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A PERFORMANCE-BASED ANALYSIS OF BALANCED MIX DESIGNS

ELIAS AARON CASTILLO

Master´s Program in Civil Engineering

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Dedication

I dedicate this thesis work to my parents, Jesus Castillo and Laura Solis. Their teachings and sacrifices have taught me to work hard to achieve everything I aspire.

A PERFORMANCE-BASED ANALYSIS OF BALANCED MIX DESIGNS

by

ELIAS CASTILLO, BSCE

THESIS

Presented to the Faculty of the Graduate School of
The University of Texas at El Paso
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of the Requirements
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MASTER OF SCIENCE

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Abstract

The Superpave design procedure was established to provide a more representative design methodology and to minimize typical pavement distresses such as fatigue cracking and permanent deformation. This Superpave design methodology was developed on the premise that the voids in mineral aggregate can evaluate the quality and constructability of asphalt mixture during the design and production phases. With the increased use of recycled materials, recycling agents, modified binders and warm mix asphalt additives, several highway agencies including the Texas Department of Transportation (TxDOT), have investigated whether the Superpave volumetric-based design method is enough to ensure appropriate performance of the final product.

This thesis study presents an investigation of several performance tests that can be used for performance-based laboratory characterization of asphalt mixtures. Performance tests are needed at different stages including the design and field production phases. Three cracking performance tests (Overlay Test, Semi-Circular Bending I-FIT Test, and Indirect Tension Test), and two permanent deformation performance tests (Hamburg Wheel Tracking Test and Flow Number) were evaluated to select the most reliable and practical alternatives. Different performance indices were assessed to select the indices that better characterize the behavior of a mixture. Several asphalt mixtures were tested to investigate the influence of fundamental mix design variables such as the aggregate gradation, performance grade of binder, and influence of recycled material content. It was concluded after investigating several performance test methods, that independently of the different design parameters, a proper mixture behavior characterization can be achieved at different stages such as the design process and field production. This assessment can be accomplished throughout a performance-based analysis methodology which includes parameters from the OT, HWT and IDEAL CT test methods.

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Chapter 1 – Introduction

One of the popular products of the Strategic Highway Research Program (SHRP) is the Superior Performing Asphalt Pavements (Superpave) design system. Superpave design system aims at producing an economical asphalt mixture consisting of adequate voids content in the mineral aggregate skeleton, enough asphalt binder for durability, acceptable workability, and suitable performance characteristics over the service life of the pavement. Superpave was developed to provide a more consistent and representative design methodology and ultimately minimize typical pavement distresses such as permanent deformation, fatigue cracking and low temperature cracking as well as the effects of aging and moisture damage on the long-term performance of the asphalt concrete layer (*Kennedy, 1994*).

The Superpave approach consists of 1) asphalt binder and aggregate selection, 2) blending of the aggregates, and 3) volumetric analysis of specimens compacted using a Superpave gyratory compactor (SGC) (*Witczak, 2002*). To produce consistently lab-molded specimens and analyze their volumetric properties, SGC requires consistent rate of gyration, compaction pressure, and angle of gyration (*Mallik, 1999*). The design of asphalt mixtures is carried out by estimating the voids in mineral aggregates (VMA) among other volumetric parameters (*Kandhal, 1997*).

Superpave was developed for simple mix designs consisting of new mineral aggregates and neat asphalt binders. With the increasing use of more complex asphalt mixtures, which contain recycled materials, recycling agents, modified binders and warm mix asphalt additives, several highway agencies have questioned whether Superpave volumetric-based design method is enough to ensure appropriate performance of the final product (e*.g. Witczak et al., 2002; Valdez et al. 2011*). With the widespread challenge of overcoming major pavement distresses such as fatigue cracking and permanent deformation, Superpave must be complemented with standardized performance-based tests to characterize the laboratory engineering properties of asphalt mixtures.

Considering the major pavement distresses, which are permanent deformation and fatigue cracking based on a survey from West et al. (*2018*), Superpave must consider performance tests to minimize the impact of these pavement distresses. The behavior of asphalt mixtures is dependent on the loading rate, temperature, aging of the binder, and air void content of the asphalt mixture (*Kaloush, 2003*). According to Zhou et al. (*2001*), fatigue cracking is not only a material problem; it is also associated with the pavement structure and environmental and traffic conditions. While permanent deformation of asphalt mixtures is a critical pavement distress mechanism that typically occurs at elevated temperatures and slow loading rates under the action of heavy traffic (*Weismann et al.,1998*).

Enhancing the current Superpave method with a performance-based analysis methodology is critical to produce asphalt mixtures that meet the structural requirements for the asphalt concrete layer of a flexible pavement. To complement the research efforts done by many State Highway Agencies (SHA) and research institutions on enhancing the design and production processes for asphalt mixtures, an experimental study with readily available performance test methods was carried out to assess the performance of typical Superpave mixtures. This thesis documents the effectiveness of performance test methods that can be implemented along with Superpave mix design.

1.1 Literature Review

The Superpave was developed to produce more stable and durable asphalt mixtures. Although the Superpave established thorough specifications and guidelines to select the mix design components (e.g. mineral aggregates and asphalt binders) and formulate a mix design, the implementation of performance tests to ensure acceptable mechanical performance was limited due to practical and economic reasons. Incorporating reliable and fundamentally sound performance tests into the current mix design process effectively is a critical step to produce asphalt mixtures with acceptable volumetric and mechanical properties.

Currently, asphalt mixtures are essentially designed through a trial-and-error process until established minimum volumetric requirements have been satisfied. Superpave was developed on the premise that the quality of a mixture is ensured if certain volumetric properties and target laboratory-molded densities are met during the design and production processes (*McDaniel and Levenberg, 2013*). Several studies (*e.g. Witczak et al., 2002; Bhasin, Button and Chowdhury, 2004; Valdes et al., 2011*) have discussed the necessity of implementing performance tests to determine the mechanical properties of asphalt mixtures.

From a mechanical performance perspective, an asphalt mixture must have satisfactory rutting and cracking resistance to perform well in the field (*Zhou et al., 2006*). The permanent deformation of asphalt mixtures was a major issue before the implementation of the Superpave. A recurring problem is the premature cracking of asphalt mixtures, particularly with the wide application of recycled materials, stiff binders and a combination of different additives. The evaluation and implementation of performance tests have been gaining more attention due to the introduction of the balanced mix design (BMD) concept for asphalt mixtures. The main objective of the BMD concept is to achieve the optimum blend of asphalt binder and mineral aggregates, and other components such as recycled materials, modified binders and additives while meeting the acceptance requirements for performance tests for a given level of traffic, climate, and pavement structure (Newcomb, *2018*). Performance testing is fundamental to the practice of a BMD procedure.

Zhou et al. (*2007*) defined cracking as a two-stage process including crack initiation and crack propagation. Even though many crack performance tests are available, none has been universally accepted. Zhou et al. (*2016*) investigated several performance tests to assess their effectiveness, variability of results, simplicity, and correlation to field results. For assessing the cracking resistance a number of tests including the indirect tensile (IDT), overlay (OT), semi-circular bending (SCB), disk-shape compact tension (DCT), and four-point bending tests can be used. Only the OT and the four-point bending are considered fatigue cracking tests since they apply repeated loading to the specimens.

Garcia et al. (*2016*) proposed the use of the OT test for evaluation cracking of mixtures using two parameters: the critical fracture energy to assess the crack initiation, and crack progression rate to assess the propagation of a crack. Several performance tests have been developed to evaluate the brittleness potential of the asphalt mixtures by applying a monotonic load to fracture the asphalt specimen. Huang (*2005*) studied the semi-circular bending (SCB) test and found that the stress in the center of the specimen corresponded to stress at the bottom of an asphalt layer. Al-Qadi et al. (*2016*) proposed the flexibility index (FI) derived from the SCB test to characterize the cracking potential of asphalt mixtures.

Kaloush (*2003*) stated that rutting distress in the field was developed in two phases for an asphalt mixture. The first phase was due to the accumulation of the permanent vertical deformation within the asphalt layer under traffic loads, while the second phase was more critical to the stability of the mixture. Performance test methods for permanent deformation include the flow number (FN) test, asphalt pavement analyzer (APA), and Hamburg wheel-tracking test (HWT). The HWT test is extensively used by many agencies, which records permanent deformation of asphalt mixture specimens with reference to the number of passes of a loaded wheel (Bhasin, 2004). HWT also accounts for moisture damage and measures moisture susceptibility of the asphalt mixture. Please refer to Appendix A for more literature review information.

1.2 Thesis Objectives

This study was carried out to investigate several performance test methods that can be used for laboratory characterization of asphalt mixtures. The main objectives of this study are the following:

1. Identify promising performance test methods for the following purposes:
   a. Lab design process
   b. Plant production and construction
2. Formulate and propose a performance-based analysis methodology
3. Evaluate several mixture types to document the effectiveness of the proposed performance-based analysis methodology

Figure 1.1 provides a flow chart of the main stages at which performance test methods were implemented for enhancing the current volumetric based design method. Stage 1 consists of the design of asphalt mixtures based on the performance of the two main distresses assed for a BMD, cracking and permanent deformation. Two different performance tests are investigated in this study. Once the performance of the mixture is deemed acceptable, the second stage of the study was implemented. The first objective of the second stage is to meet the job mix formula (JMF) during the production of the asphalt mixture.

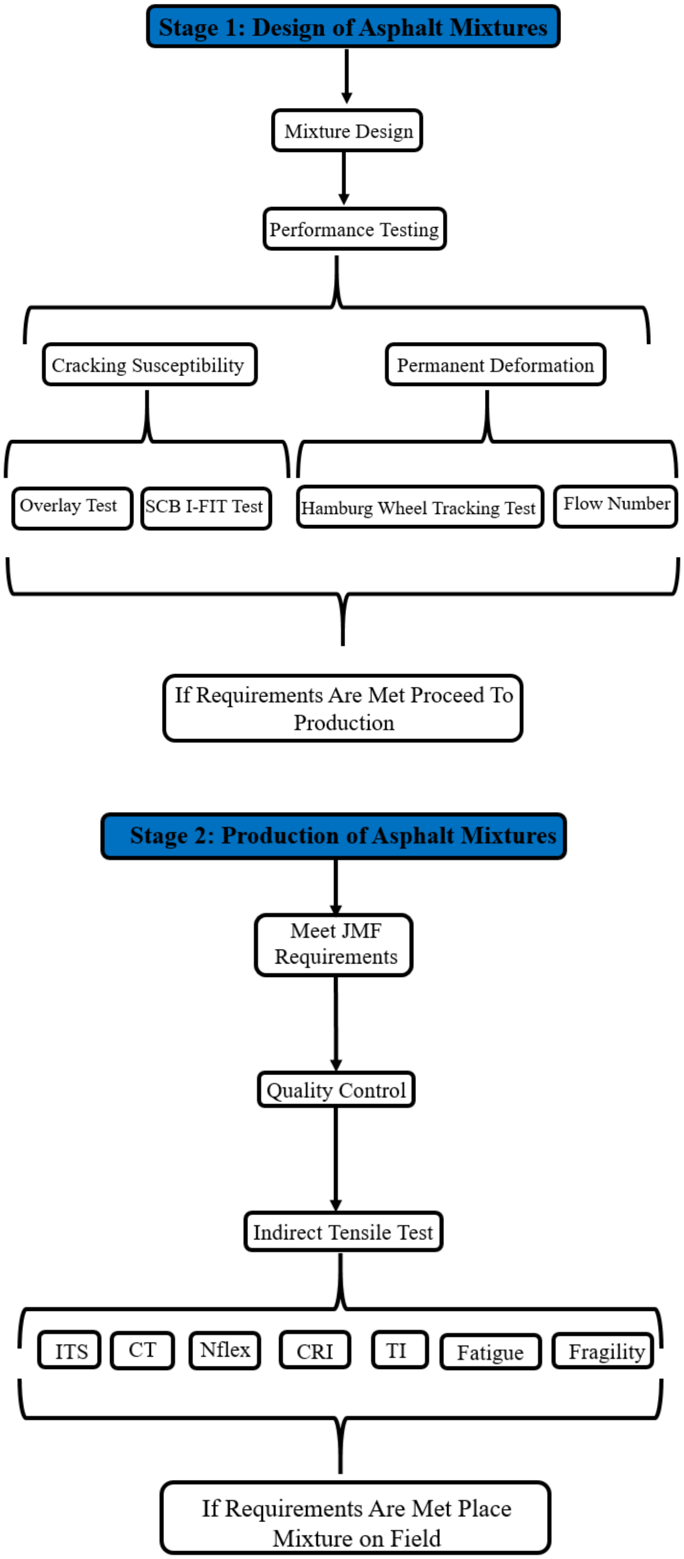


Figure 1.1 – Main Stages for Performance Test Methods

During production a quality control test is used to evaluate the mixture with the actual mixture that is being placed in the field. Different indices are examined in order to discriminate between a well and a poor performing mixture.

