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Implementation of HMA design tool to develop Balanced Mix Design based on gradation parameters

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IMPLEMENTATION OF HMA DESIGN TOOL TO DEVELOP BALANCED MIX DESIGN BASED ON GRADATION PARAMETERS

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Dedication

I dedicate this work to my beloved parents Deepak Jichkar and Sunita Jichkar and my loving wife Rujuta Bhat for their continued support and encouragement during all my endeavors.

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by

PRATHMESH DEEPAK JICHKAR

THESIS

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Abstract

With the rapid paradigm shift of pavement design methodology from an empirical-based approach toward a more mechanistic-based approach, the existing mix design processes also need a radical shift from the conventional volumetric-based methods to performance-based methods. The use of a volumetric-based design methodology has become more challenging due to the increasing use of recycled materials, modified binders, warm mix asphalt additives, compaction aids, and rejuvenators. A shift toward the more fundamentally sound 'balanced mix design' (BMD) concept is envisaged to produce asphalt concrete mixtures with acceptable performance in terms of durability and stability. Aggregate gradation plays a crucial role in achieving this balance between durability and stability. Previous studies have been carried out delineating various gradation parameters but very few studies deal with the implementation of these parameters and their relationship to asphalt concrete (AC) performance.

Improving the durability and long-term performance of AC has become a major concern after the use of Superpave specification, especially with the increase in the use of recycled materials, warm mix asphalt additives, and modified binders. The major objective of this study is to propose a gradation design tool as part of a transition towards the balanced mix design principles. The scope of the study consists of reviewing the existing gradation parameters and their relative impact on mixture volumetric and mechanical properties of Superpave mixes. This information was translated into a web-based 'Gradation Design Tool' which can be used to optimize the gradation based on different gradation parameters. This tool was then used on five test sections across Texas to study the volumetric and mechanical behavior of the proposed mixes. Each test section had a control gradation mix and at least one other mix to study their relative difference in properties.

A 'volumetric design with performance verification' method is used to ensure satisfactory mechanical performance during the balanced mix design process. TxDOT-approved performance tests are used to evaluate and balance the rutting and cracking potential of the mixes. A performance space diagram formulated with the crack progression rate from the Overlay tester test

and normalized rutting resistance index from the Hamburg wheel tracking test was utilized to characterize the mixtures' performance. To evaluate the potential of using the performance tests during the QC/QA process, the cracking tolerance index from the indirect tensile asphalt cracking test (IDEAL-CT) was used as a surrogate parameter. The optimization of the aggregate gradation is a promising approach to formulate a mixture with balanced stability and durability.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

AC	Asphalt Concrete
AQMP	Aggregate Quality Monitoring Program
BMD	Balanced Mix Design
CA	Coarse Aggregate Ratio
CFE	Critical Fracture Energy
CPR	Crack Progression Rate
CT_{Index}	Crack Tolerance Index
DOT	Department of Transportation
DG	Dense Graded Mix
ESAL	Equivalent Single Axle Loads
FA_c	Fine Aggregate Course Ratio
FA_f	Fine Aggregate Fine Ratio
FHWA	Federal Highway Administration
G_{mb}	Bulk specific gravity
G_{mm}	Theoretical maximum specific gravity
HCS	Half Control Sieve
HMA	Hot Mix Asphalt
IDT	Indirect Tensile Strength
MDL	Maximum Density Line
NMAS	Nominal Maximum Aggregate Size
NRRI	Normalized Rutting Resistance Index
OAC	Optimum Asphalt Content

PCS	Primary Control Sieve
PCSI	Primary Control Sieve Index
PG	Performance Grade
QA	Quality Assurance
RAS	Recycled asphalt shingles (RAS)
RAP	Recycled asphalt pavements
RBR	Recycled Binder Ratio
RRI	Rutting Resistance Index
SAC	Surface Aggregate Classification
SCS	Secondary Control Sieve
SHRP	Strategic Highway Research Program
SMA	Stone Mastic Asphalt
SUPERPAVE/ SP	Superior Performing Asphalt Pavements
TCS	Tertiary Control Sieve
TxDOT	Texas Department of Transportation
VMA	Voids in Mineral Aggregates
VFB	Voids filled with Bitumen

Chapter 1 – Introduction

EXECUTIVE SUMMARY

Over 94% of the US 2.6 million miles of roads are surfaced with asphalt concrete (AC, *NAPA,2021*). The three (3) major mix components of an HMA mix are aggregates, asphalt binder, and additives. The use of the volumetric-based design methods has become more challenging due to the increasing use of recycled asphalt pavements (RAP) and recycled asphalt shingles (RAS), modified binders, warm mix asphalt additives, and rejuvenators. Hence, a shift toward a more fundamentally sound balanced mix design (BMD) concept is envisaged to produce asphalt concrete mixtures with acceptable performance. Aggregates account for about 90-95% of the HMA mixture by volume and hence have a crucial role in the durability and performance of the asphalt mixes (*Manjunath et. al., 2014*). The careful selection and proportioning of the aggregate gradation need to be evaluated from the existing gradation parameters and performance threshold perspective.

The major objective of this study is to develop a gradation optimization tool incorporating the various gradation parameters to be used to achieve a balanced Mix Design. A parameter called Primary Control Sieve Index (PCSI) has been carefully studied along with other gradation parameters to reduce the number of iterations carried out for a volumetric design with performance verification approach.

OBJECTIVE AND SCOPE OF WORK

The current mix design process involves a trial-and-error process to first obtain an optimum binder content based on the aggregate gradation and then check for the performance acceptance of the designed mix. Previous studies have shown that aggregate gradation and its related gradation parameters can be studied as empirical methods to optimize the mix (*Ahlrich et. al., 1996; Khosla, N.P. et.al., 2005; Vieira et. al., 2020).*

The following objectives were envisaged while carrying out this thesis work as a stepping stone toward a practical approach for designing Superpave Balanced mixes:

- **i.** Study and evaluate the current state of the art and practice of the aggregate gradation selection, gradation parameters, and BMD approaches for Superpave mixes.
- **ii.** Develop a practical computer-based tool based on the TxDOT mix design sheet to optimize the gradation based on user-defined parameters.
- **iii.** Use the gradation tool as a design and quality assurance (QA) tool for the mixes designed and constructed across Texas.
- **iv.** Study the effect of PCSI and other parameters on the volumetric and performance test results.

ORGANIZATION OF THESIS

Including this introductory chapter, this thesis contains six chapters. Chapter 2 includes an extensive literature review on the present use of the Superpave mix design, the different gradation parameter studies carried out in conjunction with the balance mix design approach. Chapter 3 outlines the experimental design plan adopted as a part of this study. Chapter 4 describes the development of the HMA gradation design tool along with the various modules in the program. Chapter 5 demonstrates the use of this gradation tool on various mixes from different districts across Texas with due consideration to the mix volumetrics, mixture performance, and gradation parameters. Chapter 6 contains the analysis of the findings from the case studies and links it to the different gradation parameters. Finally, Chapter 7 summarizes the key takeaway points and conclusions from the study, whilst also mentioning the important contributions and future recommendations.

Chapter 2 – Literature Review

IMPLEMENTATION OF SUPERPAVE DESIGN METHOD AND TECHNOLOGY

Superpave Design Method and Technology

The Superpave (SUperior PERforming Asphalt PAVEments) Mix design method was a product of the Strategic Highway Research Program (SHRP) program funded by the Federal Highway Administration (FHWA) to develop performance-based design specifications for long-lasting pavements (*MS-2, 2014*). The Superpave mix design system uses a gyratory compactor to prepare specimens so that the volumetric properties of asphalt concrete (AC) mixtures can be evaluated and their optimum binder contents can be determined (*Kennedy et al., 1994; MS-2,2014*).

The standard specification for Superpave Volumetric Mix Design is widely referred to as the mix design guide. The Superpave mix design includes performance grading of the bitumen considering the low and high air temperatures of the desired application location. The number of gyrations and mix types are selected based on the traffic levels of the roadway (*AASHTO M:323-2013*). Based on the AASHTO mix design method, the criterion for the design of Superpave mixes is dependent on the minimum voids in mineral aggregates (VMA) corresponding to the mix nominal maximum aggregate size (NMAS); the range of voids filled with bitumen (VFB) and the acceptable range of dust-to-binder ratio. These requirements are specific to a particular design equivalent single axle loads (ESALs) as can be seen in Table 2-1.

Table 2-1: Mix design criterion (Source- AASHTO M:323- 2013)

Design ESALs, million	Required Relative Density, % of G_{mm}			VMA, % Min. Nominal Maximum Aggregate Size, mm						VFB Range,	Dust-to-Binder Ratio Range
	$N_{initial}$	N_{design}	N_{max}	37.5	25.0	19.0	12.5	9.5	4.75		
< 0.3	≤ 91.5	96.0	≤ 98.0	11.0	12.0	13.0	14.0	15.0	16.0	70-80	0.6-1.2
0.3 to < 3	≤ 90.5	96.0	≤ 98.0	11.0	12.0	13.0	14.0	15.0	16.0	65-78	0.6-1.2
3 to < 10	≤ 89.0	96.0	≤ 98.0	11.0	12.0	13.0	14.0	15.0	16.0	65-75	0.6-1.2
10 to < 30	≤ 89.0	96.0	≤ 98.0	11.0	12.0	13.0	14.0	15.0	16.0	65-75	0.6-1.2

≥ 30	≤ 89.0	96.0	≤ 98.0	11.0	12.0	13.0	14.0	15.0	16.0	65-75	0.6-1.2

Mix Design Variables for Superpave Mixes

The Superpave mix design primarily focuses on the volumetric properties of the mix to reach the desired target lab-molded density. Several studies have focused on the understanding of various mix design variables that can be altered to improve the volumetric and mechanical properties of the mixes. Some of the major approaches followed are increasing the use of polymer modified binders, regressing air voids, decreasing compaction effort (N_{design}), targeting lower air voids, and increasing design VMA (*Tran, 2019*).

Departments of Transportation (DOTs) and the paving industry have renewed their focus on the incorporation of larger amounts of recycled materials to reduce the use of virgin asphalt binder. However, despite the benefits of using higher quantities of RAP and/or RAS, DOTs have restrictions on the amount of recycled materials and recycled binder ratio (RBR) in their specifications due to concerns with durability and long-term performance.

Copeland (2011) studied the state of practice for mixes containing RAP. In many cases, the performance of pavements with up to 30% RAP was found satisfactory. Safi et. al. (2019) characterized the lab and field performances of five recycled asphalt mixes. They observed that increasing asphalt content, bumping down the PG grade of binder, or both, counterbalanced the performance of mixes with high recycled material contents. Zaumanis et. Al. (2014) studied the inclusion of rejuvenators to improve the performance of AC layers with high RAP contents. They proposed a procedure to optimize the rejuvenator dose by incorporating the variability in RAP binder properties due to different source and aging conditions. Improvements in rutting, moisture susceptibility, and cracking properties from different rejuvenators and dosage have been observed in some studies (*Moghaddam et. al., 2016 and Song et. al.,2018*).

Barros (2018) conducted a detailed study on the effects of binder grade and source along with the RAP content and source. She observed that as higher-temperature PG grade of binder was used for the same gradation, the cracking, rutting and tensile properties of the AC mixes improved; whereas the change of binder source did not show a conclusive relationship to the mechanical properties of the mixes. An increase in the RAP content of the mix led to an increase in the stiffness based on the overlay test, and more rut-resistant mixes with higher tensile strengths as can be seen in Figure 2-1.

These studies can be used as guideposts to determine which design variables can be altered during the design process to achieve the relevant volumetric and mechanical properties.

PARAMETER	FEATURES	VOL	CFE	CPR	RRI	ITS
RAP Amount ↑	Dolomite RAP Source1	↔	↑	↔	↑	↑
	Granite RAP Source1	↔	↑	↔	↑	↑
PG Grade ↑	Dolomite	↔	↑	↔	↑	↑
	Granite	↔	↑	↔	↑	↑
Binder Source ≠	Dolomite 64-22	↔	↔	↔	≠	↔
	Dolomite 70-22	↔	≠	↔	≠	≠
RAP Source ↑	Dolomite RAP Source1	↔	↑	↔	↑	↑
	ELP Dolomite RAP Source 2	↔	↑	↑	↑	↑

Figure 2-1: Influence of mix design parameters on mechanical properties (from Barros, 2018)

REVIEW OF MIX DESIGN GUIDELINES FOR AGGREGATE GRADATION

Superpave Aggregate Gradation Selection

The maximum aggregate size of an asphalt mix is based on the type of application (surface/base layer) along with the lift thickness. Once the maximum aggregate size is fixed, the nominal maximum aggregate size (NMAS) is defined as one sieve size larger than the first sieve to retain more than 10 percent of the combined aggregates. Superpave mix design requires gradation controls (upper and lower thresholds through which the gradation should pass) for determining the aggregate blend of the mixture as demonstrated in Table 2-2 based on the NMAS of the mix.

Table 2-2: Aggregate gradation control points (Source: AASHTO M:323- 2013)

Sieve Size, mm	Nominal Maximum Aggregate Size—Control Points (% Passing)									
	25 mm		19 mm		12.5mm		9.5mm		4.75mm	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
37.5	100	-	-	-	-	-	-	-	-	-
25.0	90	100	100	-	-	-	-	-	-	-
19.0	-	90	90	100	100	-	-	-	-	-
12.5	-	-	-	90	90	100	100	-	100	-
9.5	-	-	-	-	-	90	90	100	95	100
4.75	-	-	-	-	-	-	-	90	90	100
2.36	19	45	23	49	28	58	32	67	-	-
1.18	-	-	-	-	-	-	-	-	30	55
0.075	1	7	2	8	2	10	2	10	6	13

The maximum density line (a.k.a. 0.45 power maximum density curve) is used as a base for designing gradations. Aggregate gradations are termed as coarse or fine gradations based on the position of the combined aggregate gradation curve passing above or below the primary control sieve size (PCS) as can be seen in Figure 2-2. In case the curve passes above the PCS control point as specified in Table 2-3, it can be termed as a fine gradation; otherwise, it is termed as a coarse gradation.

Table 2-3: PCS control point for mixture NMAS

Sieve Size, mm	Nominal Maximum Aggregate Size (NMAS)			
	25 mm	19 mm	12.5mm	9.5mm
Primary control sieve	4.75	4.75	2.36	2.36
PCS control, % passing	40	47	39	47

The shape of the gradation curve is known to influence the stability, durability, stiffness, workability, and moisture susceptibility of the asphalt mixtures and hence is termed as one of the most important factors, influencing its performance. (*Kandhal and Cooley, 2001*).

