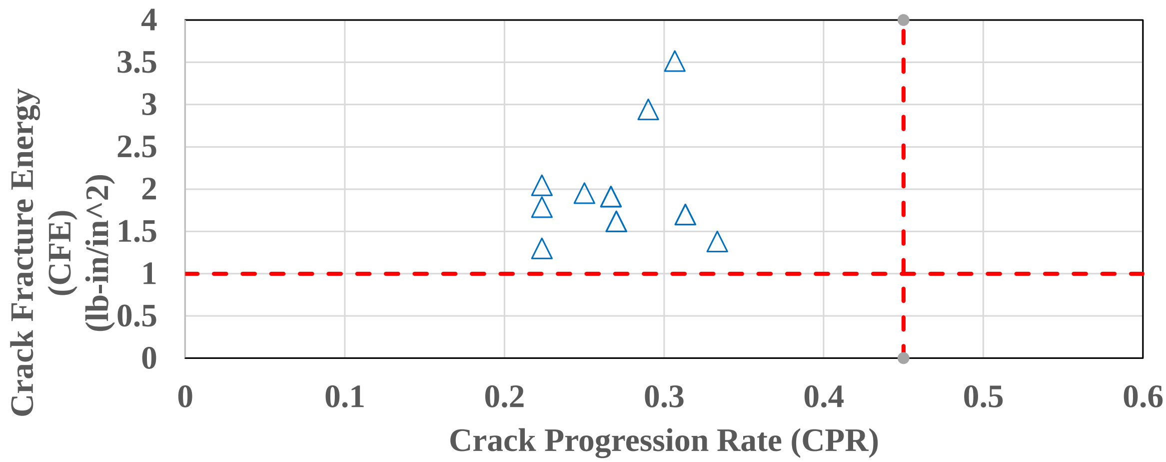


Figure 42 – Mix Design Interaction Plot for the Mix Verification Stages for Project No 7

Appendix E - Development of HMA Gradation Design Tool

Traditionally the selection of the aggregate gradation for an HMA mix is based on a trial-and-error process carried out until all the necessary volumetric design parameters are met satisfactorily. To reduce the trial-and-error process and to optimize the quantities of the aggregate bins to reach the desired aggregate gradation, an online web-based HMA gradation design tool was developed. This tool incorporates the gradation parameters and optimization options, onto the existing mix design sheet from TxDOT Site manager templates (Tx2MixDe14).

The tool is developed on Laravel©, an open-source web framework, intended for the development of web applications. The general program description along with the modules have been discussed at length in the following sections and the step-by-step instructions to use the program along with an example of a mix design optimization is given in Appendix E-2.

DESCRIPTION OF PROGRAM MODULES

The HMA gradation design tool is a single platform that can be used by the mix design engineers/technicians to design the aggregate gradations and the DOTs for approval. As shown in Figure 1, the tool contains two basic modules for Design and Approval.

a) Design Module **b) Approval Module**

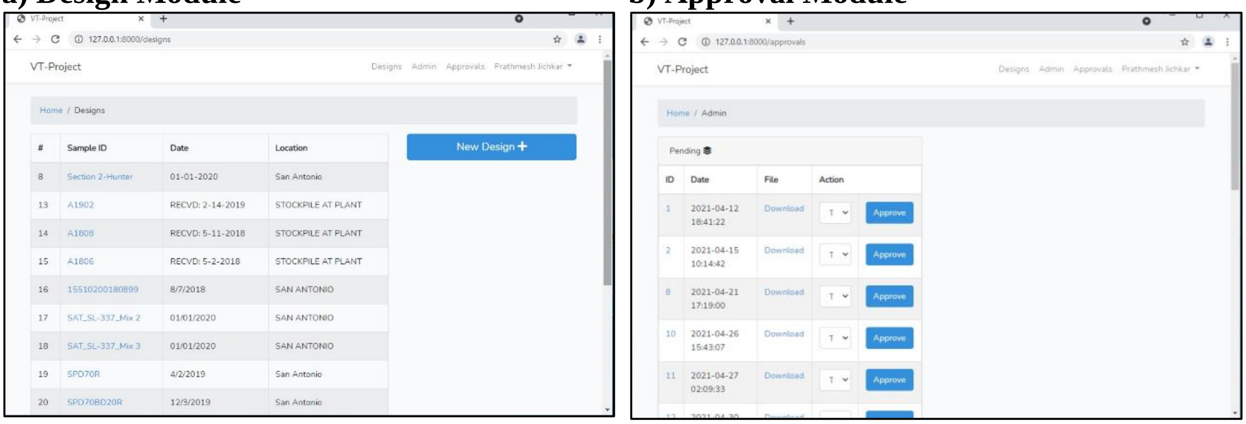


Figure 1 Program modules

Design Module

The design module is the first step of the process after logging into the program. Figure 2 shows the typical screen that the designer can see to create/ upload an existing mix design sheet.

The designer can download a template of the TxDOT mix design sheet from the 'sample_file.xlsm' as seen under the 'Guidelines' section. Once the necessary design sheet is uploaded, the design tab shows the uploaded design along with the date of the design and the project location.

Figure 3 shows the general screen once the uploaded design is selected for optimization. The following steps are carried out to optimize any given gradation:

1) *Mix Information*: In the top left corner panel, the mix information such as the Mix ID, design engineer, date of the design, project location, and most importantly the type of mix is automatically picked up based on the uploaded design sheet.

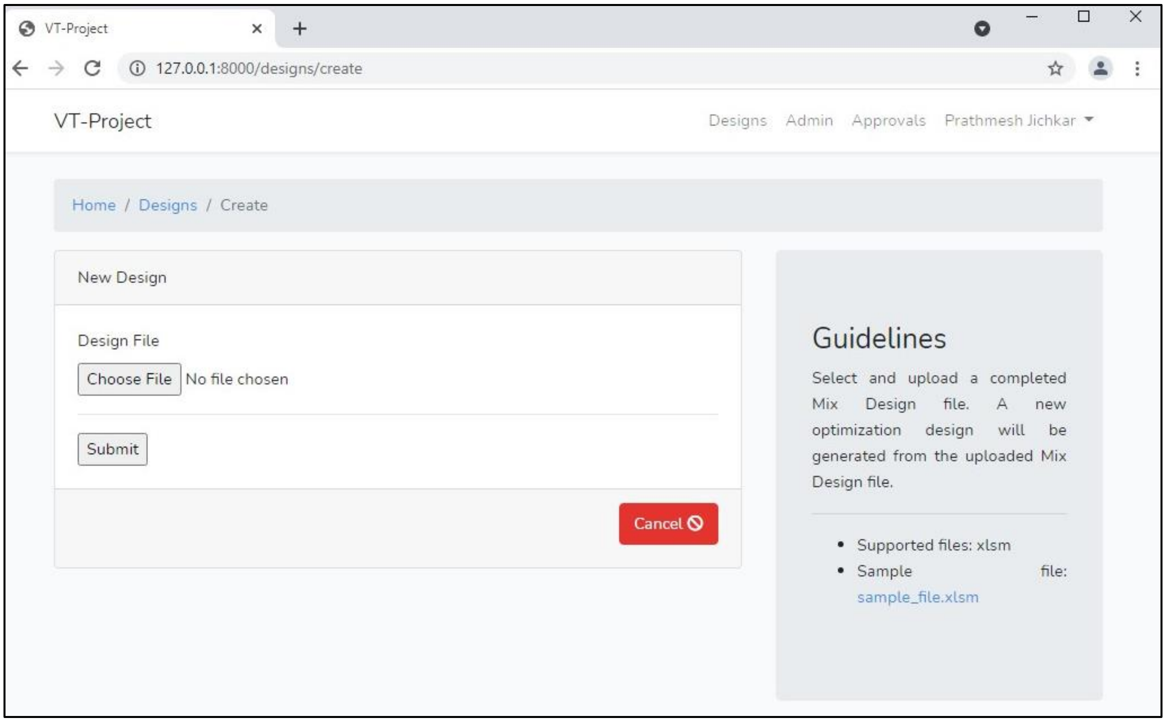


Figure 2 Creating a new design for optimization using TxDOT design template

2) *Bin Percentages and combined gradation*: From the uploaded Excel© design sheet, all the aggregate bins, their corresponding % of the mix (Section B in Figure 3), and individual bin gradations are obtained as shown in Figure 3. The bins that are not to be included as a part of the optimization process should be check marked.
3) *Interactive Gradation Plot:* The tool projects the appropriate gradation limits based on the mix type, while the maximum density line (MDL) is defined based on the NMAS of the mix. The original design is the design that is uploaded in the mix design sheet. The target design can be adjusted manually by moving the control points on the plot or entering the desired % passing (Section A in Figure 3).
4) *Gradation Parameters and Control Points:* Based on the specified NMAS, PCS, half sieve (HS), secondary control sieve (SCS), and tertiary control sieve (TCS) are selected and the subsequent percent passing of materials associated with those control points are computed based on the target gradation. Corresponding parameters such as CA, FA_c, FA_f, and PCSI are calculated and can be varied to fit into their desired ranges.
5) *Optimizing Aggregate Gradation:* The least-square optimization technique, as discussed in the next section, is then used to estimate the optimized gradation. The target aggregate gradation based on the customized curve is used to optimize the proportion of aggregates from each bin and to formulate the actual aggregate gradation for the designer (Section C in Figure 3). Once the optimization is complete the final gradation parameters can be documented and the optimized gradation can be downloaded into the TxDOT mix design format to work out the job mix formula (JMF).

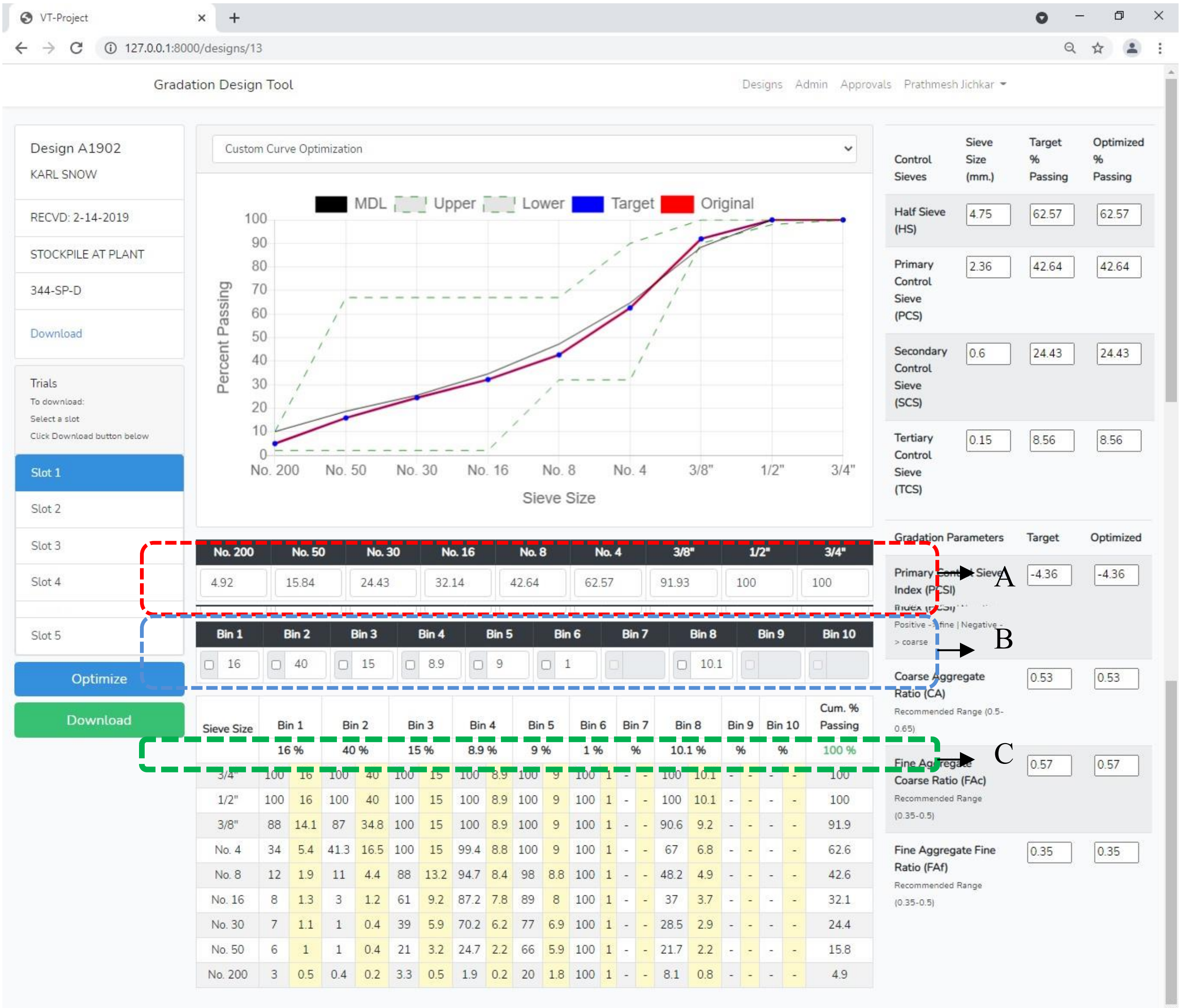


Figure 3: Gradation design program with uploaded mix design to be optimized

Approvals Module

Once the designer finalizes the design, it can be submitted for approval of the designed mix. This step will help monitor the status of the approved mixes and the ones that are pending to be reviewed.