With the implementation of reliable and consistent performance test methods, the current volumetric-based design method can be further enhanced to produce asphalt mixtures with acceptable volumetric and mechanical properties.

Organization of Thesis

Chapter 1 consists of a comprehensive review of salient literature on Superpave, introduction of a performance based analysis methodology, and background information on testing protocols used for laboratory evaluation of the performance of asphalt mixtures.

Chapter 2 presents the research methodology and experiment design plan formulated for the selection of performance test methods; assessment of a quality control test used during production of asphalt mixtures and introduces the performance interaction diagram for performance evaluation.

Chapter 3 reports the results from evaluating performance test methods for a performance-based analysis methodology for design and quality control processes. Different alternative test methods for permanent deformation, which includes Hamburg wheel tracking test and flow number test; and cracking potential test methods such as overlay test, and semi-circular bend (SCB) I-FIT test were included in this section. Similarly, an evaluation of different performance indices derived from the IDT test such as CT index, fatigue index, toughness index, cracking resistance index, N_{flex} factor, and fragility index to identify a potential performance index for characterization of an asphalt mixture during production.

Chapter 4 documents the application of the performance based analysis methodology on three case studies that focus on the influence of aggregate gradation, influence of performance grade of binder, and influence of recycled materials.

Chapter 5 summarizes key findings and conclusions of the study and enlightens the thesis contribution and importance of implementing a performance-based analysis methodology to meet structural requirements for balanced mix designs.

Chapter 2 - Research Methodology and Experiment Design

2.1 Candidate Performance Test Methods for Characterizing Balanced Mix Designs

With the rapid development of BMD concept for asphalt mixtures, the use of fundamental cracking and rutting performance tests is essential. A comprehensive evaluation and understanding of available promising performance test methods, specifically a cracking and rutting test, is paramount to formulate properly and implement robustly a performance-based process into the current volumetric-based design process.

2.1.1 Performance Tests for Permanent Deformation

The permanent deformation characteristics of the asphalt mixtures were estimated using the HWT and FN tests. A brief description of the test procedures is presented next.

Hamburg Wheel Tracking Test - *TEX-242-F* (Similar to ASTM WK64299). This test determines the rutting resistance of asphalt mixtures due to weakness in the aggregate structure, inadequate binder stiffness, and moisture susceptibility. The HWT test requires a steel wheel with a diameter of 8 in. to apply a load of 158 ± 5 lb. The equipment must be capable of doing 52 ± 2 passes/min across the test specimen. Two sets of cylindrical lab-molded specimens or filed cores are required to perform the test. The HWT test is terminated when a rut depth of 12.5 mm is reached or until a a maximum of 20,000 passes are completed. Table 2.1 summarizes the TxDOT rutting requirements from the HWT tests . In addition to the traditional data analysis, the rutting resistance index (RRI) proposed by Wu et al. (*2017*) was included in this evaluation. RRI is calculated from

$$RRI= N \times (1 - RD) \qquad (1)$$

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

The minimum RRI value corresponding to the minimum number of passes for a given performance grade (PG) asphalt binder is also shown in Table 2.1. For convenience in comparing the rutting performance of mix designs with different binder PGs, RRI is normalized with respect to the minimum RRI. Equation 2 was followed to calculate the normalized RRI (NRRI). A NRRI of unity or greater signifies an acceptable mix in terms of rutting, which simplifies the analysis of the HWT test data.

$$\text{NRRI} = \frac{Actual\ RRI}{Minimum\ RRI\ for\ Specified\ PG} \tag{2}$$

Table 2.1- Hamburg Wheel Tracking (HWT) Test Requirements

High-Temperature Binder Performance Grade	Minimum Number of Passes	Minimum RRI
PG 64 or Lower	**10,000**	**5,100**
PG 70	**15,000**	**7,600**
PG 76 or Higher	**20,000**	**10,100**

Flow Number Test - AASHTO T 378. The flow number (FN) test is conducted in a load-controlled mode at a temperature of 130 ºF (54.4 ºC), in which the specimen is subjected to a repeated compressive load pulse of 0.1 s every 1.0 s. While the FN test provides parameters such as total number of cycles, resilient strain and resilient deformation, the flow number is the main output parameter. The FN parameter is defined as the cycle corresponding to the minimum rate of change of permanent axial strain during a repeated-load test. In other words, the FN represents the cycle number at which the asphalt specimen loses its stability and deforms abruptly due to a single load application. The resulting permanent axial strains are measured as a function of cycles. Table 2 summarizes the FN test requirements for asphalt mixtures. From AASHTO T 378-17 standards, three thresholds based on the design traffic level are used to characterize the FN test.

Table 2.2 – Flow Number Requirements

Traffic level, million ESALs	HMA Minimum Flow Number
< 3	_
3 to < 10	50
10 to < 30	190

2.1.2 Performance Tests for Cracking Susceptibility

Overlay Tester Test - TEX-248-F (Similar to ASTM WK26816). The OT test is used to determine the susceptibility of asphalt mixtures to fatigue or reflective cracking. The OT test is conducted in a displacement control mode at 77ºF (25ºC) with a triangular waveform at loading rate of one cycle per 10 sec. The OT specimens are prepared in accordance with test procedure Tex-241-F (ASTM D6925-15) to a target air void content of 7± 1.0%. (Garcia et al., 2016) proposed a two-parameter approach, using the critical fracture energy (CFE) and crack progression rate (CPR), to interpret the OT test data. Figure 2.1 displays the calculations of the CFE and CPR parameters obtained from the OT test. Figure 2.1a shows the load-displacement behavior of an OT test, the calculation of the maximum load and work of fracture of the specimen tested. Figure 2.1b represents the calculation of CPR parameter with a power equation fitted into the load reduction curve. Generally, a CPR of 0.45 is recommended and was used in this evaluation to assess the cracking performance of the asphalt mixtures.

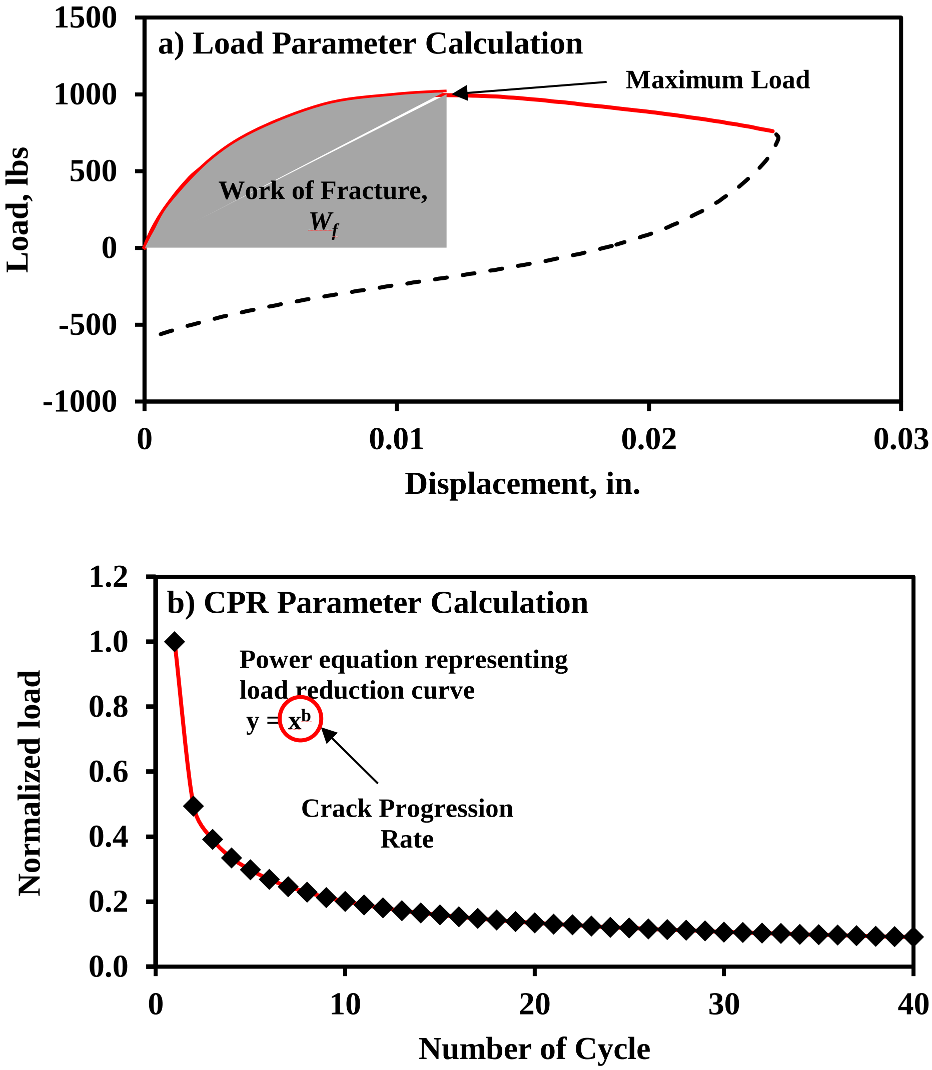


Figure 2.1 – Analysis Methodology and Parameters for Overlay Test (Garcia, 2016)

Semi-Circular Bend Test – (AASHTO TP 124). The SCB I-FIT test is performed to estimate the resistance of an asphalt mixture to cracking with an assessment of the flexibility index (FI) proposed by Al-Qadi et. al. (2016). A semi-circular specimen is loaded monotonically under a constant rate of deformation at of 2 in./min (50 mm/min) in a three-point bending load configuration until fracture failure occur at a testing temperature of 77°F (25°C). The SCB I-FIT specimen contains a 0.59 in. (15 mm) notch at the center of the specimen.

The applied displacement and acquired load time histories are measured during the test to plot the load versus displacement response curve, similar to Figure 2.2. That figure also presents the typical parameters computed from the SCB I-FIT test. The FI from the SCB I-FIT test can be calculated from

$$FI = A\ x\ \frac{G_f}{abs\ (m)} \tag{3}$$

where, A is a unit conversion factor and scaling coefficient taken as 0.01, G_f represents the fracture energy in J/m^2 (N/m), and m is the slope after peak load in kN/mm (lbs./in.).

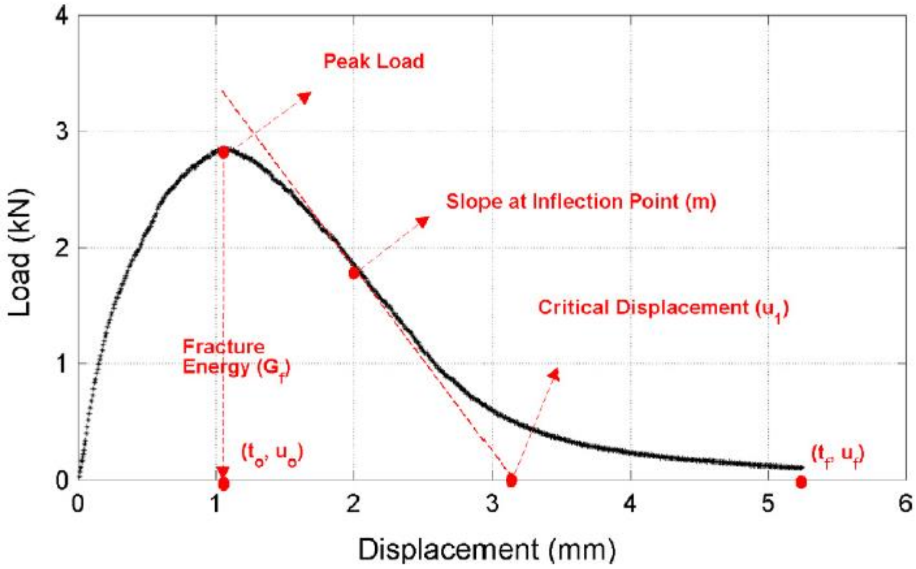


Figure 2.2 – Main Parameters for Calculation of Flexibility Index (Al-Qadi, 2016)

2.2 Performance Test for Quality Control during Production of Asphalt Mixtures

During the production of asphalt mixtures, a quality control test must be performed to assess the mixture, and make sure the JMF is met. The idea of having a quality control test to assess an asphalt mixture is to rapidly identify if a mixture is adequately performing as expected in the design stage. A simple test such as the IDT is a good candidate test to be performed at this stage. Several variations of this test, such as the IDEAL CT test, are available and are examined as options for the quality control parameter. Similarly, different indices have been proposed to evaluate a mixture after being tested in the IDT.