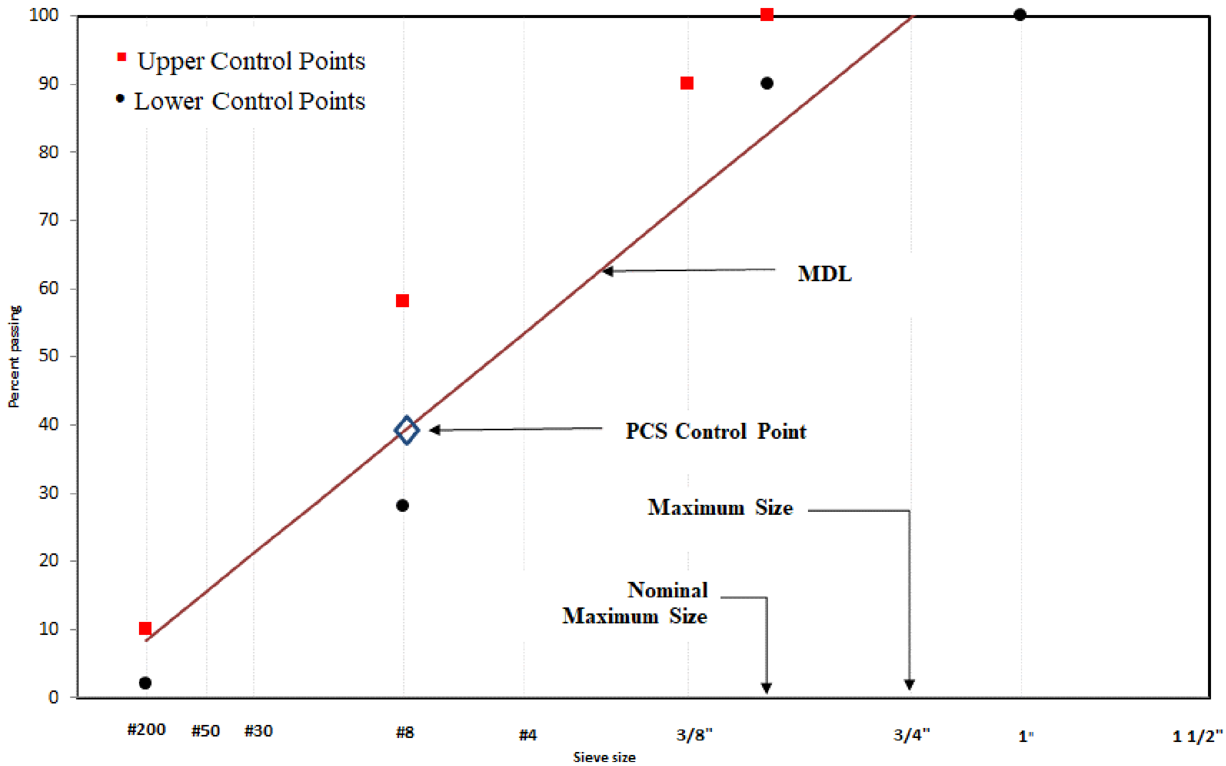


Figure 2-2: Gradation control points and PCS point for 12.5-mm NMAS

Review of Gradation Parameters

Several studies have been conducted to assess the influence of aggregate gradation on a mixture's mechanical performance. A novel method to develop and modify aggregate gradation blends known as the 'Bailey method' was developed by Robert D. Bailey of the Illinois Department of Transportation. The major objective during that time was to prepare durable and rut-resistant asphalt mixtures. This method involves a set of parameters that provide a good relationship between the voids in the aggregate skeleton and associated gradation. (*Vavrik, 2000; Vavrik et. al., 2002*). Graziani et. al. (2012) confirmed the validity of the Bailey method to design HMA mixes that fitted the European practices. They found that the compaction slope parameter, which is linked to mix workability, is related to the Bailey aggregate ratios. Horak et. al. (2017) modified the aggregate ratios used in the Bailey method to divide the gradation into three study areas namely macro, mini and micro aggregate skeletons, against the conventional coarse and fine method. These new ratios were used to relate porosity in the aggregate structure with the calculated permeability of the HMA mixtures. Figure 2-3 depicts the different sieve sizes and the associated gradation parameters/ratios that are described below:

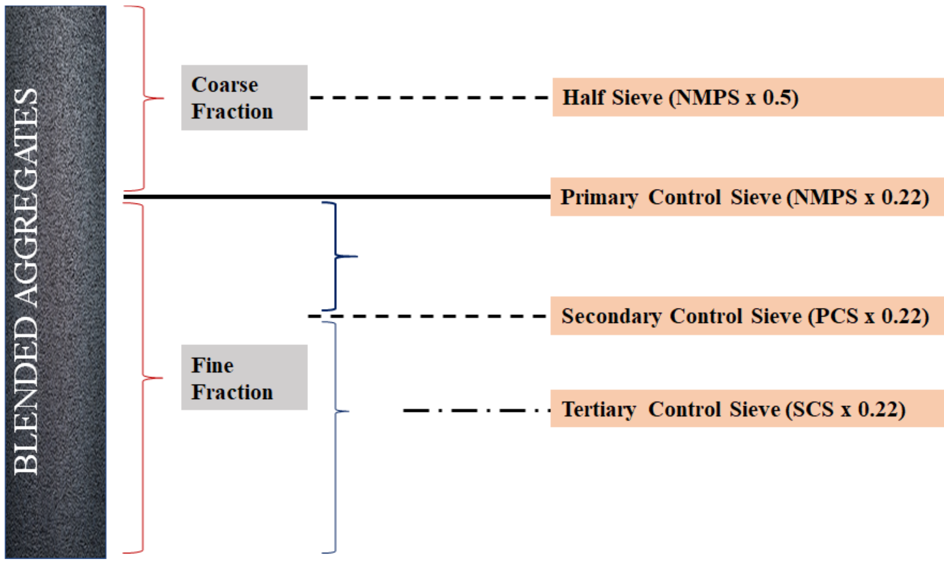


Figure 2-3: Visual representation of aggregate gradation parameters

i. **Primary Control Sieve (PCS):** The sieve size that differentiates between coarse and fine aggregate blends is called the Primary Control Sieve and is defined as:

$$PCS\ (mm) = 0.22\ \times NMAS(mm) \tag{I}$$

In Superpave mixes, the differentiating parameter of the fine and coarse aggregates is the 4.75mm sieve size; whereas, in the Bailey method, it is based on the NMAS of the mixture i.e., one sieve size larger than first to retain more than 10%.

ii. **Coarse Aggregate Ratio (CA):** The coarse fraction of the combined aggregate gradation can be evaluated using the Half Control Sieve (HCS), which is calculated based on NMAS of the mix from:

$$HCS\ (mm) = 0.5\ \times NMAS(mm) \tag{II}$$

The particles retained on the PCS are separated by the HCS in a way that particles retained on the HCS are termed as 'pluggers' and the once passing are termed as 'interceptors'. The ratio of these two factors is termed the Coarse Aggregate Ratio (CA) as defined as:

$$CA = \frac{Interceptors}{Pluggers} = \frac{P_{HCS} - P_{PCS}}{100 - P_{HCS}} \tag{III}$$

where P shows the percent passing the specified sieve size. With the increase in the CA ratio, the VMA of the mix generally increases and the workability decreases due to poor packing of the coarser fraction of the mix (*Graziani A. et. al., 2012*)

iii. **Fine Aggregate Coarse Ratio (FA_c):** Considering PCS as the NMAS for the fine fraction of the aggregate blend, the sieve that differentiates between the coarse and fine fractions of the fine aggregate is called Secondary Control Sieve (SCS) and is defined as:

$$SCS\ (mm) = 0.22\ \times PCS(mm) \tag{IV}$$

The ratio of percent passing the SCS sieve and PCS sieve is defined as the Fine Aggregate Coarse Ratio (FA_c) given by:

$$FA_c = \frac{P_{SCS}}{P_{PCS}} \tag{V}$$

iv. **Fine Aggregate Fine Ratio (FA_f):** Similar to the Secondary Control Sieve, the sieve that differentiates between the coarse and fine fractions contained between 0 and SCS is termed as Tertiary Control Sieve (TCS) and is defined as:

$$TCS\ (mm) = 0.22\ \times SCS(mm) \tag{VI}$$

The ratio of percent passing the TCS sieve and SCS sieve is defined as the Fine Aggregate Fine Ratio given by:

$$FA_f = \frac{P_{TCS}}{P_{SCS}} \tag{VII}$$

With the increase in the fine aggregate ratios (FA_c and FA_f), the VMA and air voids of the mix generally decrease, while the workability increases due to better packing potential with an improved fine aggregate fraction of the mix (*Graziani et. al., 2012*).

Table 2-4 summarizes the different sieve sizes corresponding to the gradation parameters based on the NMAS of the mix.

Leiva and West (2021) proposed a gradation parameter known as Primary Control Sieve Index (PCSI) based on the primary control sieve, which would help delineate the mixes more quantitatively than the conventional coarse-fine gradations. The study tried to correlate Bailey's parameters to the PCSI values. They observed that a lower CA ratio corresponded to positive PCSI, whereas a higher CA ratio corresponded to negative PCSI values. PCSI was also evaluated as a predictor parameter for various mix properties like VMA, compactability, permeability, and texture. They also observed that for positive PCSI values, compactability increased, permeability decreased, and texture decreased.

Table 2-4: Gradation control points for mixture NMAS

NMAS (Sieve No.)	NMAS (mm)	PCS (0.22*NMAS)	HS (0.5*NMAS)	SCS (0.22*PCS)	TCS (0.22*SCS)
No. 4	4.75	1.05 (1.18)	2.38 (2.36)	0.26 (0.30)	0.07 (0.075)
3/8	9.50	2.09 (2.36)	4.75 (4.75)	0.52 (0.60)	0.13 (0.15)*
1/2	12.50	2.75 (2.36)	6.25 (6.35)*	0.52 (0.60)	0.13 (0.15)*
3/4	19.00	4.18 (4.75)	9.50 (9.50)	1.05 (1.18)	0.26 (0.30)
1	25.00	5.50 (4.75)	12.50 (12.50)	1.05 (1.18)	0.26 (0.30)
1 1/2	37.50	8.25 (9.50)	18.75 (19.00)	2.09 (2.36)	0.52 (0.60)

* In case the sieve sizes not available can be interpolated based on nearest sieve sizes

The Primary Control Sieve Index (PCSI) is defined as the difference in percentage passing between the given gradation and the point on the maximum density line at the Primary Control Sieve (PCS). This parameter is used to characterize the extent of fineness/coarseness of the HMA gradation. Negative PCSI values denote a coarse gradation (below the density line, whereas positive PCSI values denote a finer gradation as shown in Table 2-5 and Figure 2-4. The recommended values by Vavrik, et. al. (2002) for various gradation parameters are given in Table 2-6.

Table 2-5: PCS control sieve and point for mixture NMAS (from Leiva and West, 2021)

NMAS (Sieve No.)	NMAS (mm)	PCS	PCS % Passing at MDL
#4	4.75	1.18	39
3/8	9.50	2.36	47
1/2	12.50	2.36	39
3/4	19.00	4.75	47
1	25.00	4.75	40
1 1/2	37.50	9.50	47

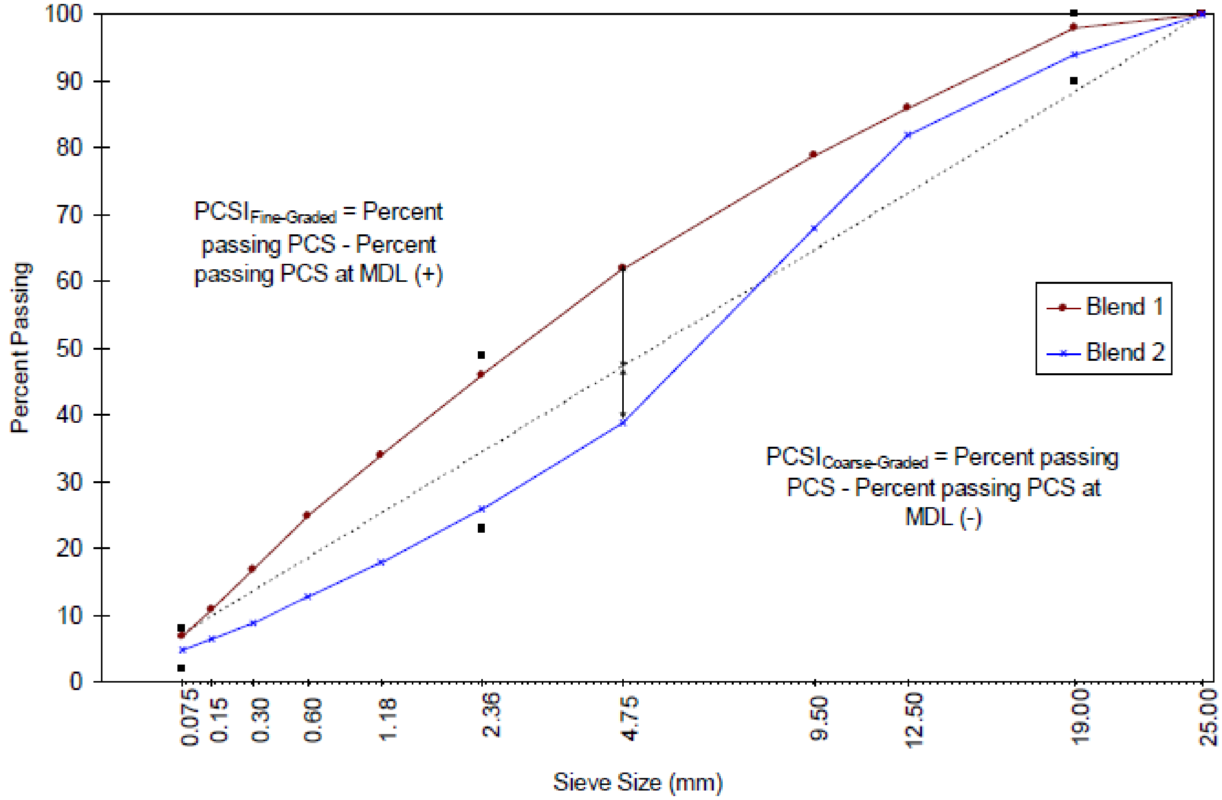


Figure 2-4: Illustration of PCSI for 19.0 mm NMAS gradations (Source: Leiva and West, 2021)

Table 2-6: Gradation parameters and recommended range (Source: Vavrik et al., 2002)

Parameter	Recommended Range
CA	NMAS: 4.75 (0.30 to 0.45) NMAS: 9.50 (0.40 to 0.55)- Superpave and (0.15-0.3)- SMA NMAS: 12.5 (0.50 to 0.65) - Superpave and (0.25-0.4)- SMA NMAS: 19.0 (0.60 to 0.75) - Superpave and (0.35-0.5)- SMA NMAS: 25.0 (0.70 to 0.85)
FA_c	0.35-0.50
FA_f	0.35-0.50
PCSI	Positive Values- Fine Gradation. Negative Values- Coarse Gradation.

State of Art and Practice

Many researchers have studied the effects of gradation on the volumetric and mechanical properties of asphalt mixes. Ahlrich (1996) evaluated the effect of aggregate gradation on the permanent deformation of mixes. He determined that, along with the shape and texture of the aggregate, HMA rutting performance is influenced by the combined aggregate gradation shape that controls the matrix void structure. Wu et. al. (2019) indicated that changes to aggregate characteristics like aggregate gradation could be made to improve both the rutting and fatigue cracking performance of a mix.

As the Bailey method was developed primarily using aggregates from Illinois, *Thompson (2006*) studied the same approach on dense-graded mixes using aggregate sources across Oregon. They observed that the design approach incorporating the bulk density of the aggregates resulted in fine mixes rather than the conventional 'S' shaped gradation curve. They concluded that the Bailey method parameters could be used as a useful tool for controlling the gradation; however, they did not provide quantitative relations with VMA and other volumetric properties. Based on the various mixes studied, they observed that fine aggregate blends played a critical role in improving mix rutting performance. *Daniel and Rivera (2009*) carried out a similar study on six typical mixes found in New Hampshire. The rutting performance of the conventional mixes and mixes based on the Bailey method's parameters were evaluated. They recommended that the Bailey method be used as an evaluation and guidance tool during the mix design process.