OPTIMIZATION OPTIONS

To match the desired combined aggregate gradation blend to the target gradation, the least square error criterion was used in the optimization program. While using this method, each sieve is compared for the least squared error between the desired and target gradation and the overall aggregate blend. The least-squares method finds the optimal parameter values by minimizing the sum, S, of squared residuals using

$$r_i = y_i - f(x_i, \beta) \quad \text{(XII)}$$

$$S = \sum_{i=1}^{n} r^2{}_i \quad \text{(XIII)}$$

Although the bin percentages of the desired gradation are obtained based on the regression function, the various options for deciding on the target gradation is provided below:

Once the optimization function is carried out, the revised bin percentages of the desired/target gradation are obtained based on the regression function discussed above. To decide on the target gradation, the designers can either use their experienced judgment (working with the aggregates and gradations used in the location) to decide on a custom gradation curve; or else carefully selecting the following gradation parameters ensuing the recommended values for each based on previous research projects:

1) *Bailey Method Ratios*
   - Coarse Aggregate Ratio (CA)
   - Fine aggregate coarse ratio (FA_c)
   - Fine aggregate fine ratio (FA_f)
2) *Primary Control Sieve Index*

The gradation parameters can act as design variables, corresponding to different portions of the gradation curve (coarse, fine, separation) and help the designer to choose which portion of the curve they want to modify in order to alter the volumetric properties of the mixes. Once the optimization is carried out, the new downloaded design sheet can be used for further evaluation of volumetric and mechanical properties.

Implementation of Gradation Tool

This chapter presents the various asphalt mixes studied across Texas, as a part of this study to implement the gradation tool. Mostly Superpave C (SP-C) and Superpave D (SP-D) mixes were used, alongside an SMA and a dense-graded traditional mixture as control mix. This section aimed to check the current mix design approaches followed in Texas by adjusting % RAP, aggregate gradations, PG of Binder, Asphalt content, etc., and studying the corresponding gradation properties. For each of the test projects under consideration, multiple mixes were evaluated varying the above-mentioned parameters individually or in combination. Each section mix was evaluated for its volumetric properties and mechanical properties as per the methodology suggested in the next section.

CASE STUDIES

Test Project 1

This test project evaluation involves three mixes all designed with Superpave D TxDOT mix design specification. The binder type, RAP, and RAS percentages along with the type of aggregate are summarized in Table 1.

Table 1 Summary of design information and material characteristics - Test section 1

Parameters		Mix 1	Mix 2	Mix 3
Design Information	NMAS		9.5 mm (3/8")- SP-D	
	Specified Binder PG	PG 76-22	PG 76-22	PG 70-22
	Number of Gyrations		50	
	Target Density, %		96	
	Aggregates Types		Sandstone, Gravel	
	RAP, %	10.0	-	11.0
	RAP asphalt content, %	4.5	-	4.5
	RAS, %	-	-	3.0
	RAS asphalt content, %	-	-	17.0

The major changes in the mixes are the percent of RAP/RAS along with the change in the binder grade (binder grade dumping) for Mix 3 to incorporate more recycled materials.

The bin-wise aggregate distributions of the various aggregate fractions along with the combined gradations of the different mixes are provided in Appendix E-1. From the plot of the combined gradation in Figure 4, all three mixes had more or less the same gradation, despite the varying RAP/ RAS contents. The gradation parameters, as well as the mix volumetric properties, are summarized in Table 2. The red cells correspond to the gradation parameters that are outside the suggested specified ranges. The CA ratios are almost close to the upper range of 0.55 for all mixes. The coarse fraction of the fine gradation (FA_c) parameters and the fine fraction of the fine gradation (FA_f) parameters are greater than the desired upper threshold of 0.50, and less than or equal to the desired lower limit of 0.35 respectively, making the gradation close to the MDL towards the fines portion of the blend. The PCSI values for these three mixes are almost the same as they all had similar PCS (2.36 mm sieve).

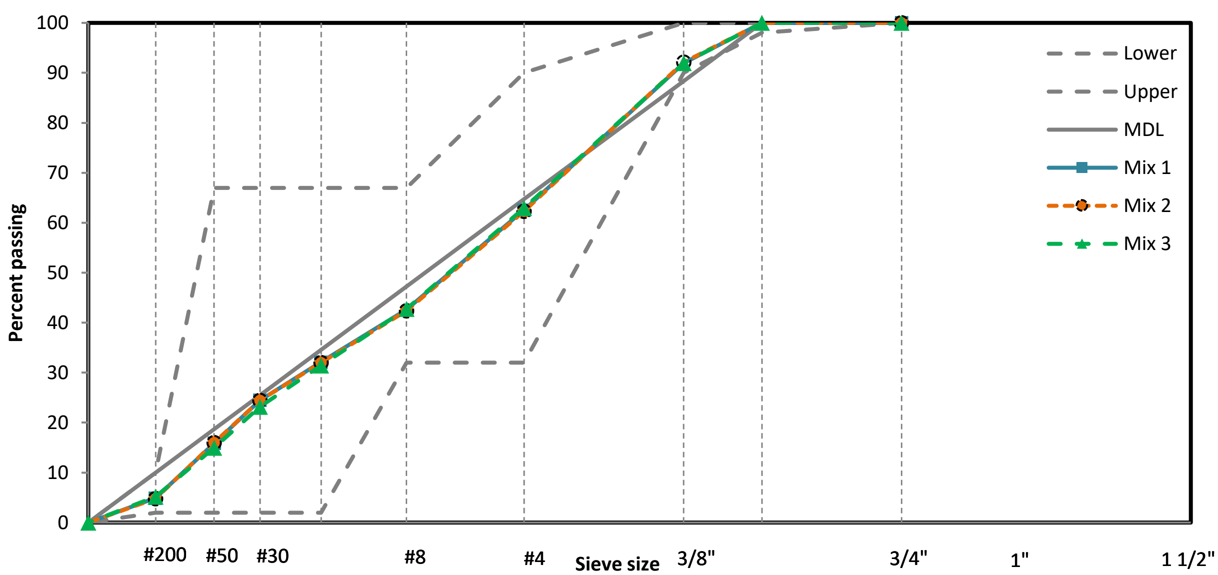


Figure 4 Particle size distribution of test section 1 mixtures

The mechanical properties, in terms of OT, HWT, and IDT tests, are summarized in Table 3. For better visualization of the results towards the balanced mix design approach, Figure 5 depicts the performance interaction diagram. All three mixes are balanced in both rutting and cracking. The three mixes have similar cracking resistance with a slightly higher value for Mix 3 due to the highest % RAP and RAS. All mixes have similar rutting resistance as, when the quantity of recycled materials is increased, a softer binder grade is used. Hence with similar PCSI values, analogous rutting and cracking performance are observed.

Table 2: Summary of gradation parameters and volumetric properties - Test section 1

Parameters		Mix 1	Mix 2	Mix 3
Gradation Parameters	Coarse Aggregate Ratio (CA)	0.53	0.53	0.54
	Fine aggregate coarse ratio (FA_c)	0.57	0.58	0.57
	Fine aggregate fine ratio (FA_f)	0.35	0.35	0.34
	PCS (Primary Control Sieve)	2.36	2.36	2.36
	Primary Control Sieve Index (PCSI)	-4.4	-4.6	-4.2
Volumetric Properties	Optimum Asphalt Content, % (OAC)	5.5	5.6	5.5
	Voids in Mineral Aggregates, % (VMA)	17.0	17.0	17.2
	Bulk Specific Gravity (G_{mb})	2.288	2.274	2.282
	Maximum Specific Gravity (G_{mm})	2.400	2.387	2.404
	Recycled Binder Ratio, % (RBR)	8.2	0	18.3

Table 3: Summary of performance test results for test section 1 mixtures

Parameters			Mix 1	Mix 2	Mix 3
OT	**CPR**	Avg.	0.30	0.30	0.33
		COV	2%	3%	3%
	CFE	Avg.	2.76	3.17	2.97
		COV	5%	3%	15%
HWT	**Rut Depth (mm)**	Rut Depth (mm)	1.7	3.2	3.2
	RRI	RRI	18,638	17,457	17,520
	NRRI	NRRI	1.8	1.7	1.7
IDT	**IDT Strength**	Avg.	168.6	172.4	173.7
		COV	3%	7%	3%
	CT Index	Avg.	84.7	106.8	37.2
		COV	17%	29%	22%

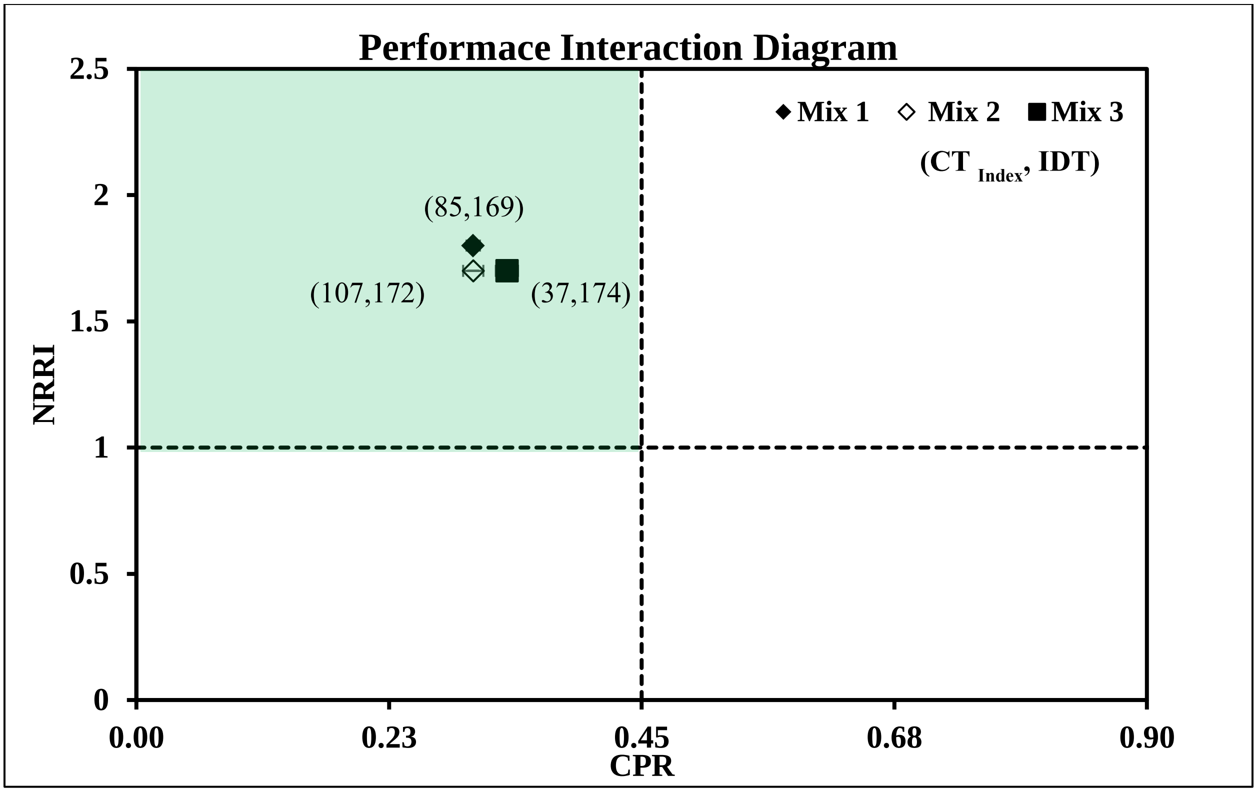


Figure 5: Performance interaction diagram for test section 1 mixtures

Test Project 2

This project involves three mixes, where the Control Mix (Mix 1) is a dense-graded mix and the other mixes being Superpave C mixes. The Binder type, number of gyrations, RAP percentage, and the type of aggregate is summarized in Table 4. The major change in the mixes is the change of % RAP in the three mixes. The numbers of gyration were increased in Mix 2 and 3 to include more binder into the mix to achieve the same density levels. The aggregates used for this project are all SAC-B aggregates.

The bin-wise aggregate distributions of the various aggregate fractions along with the combined gradations of the different mixes are provided in Appendix E-1. As shown in Figure 6, all three mixes were designed as course mixes, with almost similar coarse fractions but different fine fractions while incorporating higher % RAP. The gradation parameters, as well as the mix volumetric properties, are summarized in Table 5. The CA parameters were designed above the desired upper threshold of 0.65 for the three mixes, whereas the FA_f parameters were above or equal to the desired upper limit of 0.5. The PCSI values of the three mixes were increased, by increasing the % passing at the primary control sieve, shifting the mixes further away from the MDL to add more binder in the mix.