2.2.1 Indirect Tension Test (IDT) - TEX-226-F (Similar to ASTM D6931-17)

The IDT test is performed on specimens with a 5.9-in. (150-mm) diameter, and a 2.4 ±0.1 in. (75±2 mm) height. The specimens are produced with a target density of 93±1%. The specimens are tested under a monotonic load of 2 in./min (50 mm/min) at a temperature of 77 ± 2°F (25 ± 1°C). The primary outcome of the IDT test is the indirect tensile strength (ITS) of the mixtures, with a minimum acceptance limit of 85 psi (600 kPa) and a maximum allowable strength of 200 psi (1400 kPa), which can be calculated following:

$$S_t = \frac{2P}{\pi(HD)} \tag{4}$$

where, S_t represents the indirect tensile strength in psi (kPa), P is the maximum load at failure in lb (kN), and H and D are the height and diameter of the specimen in in. (mm.), respectively.

2.2.2 IDEAL Cracking Test (CT Index)

Recent development of the IDEAL-CT Index was proposed in which the test similar to the typical indirect tensile strength test at a loading rate of 2 in./min. (50 mm/min; Zhou et al. 2017). The parameters used for the calculation of this index are fracture energy, and post-peak slope:

$$CT_{Index} = \frac{t}{2.4} \times \frac{l_{75}}{D} \times \frac{G_f}{|m_{75}|} \times 10^6 \tag{5}$$

where CT Index = Cracking tolerance index normalized to 2.4 in. thick specimen, G_f = Failure energy, lb./in., $|m_{75}|$ = Absolute value of the post-peak slope m_{75}, lb./in., l_{75} = Displacement at 75% the peak load after the peak, in., h = Thickness of specimen, in., D = Diameter of specimen, in.

2.3 Performance Interaction Diagram for Characterization of Balanced Mix Designs

Since the BMD concept should consider multiple mechanical properties for designing an asphalt mixture, a performance interaction diagram that considers the main parameters from the selected performance tests (e.g. cracking and rutting parameters) should be formulated. A three-dimensional performance interaction diagram is used in this study to analyze the cracking susceptibility and rutting potentials during the design process, and brittleness during the production process. The concept of the performance interaction diagram for design and production of asphalt mixtures is shown in Figure 2.3. The acceptance limits associated with the selected performance parameters for the design process are also shown in the graph.

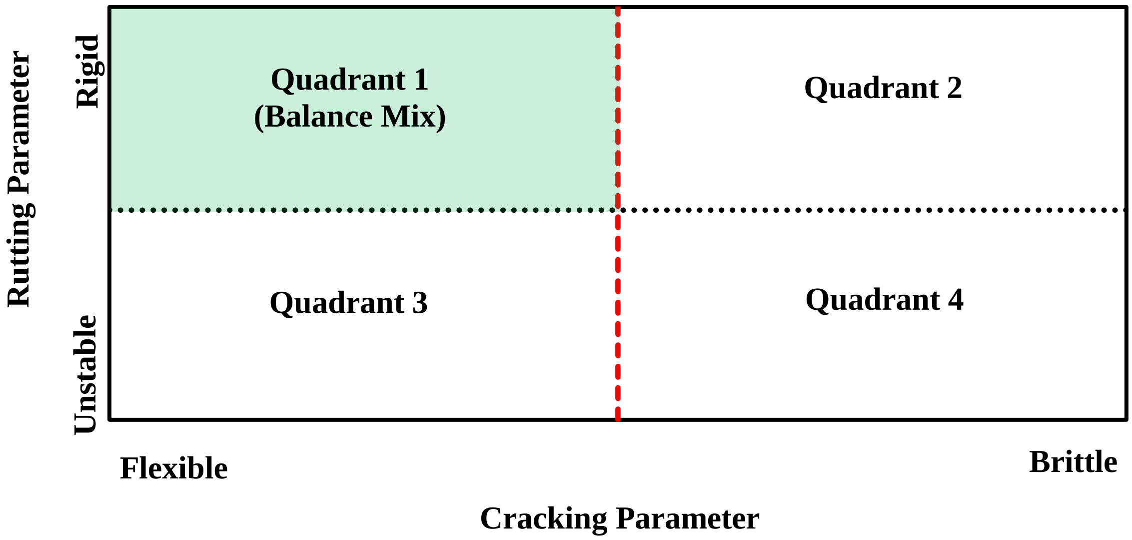


Figure 2.3 - Performance Interaction Diagram for Asphalt Mixtures

From the performance interaction diagram, the asphalt mixtures at OAC can be preliminarily divided into the following four general categories:

- Quadrant 1: passes both rutting and cracking requirements, as expected from a BMD.
- Quadrant 2: passes only the rutting requirements.
- Quadrant 3: passes the cracking requirements.

- Quadrant 4: fails both cracking and rutting requirements.

In addition, the minimum quality control (QC) acceptance limit for the asphalt mixtures during production is shown as a data label for each mix design evaluated on the performance interaction diagram. During the production process, the minimum QC acceptance limit reported from the evaluation of the asphalt mixture during the design process must be met.

2.4 Description of Mix Designs and Pavement Materials for Laboratory Testing

Twelve Superpave mixes, designed according to TxDOT Item 344 “Superpave Mixtures,” were sampled from ongoing pavement construction projects. All sampled asphalt mixtures were designed at 50 gyrations and using a target density of 96%. The asphalt mixtures were designed with either a 12.5 mm (called SP C hereafter) or a 9.5 mm (called SP D hereafter) nominal maximum aggregate size (NMAS). SP C and SP D mixtures met a minimum VMA of 15% and 16%, respectively.

2.4.1 Mixture Properties

Mix ID	Mix Type	Original Binder	VMA %	OAC %	Gmm	RAP %	RAS %	ABR Ratio	Aggregate Type
1	SP-C	70-28	14.8	4.6	2.490	N/A	4.0	15.2	Limestone/Dolomite
2	SP-C	76-22	16.9	5.5	2.524	19.7	N/A	16.2	Limestone/Dolomite
3	SP-C	70-28	15.0	4.6	2.490	N/A	4.0	15.2	Limestone/Dolomite
4	SP-C	76-22	15.2	5.0	2.435	10	N/A	17.0	Sandstone
5	SP-D	76-22	15.7	5.2	2.424	10	N/A	10.0	Limestone/Dolomite
6	SP D	76-22	16.5	5.5	2.397	N/A	N/A	N/A	Igneous
7	SP-D	70-22	16.0	5.3	2.423	14	N/A	13.2	Limestone/Dolomite
8	SP D	64-22	16.1	6.5	2.697	16	N/A	16.0	Igneous
9	SP-D	64-22	16.1	6.5	2.697	16	N/A	16.0	Igneous

10	SP-D	70-22	16.4	5.3	2.470	10	3.0	19.6	Limestone/Dolomite
11	SP-D	64-22	16.2	5.4	2.440	15	3.0	24.4	Limestone/Dolomite
12	SP-D	70-22	16.5	5.4	2.480	N/A	5.0	16.7	Limestone/Dolomite

Table 2.3 reports the relevant mix design information of the sampled asphalt mixtures. Information such as the aggregate type and source, optimum asphalt content (OAC), VMA, maximum specific gravity (G_{mm}), recycled asphalt pavement (RAP) and/or recycled asphalt shingles (RAS), and recycled binder replacement (RBR) ratio are presented for each mix. The asphalt mixtures were designed to meet the requirements for asphalt binders with PGs of 64-22, 70-22, 76-22, and 76-28. The OAC varied from 4.6% to 6.5%. The RAP and RAS contents ranged from 0% to 20% and from 0% to 4%, respectively. Please refer to appendix B for more information on mixture design and material properties.

Table 2.3 - Mix Design Information and Volumetric Properties

Mix ID	Mix Type	Original Binder	VMA %	OAC %	Gmm	RAP %	RAS %	ABR Ratio	Aggregate Type
1	SP-C	70-28	14.8	4.6	2.490	N/A	4.0	15.2	Limestone/Dolomite
2	SP-C	76-22	16.9	5.5	2.524	19.7	N/A	16.2	Limestone/Dolomite
3	SP-C	70-28	15.0	4.6	2.490	N/A	4.0	15.2	Limestone/Dolomite
4	SP-C	76-22	15.2	5.0	2.435	10	N/A	17.0	Sandstone
5	SP-D	76-22	15.7	5.2	2.424	10	N/A	10.0	Limestone/Dolomite
6	SP D	76-22	16.5	5.5	2.397	N/A	N/A	N/A	Igneous
7	SP-D	70-22	16.0	5.3	2.423	14	N/A	13.2	Limestone/Dolomite
8	SP D	64-22	16.1	6.5	2.697	16	N/A	16.0	Igneous
9	SP-D	64-22	16.1	6.5	2.697	16	N/A	16.0	Igneous
10	SP-D	70-22	16.4	5.3	2.470	10	3.0	19.6	Limestone/Dolomite
11	SP-D	64-22	16.2	5.4	2.440	15	3.0	24.4	Limestone/Dolomite
12	SP-D	70-22	16.5	5.4	2.480	N/A	5.0	16.7	Limestone/Dolomite

2.4.2 Laboratory Molded Specimen Preparation Process

Plant-mixed lab-compacted (PMLC) specimens were utilized for the performance characterization. Each material was reheated in the laboratory for two hours at compaction temperature in accordance to TxDOT specifications (Tex-206-F) for short-term oven aging. Laboratory molded specimens were then compacted, and prepared for the selected test methods after the compaction temperature is reached.

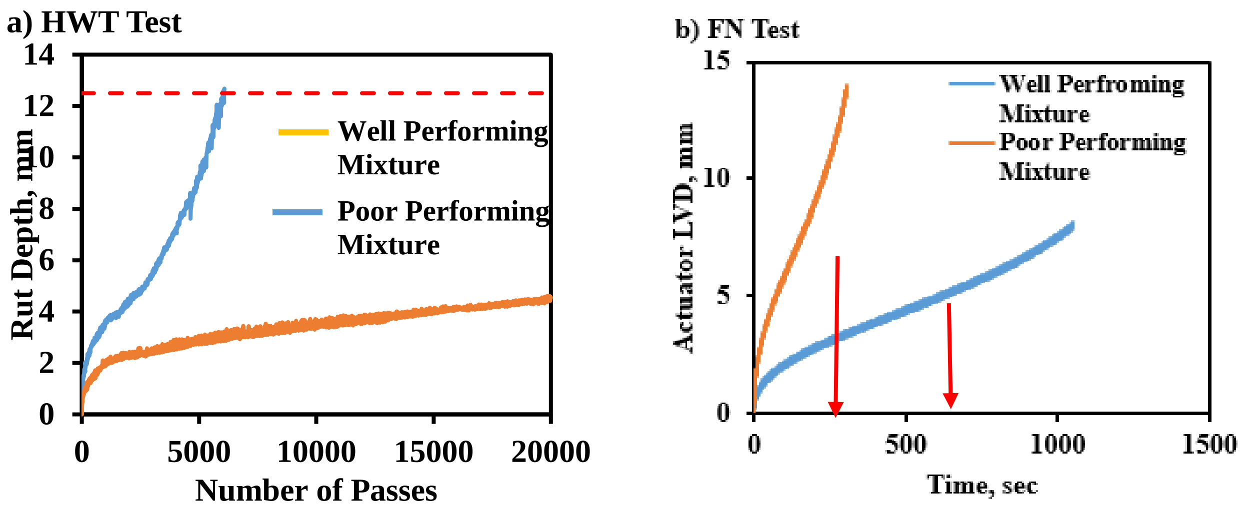
Chapter 3 - Analysis of Results for Design and Quality Control Processes

3.1 Performance Tests for Permanent Deformation Characterization

A comparative evaluation of the Hamburg wheel tracking (HWT) and flow number (FN) tests was carried out to evaluate their effectiveness and consistency on assessing the rutting resistance of Superpave mixtures. While the HWT test has been widely used to assess the rutting resistance of Superpave mixtures, the FN test is a relatively easy test that can be also employed to measure the resistance of asphalt mixtures to permanent deformation. Figure 3.1a compares the typical HWT test results from a well and poor performing mixture. The well performing mixture was able to resist the maximum number of passes (e.g. 20,000 passes) but the poor performing mixture reached the maximum rut depth (RD) of 12.5 mm at only 6,000 passes. Similarly, Figure **3.1**3.1b displays two typical FN test response curves for a well and poor performing mixture. The axial strain (deformation) is plotted along the y-axis, and the time along the x-axis. Considering that a loading cycle is applied every one second, the well performing mixture resisted over 1200 cycles with a flow number of 461 while the poor performing mixture only lasted for close to 300 cycles with a flow number of 133.