Currently, TxDOT does not have a specification to exclusively design aggregate gradation for HMA mixtures. Their method of designing Superpave mixes (Tex-344 and SS-3077) closely follows the AASHTO method of Superpave mix design. The quality of aggregates used is based on a surface aggregate classification (SAC) provided by the Aggregate Quality Monitoring Program (AQMP). The premium aggregate sources like granite are termed as SAC A aggregates whereas aggregate sources like that of limestone-dolomite are considered as SAC B. Several research studies have been carried out in Texas to study the effect of gradation on mixture properties. Garcia et al. (2017) changed the coarse and fine portions of mixes with two different aggregates to study the influence of volumetric and stiffness parameters. They found that a balance of coarse and fine aggregates is necessary to design mixes with acceptable volumetric properties. Vieira et. al. (2020), based on a laboratory study, suggested that the optimization of the aggregate gradation was a promising approach to formulate a balanced mixture with adequate stability and durability.

BALANCED MIX DESIGN

The Balanced Mix Design (BMD) concept is defined by the FHWA Expert Task Group as "an 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" (*Aschenbrener, 2016*).

Mix Design Approaches

The BMD approach incorporates two or more performance tests based on the critical forms of distress expected in a specific pavement project. Ideally, an asphalt mixture must have a balance of stability (in the form of rutting) and durability (in the form of fatigue cracking) to perform well in the field. The following three main BMD approaches have been proposed as depicted in Figure 2-5 (*West, 2018*):

1) Volumetric Design with Performance Verification approach consists of a commonly used volumetric-based design to select the optimum asphalt content (OAC) followed by performance testing of the asphalt mixture. This approach, which is a trial-and-error process until the performance criteria are met, is the most commonly used approach amongst various agencies.
2) Performance Modified Volumetric Design approach is based on preliminarily selecting the asphalt content based on the volumetric analysis. If performance requirements are not satisfied, the asphalt content is modified to meet the performance requirements since the final asphalt mixture does not need to meet all volumetric requirements.
3) Performance-Based Design approach is based on selecting the OAC for an asphalt mixture based on the performance test results of the mix at different asphalt contents.

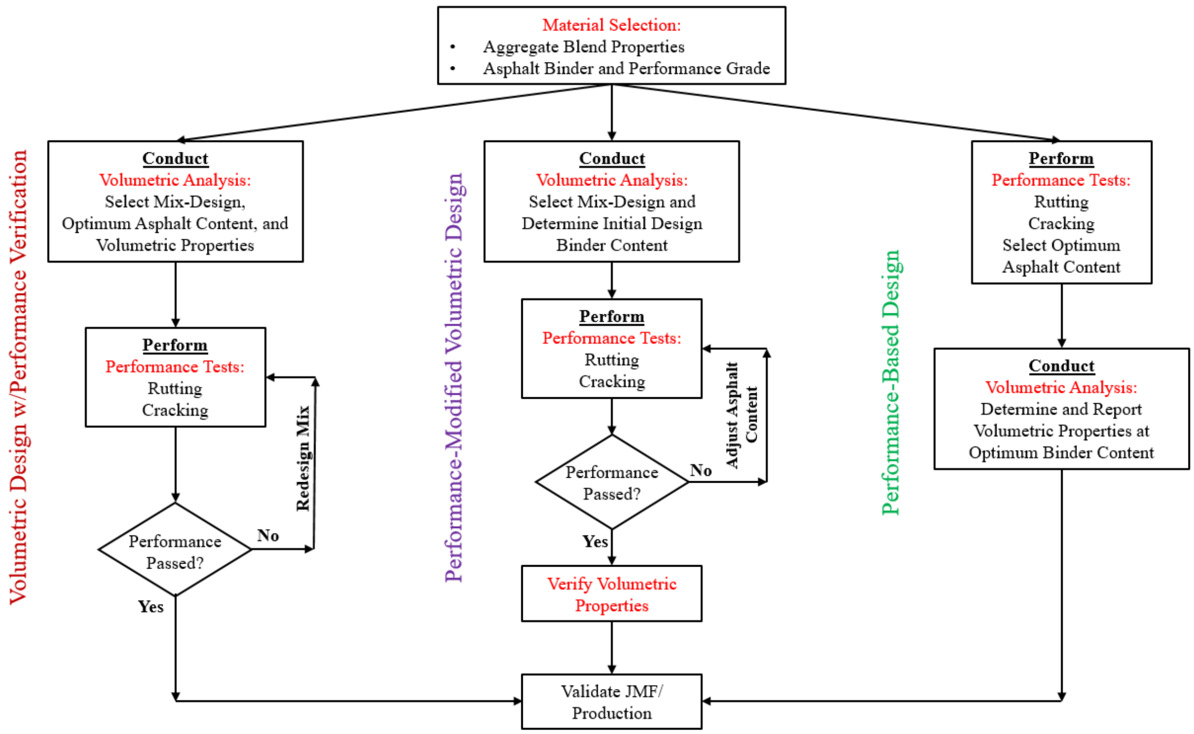


Figure 2-5: Balanced mix design approaches (Source: West, R., 2018)

Performance Test Methods for Asphalt Mixtures

The performance tests are a part of the Balanced Mix Design approach. The selection of the performance tests is based on the prevailing pavement distresses in the location. The performance tests should have a strong correlation to the field performance, should be feasible to carry out, and should be cost-effective.

Texas Overlay Tester (OT) Test

Based on the TxDOT specifications, the Overlay tester (OT) per test procedure Tex-248-F is used to evaluate the cracking potential of the mix. The test is conducted in a displacement control mode at a loading rate of one cycle per 10 sec. with the sliding platen following a cyclic triangular waveform at a test temperature of 77°F (25°C). The OT specimens are nominally 5.9 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) and the critical fracture energy (CFE) parameters are obtained from the OT test as output. As per the current TxDOT specifications, the acceptance limit for CPR and CFE are selected as 0.45(maximum) and 1(minimum), which is calculated by testing three (3) specimens for each mix.

Hamburg Wheel Tracking (HWT) Test

The HWT test is conducted to determine the permanent deformation and moisture susceptibility of AC mixtures per Tex-242-F. 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 ± 2ºF (50 ± 1°C) is used to condition the specimens. The specimens are nominally 5.9 in. (150 mm) in diameter and 2.4 in. (62 mm) in height. As per the testing protocol, two specimens (1 set) are tested for each mix. The main output parameters from the HWT test are the number of passes and rut depth. Wen et al. recommended rutting resistance index (RRI) for evaluating the HWT results using Equation (VIII) (Wen et. al.,2016):

$$RRI = N\ x\ (1 - RD) \quad \text{(VIII)}$$

where N is the number of cycles and RD is the rut depth (in.). The minimum RRI requirement for PG binders is different based on their respective minimum number of passes as can be seen from Table 2-7. For convenience, RRI is normalized with respect to the minimum RRI for comparing mixes with different PG binders. Normalized RRI (NRRI) is calculated from Equation (IX) and NRRI of unity or greater means an acceptable mix in terms of rutting:

$$NRRI = \frac{Actual\ RRI}{Minimum\ RRI\ for\ Specified\ PG} \quad \text{(IX)}$$

Table 2-7: Hamburg Wheel Tracking (HWT) test requirements

High-Temperature Performance Grade	Minimum Number of Passes	Minimum RRI
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

IDEAL CT Test

For quality control, the indirect tensile asphalt cracking test (IDEAL-CT) per Tex-250-F is implemented by TxDOT, to evaluate stiffness properties of the mix and also as a quality control tool. The IDT specimens, which are nominally 5.9 in. (150 mm) in diameter and 2.4 in. (62 mm) in height, are placed in an environmentally 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 and the minimum load reaches 22 lb. During the testing period, the time, load, and displacement at a minimum sampling rate of 40 data points per second are recorded and Four (4) specimens need to be tested for each mix.

The work of failure (W_f), as the area under the load versus displacement curve, the cross-sectional area of the specimen are used to calculate the failure energy (G_f) using the formula:

$$G_f = \frac{W_f}{Dt} \quad \text{(X)}$$

where t and D, are the thickness and diameter of the specimen. The cracking tolerance index (CT_{Index}) is calculated using the parameters obtained using the load-displacement curve (Zhou et. al., 2016).

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

where, $|m_{75}|$ is the absolute value of the post-peak slope and l_{75} is the associated displacement at 75% of the peak load located after the peak. The same test results can be used to analyze the Indirect Tensile Strength (IDT) as well.

Performance Space Diagram

A performance interaction diagram (Figure 2-6) is formulated with the cracking and rutting parameters to analyze the characteristics of asphalt mixtures. The performance interaction diagram provides a three-dimensional analysis of the cracking, rutting, and strength properties of the mixes. The CPR from the OT test is plotted on the abscissa of the performance diagram with a corresponding preliminary acceptance limit of 0.45, while NRRI from the HWT test is plotted on the ordinance with an acceptable limit of 1.0. IDT and CT_{Index} values are plotted as data labels for a quality control reference.

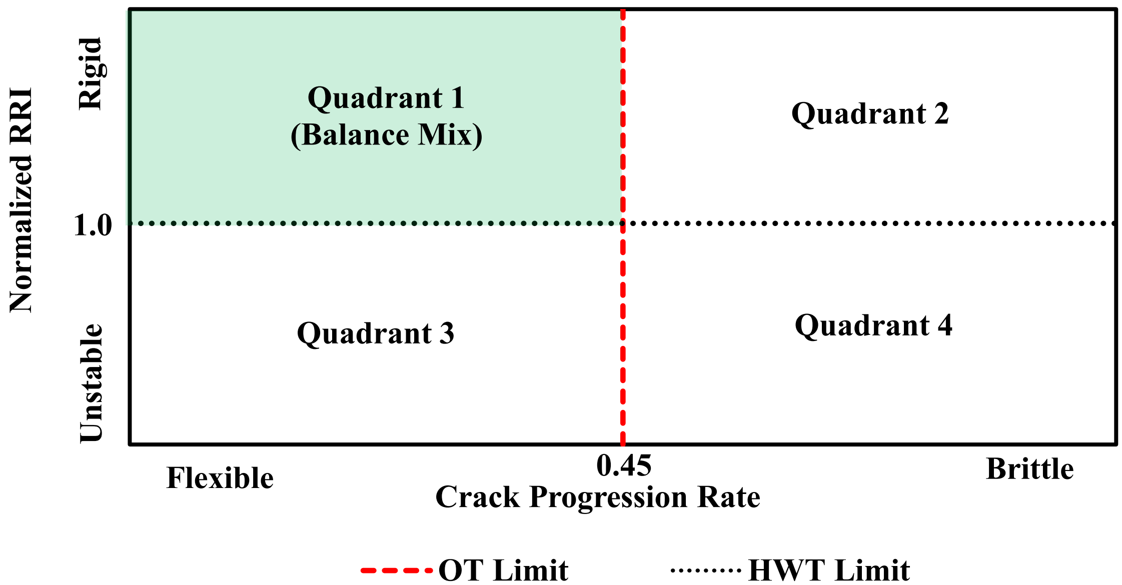


Figure 2-6: Performance space diagram for balanced mix design

The performance of the evaluated mixes can be preliminarily divided into the following four 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).

Any AC mix with properties that plots within the green shaded area in Figure 2-6 is considered acceptable and can be termed as a balanced mix.

RESEARCH GAP

Although it is known from the previous studies that the Bailey method parameters and PCSI provide empirical guidelines or predictor variables to manage the volumetric and compactability properties of the mix, their relationship to mixture performance in a balanced mix design approach has not been extensively evaluated. This study attempts to address this limitation, while still moving towards a BMD design approach that might be used by TxDOT professionals.

Chapter 3 – Experiment Design and Research Methodology

This study expands on the work presented in Garcia et. al. (2020). A laboratory investigation was carried out on several asphalt mixes, especially Superpave mixes, focusing on the selection of aggregate gradation used across Texas. These mixes were designed based on the BMD process following a volumetric design with performance verification approach. The outcome of this experimental work was used to relate the volumetric and mechanical properties and the gradation parameters.

As a part of the study, 15 asphalt concrete mixtures were evaluated from five test projects (different aggregate and binder sources) spread across Texas. These mixes were either designed by the research team or were evaluated based on the designs carried out by the contractors in consultation with TxDOT. Information about the mixture types, binder PGs, and aggregate types are summarized in Table 3-1.

Table 3-1 Summary of overall project description

Parameters		Project 1	Project 2	Project 3	Project 4	Project 5
Project Description	Number of Mixes	3	3	3	4	2
	Mix Types	SP-D	DG-C SP-C	SP-D	SMA- D SP-C	SP-C
	Binder Grade	PG 76-22 PG 70-22	PG 70-22	PG 70-22 PG 64-22	PG 76-22 PG 70-22	PG 64-22
	RAP, % (Range) RAS, % (Range)	0-11% 0-3%	0-25.2% -	15-30% -	0-25% -	20-30% -
	Additive (Yes/No)	No	Yes	Yes	Yes	No
	Aggregates Types	Sandstone, Gravel	Igneous; Limestone -Dolomite	Limestone -Dolomite	Igneous	Gravel; Sandstone

Figure 3-1 displays the flow chart outlining the overall scope of work for the laboratory evaluation phase of this study. The mixes were either designed or evaluated as per TxDOT special specification SS-3074: Superpave Mixtures – Balanced Mix Design. The design process is based on selecting the optimum asphalt content (OAC) using design gyrations and targeting a 4% air void content. A Superpave gyratory compactor was used to produce the lab-molded specimens.

Throughout this study, local aggregates, RAP, and binders were used. The gradation parameters like NMAS, PCS, CA, FA_c, FA_f, and PCSI were also documented.

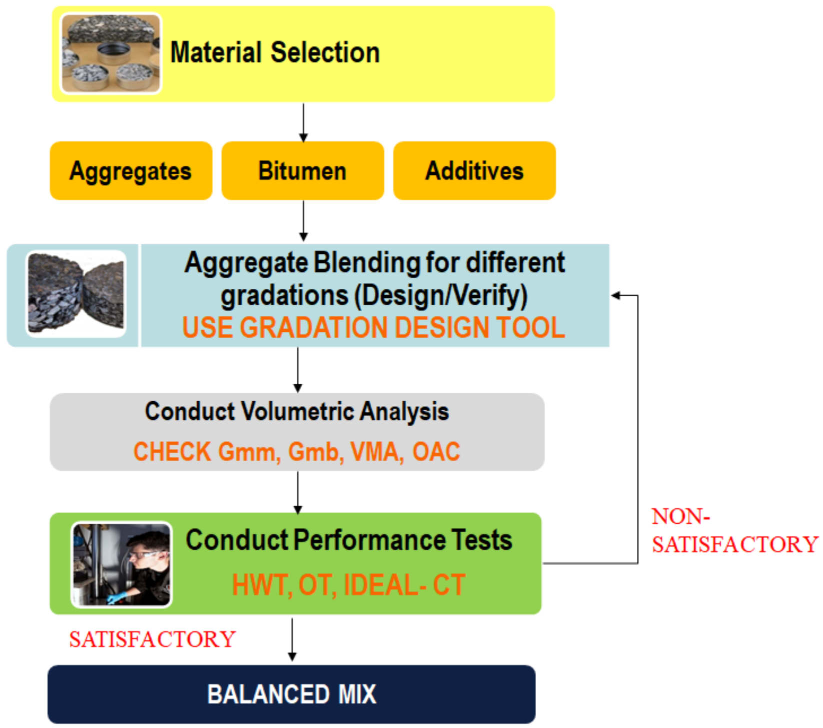


Figure 3-1: Flow chart showing project methodologies

Based on the current TxDOT specification, the maximum allowable RAP is 35% with or without up to 5% RAS as long as the performance is not compromised. The volumetric properties such as the optimum asphalt content (OAC, %); voids in mineral aggregates (VMA, %); dust/asphalt binder ratio; recycled binder ratio (RBR%); bulk specific gravity (G_{mb}) and theoretical maximum specific gravity (G_{mm}) were determined for each mix. Once the major volumetric properties were met, the mix was tested for its mechanical properties.