Table 4 Summary of design information and material characteristics- Test section 2

Parameters		Mix 1	Mix 2	Mix 3
Design Information	NMAS	12.5 mm (1/2") – DG-C and SP-C		
	Specified Binder PG	PG 70-22		
	Number of Gyrations	35	50	50
	Target Density, %	96		
	Aggregates Types	Igneous; Limestone-Dolomite		
	RAP, %	14.8	-	25.2
	RAP asphalt content, %	6.0	-	6.0

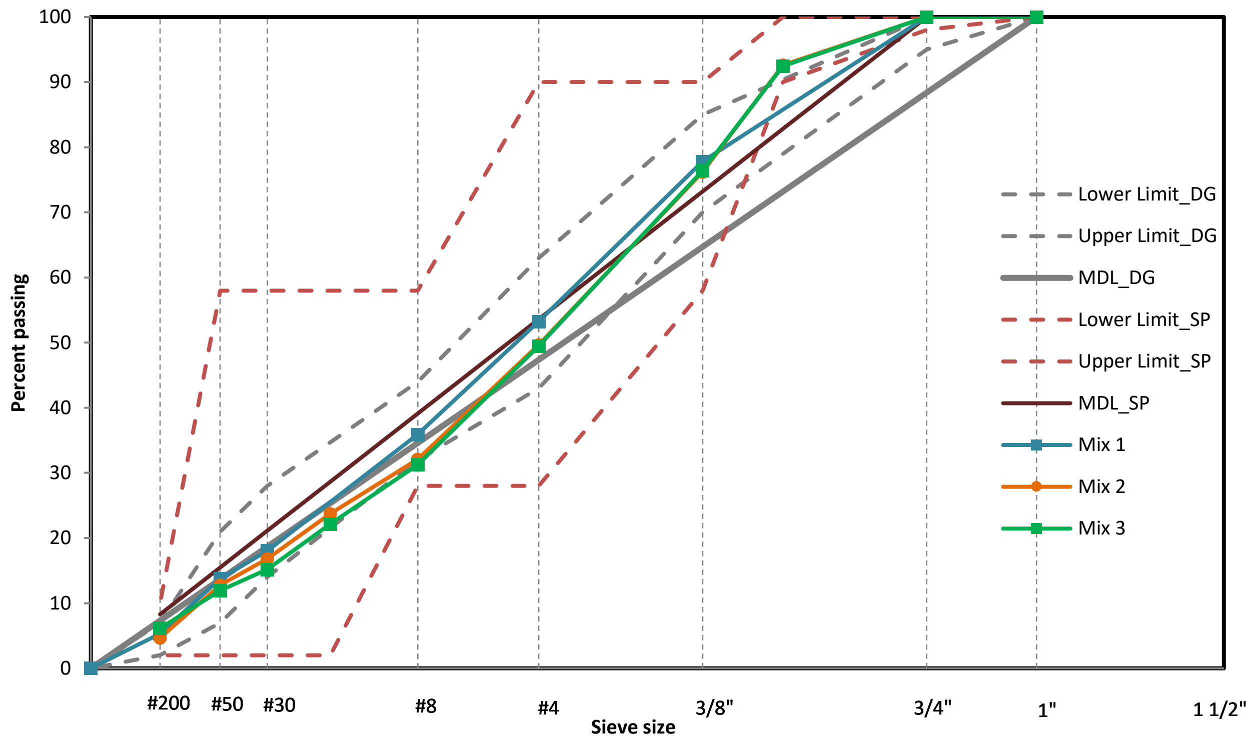


Figure 6 Particle size distribution of test section 2 mixtures

Table 5: Summary of gradation parameters and volumetric properties for test section 2

Parameters		Mix 1	Mix 2	Mix 3
Gradation Parameters	Coarse Aggregate Ratio (CA)	0.67	0.64	0.66
	Fine aggregate coarse ratio (FA_c)	0.50	0.52	0.49
	Fine aggregate fine ratio (FA_f)	0.45	0.44	0.53
	PCS (Primary Control Sieve)	2.36	2.36	2.36
	Primary Control Sieve Index (PCSI)	-3.1	-6.9	-7.7
Volumetric Properties	Optimum Asphalt Content, % (OAC)	5.2	5.7	5.4
	Voids in Mineral Aggregates, % (VMA)	16.0	17.3	16.7
	Bulk Specific Gravity (G_{mb})	2.397	2.406	2.420
	Maximum Specific Gravity (G_{mm})	2.495	2.504	2.521
	Recycled Binder Ratio, % (RBR)	17.9	0	28.0

The mechanical properties of the mixes are summarized in Table 6 and Figure 7. Mixes 2 and 3 are balanced in both rutting and cracking. The three mixes exhibited different cracking resistance with Mix 1 (the failing mix) being the one closest to the maximum density line with the least asphalt content and lowest absolute PCSI value.

Table 6: Summary of performance test results for test Section 2 mixtures

Parameters			Mix 1	Mix 2	Mix 3
OT	CPR	Avg.	0.53	0.32	0.38
		COV	23%	13%	5%
	CFE	Avg.	2.2	2.0	3.2
		COV	19%	16%	7%
HWT	Rut Depth (mm)	Rut Depth (mm)	5.29	11.89	6.96
	RRI	RRI	15835	10638	14520
	NRRI	NRRI	2.08	1.40	1.91
IDT	IDT Strength	Avg.	162.2	106.5	147.7
		COV	4%	14%	4%
	CT Index	Avg.	45.4	230.4	75.4
		COV	23%	22%	12%

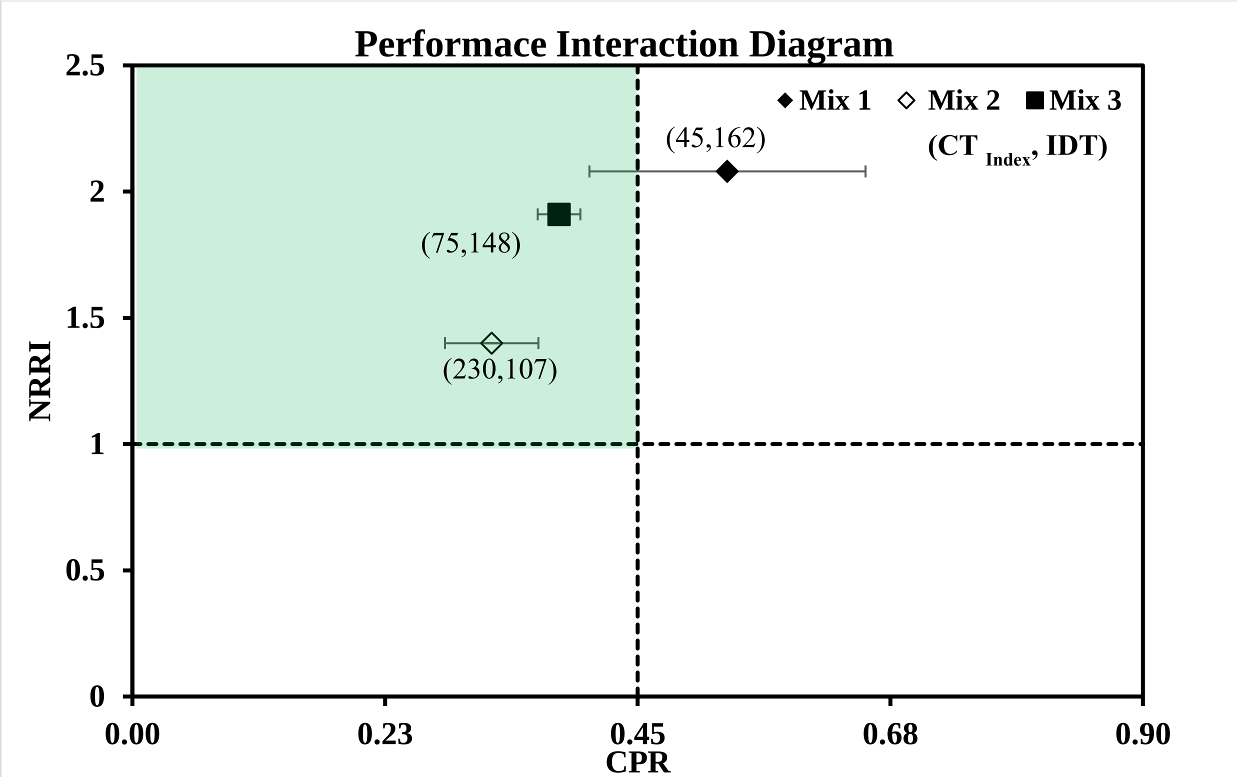


Figure 7 Performance interaction diagram for test section 2 mixtures

Test Project 3

In this project, three Superpave D mixes as per TxDOT mix design specification were evaluated. The binder type, RAP percentages, number of gyrations, type of aggregates, and type and amount of additive are summarized in Table 7. The major difference among the mixes is the change of RAP content. Different WMA additives and rejuvenators (WMA_1 and Rej_1) in varying quantities were used as a part of the mix design.

The bin-wise aggregate distributions of the various aggregate fractions along with the combined gradations of different mixes are provided in Appendix E-1. From the combined gradations in Figure 8, the first two mixes were designed as course mixes, with totally distinct coarse and fine fractions, whereas Mix 3 was designed to have similar gradation as Mix 2.

The gradation parameters, along with the volumetric properties of the mixes are summarized in Table 8. The CA parameters were above the desired upper limits and the FA_c values were above the desired upper limit of 0.5. The absolute values of PCSI for these three mixes were high, shifting them away from the MDL to add more binder in the mix.

The mechanical properties of the three mixes are summarized in Table 9 and Figure 9. Al three mixes were found to be balanced in both rutting and cracking potential. Mix 1 exhibits marginal cracking susceptibility. Even if the designed mixes do not satisfy the recommended Bailey parameters, the performance testing of the mixes shows that they can potentially perform well on the field.

Table 7: Summary of design information and material characteristics- Test Section 3

	Parameters	Mix 1	Mix 2	Mix 3
Design Information	NMAS		9.5 mm (3/8")- SP-D	
	Specified Binder PG	PG 70-22	PG 70-22	PG 64-22
	Number of Gyrations	50	35	35
	Target Density, %		96	
	Aggregates Types		Limestone-Dolomite	
	RAP, %	20.0	30.0	30.0
	RAP asphalt content, %	4.8	4.8	4.8
	Name of additive	Rej_1	Rej_1	WMA_1
	Additive, %	1	3	0.5

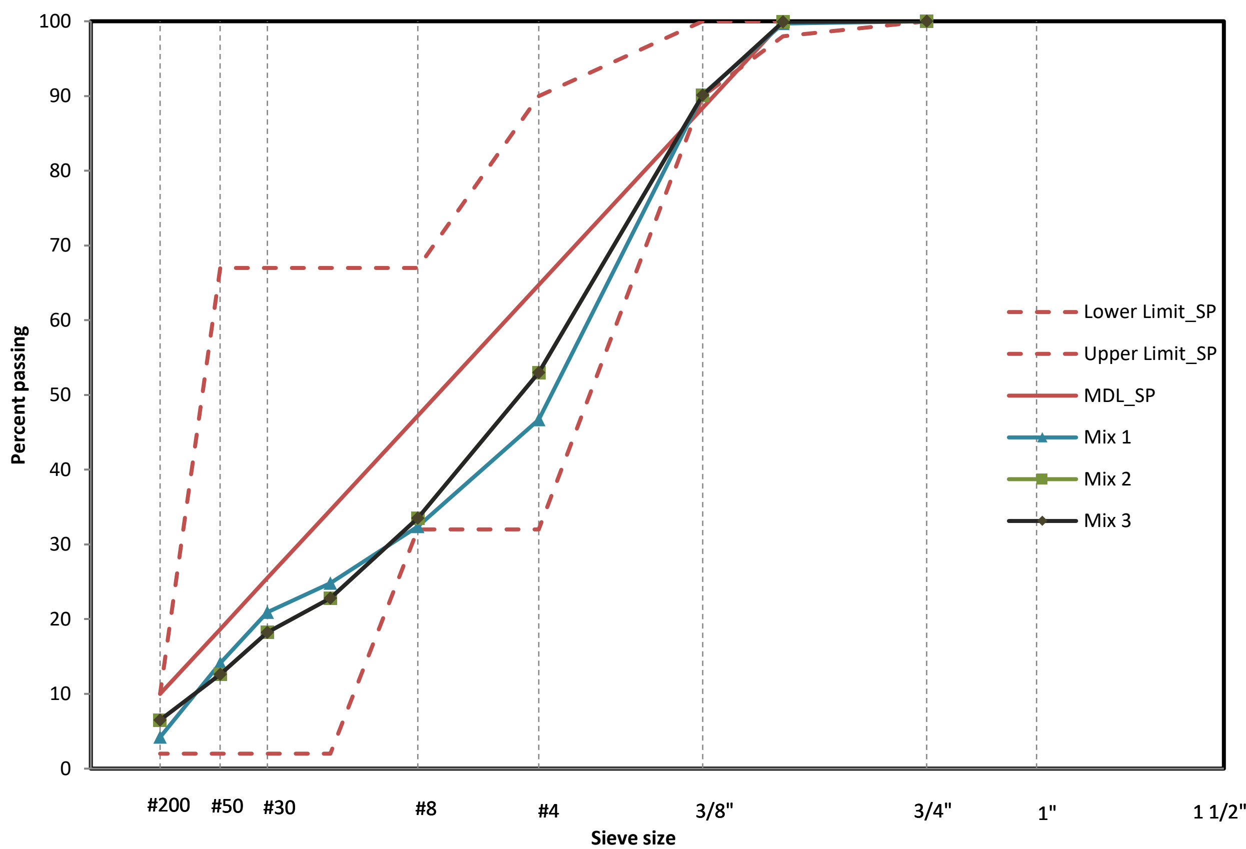


Figure 8 Particle size distribution of test section 3 mixtures

Table 8: Summary of gradation parameters and volumetric properties for test section 3