Figure 3.2a displays the HWT test results for the twelve Superpave mixtures. The data labels represent the NRRI values. Mixtures displaying an NRRI greater than one are passing the HWT test, while mixtures with NRRI values of less than one do not meet the rutting requirements. Eleven out of the twelve mixtures satisfactorily passed the HWT test requirements.

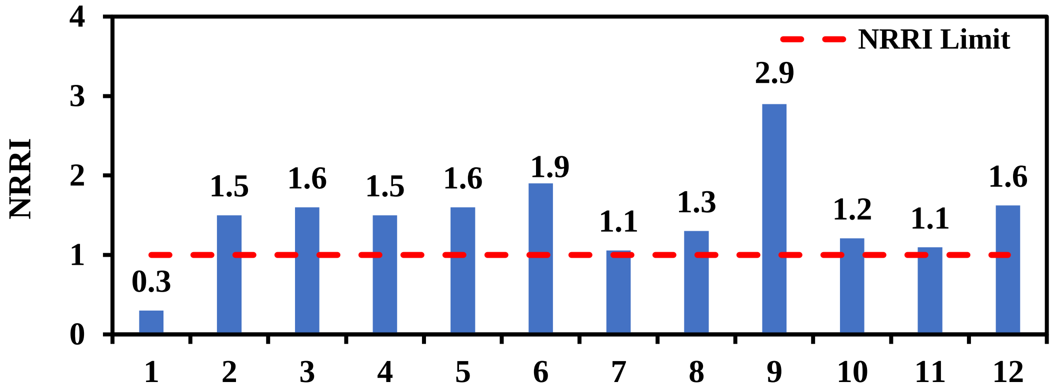
For the FN test results presented in Figure 3.2b, the acceptance limits of 50 and 190 cycles are used for two traffic levels of 3 to 10 million ESALs and 10 to 30 million ESALs, respectively. Five out of the twelve Superpave mixtures demonstrate FN values ranging between 50 and 190,


a) HWT Test

b) FN Test

Figure 3.1 –Comparison of Permanent Deformation Results

a) Normalized RRI



b) Flow Number

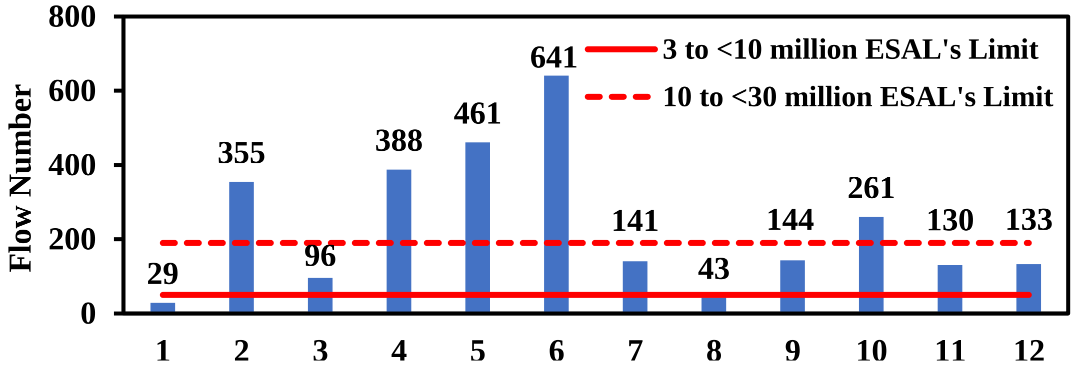


Figure 3.2 – Permanent Deformation Performance Parameters

which means they pass the minimum requirement for a traffic level of 3 to 10 million ESALs. Five mixtures satisfactorily met the minimum flow number of 190 for a highway with a 10 to 30 million ESALs. Two mixtures did not meet the minimum FN limit for 3 million to 10 million ESALs. For both HWT and FN tests, Mixture 1 is not acceptable regardless of the binder PG related or traffic level requirements established from the HWT and FN tests. Please refer to appendix B for more information on permanent deformation test results.

Duplicate tests were carried out for the HWT and FN tests to account for consistency in the results. Table 3.1 summarizes the test results for HWT and FN tests. The HWT test showed consistent results among duplicate specimens, except for three mixtures that yielded a difference of around 2500 units for the RRI parameter. The maximum difference on FN values for the duplicate specimens from the same mixture was 175 units. Regardless of the differences the results from duplicate specimens did not contradict each other. This means the well and poor performing mixtures can be delineated with both performance test methods.

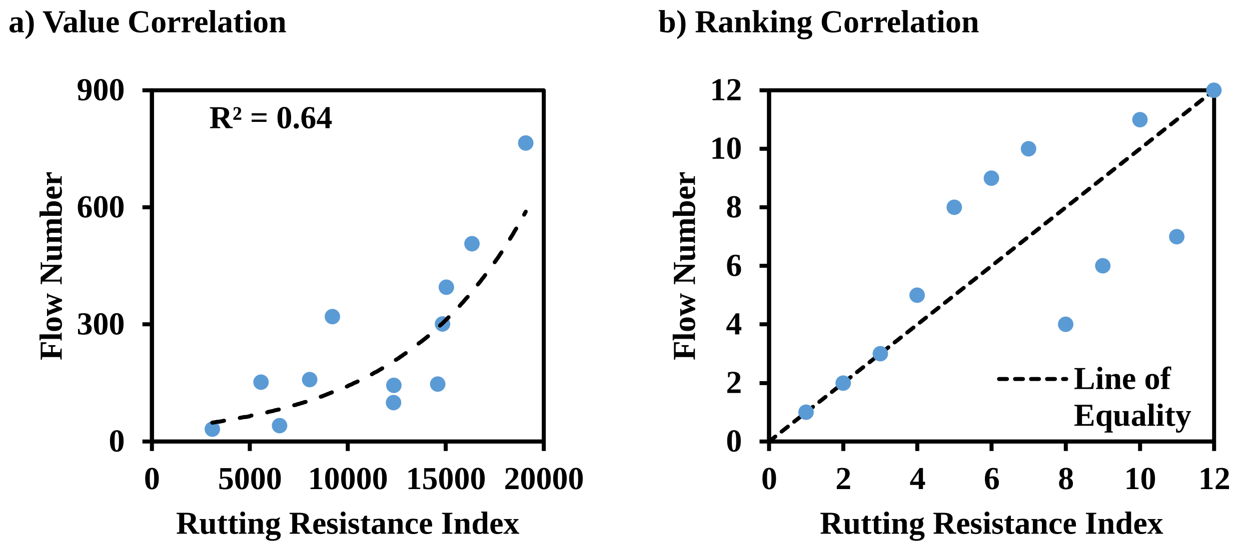
A correlation analysis was performed among the RRI and FN parameters from the HWT and FN tests as shown in Figure 3.3. Figure 3.3a shows that an exponential relationship can describe the correlation between the RRI and FN values with a coefficient of determination (R^2) of 0.64. Therefore, asphalt mixtures with high RRI values will also exhibit high FN values.

Figure 3.3b shows a comparison of a numerical ranking of the RRI and FN values. The ranking was performed by assigning larger numbers to the lower performing mixes (RRI or FN values). Table 3.2 summarizes the values used for the correlation analyses shown in this section. The best performing mixture is assigned a rank of 1, while the worst performing mixture is assigned a rank of 12. The HWT and FN tests showed good agreement on the three best and the worst asphalt mixtures, while for the other asphalt mixtures the rankings changed considerably.

Table 3.3summarizes the key observations from evaluating alternative promising permanent deformation tests in terms of acceptance potential, variablity of the tested specimens, correlation to RRI, and the expereince with field perfromance. Information such as the main perfromance index for analyzing the behavior of the mixture is presented, testing requirements in terms of speciemen preparation and testing time of each is presented. Table 3.3 is used to analyze the advanatges and limitations of each test method, and helps to select the best perfromance test.

Table 3.1 – Summary of HWT and FN Test Results

Mixture	Specimen	Hamburg Wheel Test			Flow Number	
		Rut Depth, mm	Number of Passes	RRI	Flow Number	Cycles
1	1	13.0	5,580	2,722	32	89
	2	12.6	6,830	3,434	26	70
2	1	5.8	20,000	15,449	395	1,183
	2	6.9	20,000	14,598	315	986
3	1	7.2	20,000	14,323	100	344
	2	12.3	20,000	10,346	92	270
4	1	5.1	20,000	16,000	301	1,060
	2	8.1	20,000	13,661	475	1,397
5	1	4.6	20,000	16,417	507	1,623
	2	4.8	20,000	16,260	415	1,238
6	1	1.3	20,000	18,976	765	2,213
	2	1.0	20,000	19,181	516	1,454
7	1	13.4	18,380	8,705	159	472
	2	12.8	14,900	7,403	122	359
8	1	12.7	11,100	5,572	41	128
	2	12.7	14,850	7,443	44	141
9	1	6.6	20,000	14,811	147	473
	2	7.2	20,000	14,362	140	411
10	1	12.6	18,120	9,167	320	516
	2	12.6	18,320	9,254	201	512
11	1	13.1	13,079	6,313	152	436
	2	12.6	9,530	4,810	108	318
12	1	10.2	20,000	11,969	144	356
	2	9.2	20,000	12,740	122	305


a) Value Correlation

b) Ranking Correlation

Figure 3.3 – Correlation of Value and Rank of Permanent Deformation Tests

Table 3.2 - Summary of Value and Rank for Permanent Deformation Tests

Mixture	Rutting Performance Tests			
	FN		RRI	
	Value	Rank	Value	Rank
1	32	12	3078	12
2	395	3	15024	3
3	100	10	12335	7
4	301	5	14831	4
5	507	2	16339	2
6	765	1	19079	1
7	159	6	8054	9
8	41	11	6507	10
9	147	8	14587	5
10	320	4	9210	8
11	152	7	5561	11
12	144	9	12354	6

Table 3.3 - Permanent Deformation Tests Key Observations

Test	Index	Variability	Testing Requirements	Correlation to RRI
HWT	Rutting Resistance Index	Low	One cut Long Testing time	-
FN	Flow Number	Low	Drilling specimen Long Testing time	Medium

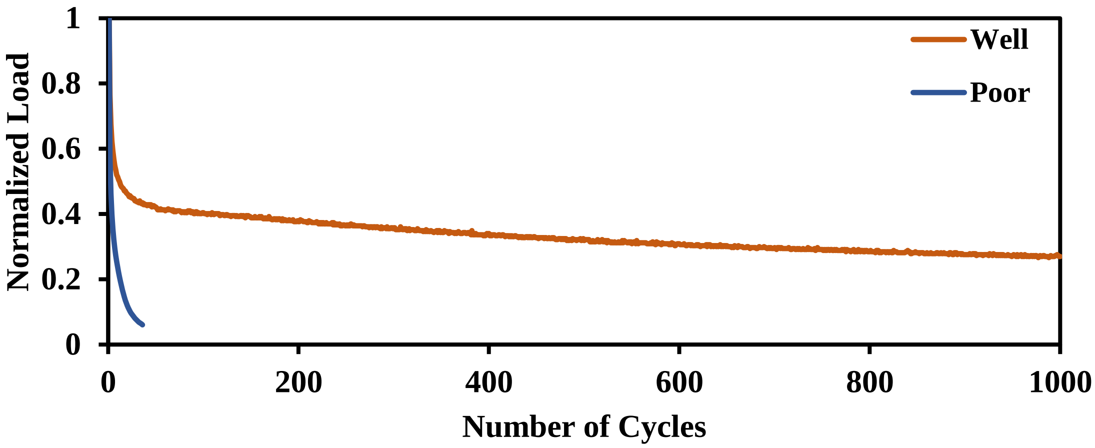
3.2 Performance Tests for Cracking Susceptibility Characterization

The OT test has been widely used in Texas as the main cracking performance test for the last decade. More simple tests, such as the SCB I-FIT (AASHTO TP 124) and IDEAL CT (Tex-250-F), have also been considered by TxDOT and other highway agencies. This section documents typical results from the OT, IDEAL CT and SCB I-FIT tests.