The performance tests and analysis methods used are depicted in Figure . For the design stage, the Overlay tester (OT) and the Hamburg wheel tracking (HWT) test were used to balance the cracking and rutting potentials of the mix, respectively. For quality control, the indirect tensile asphalt cracking test (IDEAL-CT) was implemented. Based on the TxDOT specifications, triplicate specimens were tested with OT, duplicate specimens with HWT, and four replicate

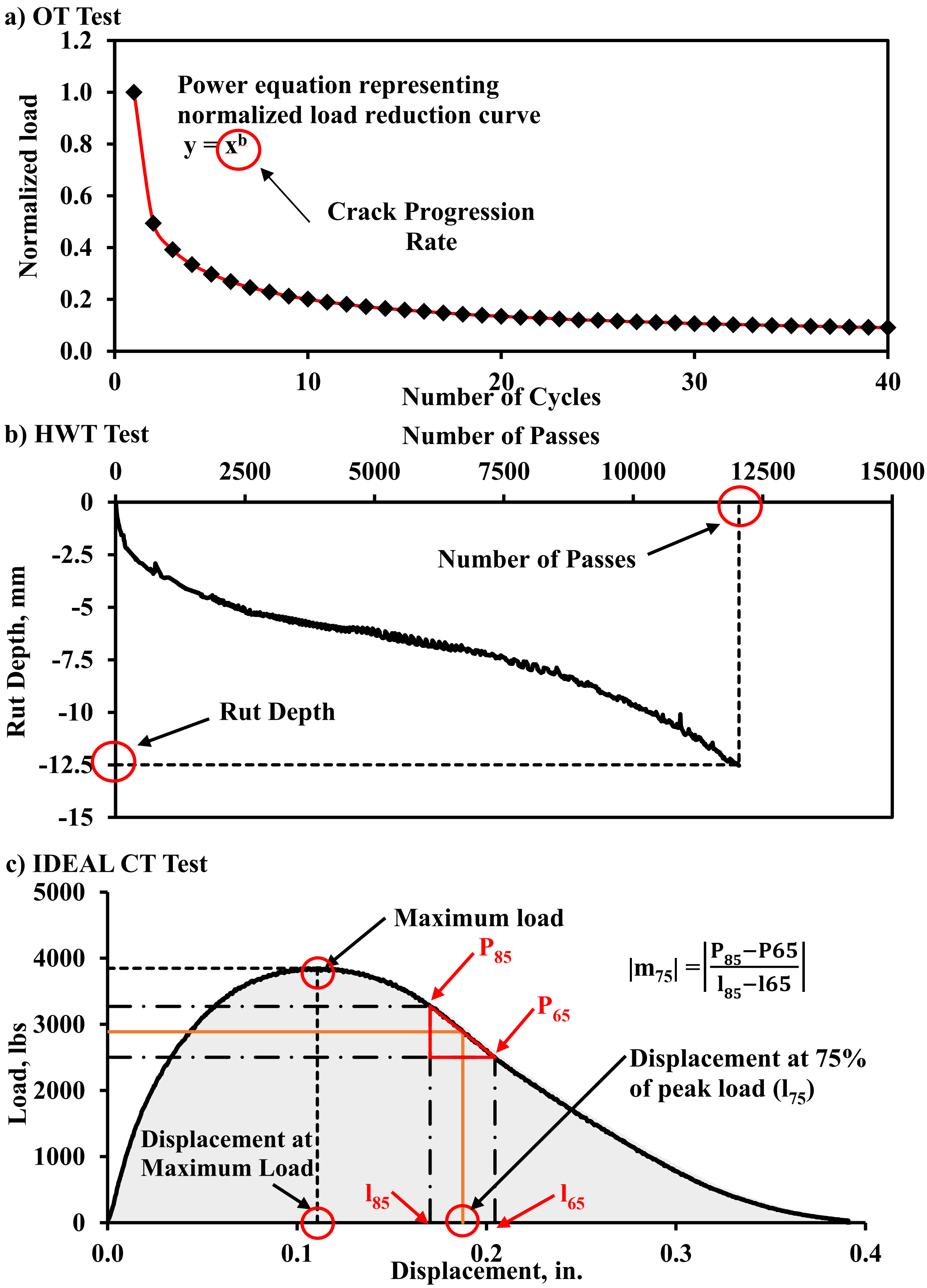


Figure 3-2 Performance tests and analysis methodologies

specimens for IDT. These results were superimposed on the performance space diagram to check whether the mix is balanced. The acceptance thresholds selected for the performance parameters associated with these tests are provided in Table 3-2. In cases when the mix failed the performance criteria, the mix design was repeated by changing the relevant mixture gradation.

Table 3-2: Acceptance thresholds for performance tests to be carried out

Test	**Criteria**	**Threshold Value**
HWT	Normalized Rut Resistance Index, Minimum	1
OT Test	Crack Progression Rate, Maximum	0.45
	Critical Fracture Energy (CFE), in.-lb/in.^{2}, Min	1
IDEAL CT Test	IDT Strength	85-200 psi
	CT_{Index}	-NA-

Chapter 4 – 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 B.

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 4-1, the tool contains two basic modules for Design and Approval.

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

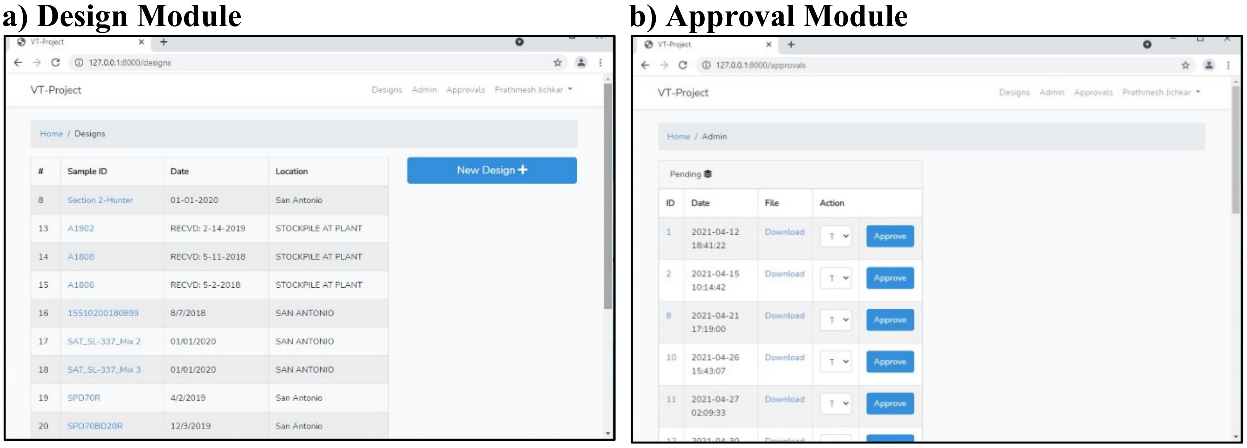


Figure 4-1 Program modules

Design Module

The design module is the first step of the process after logging into the program. Figure 4-2 shows the typical screen that the designer can see to create/ upload an existing mix design sheet.

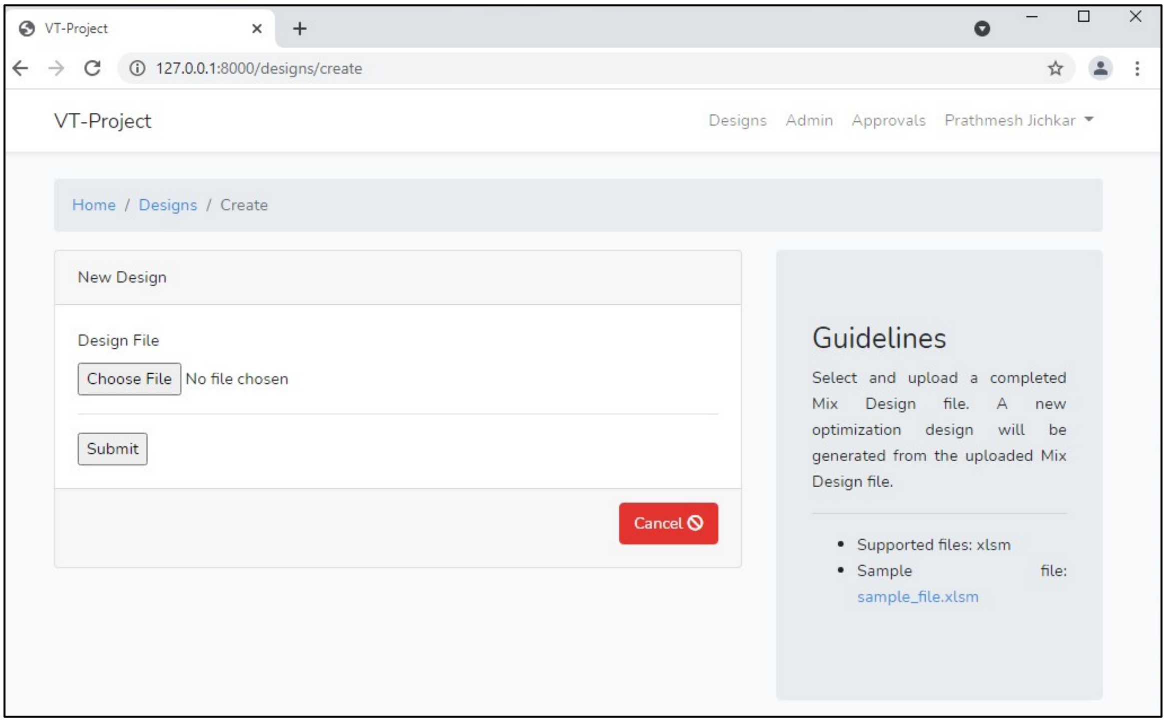


Figure 4-2 Creating a new design for optimization using TxDOT design template

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 4-3 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.
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 4-3), and individual

bin gradations are obtained as shown in Figure 4-3. The bins that are not to be included as a part of the optimization process should be check marked.

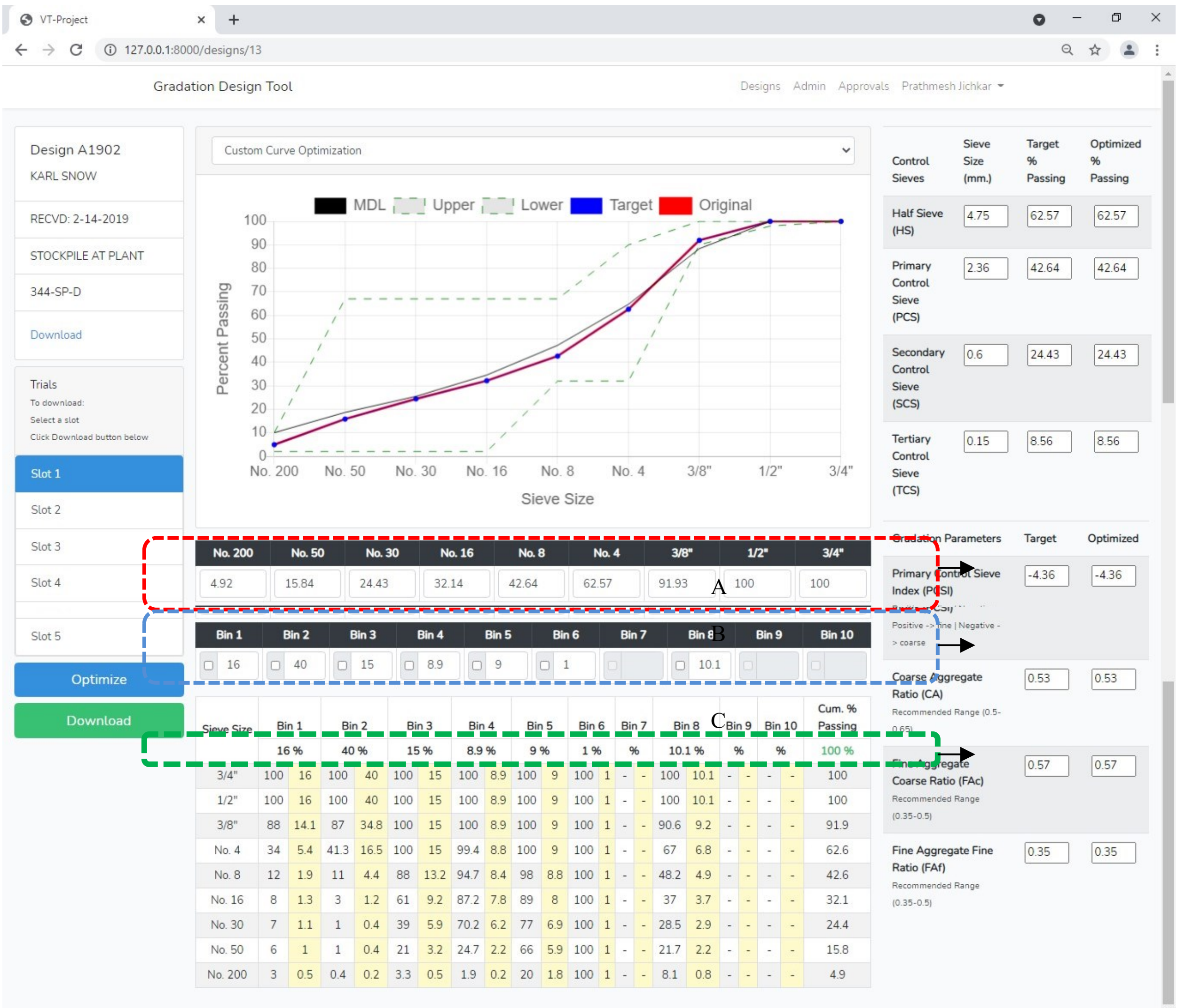


Figure 4-3 Gradation design program with uploaded mix design to be optimized

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 4-3).

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 4-3). 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).

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.

Chapter 5 – 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 Chapter 3.

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 5-1.

Table 5-1 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 A. From the plot of the combined gradation in Figure 5-1, 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 5-2. 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).