	Parameters	Mix 1	Mix 2	Mix 3
Gradation Parameters	Coarse Aggregate Ratio (CA)	0.7	0.93	0.93
	Fine aggregate coarse ratio (FA_c)	0.65	0.54	0.54
	Fine aggregate fine ratio (FA_f)	0.35	0.47	0.47
	PCS (Primary Control Sieve)	2.36	2.36	2.36
	Primary Control Sieve Index (PCSI)	-11.9	-13.5	-13.5
Volumetric Properties	Optimum Asphalt Content, % (OAC)	5.7	6.0	6.1
	Voids in Mineral Aggregates, % (VMA)	16.6	17.2	17.6
	Bulk Specific Gravity (G_{mb})	2.300	2.295	2.291
	Maximum Specific Gravity (G_{mm})	2.395	2.391	2.387
	Recycled Binder Ratio, % (RBR)	16.8	24.0	23.6

Table 9: Summary of performance test results for test section 3 mixtures

Parameters			Mix 1	Mix 2	Mix 3
OT	**CPR**	Avg.	0.41	0.28	0.34
		COV	19%	11%	1%
	CFE	Avg.	3.56	1.34	1.39
		COV	8%	14%	4%
HWT	**Rut Depth (mm)**		3.9	12.8	11.6
	Number of Passes		20000	17510	20000
	RRI		16929	8721	10835
	NRRI		2.22	1.14	1.42
IDT	**IDT Strength**	Avg.		83	105
		COV		6%	3%
	CT Index	Avg.		247	229
		COV		7%	10%

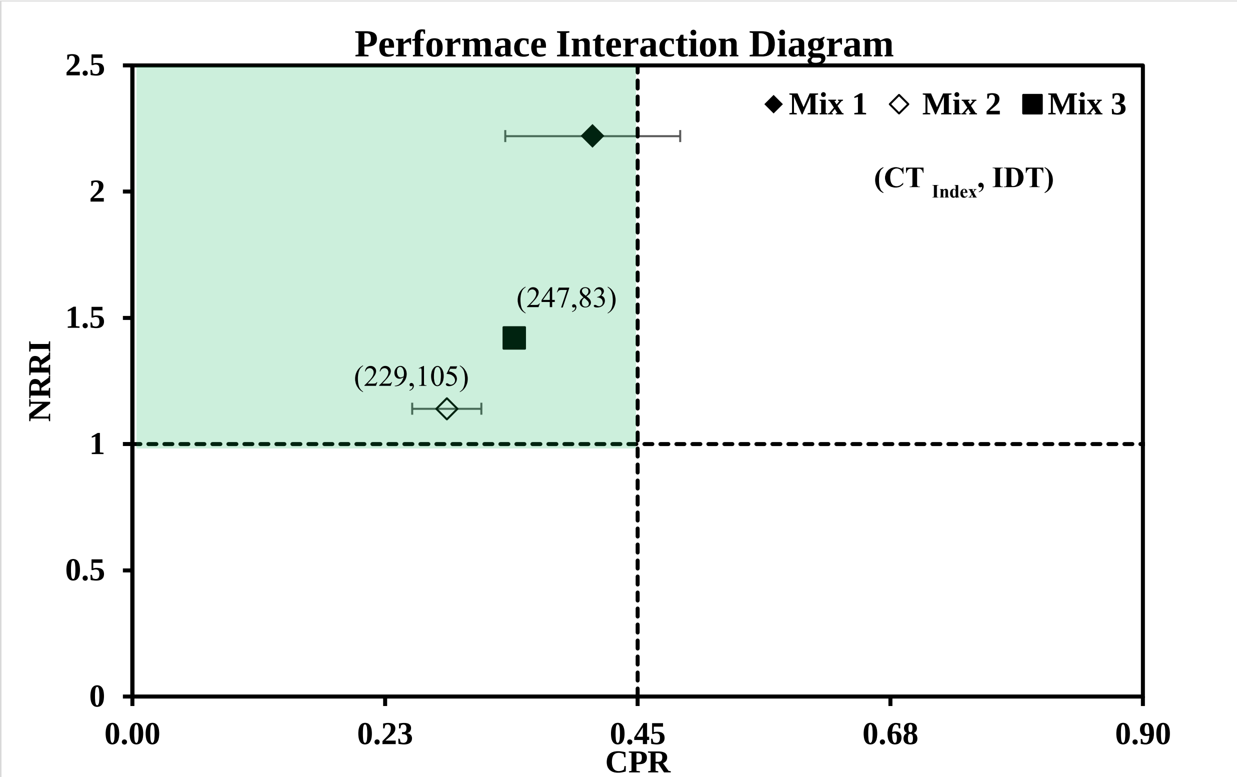


Figure 9: Performance interaction diagram for test section 3 mixtures

Test Project 4

This project involves the control mix as an SMA-D and three other mixes Superpave C mixes. The binder type, number of gyrations, RAP percentages, and the type of aggregates are summarized in Table 10. The major difference among the mixes is the RAP contents. The aggregates used for this study were SAC A aggregates.

Table 10: Summary of design information and material characteristics-Test section 4

Parameters		Mix 1	Mix 2	Mix 3	Mix 4
Design Information	NMAS	9.5 mm (3/8")- SMA-D and 12.5 mm (1/2") - SP-C			
	Specified Binder PG	PG 76-22	PG 70-22	PG 70-22	PG 70-22
	Number of Gyrations	35	50	50	50
	Target Density, %	96			
	Aggregates Types	Igneous			
	RAP, %	-	10.0	15.0	25.0
	RAP asphalt content, %	-	5.8	5.8	5.8

The bin-wise aggregate distributions of the various aggregate fractions, along with the combined gradations of different mixes are presented in Appendix E-1. As shown in Figure 10, the three Superpave mixes were designed as coarse mixes, with similar coarse and fine fractions while incorporating higher RAP contents.

The gradation parameters, along with the volumetric properties are summarized in Table 11. The CA parameters were designed above the desired upper threshold of 0.65 for the Superpave mixes and 0.3 for the SMA mix. The FAc parameters were slightly greater than the desired upper limit of 0.5 and FAf parameters were slightly higher than the desired upper limit of 0.5 for the Superpave mixes. The high absolute PCSI values for all the mixes suggest that these gradations are designed away from the MDL to allow more binder into the mixes.

The mechanical properties of the four mixes are summarized in Table 12 and Figure 11. All four mixes were found to be balanced in both rutting and cracking potential. Mix 1 with the highest PCSI shows the lowest crack propagation rate; whereas, the other three Superpave mixes with comparable PCSI values have similar cracking and rutting resistance. Also, even if the designed mixes do not satisfy the recommended Bailey method parameters, the performance testing of the mixes shows that they can potentially perform well in the field.

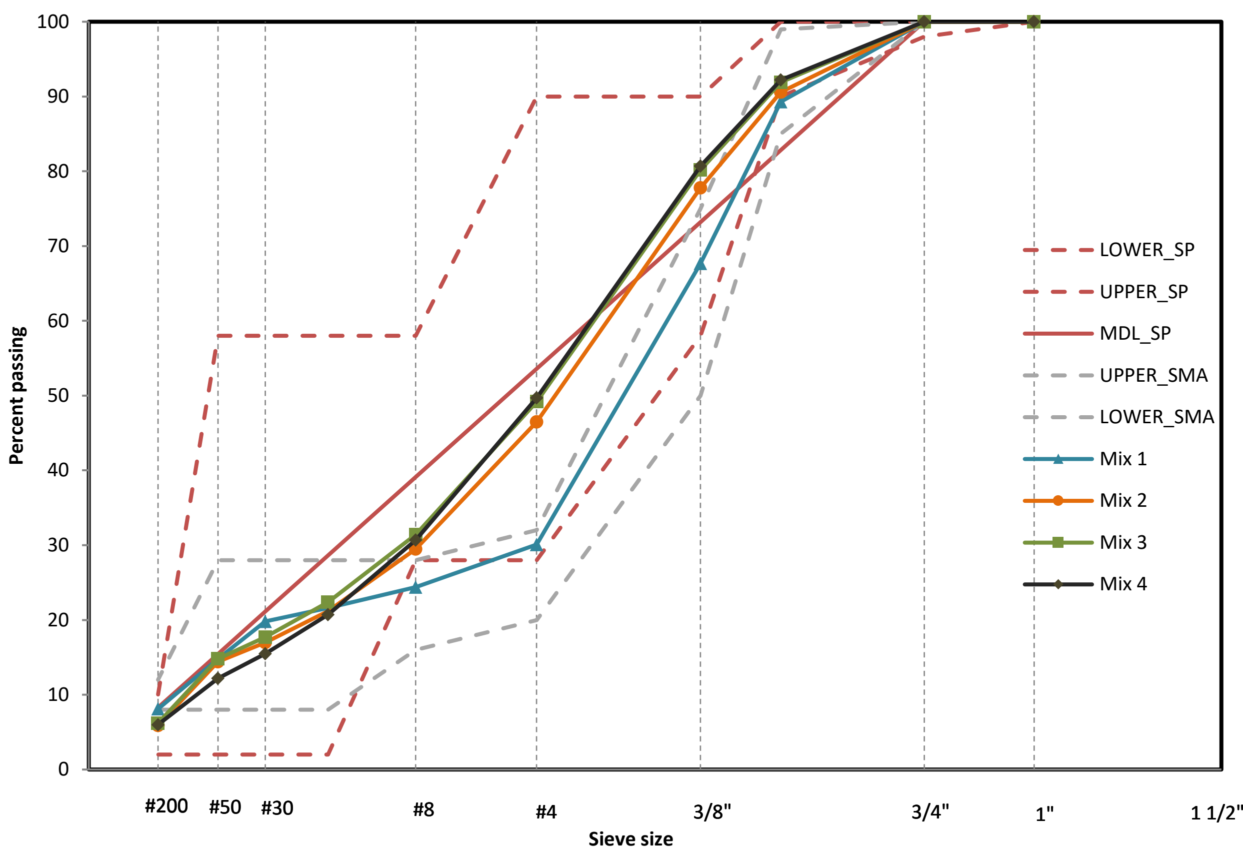


Figure 10: Particle size distribution of test section 4 mixtures

Table 11: Summary of gradation parameter and volumetric properties for test section 4

Parameters		Mix 1	Mix 2	Mix 3	Mix 4
Gradation parameters	Coarse Aggregate Ratio (CA)	0.32	0.64	0.70	0.74
	Fine aggregate coarse ratio (FA_c)	0.81	0.58	0.56	0.50
	Fine aggregate fine ratio (FA_f)	0.52	0.51	0.51	0.51
	PCS (Primary Control Sieve)	2.36	2.36	2.36	2.36
	Primary Control Sieve Index (PCSI)	-14.6	-9.5	-7.6	-8.3
Volumetric Properties	Optimum Asphalt Content, % (OAC)	6.3	5.4	5.3	5.6
	Voids in Mineral Aggregates, % (VMA)	18.4	16.6	16.3	17.1
	Bulk Specific Gravity (G_{mb})	2.350	2.384	2.383	2.379
	Maximum Specific Gravity (G_{mm})	2.448	2.483	2.483	2.478
	Recycled Binder Ratio, % (RBR)	0	10.7	16.4	25.9

Table 12: Summary of performance test results for test section 4 mixtures

Parameters			Mix 1	Mix 2	Mix 3	Mix 4
OT	**CPR**	Avg.	0.28	0.29	0.36	0.33
		COV	7%	9%	8%	11%
	CFE	Avg.	1.84	2.20	1.82	3.24
		COV	4%	22%	30%	3%
HWT	**Rut Depth (mm)**	Rut Depth (mm)	3.22	3.06	3.98	1.80
	RRI	RRI	17465	17591	16866	18582
	NRRI	NRRI	1.72	1.73	1.66	1.83
IDT	**IDT Strength**	Avg.	96	146	162	190
		COV	5%	3%	5%	1%
	CT Index	Avg.	298	162	134	55
		COV	10%	16%	3%	13%

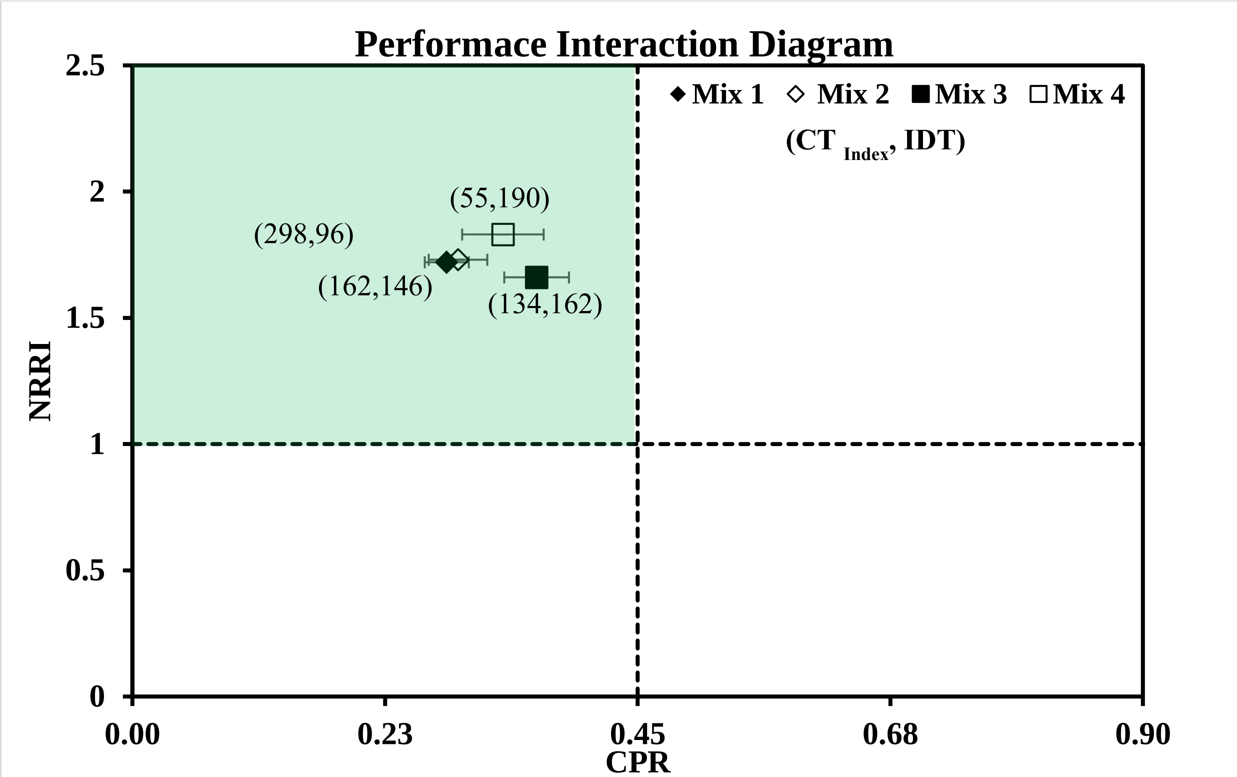


Figure 11: Performance interaction diagram for test section 4 mixtures

Test Project 5

This project involves two Superpave C (SP-C) mixes designed on either side of the MDL. The binder grade, design gyrations, RAP percentages, and the type of aggregates are summarized in Table 13. The major difference between the two mixes is the RAP content.