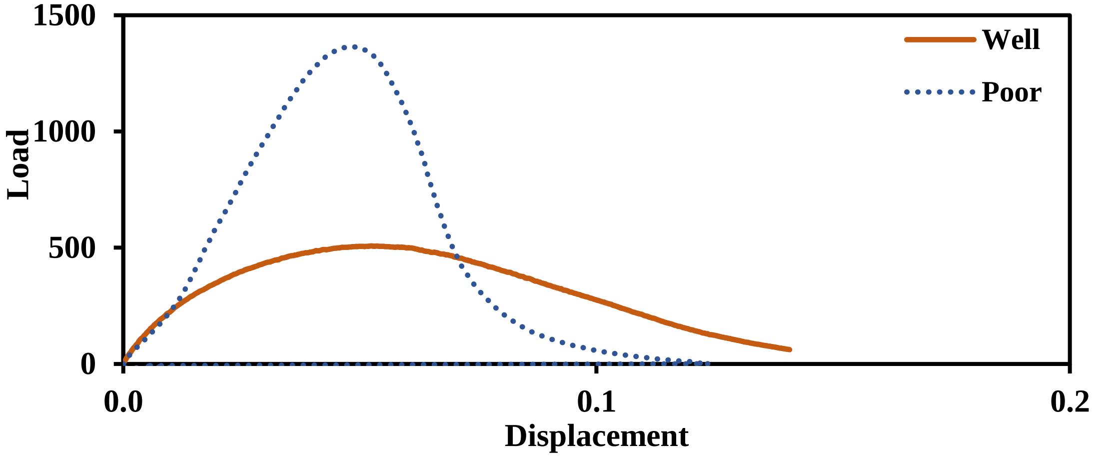
Figure 3.4 shows typical test results for a well and a poor performing mixture from the selected cracking performance tests. As shown in Figure 3.4a, the OT test results are shown as the normalized load reduction curves, which consists of cross plotting the normalized cyclic peak load versus the number of cycles to failure. The well performing mixture reached 1,000 cycles while the poor performing mixture failed in less than 50 cycles. Figure 3.4b and 3.4c present the load versus displacement curves for the SCB I-FIT and IDEAL CT tests, respectively. In both cases, the poor performing mixture yielded a higher peak, but exhibited a steeper slope post peak, which negatively affects the proposed cracking indices used for assessing cracking resistance.

Figure 3.5 displays the cracking performance of each mixture for all three cracking tests. The main parameters used to asses to performance of a mixture in each test are the CPR for OT test, FI for SCB I FIT test, and the CT Index for IDEAL CT test. Acceptance limits are presented for all parameters, 0.45 is used for CPR, 8 for FI (Al-Qadi, 2016), and 80 for CT (Newcomb, 2018).

a) OT Test



b) SCB Test



c) IDT Test

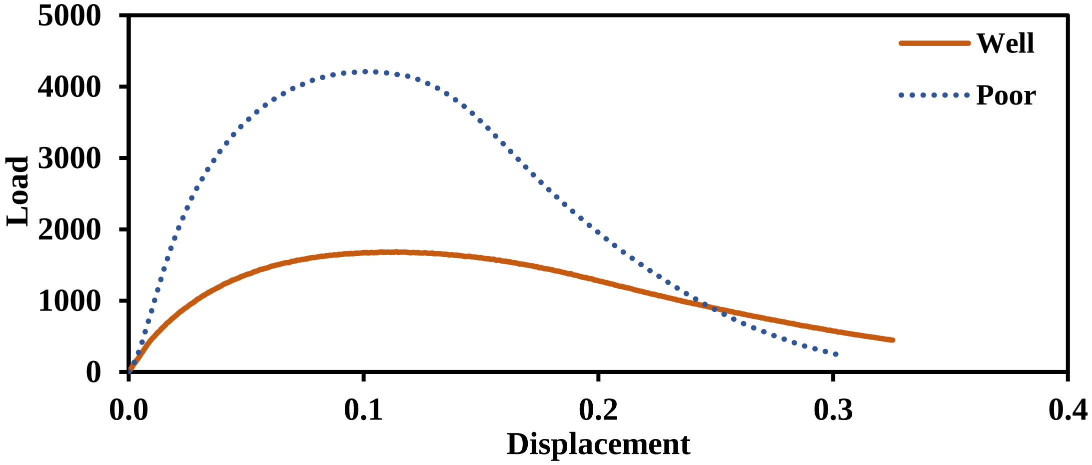
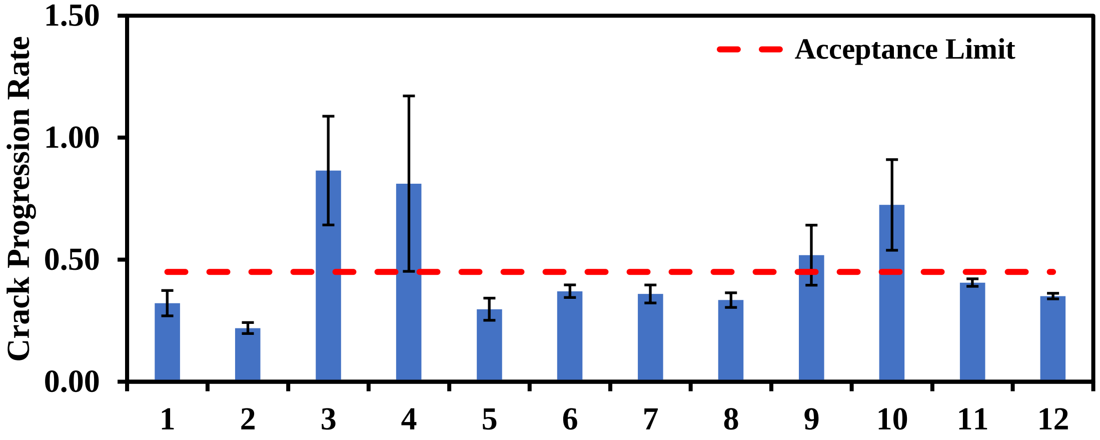
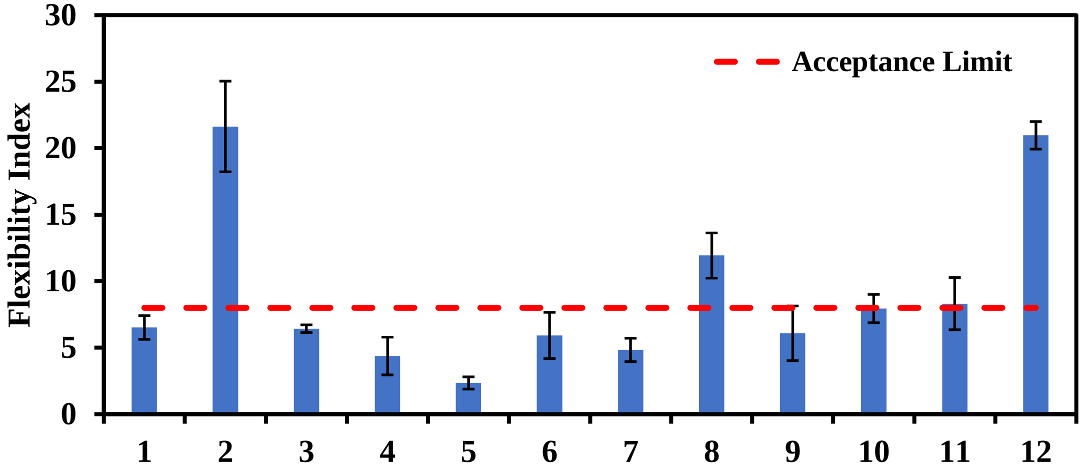


Figure 3.4 - Mixture Comparison of Cracking Tests Main Parameters

a) Crack Progression Rate



b) FI Index



c) CT Index

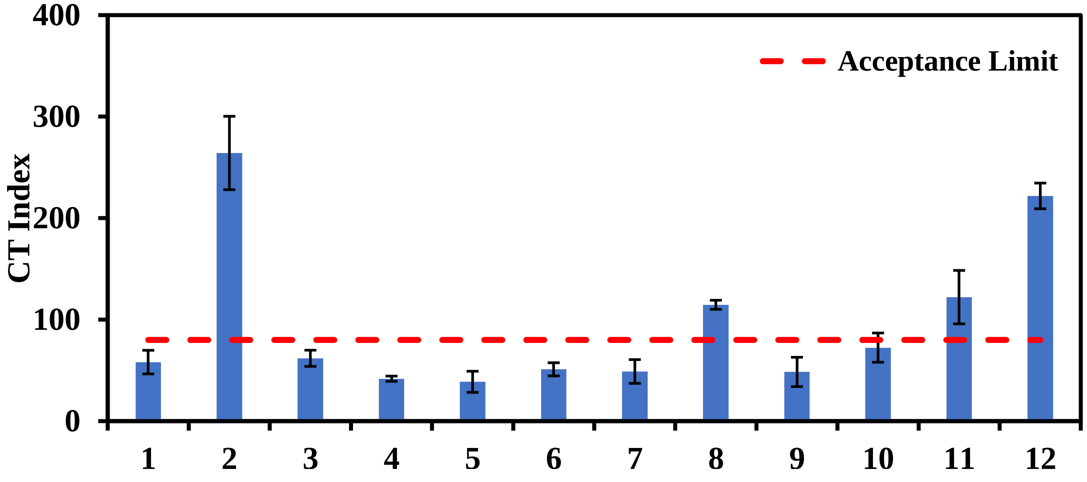


Figure 3.5 – Cracking Resistance Performance

Figure **3.5**3.5a shows the CPR of each mixture. The error bars on the graph represent the variability of the tested specimens based on their respective standard deviation. Eight of the twelve mixtures yielded CPR values less than the maximum acceptance limit of 0.45, which are considered mixtures with acceptable cracking resistance. Figure 3.5b displays the FI values from the SCB I-FIT. Only five asphalt mixtures exhibited a FI value greater than the minimum requirement of 8. Similarly, Figure 3.5c shows the test results for CT Index obtained from the IDEAL CT test. Four asphalt mixtures yielded acceptable CT Index values. (Refer to appendix B for more information.)

The repeatability of the test results should be taken into consideration when evaluating performance tests.

c) FI Index vs CT Index

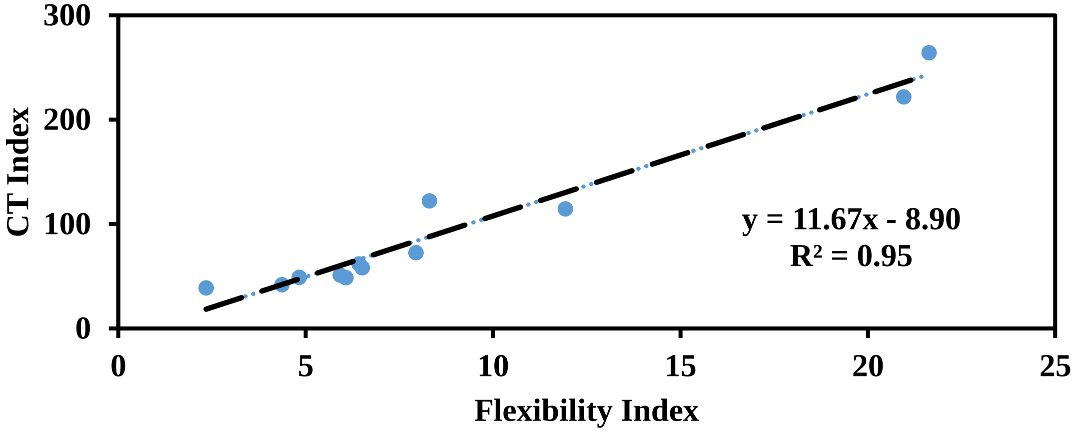


Figure **3.6a** and 3.6b show the correlation of CPR with CT and FI indices, respectively. As CPR decreased, FI and CT indices increased. However, the trend was not clearly defined resulting on a significantly low correlation. Figure 3.6c shows the correlation between CT Index and FI Index in which a 95% is found, mainly because both parameters are calculated similarly.