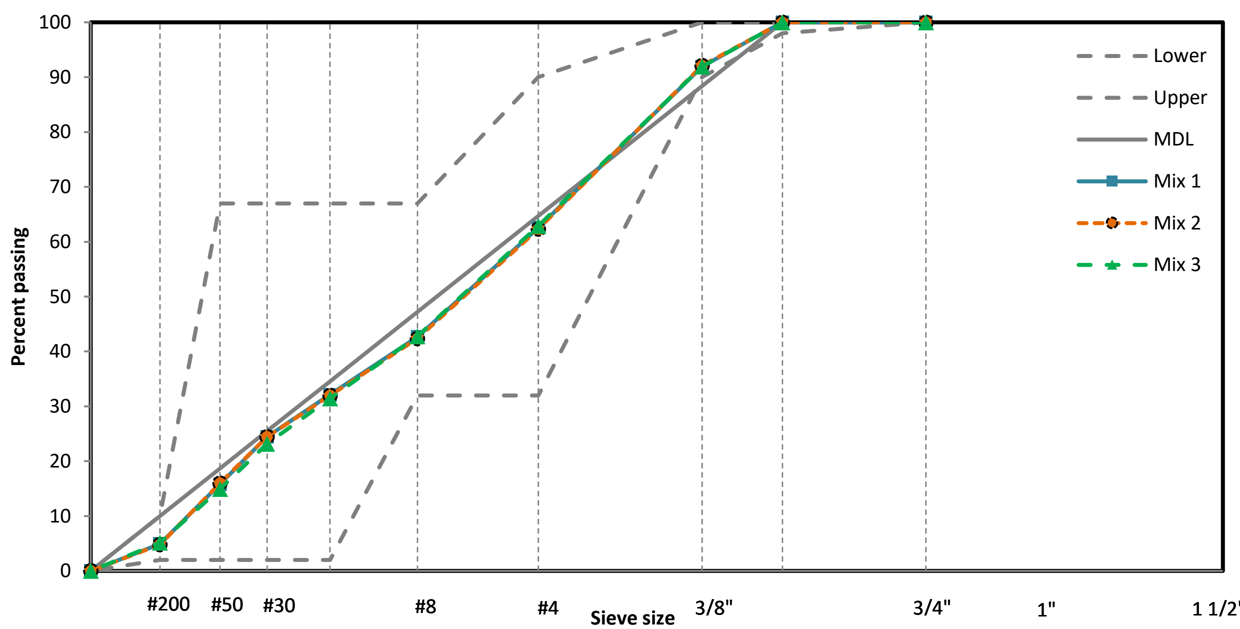


Figure 5-1 Particle size distribution of test section 1 mixtures

The mechanical properties, in terms of OT, HWT, and IDT tests, are summarized in Table 5-3. For better visualization of the results towards the balanced mix design approach, Figure 5-2 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 5-2: 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 5-3: 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%

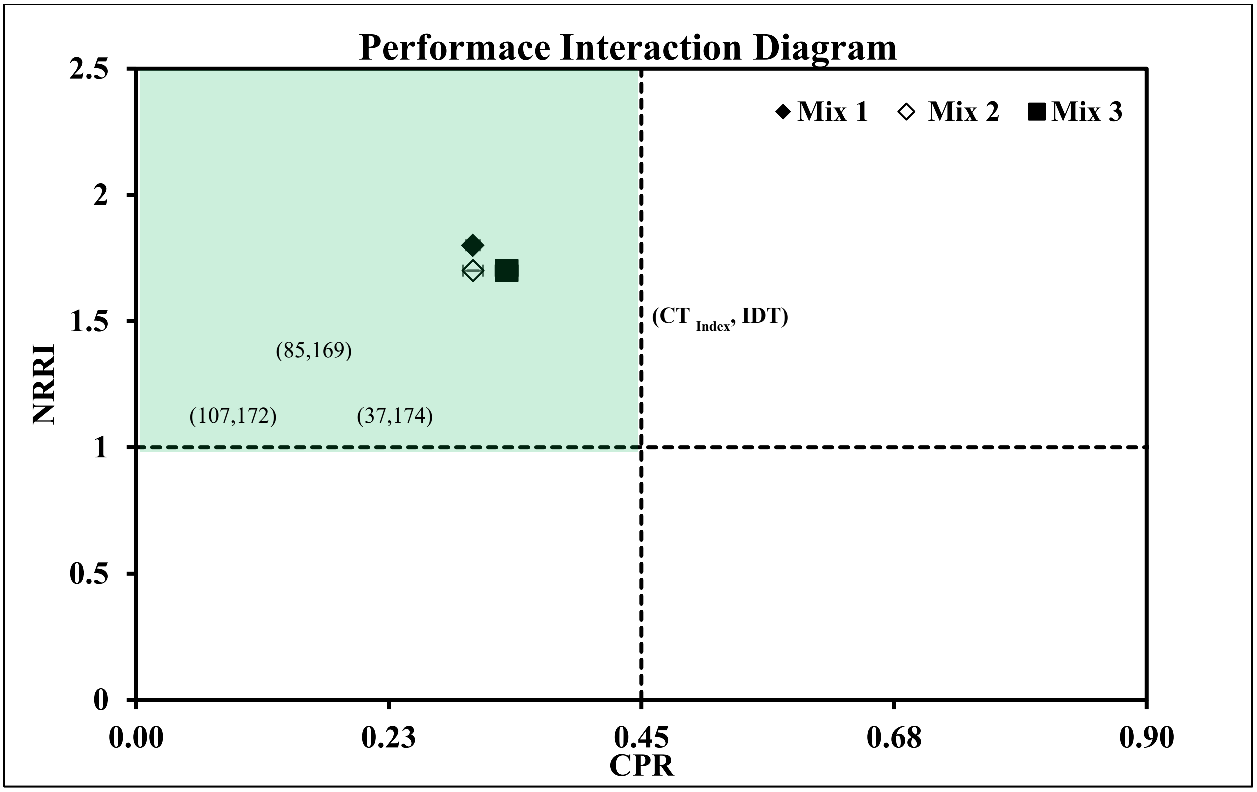


Figure 5-2: Performance interaction diagram for test section 1 mixtures

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 5-4. 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 A. As shown in Figure 5-3, 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 5-5. 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 5-4 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

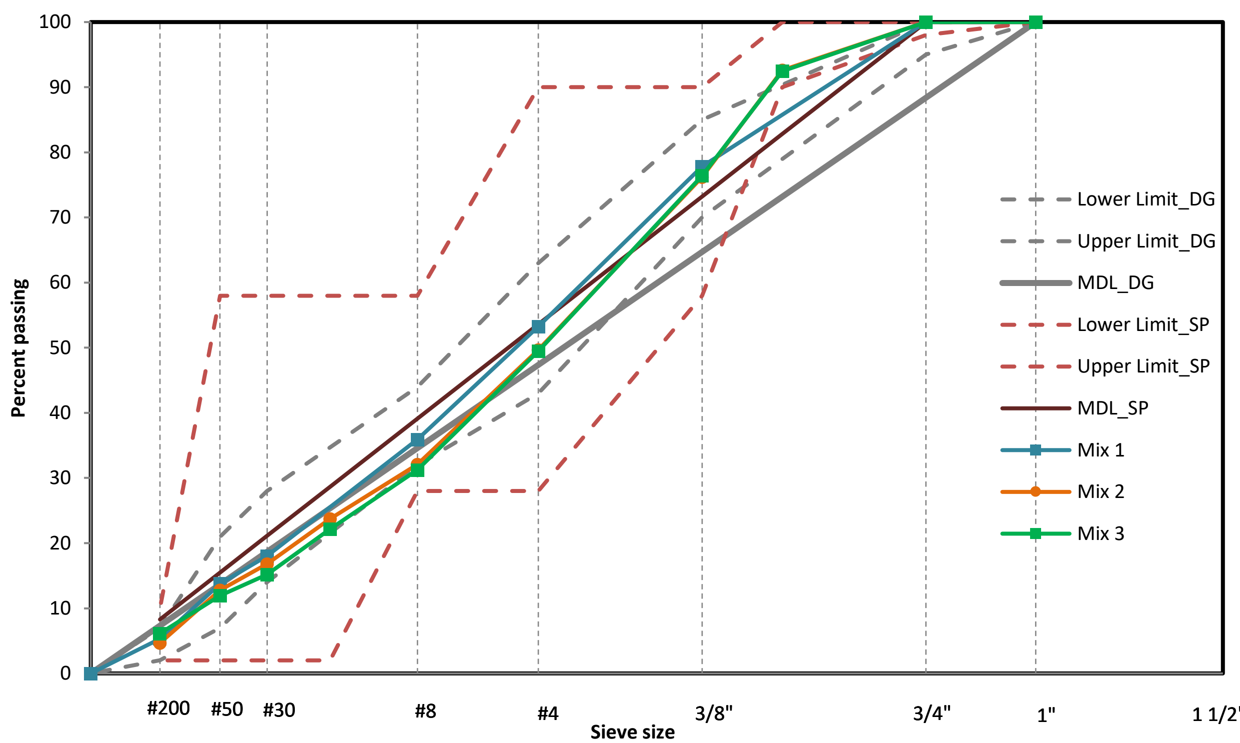


Figure 5-3 Particle size distribution of test section 2 mixtures

Table 5-5: 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 5-6 and Figure 5-4. 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 5-6: 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%

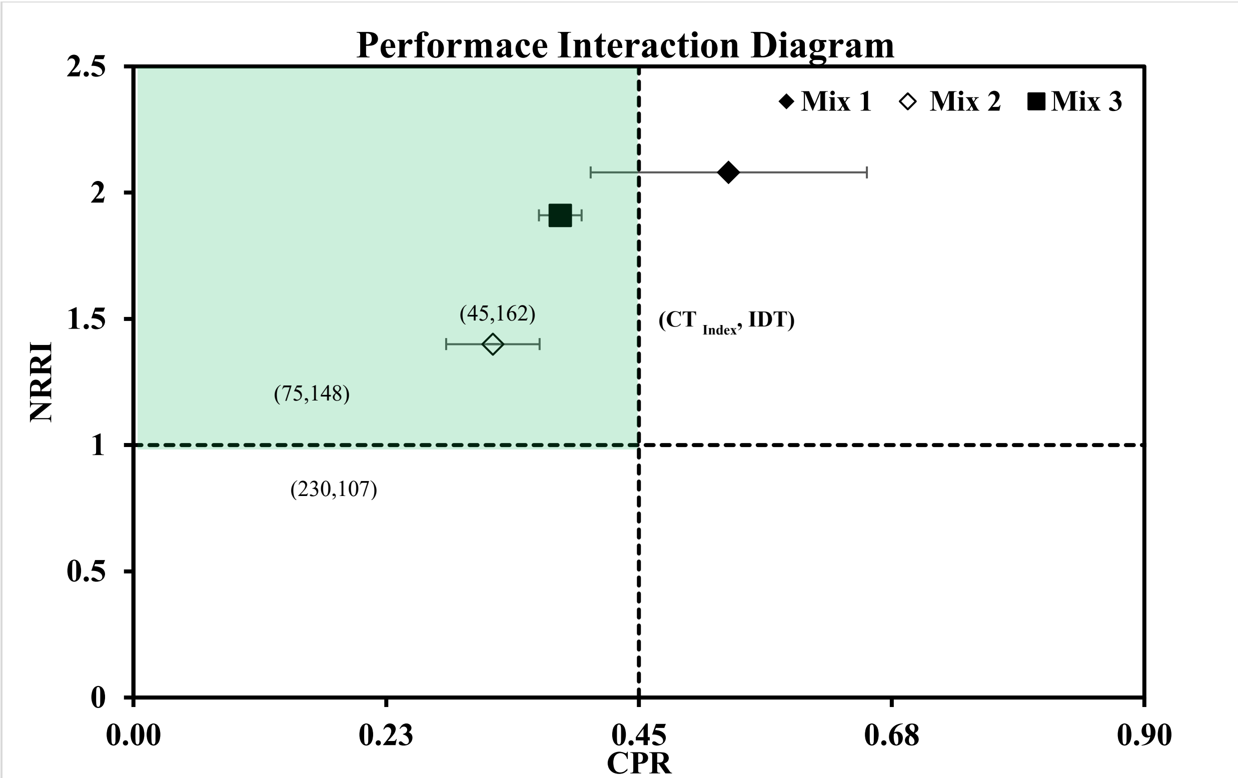


Figure 5-4 Performance interaction diagram for test section 2 mixtures

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 5-7. 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 A. From the combined gradations in Figure 5-5, 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.

Table 5-7 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

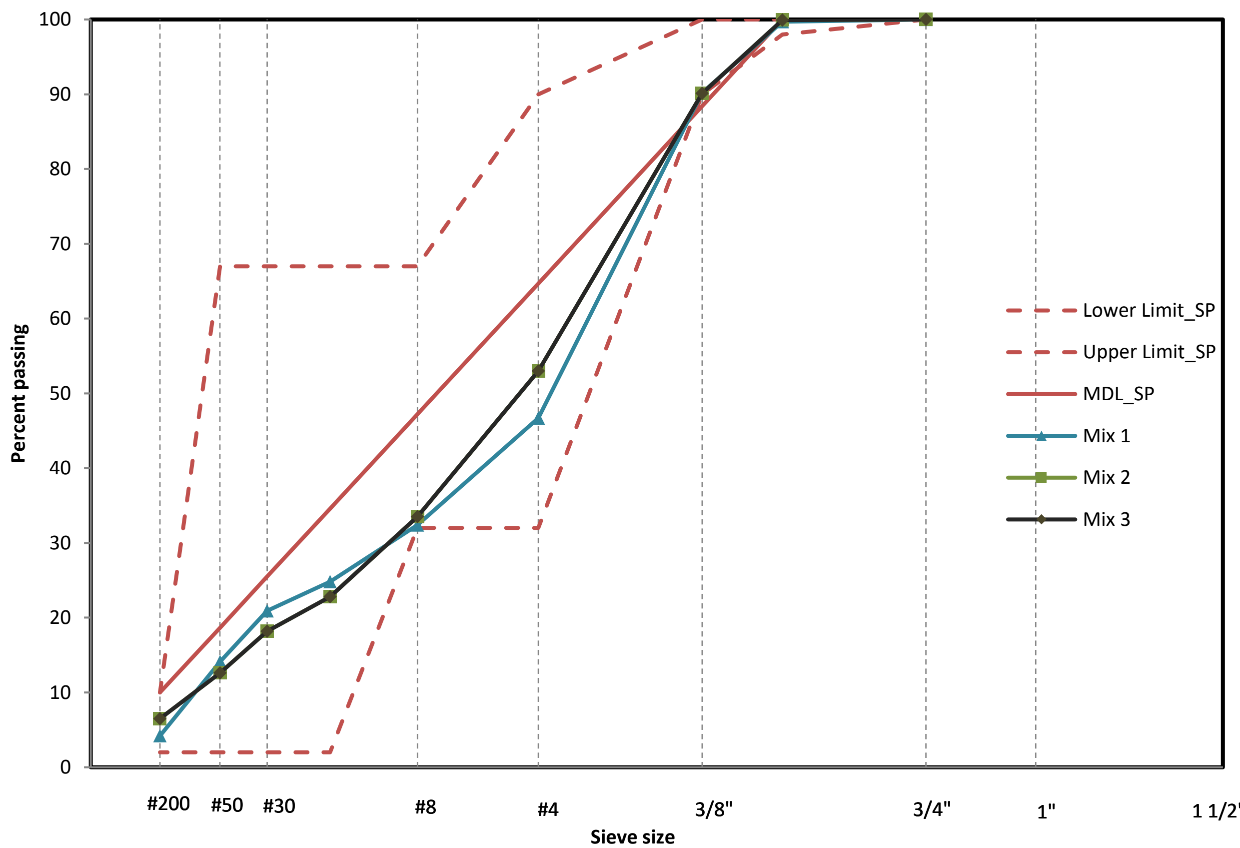


Figure 5-5 Particle size distribution of test section 3 mixtures

The gradation parameters, along with the volumetric properties of the mixes are summarized in Table 5-8. The CA parameters were above the desired upper limitsand 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.