Table 13 Summary of design information and material characteristics-Test section 5

	Parameters	Mix 1	Mix 2
Design Information	NMAS	12.5 mm (1/2")- SP-C	
	Specified Binder PG	PG 64-22	
	Number of Gyrations	50	
	Target Density, %	96	
	Aggregates Types	Gravel; Sandstone	
	RAP, %	29.6	19.8

The bin-wise aggregate distributions of the various aggregate fractions, along with the combined gradations of the mixes are compiled in Appendix E-1. From Figure 12, the two mixes are designed on either side of MDL so that one of them is a coarse mix and the other a finer mix.

The gradation parameters along with the volumetric properties of the mixes are compiled in Table 14. Neither of the mixes satisfies any of the Bailey method parameter ratios. The CA and FA_c parameters are greater than the desired upper thresholds of 0.65 and 0.5, respectively, whereas, the FA_f parameters are within the desired limit of 0.35 and 0.5. The PCSI of the coarser mix is negative and the one with fine gradation is positive.

The mechanical properties of the two mixes are summarized in Table 15 and Figure 13. Both mixes are balanced in rutting and cracking potential. Even if the designed mixes do not satisfy the recommended Bailey method ratios, the performance testing of the mixes shows that they can potentially perform well in the field.

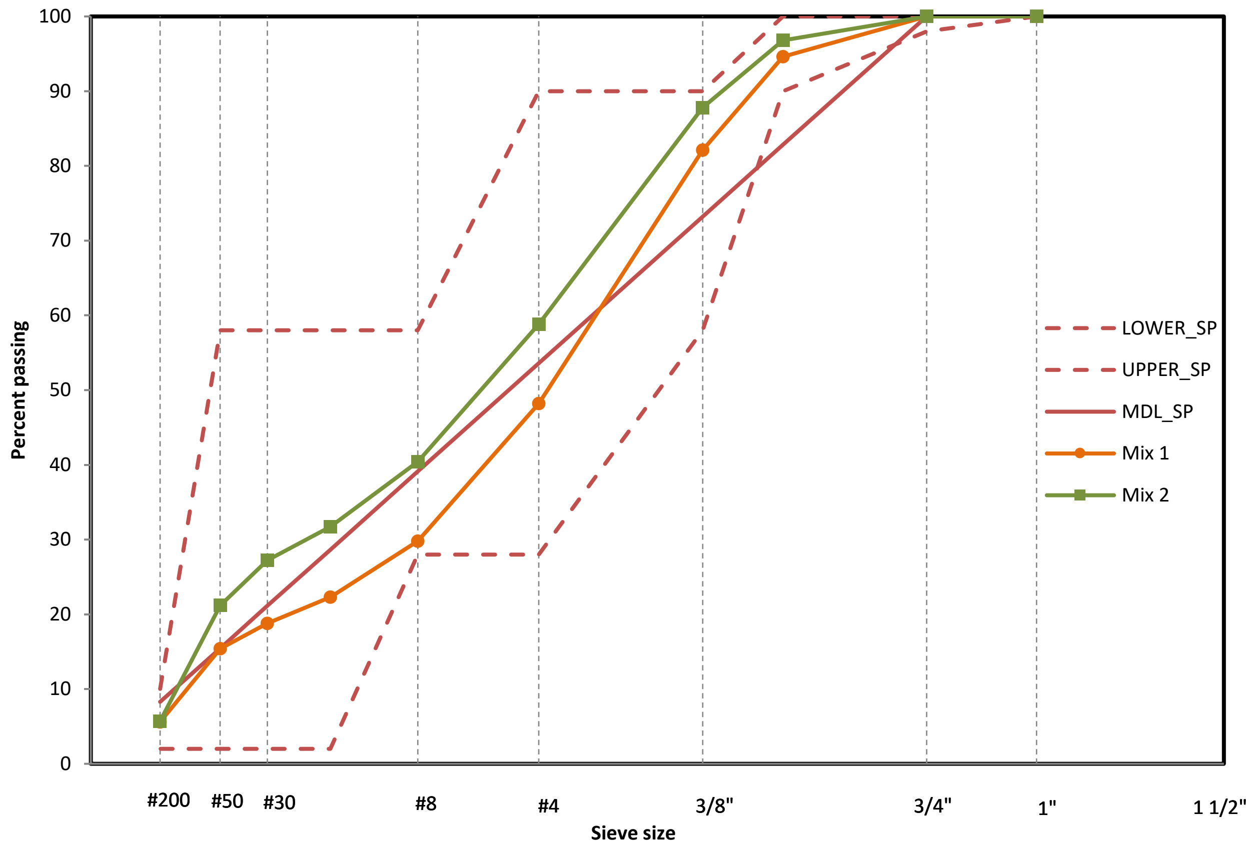


Figure 13 Particle size distribution of test section 5 mixtures

Table 14: Summary of gradation parameter and volumetric properties for test section 5

	Parameters	Mix 1	Mix 2
Gradation Parameters	Coarse Aggregare Ratio (CA)	0.74	0.90
	Fine aggregate coarse ratio (FA_c)	0.63	0.67
	Fine aggregate fine ratio (FA_f)	0.47	0.40
	PCS (Primary Control Sieve)	2.36	2.36
	Primary Control Sieve Index (PCSI)	-9.2	1.4
Volumetric Properties	Optimum Asphalt Content, %	5.9	5.4
	Voids in Mineral Aggregates, %	17.3	16.3
	Bulk Specific Gravity	2.281	2.300
	Maximum Specific Gravity	2.376	2.396
	Recycled Binder Ratio	22.6	16.5

Table 15: Summary of performance test results for test section 5 mixtures

Parameters			Mix 1	Mix 2
OT	**CPR**	Avg.	0.35	0.34
		COV	4%	6%
	CFE	Avg.	2.34	2.11
		COV	14%	6%
HWT	**Rut Depth (mm)**		3.29	1.09
	Number of cycles		10000	10000
	RRI		8704.7	9571
	NRRI		1.71	1.88
IDT	**IDT Strength**	Avg.	138.9	141.8

OBSERVATIONS

The results from the volumetric and mechanical properties of the mixes were compiled along with the gradation parameters. The following key observations were made are:

- The Bailey method parameter corresponding to the coarse fraction (CA ratios) was found to be either within the suggested range or above the upper limit.
- In almost all mix designs the coarse fractions of the fine aggregate blends (FA_c) were either within or greater than the upper limit (> 0.5), and the fine fractions of the fine aggregate blends (FA_f) were within or close to the desired range of (0.35 and 0.5).

- Expect for one mix, the PCSI values for all mixes were negative which suggests that they are coarse gradations.
- All but one mix evaluated were balanced in both rutting and cracking susceptibility, even with higher percentages of recycled materials.
- Mixes with similar PCSI values and SAC-A aggregate sources (igneous, sandstone, gravel) show similar performance.

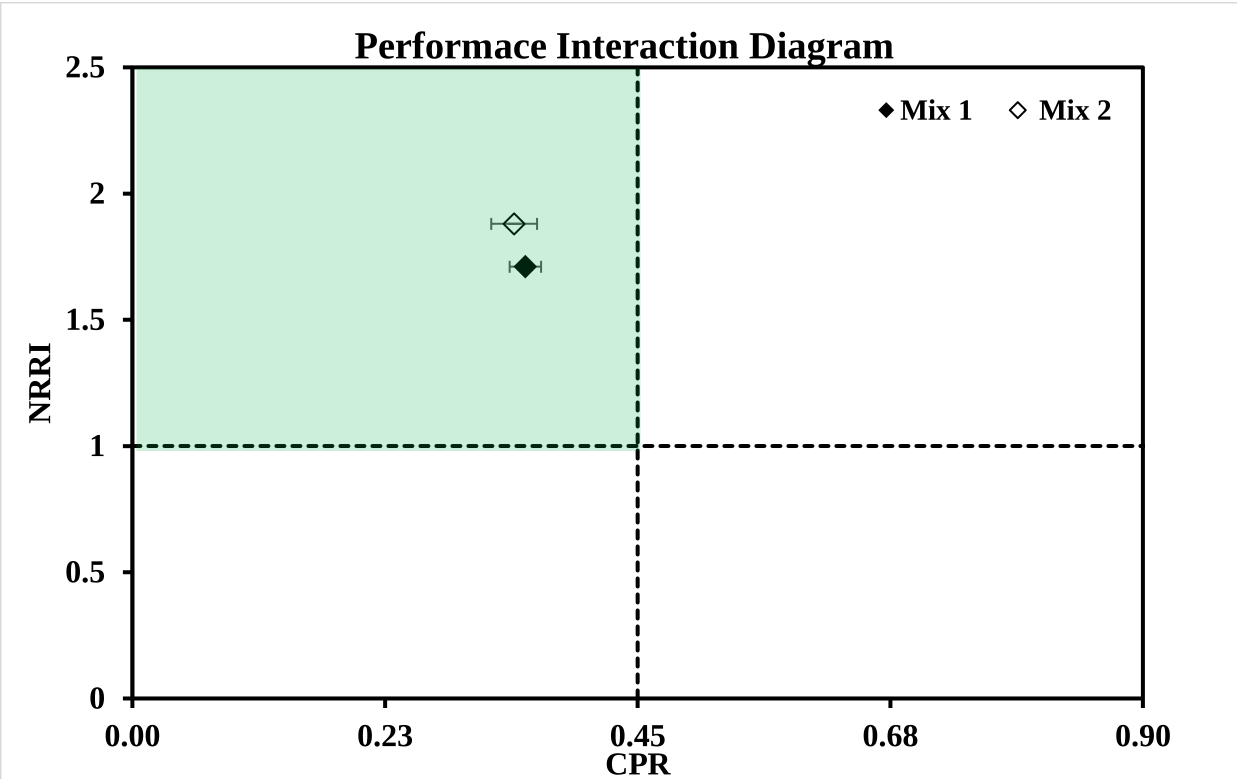


Figure 14: Performance interaction diagram for test section 5 mixtures

Analysis of Results

In this section, the influence of PCSI and Bailey method parameters are investigated based on the different test sections evaluated. All Superpave mixes were considered for this analysis, and the SMA and the dense-graded mix were excluded.