As shown in Figure 3.7, the rankings were not favorably correlated when comparing CPR to CT Index and FI Index. The rank correlation between FI and CT is stronger, meaning they rank the mixture in a similar way.

Table 3.4 summarizes the average and COV values for the test results of all asphalt mixtures. The COVs for the CPR ranged between 3% and 26%, except for Mixture 4 that yielded a COV of 44% due to an outlier data point on the results. For the FI index, the COVs varied from 5% to 34%. The COVs for the CT Index from the IDEAL CT tests ranged from 6% to 30%. In addition, an evaluation of the rankings from each parameter was carried out, as summarized in Table 3.4. A rank of "1" was assigned to the highest flexibility index and CT index, similarly to the lowest CPR. A rank of "12" was assigned to the lowest flexibility index and CT index as well as to the highest CPR.

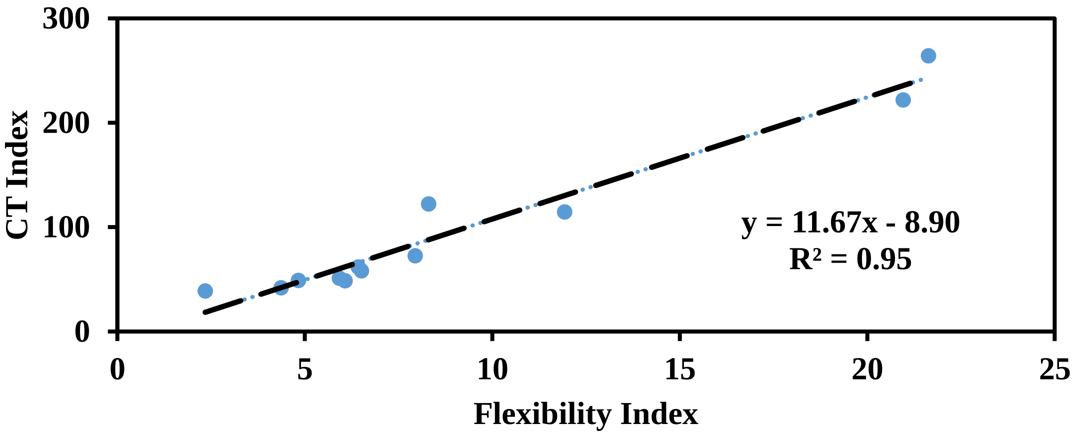

c) FI Index vs CT Index

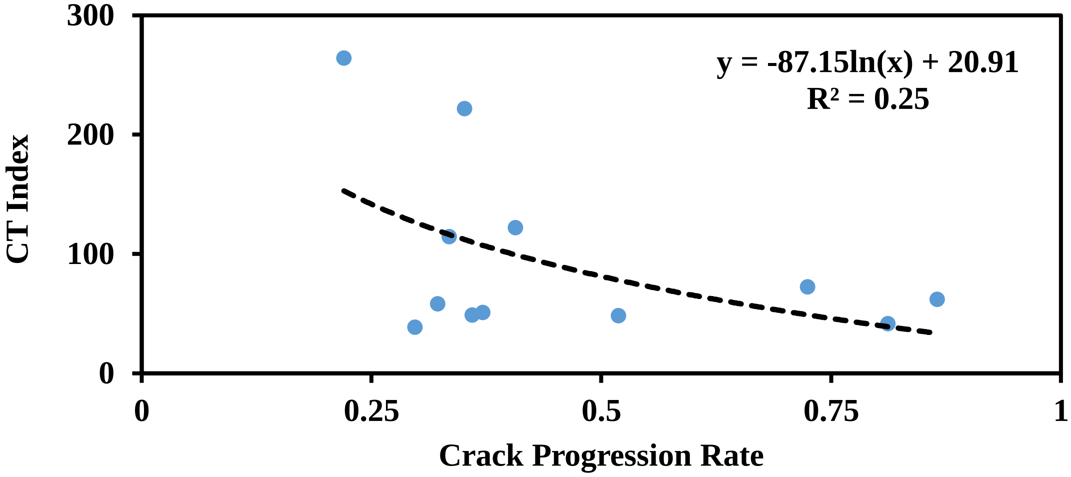
Figure **3.6**a and 3.6b show the correlation of CPR with CT and FI indices, respectively. As CPR decreased, FI and CT indices increased. However, the trend was not clearly defined resulting on a significantly low correlation. Figure 3.6c shows the correlation between CT Index and FI Index in which a 95% is found, mainly because both parameters are calculated similarly.

As shown in Figure 3.7, the rankings were not favorably correlated when comparing CPR to CT Index and FI Index. The rank correlation between FI and CT is stronger, meaning they rank the mixture in a similar way.

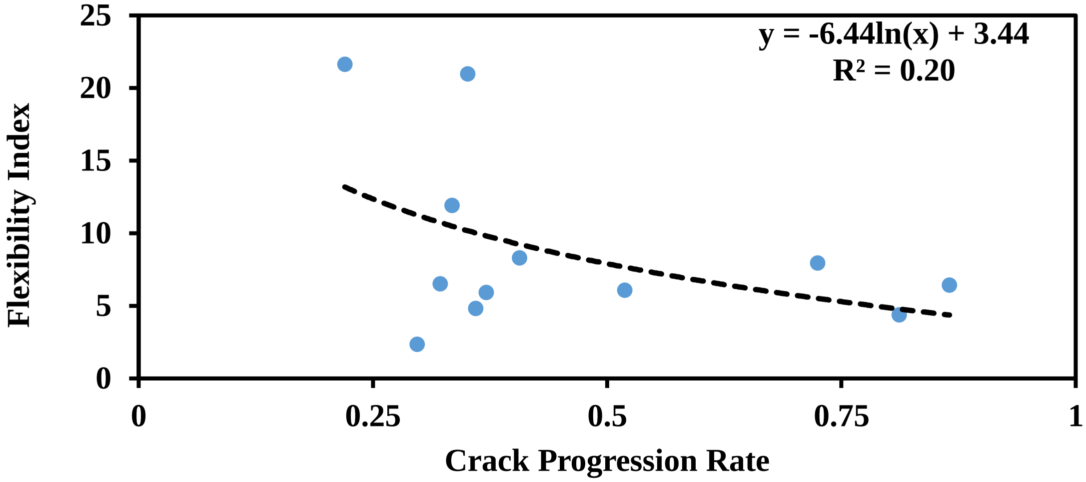
Table 3.4 – Summary of Statistical Parameters from Cracking Test Results

Mixture	CPR			FI Index			CT Index		
	AVG	COV	Rank	AVG	COV	Rank	AVG	COV	Rank
1	0.32	16%	3	6.5	14%	6	58.2	20%	7
2	0.22	10%	1	21.6	16%	1	264.2	14%	1
3	0.87	26%	12	6.4	5%	7	61.9	13%	6
4	0.81	44%	11	4.4	33%	11	41.8	6%	11
5	0.30	15%	2	2.3	20%	12	38.8	27%	12
6	0.37	7%	7	5.9	29%	9	51.1	13%	8
7	0.36	10%	6	4.8	18%	10	48.9	24%	9
8	0.33	9%	4	11.9	14%	3	114.6	4%	4
9	0.52	24%	9	6.1	34%	8	48.5	30%	10
10	0.72	26%	10	7.9	13%	5	72.4	20%	5
11	0.41	4%	8	8.3	24%	4	122.2	22%	3
12	0.35	3%	5	21	5%	2	221.9	6%	2

a) CPR vs CT Index



b) CPR vs FI Index



c) FI Index vs CT Index

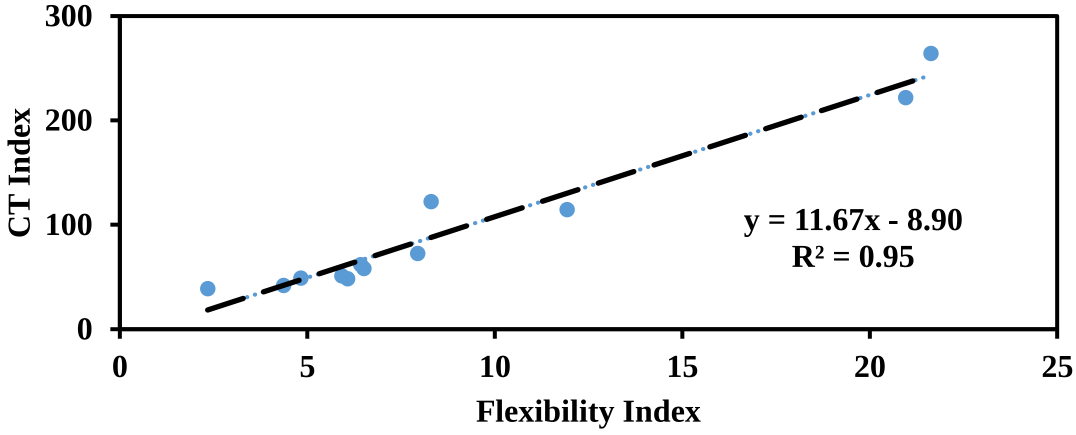
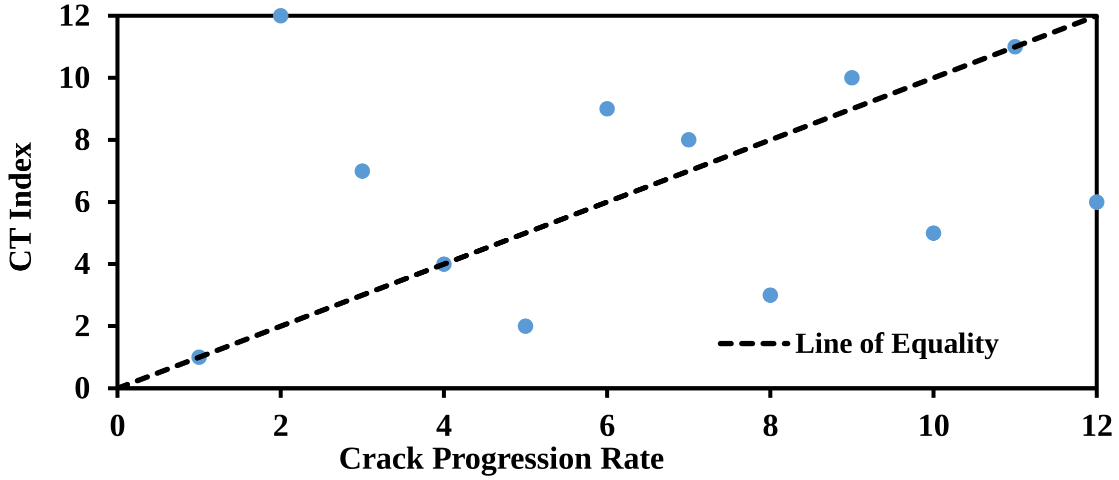
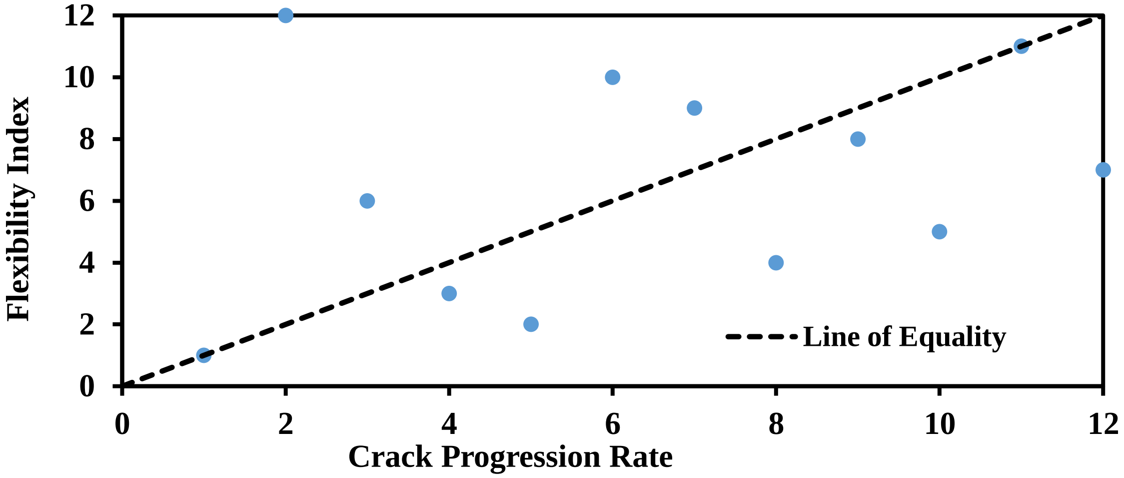