Table 5-8: 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

The mechanical properties of the three mixes are summarized in Table 5-9 and Figure 5-6. 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 5-9: 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%

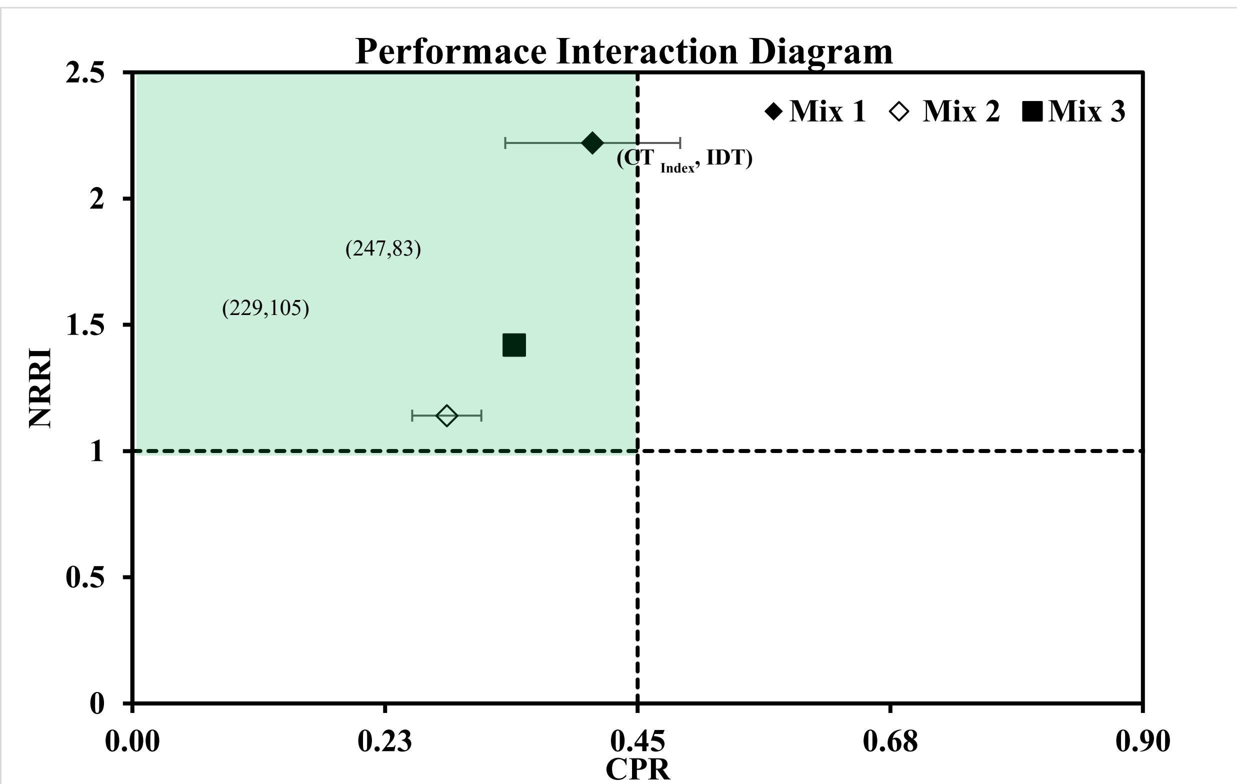


Figure 5-6: Performance interaction diagram for test section 3 mixtures

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 5-10. The major difference among the mixes is the RAP contents. The aggregates used for this study were SAC A aggregates.

Table 5-10: 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 A. As shown in Figure 5-7, 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 5-11. 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 5-12 and Figure 5-8. 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.

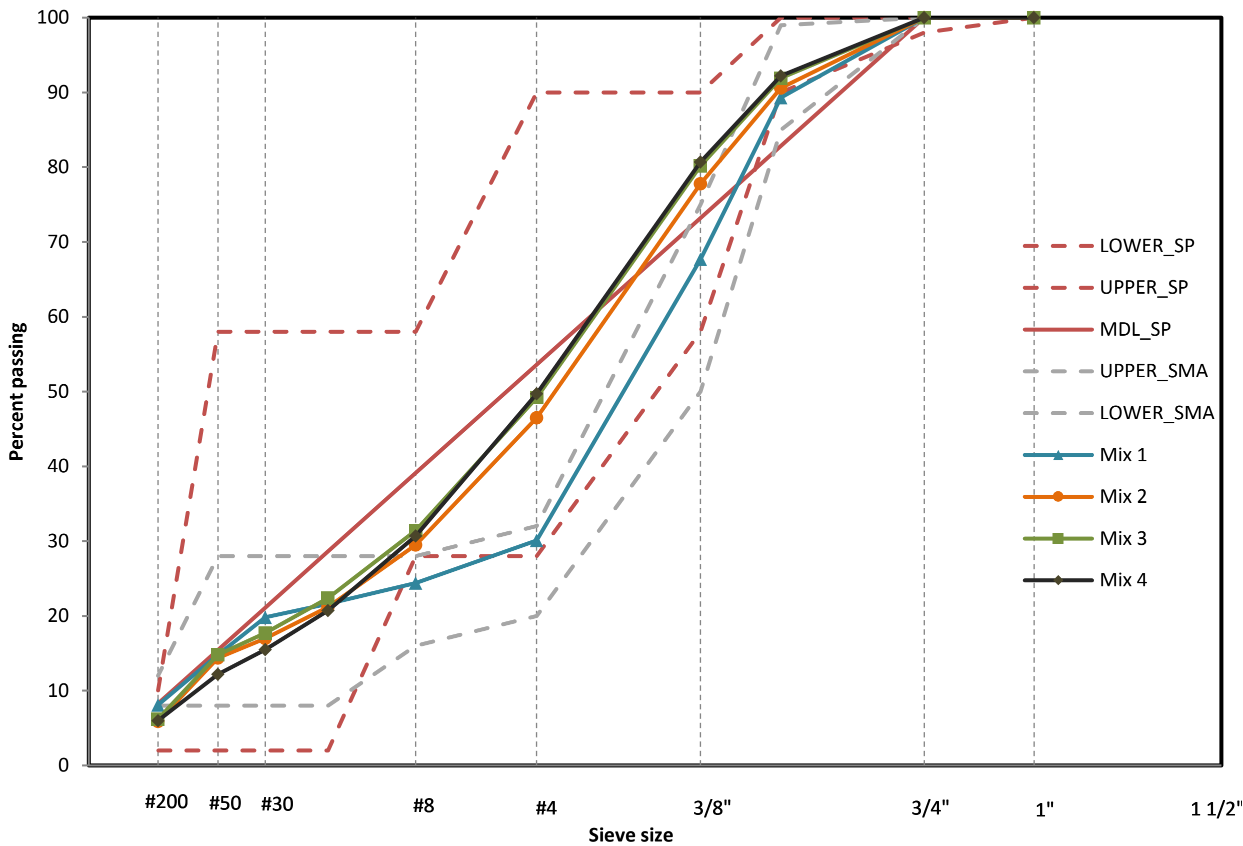


Figure 5.7 Particle size distribution of test section 4 mixtures

Table 5-11: 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 5-12: 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%

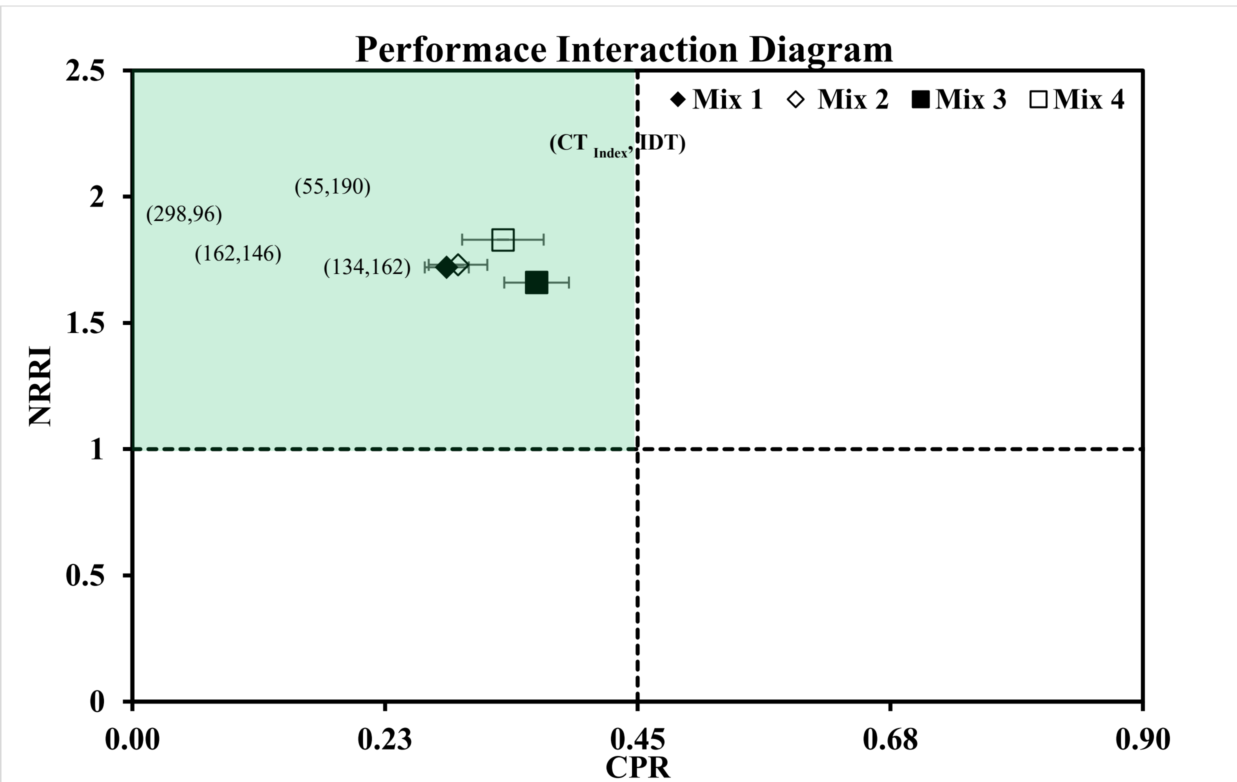


Figure 5-8: Performance interaction diagram for test section 4 mixtures

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 5-13. The major difference between the two mixes is the RAP content.

Table 5-13 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 A. From Figure 5-9, 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 5-14. 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 5-15 and Figure 5-10. 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.

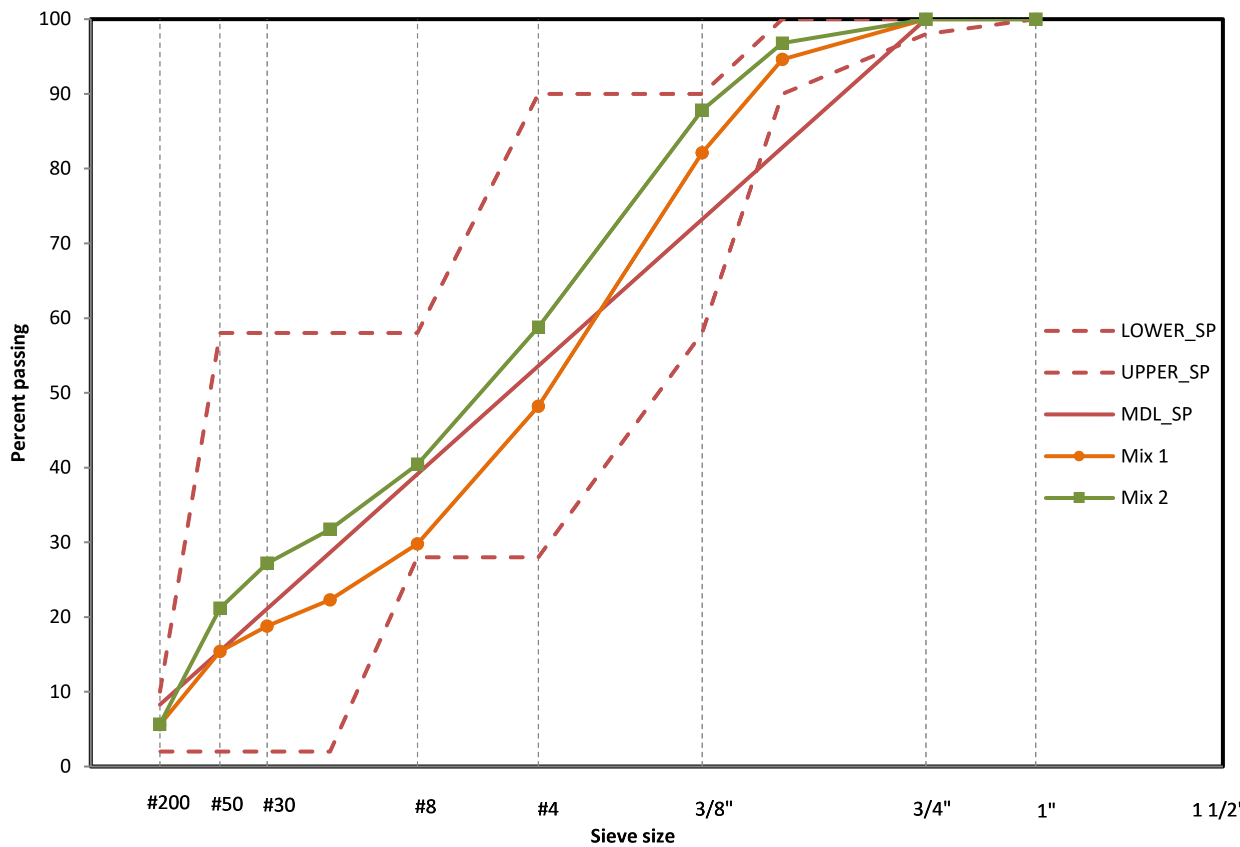


Figure 5-9 Particle size distribution of test section 5 mixtures

Table 5-14: 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 5-15: 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

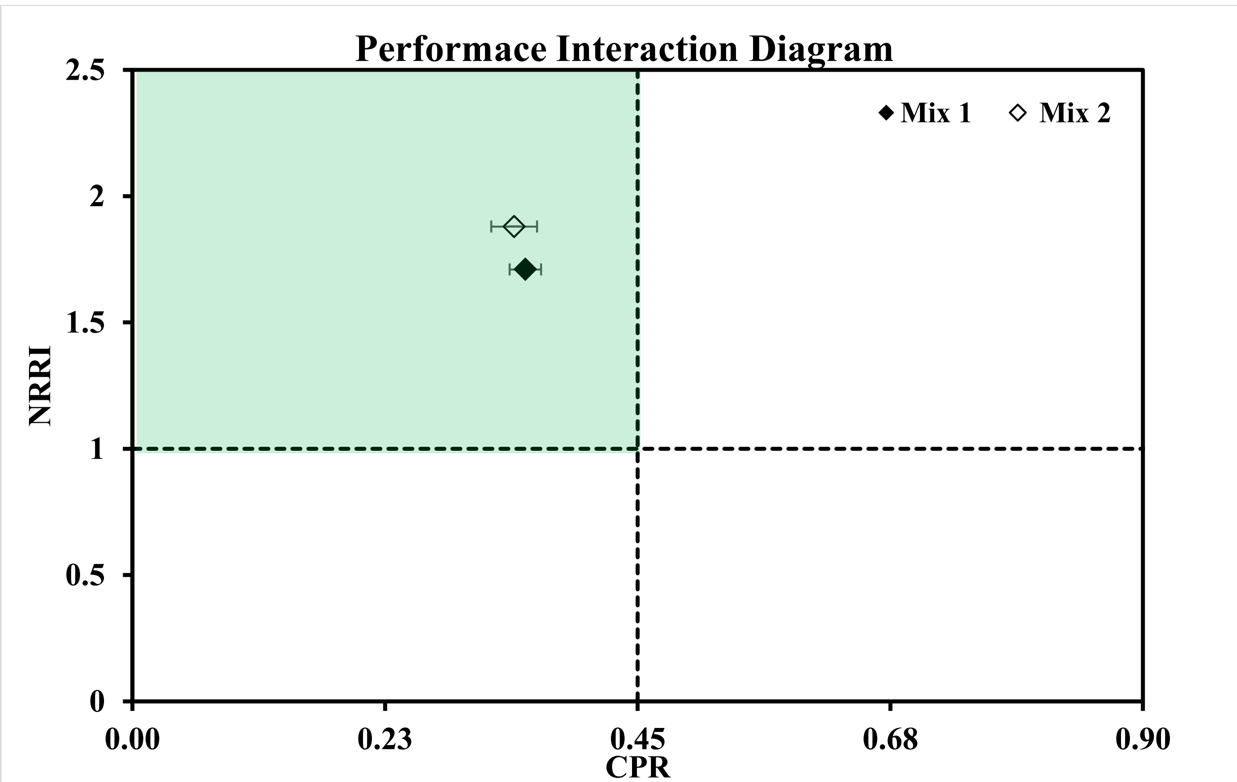


Figure 5-10 Performance interaction diagram for test section 5 mixtures

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.