Influence of PCSI

Parameter PCSI, which is based on the percent of the aggregates in the mix that passes through the PCS, determines whether the mix is coarse-graded (negative PCSI) or fine-graded (positive PCSI). As shown in Figure 15, as the PCSI values tend toward zero, the OAC and VMA tend to decrease. For the coarse graded mixes (PCSI< 0), as the absolute value of PCSI approaches zero, the gradation curve approaches MDL, leading to lower binder content and voids in mineral aggregate.

a) PCSI v/s OAC **b) PCSI v/s VMA**

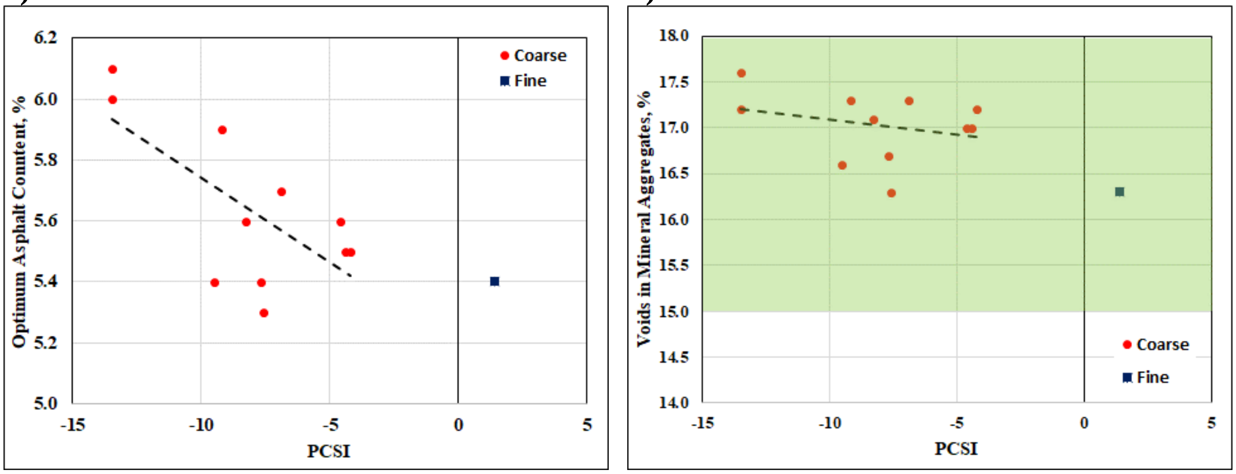


Figure 15: Influence of PCSI on mix volumetric properties

Figure 16 shows the influence of PCSI on the OT, HWT, and IDT performance parameters for coarse mixes, along with the corresponding acceptable range marked as shaded areas, when applicable. The CPR values from the OT tests do not show any significant trend as the PCSI increases (Figure 16-a). As expected, the CFE value tends to increase as the PCSI value approaches zero, indicating that the mix becomes stronger or less brittle as the mix gradation for coarse-grained mixes get closer to MDL (Figure 16-b). The relationship between the IDT strength and PCSI in Figure 16-c tends to confirm the trend observed for CFE that the mix becomes stronger as PCSI increases. The CT_{Index} parameter decreases with a reduction in PCSI values as shown in Figure 16-d, indicating that the mix becomes more crack susceptible. As shown in Figure 16-e, a clear trend can be observed between the NRRI values obtained from HWT tests and PCSI. The rutting potential of the mixes seems to improve as PCSI increases.

Influence of Coarse Aggregate Fraction (CA)

The CA ratio represents the coarse fraction of the AC mix aggregate blend. As shown in Figure 17-a, the OAC tends to increase as the CA ratio increases. The VMA seems to increase slightly as the CA ratio increases (Figure 17-b).

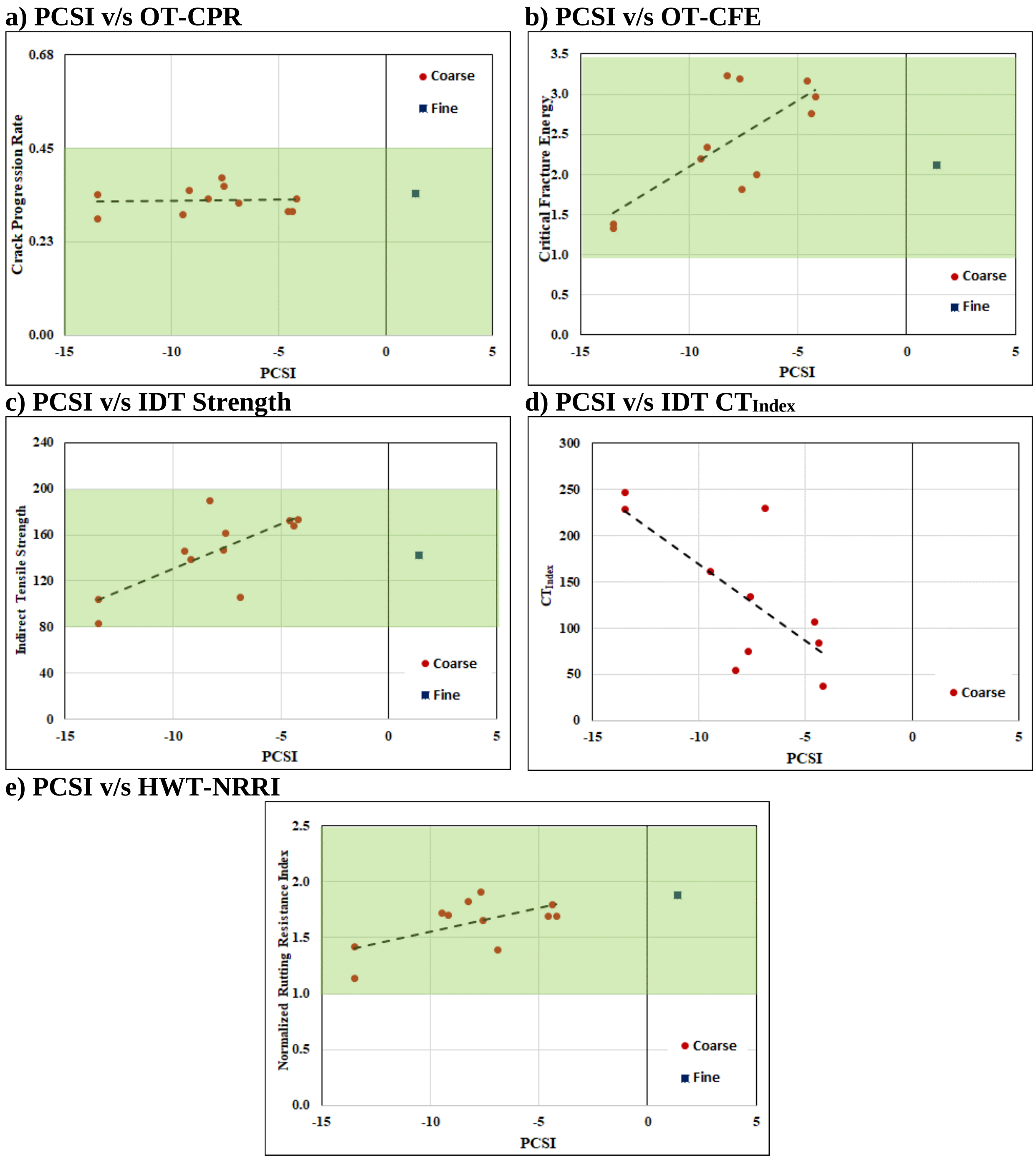


Figure 16: Influence of PCSI on the mix mechanical properties

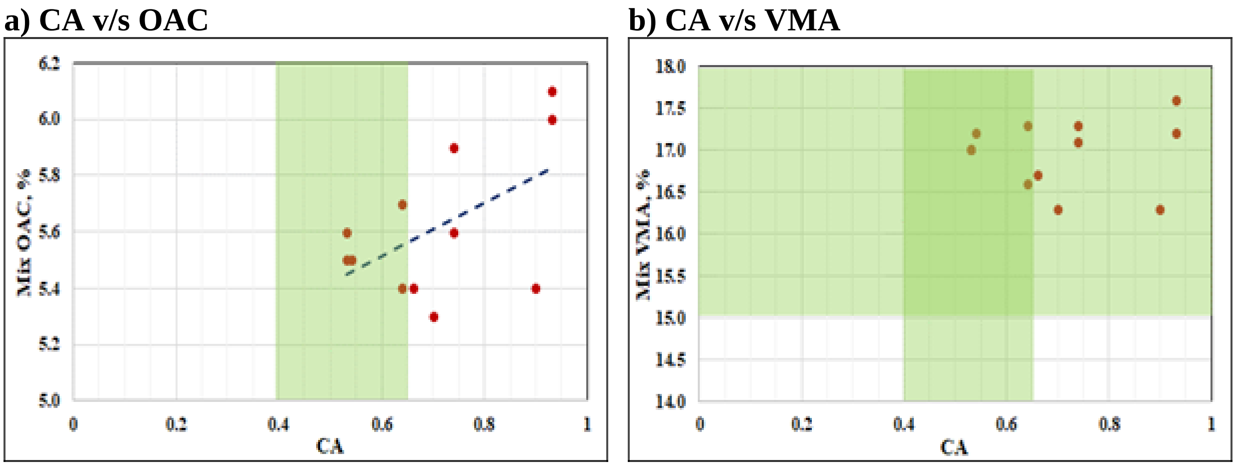
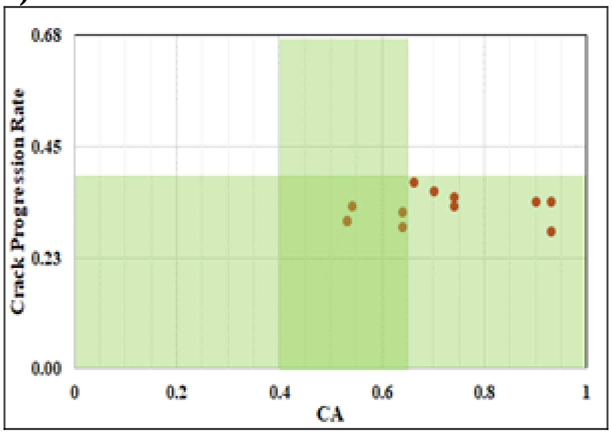


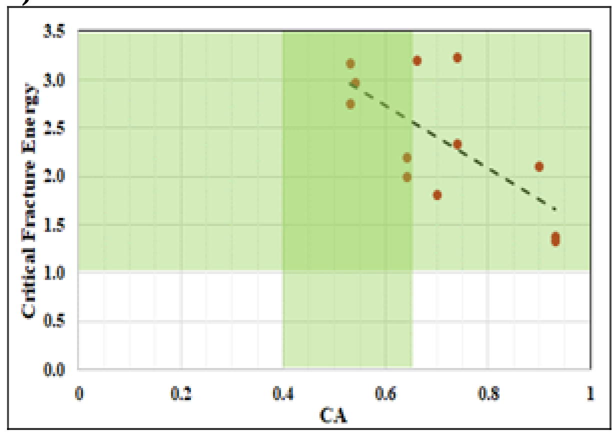
Figure 17: Influence of CA on the mix volumetric properties

As shown in Figure 18a, the CPR value does not change significantly whereas as per Figure 18b, the CFE tends to decrease with the increase in the CA ratio, indicating that as the CA ratio increases, the mix becomes less crack susceptible. In terms of stiffness, although the IDT strength decreases and CT Index increases with the increase in CA, the correlation between them is not very strong. It can be seen that there are few data points with CA close to 0.55 that correspond to mixes with all SAC A aggregates. In terms of the rutting susceptibility of the mixes, there is a clear trend showing an decrease in NRRI as the CA ratio increases. Although the CA ratios for many mixes are outside the recommended range, they do satisfy volumetric and mechanical properties as per the current specifications. Hence, the range of the CA ratio can be satisfactorily increased without compromising the quality of the HMA mix. It seems that the CA ratio is a better indicator of the performance of the mixes in rutting and cracking than PCSI.

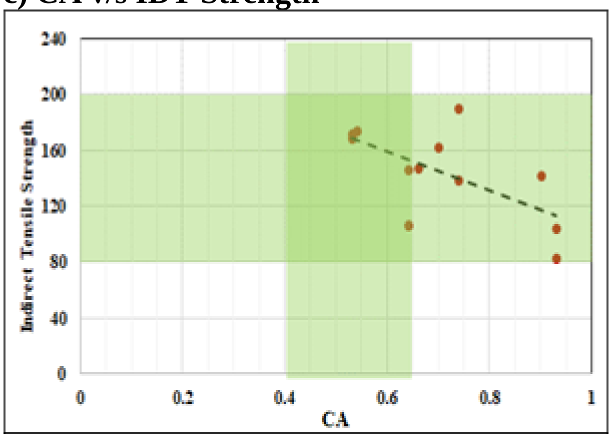
a) CA v/s OT-CPR



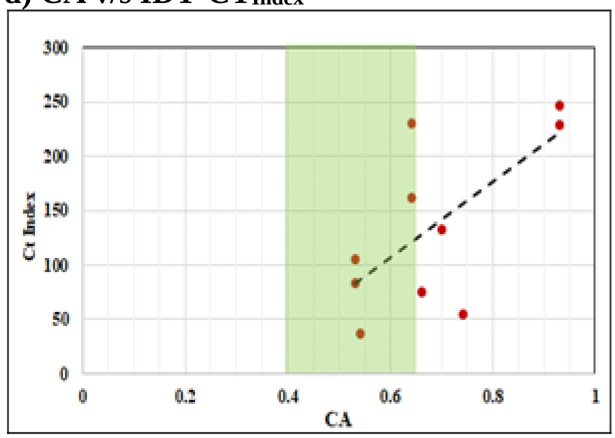
b) CA v/s OT-CFE



c) CA v/s IDT Strength



d) CA v/s IDT-CT$_{Index}$



e) CA v/s HWT-NRRI

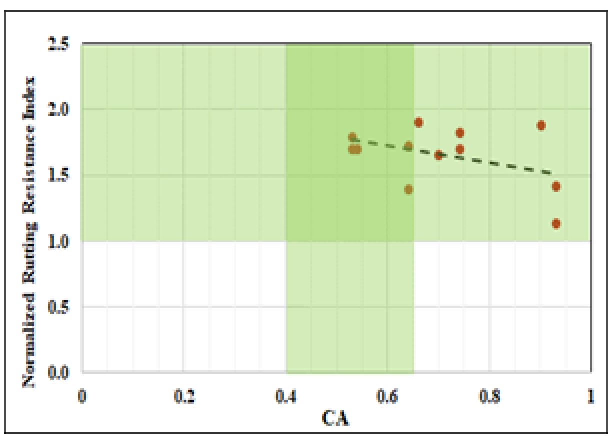


Figure 18: Influence of CA on the mix mechanical properties

Influence of Fine Aggregate fraction

The FA_c ratio depicts the coarse fraction of the fine aggregate blend and the FA_f ratio denotes its fine fraction. As shown in Figure 19, FA_c or FA_f only minimally to marginally impact OAC or VMA of the mixes. There is a weak tendency for the OAC and VMA to decrease when either FA_c or FA_f increases.