Figure 3.6 – Value Correlation of Cracking Tests

a) CPR vs CT Rank



b) CPR vs FI Rank



c) CT Rank vs FI Rank

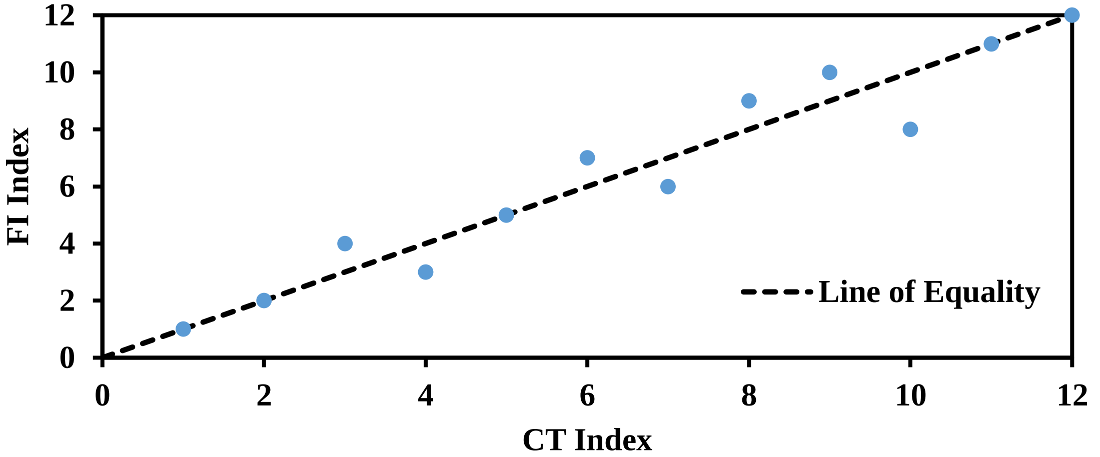


Figure 3.7 - Rank Correlation of Cracking Tests

Table 3.6 summarizes the key observations from evaluating alternative promising cracking resisatnce tests in terms of acceptance potential, variablity of the tested specimens, expereince with field perfromance, and the test requirements and limitations each one presents.

Table 3.6 - Cracking Susceptibility Tests Key Observations

Candidate Cracking Performance Tests				
Cracking Test	Performance Index	Variability	Relationship with Field Performance	Test Requirements
OT	Crack Progression Rate	< 40%	High	Cutting Gluing specimens to steel plates Testing time up to 3 hrs.
SCB	Flexibility Index	< 30%	Low	Cutting Notch Testing time < 10 min.
IDT	CT Index	< 30%	Low	No cutting No notch Testing time <10 min.

3.3 Performance Based Analysis of Asphalt Mixtures for Production and Quality Control

Given the practicality and ease of use, TxDOT currently uses IDT to assess the brittleness of asphalt mixtures in order to minimize crack-susceptible asphalt mixtures that contained stiff binders and high recycled material contents. Several parameters have been developed and proposed by several researchers (*Zhou et al., 2016; Omranian, 2018; Yin, 2018; Kaseer, 2018; Perez-Jimenes, 2013*) as indicators of the brittleness of asphalt mixtures. These parameters are summarized in Table 3.7. Figure 3.8 presents a visual representation of the parameter computation and required parameters from the load versus displacement curve.

Table 3.7 – Candidate IDT Indices

Cracking Parameter	Reference	Formula	Description of Parameters
ITS	TEX-226-F	$S_t = \frac{2P}{\pi(HD)}$	S_t = Indirect Tensile strength, psi P = Total applied vertical load at failure, lb. H = Height of specimen, in. D = Diameter of specimen, in
$FI_{Fragility}$	Omranian, 2018	$FrI = \frac{G_{fpeak}}{G_f}$	G_f = Fracture energy, lb./in. $G_{f\ peak}$ = Fracture energy at peak
CT	Zhou, 2016	$CT_{Index} = \frac{t}{2.4} \times \frac{l_{75}}{D} \times \frac{G_f}{\lvert m_{75} \rvert} \times 10^6$	CT Index = Cracking tolerance index normalized to 2.4 in. thick specimen G_f = Failure energy, lb./in. $\lvert m_{75} \rvert$ = Absolute value of the post-peak slope m_{75}, lb./in. l_{75} = Displacement at 75% the peak load after the peak, in. h = Thickness of specimen, in. D = Diameter of specimen, in.
TI	Perez-Jimenes, 2013	$TI = (G_F - G_{Fmax}) \cdot (\Delta_{mdp} - \Delta_{Fmax}) \cdot 10^3$	IT = Toughness Index, J/m; G_{Fmax} = Fracture Energy until Δ_{Fmax}, J/m^2 Δ_{mpd} = Displacement at 50% of post-peak load, mm Δ_{Fmax} is the displacement at maximum load, mm
CRI	Kaseer, 2018	$CRI = \frac{G_f}{\lvert P_{max} \rvert}$	G_f = Failure energy, lb./in P_{max}= Peak Load
$FI_{Fatigue}$	Barman, 2018	$FI = \frac{-U_f}{(\frac{dTI}{d\varepsilon})}$	U_f =Fracture Energy Derivation of TI, based on slope
N_{flex}	Yin, 2018	$N_{flex}\,Factor = \frac{T_{inf}}{\lvert m \rvert}$	m= Slope T_{inf}= Toughness at inflection point

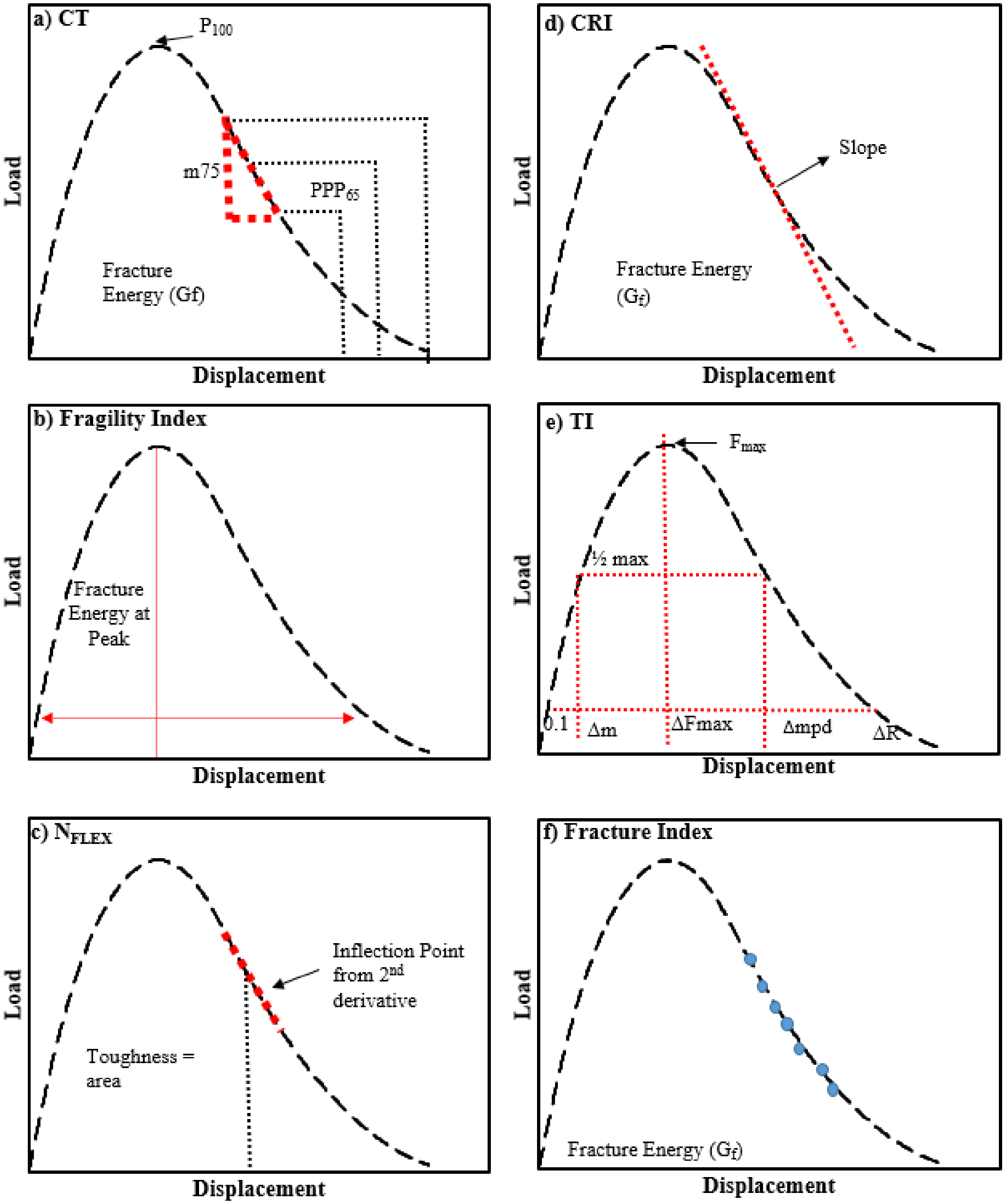


Figure 3.8 – Performance Indices Derived from IDT Test Data

Zhou et al. (2016) recently proposed the CT index extracted from the IDT test (renamed to IDEAL CT test) results. Figure 3.8a depicts the parameters required to compute the CT Index. As shown on Figure 3.8b, the Fragility Index can be computed considering the critical and total fracture energies (Omranian, 2018). Similarly to the CT , the Nflex factor considers the post-peak slope but the work of fracture under the load versus displacement curves is slightly refined as shown on Figure 3.8c (Yin, 2018). The crack resistance index (CRI) is a simpler parameter that can be computed as shown in Figure 3.8d (Kaseer, 2018). The toughness index (TI) proposed by Perez-Jimenes (2013) considers a few areas under the load-displacement curve, see Figure 3.8e. Figure 3.8f shows the information required to compute the Fatigue Index (Barman, 2018). Although some parameters have been proposed for either IDT or SCB test methods, all parameters were derived from the IDT test configuration.

The selected parameters were computed from four replicate IDT tests performed for each of the twelve asphalt mixtures. Figure 3.9 displays the variability, distribution and consistency of these parameters were investigated in this section. Since different parameters have different magnitudes, box plots were created with the normalized values. The normalized values is defined as the measured parameter from a given mix divided by the corresponding median value from the twelve asphalt mixtures. The data label shows the range of normalized values. The greater the range of normalized values is, the greater the ability for the index to discriminate asphalt mixtures will be.