Chapter 6 – 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 6-1, 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.

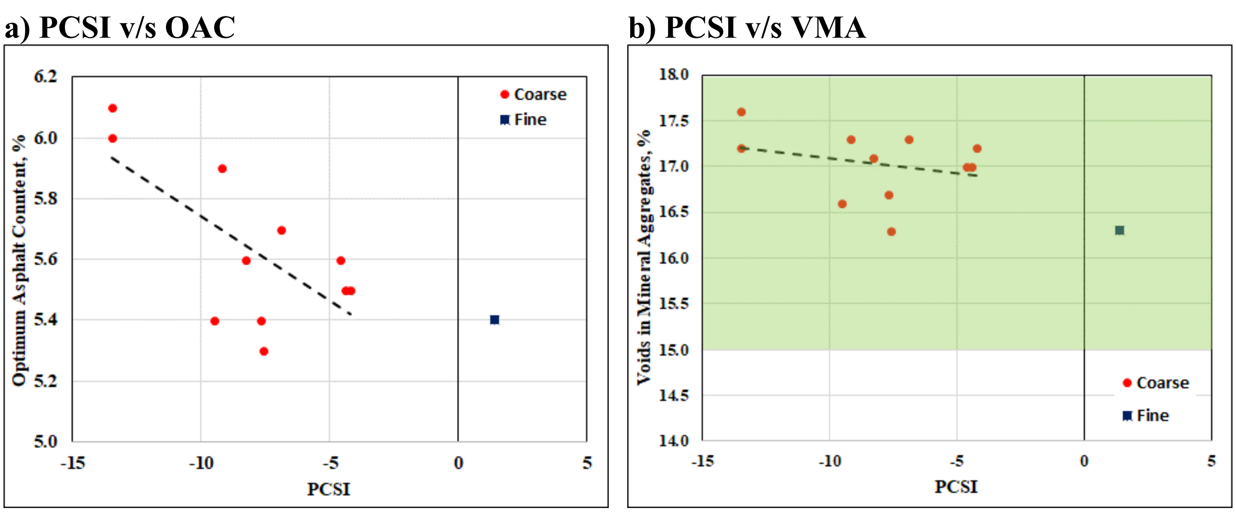


Figure 6-1 Influence of PCSI on mix volumetric properties

Figure 6-2 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 6-2a). 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

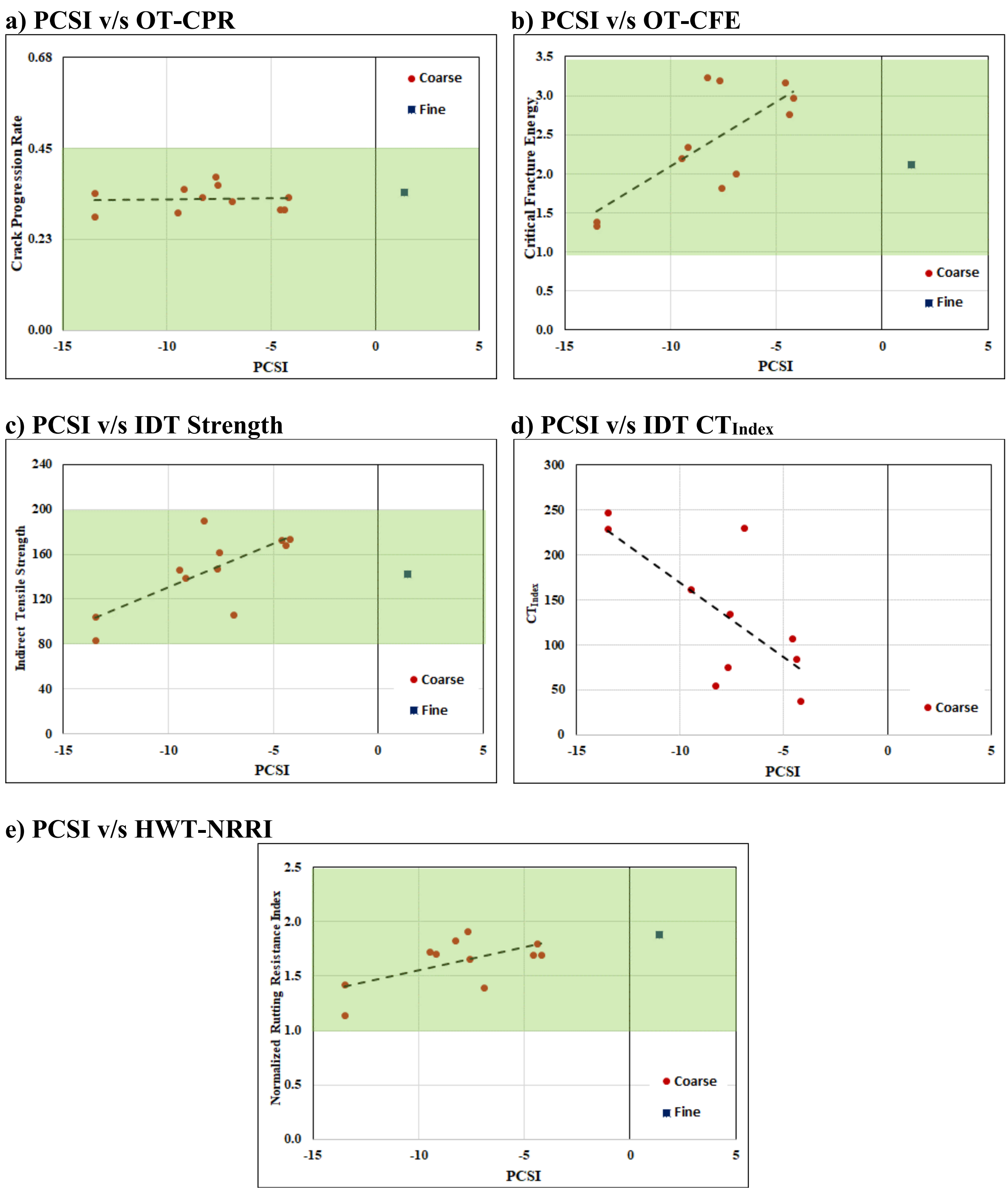


Figure 6-2 Influence of PCSI on the mix mechanical properties

mixes get closer to MDL (Figure 6-2b). The relationship between the IDT strength and PCSI in Figure 6-2c 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 6-2d, indicating that the mix becomes more crack susceptible. As shown in Figure 6-2e, 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 6-3a, the OAC tends to increase as the CA ratio increases. The VMA seems to increase slightly as the CA ratio increases (Figure 6-3b).

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

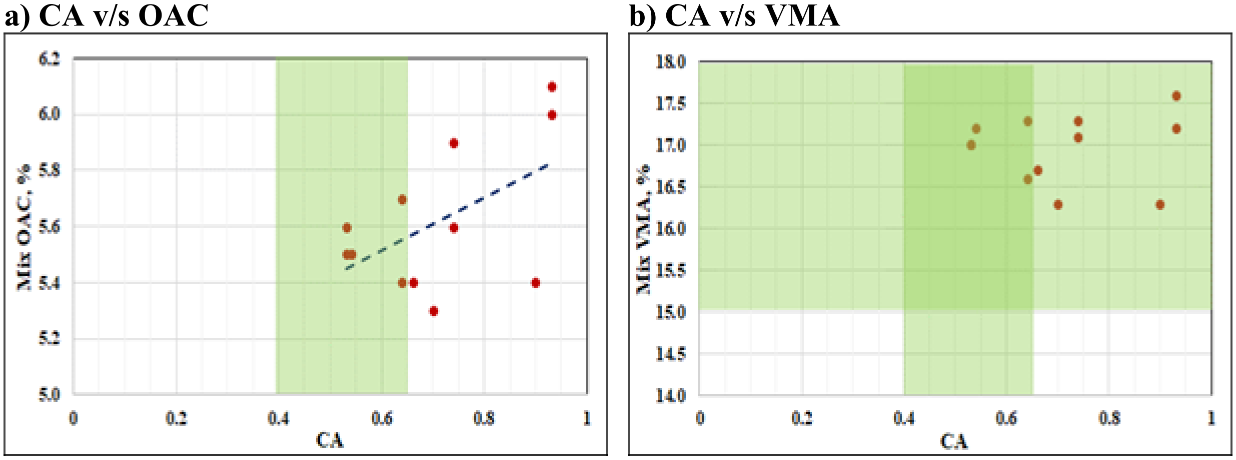
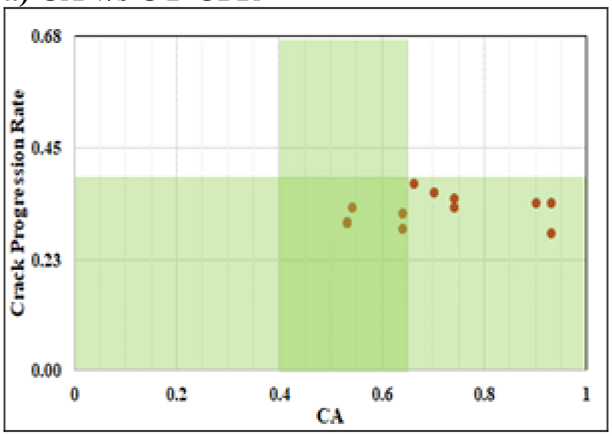


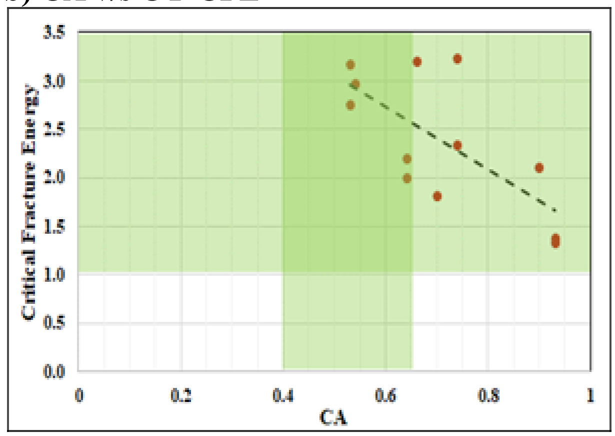
Figure 6-3 Influence of CA on the mix volumetric properties

As shown in Figure 6-4a, the CPR value does not change significantly whereas as per Figure 6-4b, 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.

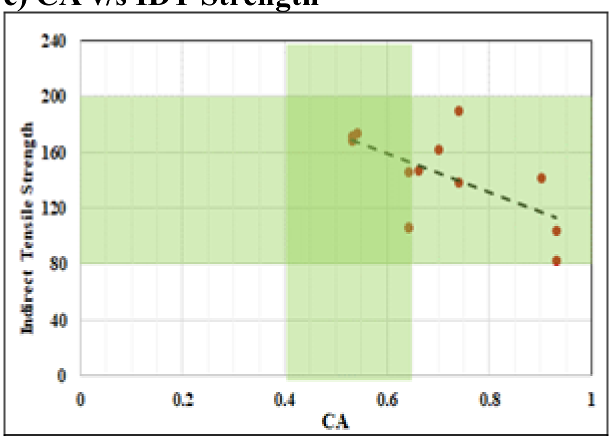
a) CA v/s OT-CPR



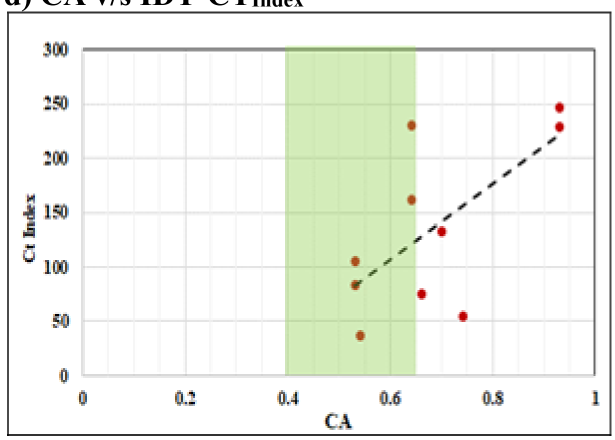
b) CA v/s OT-CFE



c) CA v/s IDT Strength



d) CA v/s IDT-CT_{Index}



e) CA v/s HWT-NRRI

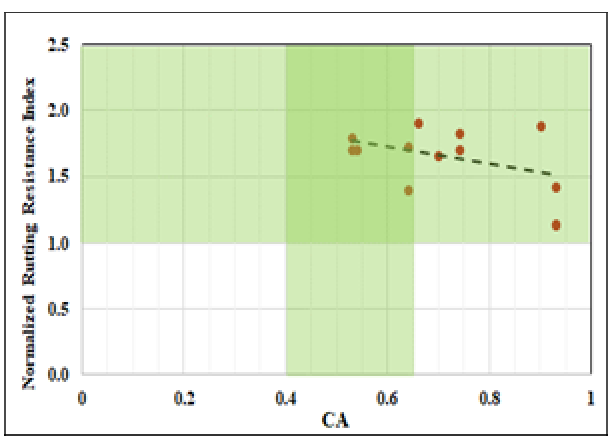


Figure 6-4 Influence of CA on the mix mechanical properties

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 6-5, 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**

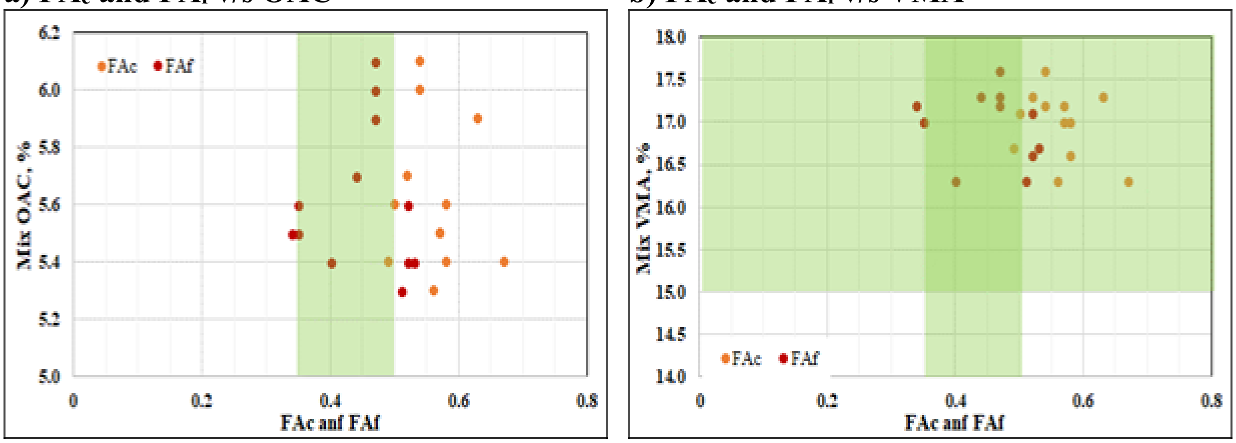


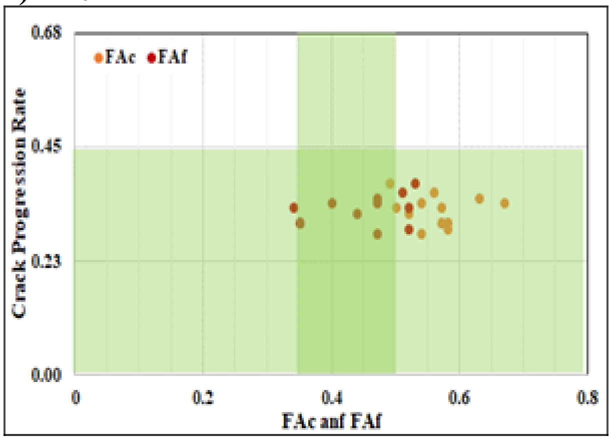
Figure 6-5 Influence of FA_c and FA_f on the mix volumetric properties

Figure 6-6 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.