a) FA_c and FA_f v/s OAC **b) FA_c and FA_f v/s VMA**

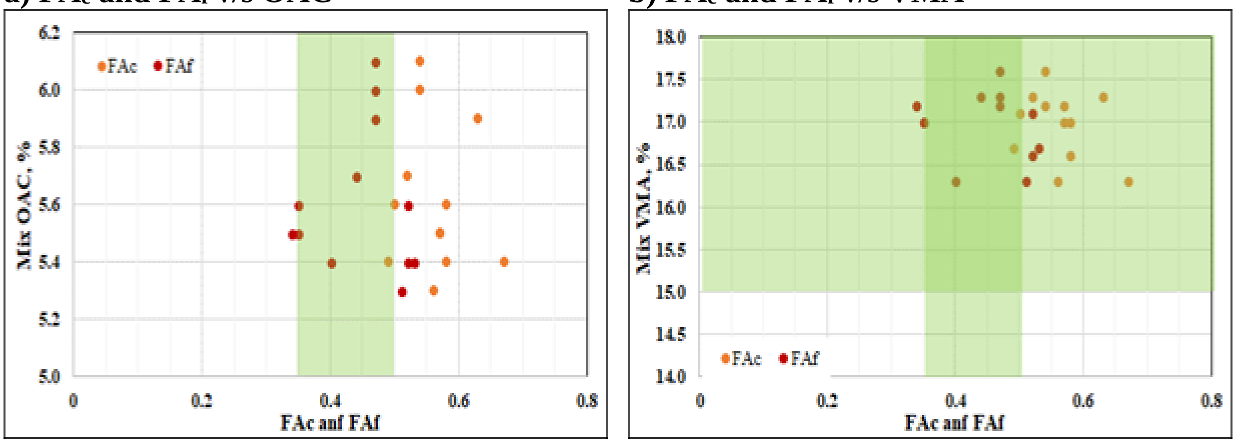


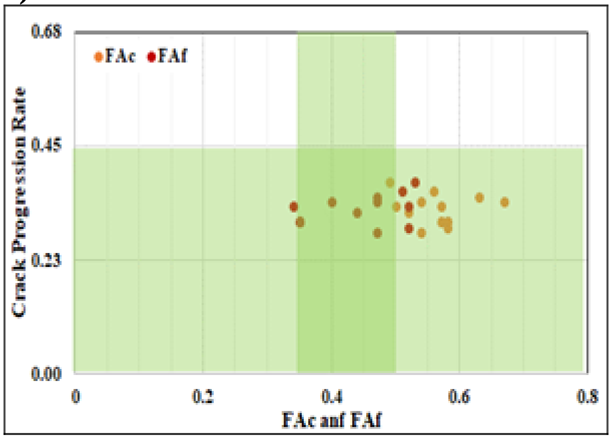
Figure 19: Influence of FA_c and FA_f on the mix volumetric properties

Figure 20 indicates that neither FA_c nor FA_f demonstrates a coherent reaction to any of the performance parameters obtained for the OT, HWT, or IDT.

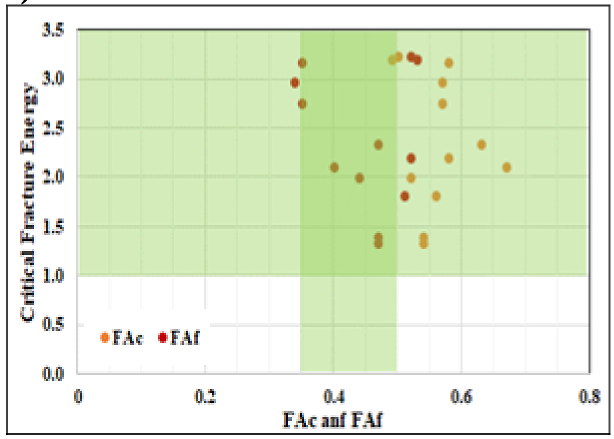
Table 16 summarizes the correlation coefficients (denoted as R) from the correlation analysis for the coarse mixes. The combination of PCSI and CA explains the volumetric and mechanical performance of the mixes well. FA_f seems to influence the VMA, while, RBR influence the crack propagation performance of the Superpave mixes.

Table 17 serves as a guideline that can be used to improve the desired volumetric and mechanical properties of the mixes by altering the different gradation parameters and help design a Balanced Mix while reducing the number of iterations to reach the final gradation.

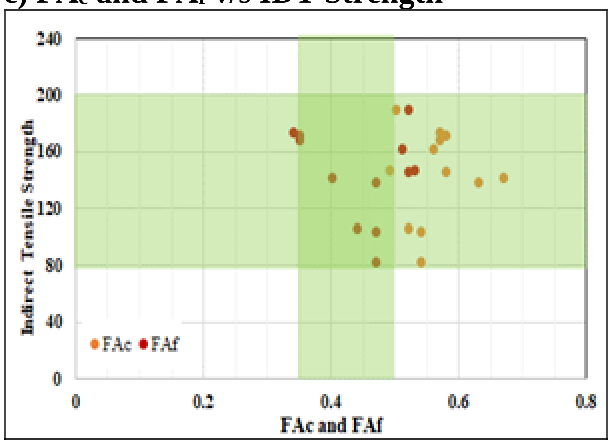
a) FA_c and FA_f v/s OT-CPR



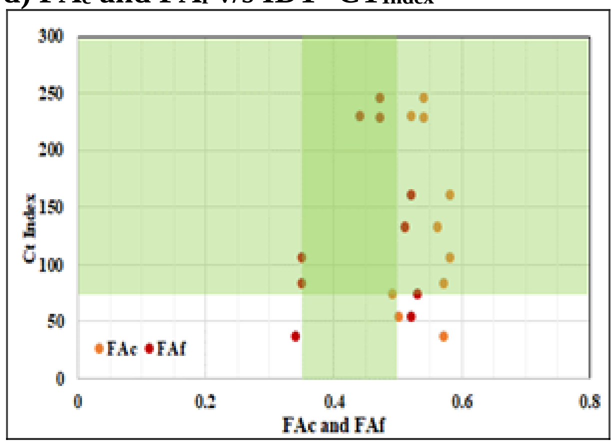
b) FA_c and FA_f v/s OT-CFE



c) FA_c and FA_f v/s IDT Strength



d) FA_c and FA_f v/s IDT- CT_{Index}



e) FA_c and FA_f v/s HWT-NRRI

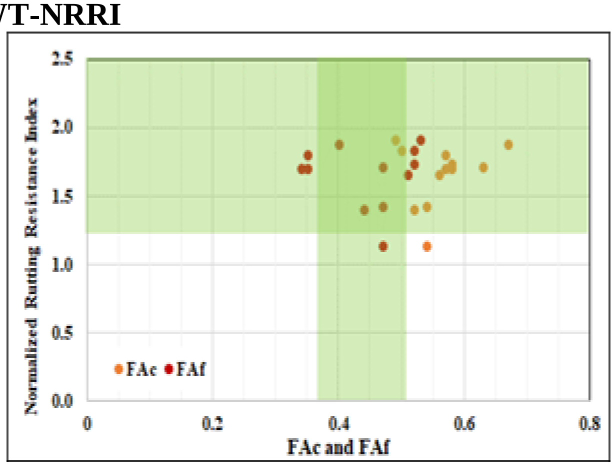


Figure 20: Influence of FA_c and FA_f on the mix mechanical properties

Table 16: Summary of correlation coefficients

Gradation Parameter	Correlation Coefficient (R)						
	OAC, %	VMA, %	CPR	CFE	NRRI	IDT	CT_{Index}
PCSI	-0.68	-0.29	0.06	0.74	0.62	0.74	-0.72
CA	0.73	0.36	0.05	-0.72	0.64	-0.69	0.66
FA_c	0.09	0.03	-0.24	-0.11	0.04	0.10	-0.01
FA_f	-0.02	-0.34	0.39	-0.27	0.02	-0.23	0.25
RBR, %	0.24	0.08	0.48	-0.07	0.05	-0.09	-0.13

Table 17: Influence of Gradation Parameters on Mix Properties

Gradation Parameter	OAC	VMA	CPR	CFE	NRRI	IDT	CT_{Index}
PCSI ↑	↓	-	-	↑	↑	↑	↓
CA ↑	↑	↑	-	↓	↑	↓	-
FA_f ↑	-	↓	-	↓	-	-	-

* *- The results were not conclusive*

Based on the gradation parameters and corresponding volumetric/mechanical properties of the HMA mixes, none of the balanced mixes designed fell within all the three suggested Bailey method aggregate parameters. This suggests that based on the Balanced Mix design concept, the Bailey method aggregate parameters can be suitably altered to design mixes that not only satisfy the volumetric requirements but also perform well in the field.

Conclusions and Recommendations

A web-based gradation optimization tool was developed to give stakeholders the flexibility to design the target gradation. Based on the study, guidelines to check and alter the gradation parameters to influence the volumetric and mechanical properties were established which can be used by designers to reduce the number of iterations of gradation designs to reach a balanced mix.

The influence of the various gradation parameters, especially PCSI and those recommended by the Bailey method, on the volumetric and mechanical properties were studied and documented. Five test projects across Texas that used the Superpave mix design process were considered for preliminary testing of this gradation tool. Almost all mixes met the balanced mix design concept in rutting and cracking.

CONCLUSIONS

From this study, the following conclusions can be drawn:

1. Aggregate gradation parameters have the potential to decrease the number of trials to obtain a balanced mix.
2. The combination of PCSI and CA ratio can be used to accelerate the selection of the gradation to achieve a balanced mix design. The FA_f and RBR also influence some of the volumetric and cracking parameters.

RECOMMENDATIONS

The following recommendations are provided to continue this study further:

1. Most of the mixes in the study were coarse graded mixes and hence had positive PCSI value. More fine graded mixes should be incorporated in the future to check the relation of fine-graded mixes with the volumetric and mechanical properties.
2. Multivariate analysis can be explored with a larger dataset to prepare a prediction model involving aggregate gradation parameters like PCSI; binder properties like actual high and low PG grade; quantity and quality of RAP etc. to predict the mixture performance.
3. With a larger dataset of mixes used across Texas, the suitable gradation parameters can be established to design balanced mixes with gradation parameters as predictor variables.

Appendix – E-1

COMBINED GRADATION FOR EACH MIX

Project 1

Table A-1: Optimized bin percentages for aggregate gradation - Test section 1 mixtures

	AGGREGATE BIN FRACTIONS							RECYCLED MATERIALS		
Aggregate	Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.5	Bin No.6	Bin No.7	Bin No.8	Bin No.9	Bin No.10
Source:	Sandstone	Gravel	Gravel	Gravel	Sandstone			Fractionated RAP	RAS	
Sample ID:	Ty 'D' C.A.	Ty 'D' C.A.	Screenings	Field Sand	Find Dry Screenings	Lime		Fine 1/2"		
Mix 1	16.0	40.0	15.0	8.9	9.0	1.0		10.1		
Mix 2	17.0	45.0	16.0	9.0	12.0	1.0				
Mix 3	15.0	40.0	18.0	7.3	5.0	1.0		11.1	2.6	

Table A-2: Master asphalt mix gradations - Test section 1 mixtures

Sieve Size	Sieve Size (mm)	Master Gradations		
		Mix 1	Mix 2	Mix 3
3/4"	19.00	100.0	100.0	100.0
1/2"	12.50	100.0	100.0	100.0
3/8"	9.50	91.9	92.1	92.0
#4	4.75	62.6	62.3	62.9
#8	2.36	42.6	42.4	42.8
#16	1.18	32.1	32.0	31.4
#30	0.60	24.4	24.4	23.2
#50	0.30	15.8	16.0	15.0
#200	0.075	4.9	4.8	5.1

Project 2

Table A-3: Optimized bin percentages for aggregate gradation - Test section 2 mixtures

	AGGREGATE BIN FRACTIONS							RECYCLED MATERIALS		
Aggregate	Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.5	Bin No.6	Bin No.7	Bin No.8	Bin No.9	Bin No.10
Source:	Igneous	Igneous	Limestone-Dolomite	Limestone-Dolomite	Limestone-Dolomite			Fractionated RAP		
Sample ID:	Trap C-Rock	Trap D-Rock	D-Rock	F-Rock	Man Sand	Silica Sand		Fine 1/2"		
Mix 1	15.0	10.0	12.0	18.0	25.0	5.0		15.0		
Mix 2	15.0	12.0	12.0	19.0	25.0	9.0		0.0		
Mix 3	15.0	13.0	12.0	15.0	20.0	0.0		25.0		

Table A-4: Master asphalt mix gradations - Test section 2 mixtures

Sieve Size	Sieve Size (mm)	Master Gradations		
		Mix 1	Mix 2	Mix 3
1 in.	25.00	100.0	100.0	100.0
3/4 in.	19.00	100.0	100.0	100.0
1/2 in.	12.50		92.6	92.5
3/8 in.	9.50	77.8	76.2	76.4
#4	4.75	53.3	49.7	49.5
#8	2.36	35.9	32.1	31.3
#16	1.18		23.7	22.1
#30	0.60	18.0	16.8	15.2
#50	0.30	13.7	12.8	11.9
#200	0.075	5.3	4.7	6.1