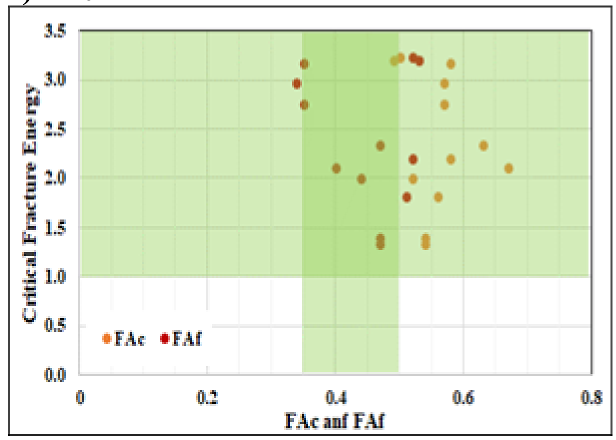
Table 6-1 summarizes the correlation coefficients (denoted as R) from the correlation analysis for the coarse mixes. The combination of PCSI and CA explains the volumetric and mechanical performance of the mixes well. FA_f seems to influence the VMA, while, RBR influence the crack propagation performance of the Superpave mixes.

Table 6-2 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.

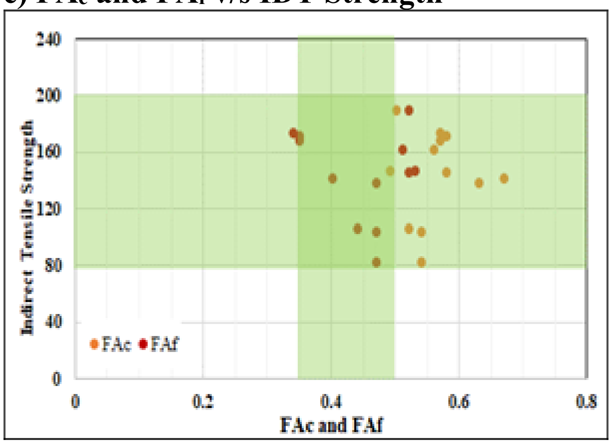
a) FA_c and FA_f v/s OT-CPR



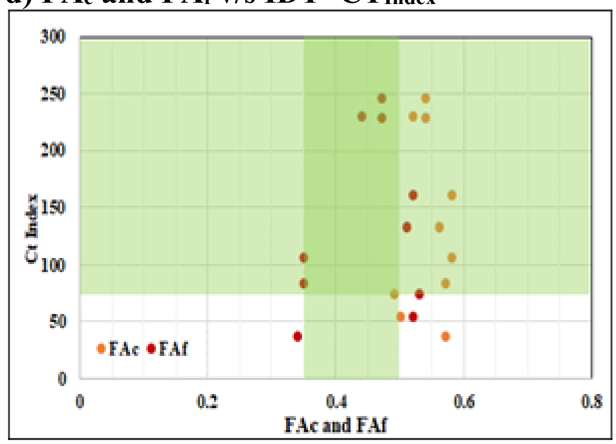
b) FA_c and FA_f v/s OT-CFE



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

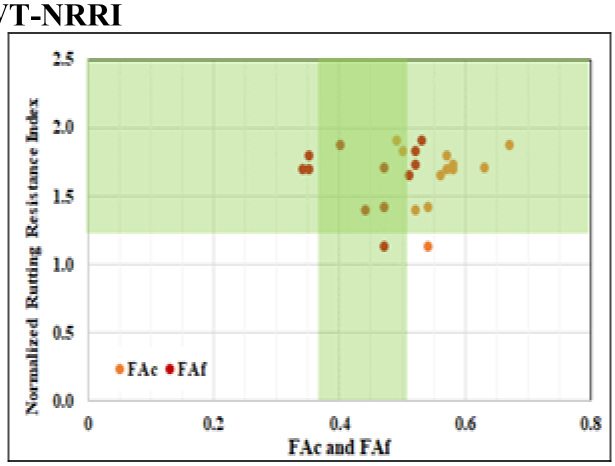


Figure 6-6 Influence of FA_c and FA_f on the mix mechanical properties

Table 6-1: 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 6-2: 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.

Chapter 7 – 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.

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Appendix - A

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 - B

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.

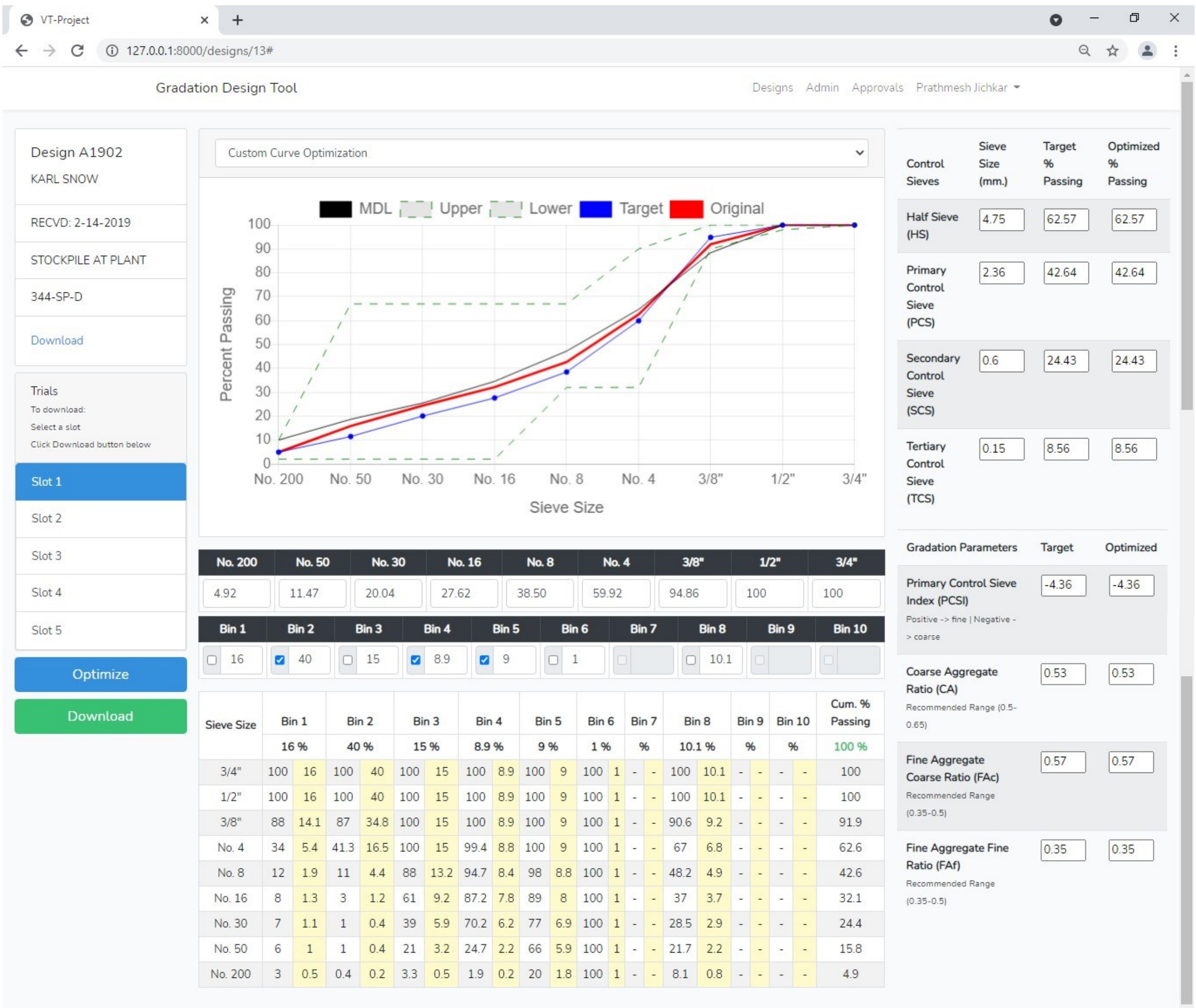

Figure B-1: Design tool before the optimization process is carried out

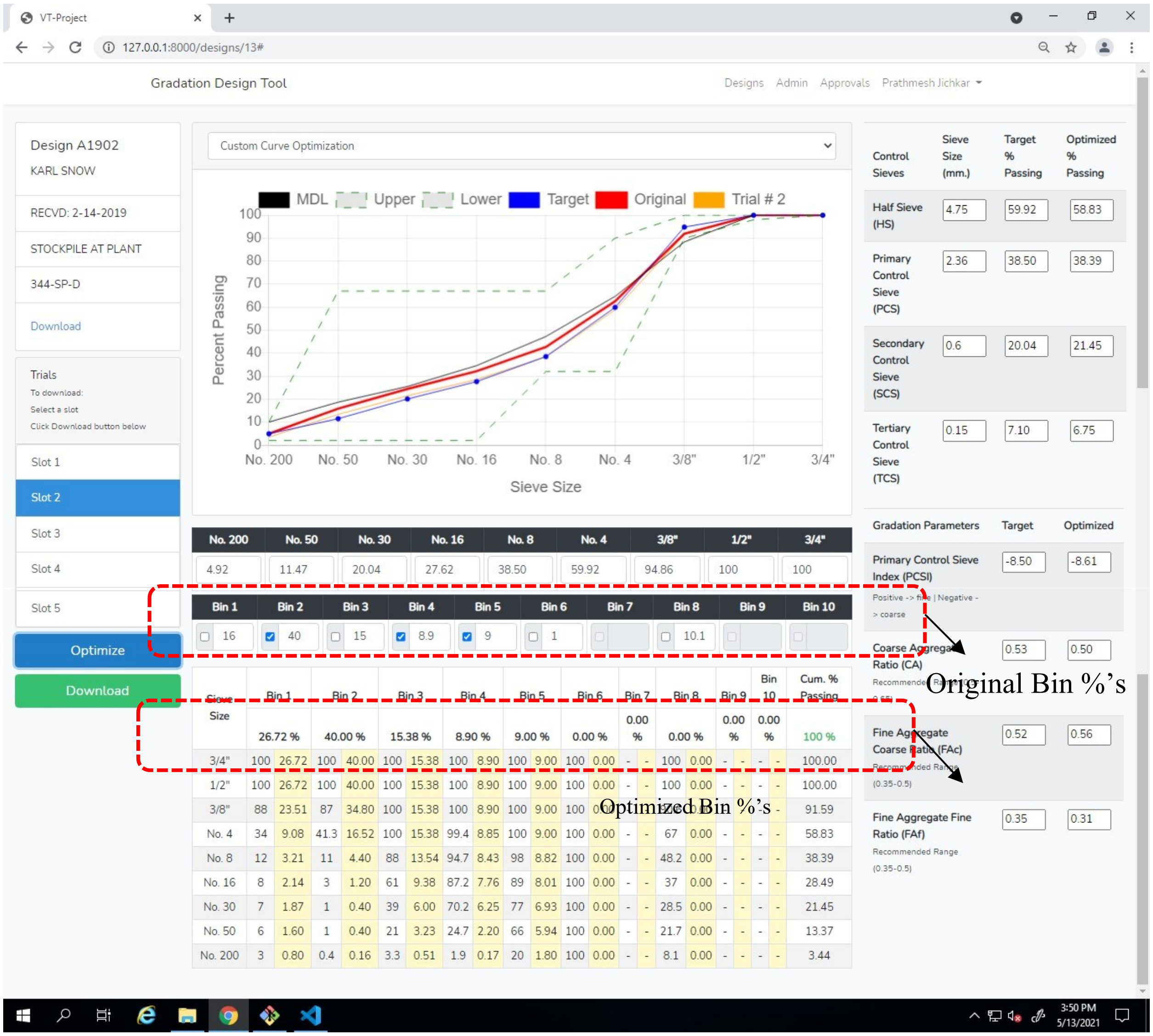

Figure B-2: Design tool after the optimization process is carried out

Vita

Prathmesh Deepak Jichkar was born in India where he received his Master of Technology in Transportation Engineering from the Indian Institute of Technology- Kharagpur in July 2015 and Bachelor of Technology in Civil Engineering from the National Institute of Technology-Nagpur in August 2013. Prathmesh is currently a civil engineering graduate student at The University of Texas at El Paso (UTEP). He is also a Graduate Research Associate at the Center for Transportation Infrastructure Systems (CTIS), which is the research center that generates and shares knowledge in different aspects of transportation infrastructure at UTEP. Before joining UTEP, he was working for almost three years as a Deputy Engineer in the Highways Division at one of the sought-after consulting firms serving the Engineering and Planning sectors with projects spread over Asia and Africa. During his tenure there, he was given the opportunity to work on various highway infrastructure projects in India and East African countries like Tanzania, Uganda, and Rwanda. He is experienced in several roles and duties including field surveys and investigations; pavement analysis and design; pavement rehabilitation and maintenance strategies; soil and material investigations; road safety audit; economic and traffic analysis. He is currently working on a TxDOT-funded project to improve the durability and longevity of the asphalt pavements both in rutting and cracking using high quantities of Recycled Asphalt pavements (RAP) while coming up with the specifications to build performance engineered roads.

Prathmesh has published a technical paper on the calculation of carbon footprints for highway pavements and has passed the Fundamentals of Engineering (FE) exam conducted by the Texas Board of Professional Engineers. Moreover, he completed a Federal Highway Administration (FHWA) certification course on ‘Sustainable Pavement Systems’. In his leisure time, he likes to travel, create wall paintings, and loves hiking to connect with nature.

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This thesis was typed by Prathmesh Deepak Jichkar