Project 3

Table A-5: Optimized bin percentages for aggregate gradation - Test section 3 mixtures

	AGGREGATE BIN FRACTIONS							RECYCLED MATERIALS		
Aggregate	Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.5	Bin No.6	Bin No.7	Bin No.8	Bin No.9	Bin No.10
Source:	Sandstone	Gravel	Gravel	Gravel				Fractionated RAP		
Sample ID:	Gr.4	D/F Blend	Man Sand	Silica Sand				Fine 1/2"		
Mix 1	37.0	15.0	22.9	10.0				15.1		
Mix 2	29.9	14.0	25.7	0.0				30.4		
Mix 3	29.9	14.0	25.7	0.0				30.4		

Table A-6: Master asphalt mix gradations - Test section 3 mixtures

Sieve Size	Sieve Size (mm)	Master Gradations		
		Mix 1	Mix 2	Mix 3
3/4 in.	19.00	100.0	100.0	100.0
1/2 in.	12.50	99.7	99.9	99.9
3/8 in.	9.50	90.2	90.1	90.1
#4	4.75	46.7	53.0	53.0
#8	2.36	32.4	33.5	33.5
#16	1.18	24.8	22.8	22.8
#30	0.60	20.9	18.2	18.2
#50	0.30	14.1	12.6	12.6
#200	0.075	4.2	6.5	6.5

Project 4

Table A-7: Optimized bin percentages for aggregate gradation - Test Section 4 Mixtures

	AGGREGATE BIN FRACTIONS							RECYCLED MATERIALS		
Aggregate	Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.5	Bin No.6	Bin No.7	Bin No.8	Bin No.9	Bin No.10
Source:	Igneous	Igneous	Igneous					Fractionated RAP		
Sample ID:	5/8"	1/2"	Screenings	Field Sand	AR1	Nepheline Syenite	Lime	Fine 1/2"		
Mix 1	20.0	-	9.0	-	55.0	15.0	1.0	-		
Mix 2	20.0	42.0	22.0	6.0	-	-	-	10.0		
Mix 3	17.0	40.0	23.0	5.1	-	-	-	14.9		
Mix 4	16.0	36.0	23.1	-	-	-	-	25.0		

Table A-8: Master Asphalt Mix Gradations - Test Section 4 Mixtures

Sieve Size	Sieve Size (mm)	Master Gradations			
		Mix 1	Mix 2	Mix 3	Mix 4
1 in.	25.00	100.0	100.0	100.0	100.0
3/4 in.	19.00	100.0	100.0	100.0	100.0
1/2 in.	12.50	89.3	90.6	91.9	92.2
3/8 in.	9.50	67.7	77.8	80.2	80.7
#4	4.75	30.1	46.5	49.2	49.7
#8	2.36	24.4	29.5	31.4	30.7
#16	1.18	21.6	21.2	22.4	20.7
#30	0.60	19.8	17.0	17.7	15.5
#50	0.30	14.8	14.4	14.8	12.2
#200	0.075	8.1	5.9	6.2	6.0

Project 5

Table A-9: Optimized bin percentages for aggregate gradation - Test section 5 mixtures

	AGGREGATE BIN FRACTIONS							RECYCLED MATERIALS		
Aggregate	Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.5	Bin No.6	Bin No.7	Bin No.8	Bin No.9	Bin No.10
Source:	Sandstone	Sandstone	Gravel	Sandstone	Sandstone			Fractionated RAP		
Sample ID:	C Rock	D Rock	F Rock	Man. Sand	Screenings	Armco Sand		Fine 1/2"		
Mix 1	17.0	30.0	10.0	7.0	6.0			30.0		
Mix 2	10.0	27.0	13.0	10.0	12.0	8.0		20.0		

Table A-10: Master asphalt mix gradations - Test section 5 mixtures

Sieve Size	Sieve Size (mm)	Master Gradations	
		Mix 1	Mix 2
1 in.	25.00	100.0	100.0
3/4 in.	19.00	100.0	100.0
1/2 in.	12.50	94.6	96.8
3/8 in.	9.50	82.1	87.8
#4	4.75	48.2	58.8
#8	2.36	29.8	40.4
#16	1.18	22.3	31.7
#30	0.60	18.8	27.2
#50	0.30	15.4	21.1
#200	0.075	5.6	5.7

Appendix – E-2

A WORKING EXAMPLE OF USING GRADATION DESIGN TOOL

To understand the use of the gradation design tool, step-by-step instructions are provided below.

1. Project 1- Mix 1, an SP-D mix with NMAS of 3/8" (9.5mm) is selected by uploading the mix design sheet.
2. Once the design is uploaded, the screen shown in Figure B-1 appears that provides the actual gradation of the uploaded mix (original), upper and lower limits based on the mix type, and MDL based on NMAS.
3. The target gradation is the dynamic gradation that can be set by the designer either by dragging the control points or entering the % passing values associated with the sieve sizes in the boxes provided below the graph. The target gradation can be decided based on the designer's experience with the material or the recommended values by Vavrick (2002) of the gradation parameters can be used as a reference.
4. Once the target gradation is set, the next step is to choose which bins need to be altered to achieve the desired target gradation. The bins that are not to be altered, have to be 'tick' marked so that the optimization function will exclude those bins. As an example, in this case, only Bin Numbers 1, 3, 6, and 8 are considered in the optimization as seen in Figure B-1 and Figure B-2.
5. Multiple optimization trials (referred to as slots in the program) can be used to try out multiple iterations (Maximum 5) by changing the desired gradation, bin proportions, bin selection, etc. The final gradations from different iterations can be seen on the same plot as shown in Figure B-2. The bin percentages for the chosen gradation curve can be obtained from the table underneath the graph.
6. The desired trial gradation can be downloaded for laboratory evaluation and can also be sent to the authorized person for approval.

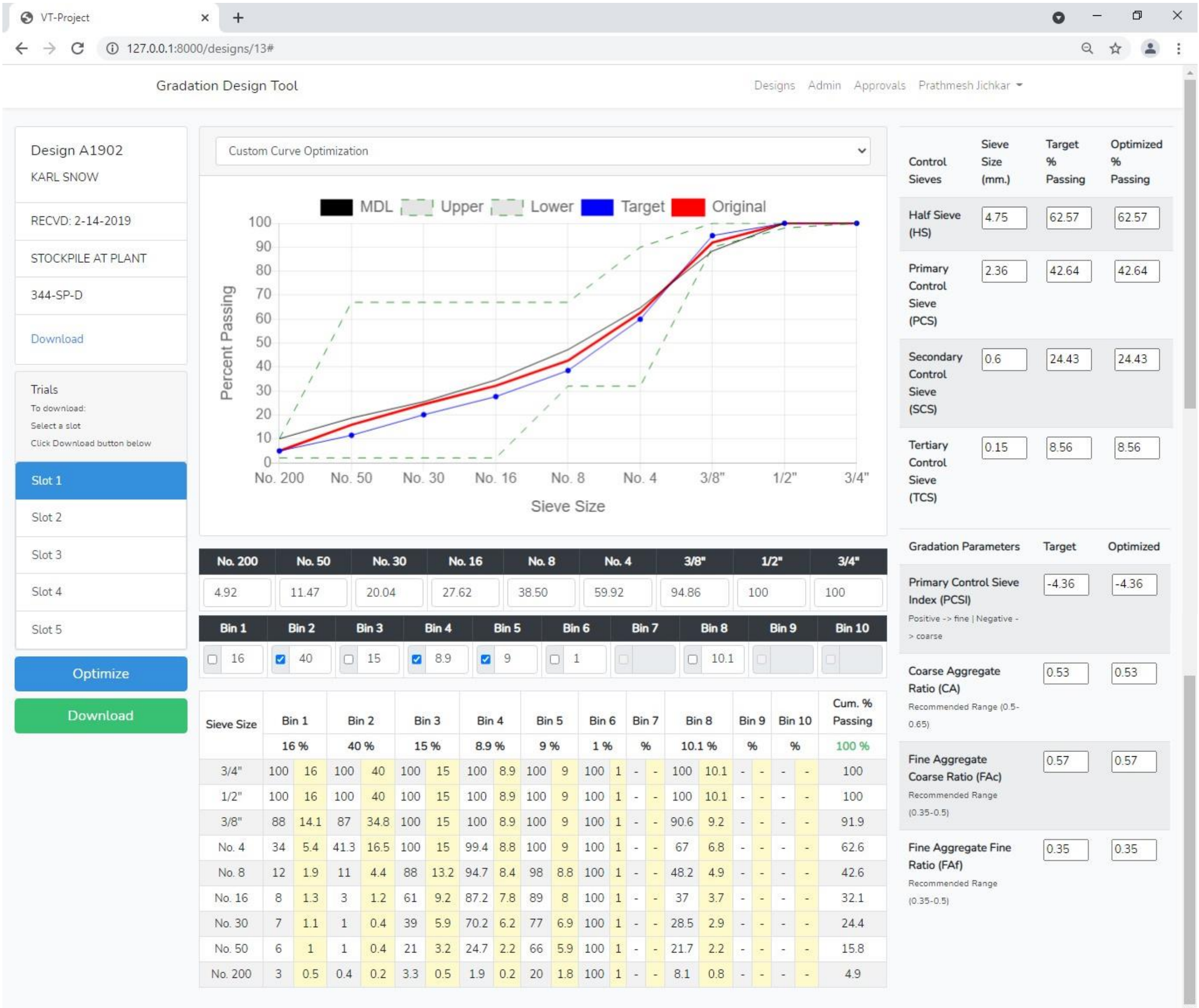


Figure B-1: Design tool before the optimization process is carried out

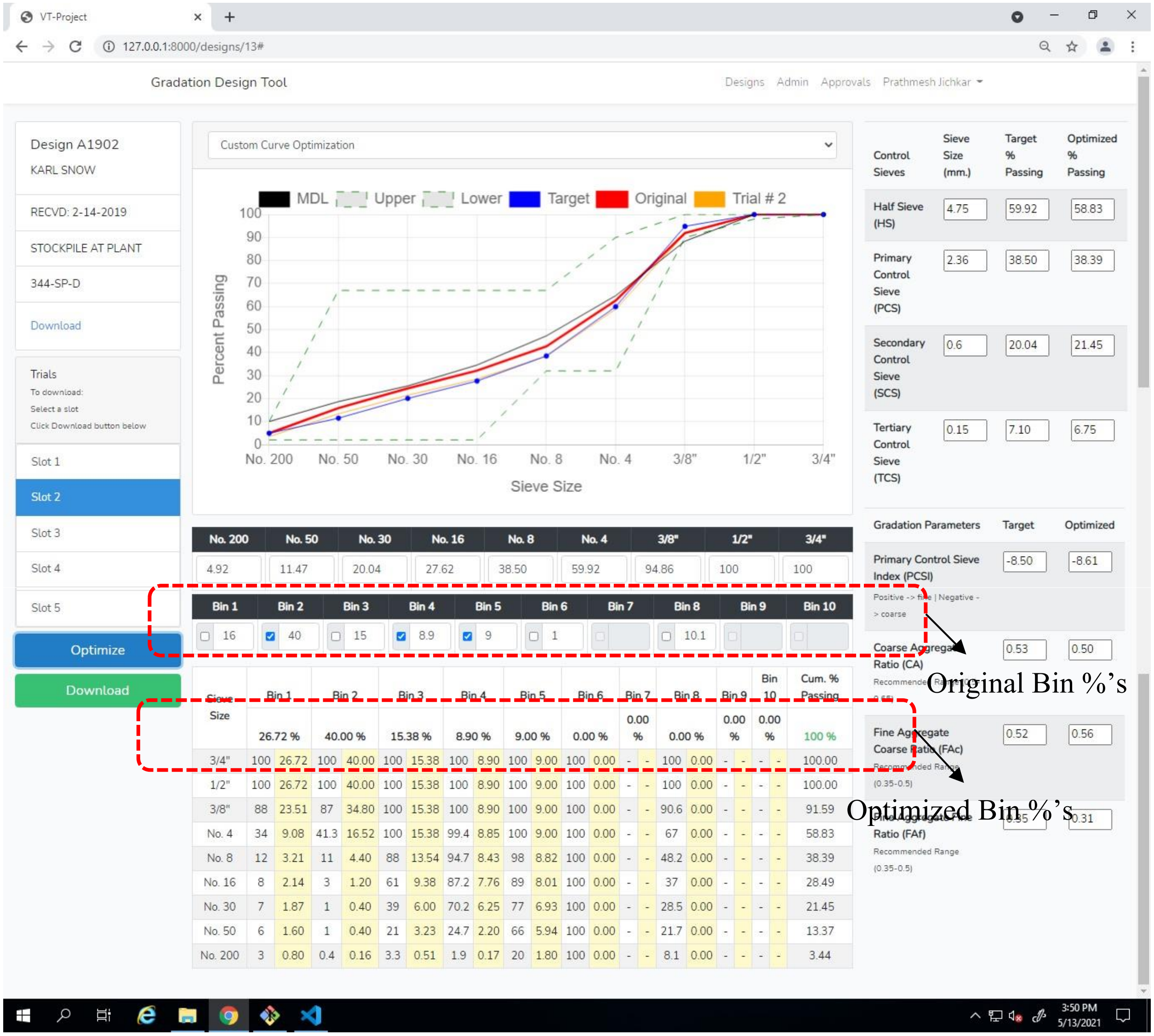


Figure B-2: Design tool after the optimization process is carried out