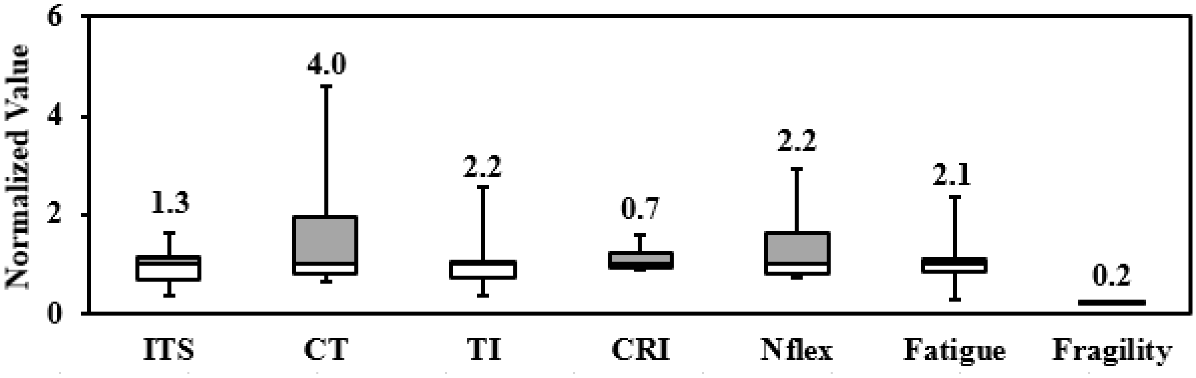


Figure 3.9 - Normalized Value of Candidate Indices

Table 3.8 reports the average and COV values for all parameters and mixtures. The most repeatable parameter is ITS, with a maximum COV of 8%. The second most consistent parameter is CRI with COVs between 2% and 12%. Fragility Index also demonstrates a low variability of results with COVs between 3% and 12%. TI and N_{flex} indices yielded a maximum COV value of 22%. Fatigue Index yielded COV between 3% and 18%, but one mixture exhibited a COV of 55%. CT Index yielded COVs ranging from 5% to 34%. The investigated cracking indices consider different parameters from the load versus displacement curve, which can introduce a higher or lower variability (ex. ITS only considers the acquired maximum load and showed lowest variability).

¡Error! No se encuentra el origen de la referencia. summarizes the results of correlation analyses between CPR from the OT test and the investigated cracking indices from the IDT tests. The maximum coefficient of correlation was found between the CT Index and CPR parameter. Although N_{flex} Factor also yielded a similar R, CT Index was selected as the best parameter to characterize an asphalt mixture because of the greater range of values. In terms of variability both indices are similar, with COV's of less than 35%.

Table 3.8 - Variability of Cracking Indices

Mix	ITS		CT		TI		CRI		Nflex		Fracture		Fragility	
	AVG	COV	AVG	COV	AVG	COV	AVG	COV	AVG	COV	AVG	COV	AVG	COV
1	39	2%	58	23%	3.8	16%	5800	7%	13.8	14%	50	17%	33.8	7%
2	80	3%	276	17%	5.1	16%	9974	5%	41.3	13%	302	10%	34.5	8%
3	71	5%	62	15%	7.2	9%	6338	2%	14.3	14%	116	14%	36.4	6%
4	157	2%	42	7%	11.8	14%	5860	4%	10.5	8%	195	9%	41.3	12%
5	179	4%	39	31%	11.2	20%	5515	10%	10.1	22%	185	55%	43.7	5%
6	113	3%	51	15%	8.4	15%	5772	5%	12.3	11%	145	11%	41.4	3%
7	122	3%	49	28%	9.5	10%	5954	8%	11.5	15%	165	18%	40.8	4%
8	72	2%	115	5%	11.0	7%	7621	2%	22.5	4%	184	12%	35.8	4%
9	130	8%	49	34%	11.1	19%	6214	12%	11.2	21%	200	16%	39.4	9%
10	111	4%	72	23%	11.4	22%	6776	6%	15.7	17%	195	10%	41.8	7%
11	95	3%	122	25%	15.3	12%	7981	7%	23.0	18%	220	16%	37.6	7%
12	124	2%	227	7%	28.4	5%	9869	1%	35.0	6%	445	3%	40.4	3%

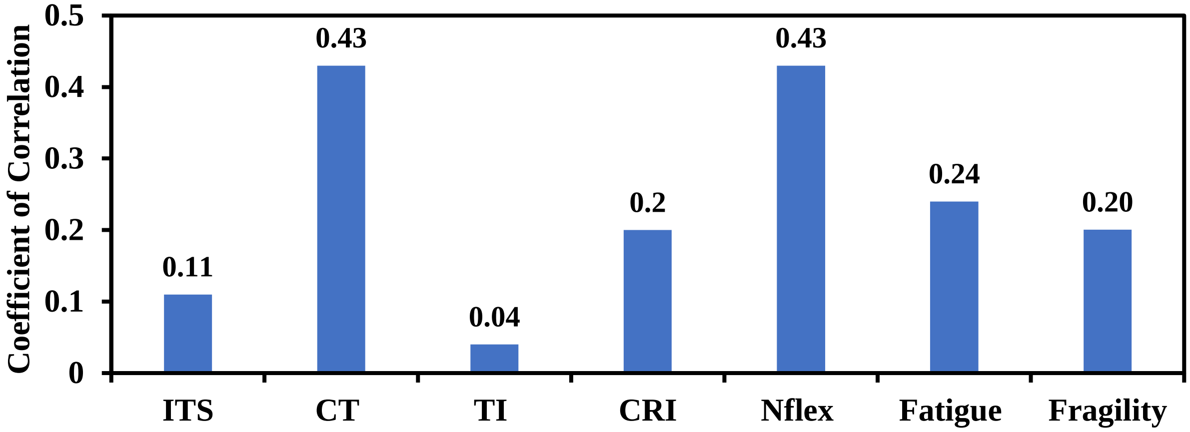


Figure 3.10 – Correlation of IDT Parameters and CPR

A simple performance parameter must be selected and implemented for quality control during the production of asphalt mixtures. A quick test such the IDT test is convenient because of the short period of time the test takes, which enables its application during production process. Further research must be carried out to properly introduce the use of a quality control parameter for performance acceptance of asphalt mixtures during production.

3.4 Performance Interaction Diagram

The performance-based analysis formulated in this study consists of three performance parameters to measure the cracking susceptibility, rutting resistance and brittleness of the asphalt mixtures on a performance interaction diagram. The cracking susceptibility of asphalt mixtures is assessed using the CPR from the OT test with an acceptance limit of 0.45. The NRRI parameter from the HWT test is proposed to simplify the rutting resistance evaluation of asphalt mixtures with a minimum requirement of 1. The third performance parameter, CT Index, is shown as a data label and intended to be a reference during the quality control process during the production of the asphalt mixture. Figure 3.11 displays all twelve mixtures in the performance interaction diagram.

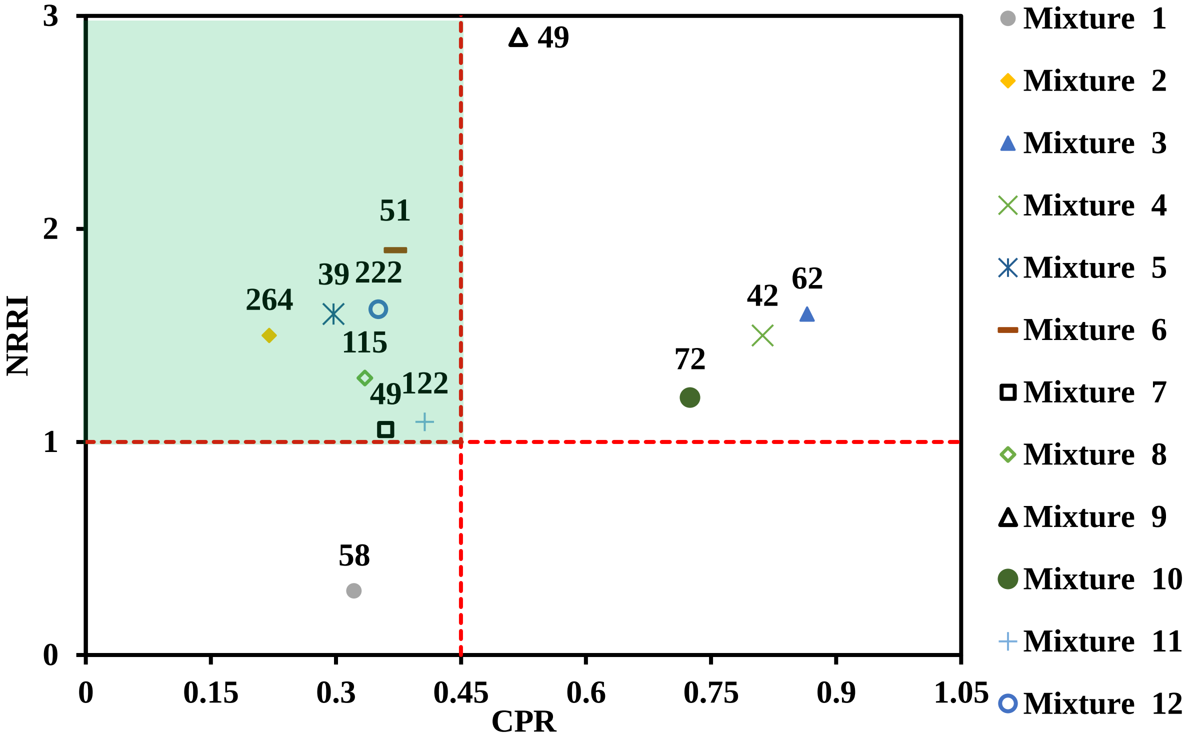


Figure 3.11 - BMD Performance Interaction Diagram

In general, seven mixtures yielded acceptable mechanical performance in terms of cracking susceptibility and rutting resistance. Four mixtures showed satisfactory permanent deformation performance but failed to meet the cracking acceptance criterion. Only one mixture exhibited a satisfactory cracking performance but did not meet the minimum requirements for permanent deformation. Asphalt mixtures located within the green shaded area are considered BMD.

The use of performance tests, especially the OT, HWT and IDT tests showed potential in characterizing the mechanical properties of asphalt mixtures consistently. The following comments can be made about the underperforming asphalt mixtures:

- Mixture 1 yielded a low NRRI. This asphalt mixture is recommended to conduct a parametric study on the mix design variables that can potentially improve its rutting and tensile strength such as aggregate gradation, binder PG and recycled material content.

- Mixture 3 exhibited poor cracking performance with a CPR value of 0.87. Mix design variables such as binder PG, aggregate gradation and asphalt content may be investigated to improve the mechanical performance of this mix design.
- Mixture 4 presented poor cracking performance with a CPR value of 0.81 but acceptable rutting resistance. Mix design variables such as asphalt content, aggregate gradation, recycled material content and binder PG can be adjusted to improve the mechanical performance of this mix design.
- Mixture 9 exhibited marginal cracking performance with a CPR value of 0.52, while the an NRRI of 2.9 was obtained. Mix design variables such as binder PG substitution and recycled material content should be considered to improve the mechanical performance of this mix design.
- Mixture 10 showed poor cracking performance with a CPR value of 0.72, but an acceptable NRRI. Mix design variables such as binder PG, aggregate gradation and asphalt content may be investigated to improve the mechanical performance of this mix design.

Chapter 4 – Evaluating Superpave Mixtures with Performance-Based Analysis Methodology

The objective of this section is to evaluate a few mix designs from the previous section and reformulate the mix design to meet the BMD performance requirements. This activity was performed to investigate the influence of key mix design variables such as aggregate gradation, performance grade of binder, and influence of recycled material content.

4.1 Influence of Performance Grade of Binder

An experiment design plan that consists of substituting the binder PG, in the same mixture was performed. Five different binders from the same source but different PG (including PGs 58-28, 64-22, 70-22, 70-28, and 76-22) were used in this evaluation. Table 4.1 provides the mix design information and properties for the original SP C, which yielded an OAC of 5.2% and a VMA of 15.1%. The mix, which contained 10% RAP, and 3% RAS, was originally designed with a PG 70-22.

The aggregate gradation is shown in Figure 4.1.A gradation with a nominal maximum aggregate size (NMAS) 12.5 mm was selected for the mix design. The aggregates sources were limestone-dolomite aggregate. This Superpave mixture was design with a target density of 96% at 50 gyrations.

The results of the performance tests for all different PGs are shown in Figure 4.2. The only modification done to the design was the change of binder PG. Figure 4.2a shows the results of the OT tests, in which all five binders yielded CPRs below the maximum allowable limit of 0.45. The cracking susceptibility of this mixture was not affected by the change in the binder PG. Figure 4.2b represents the NRRI of the asphalt mixtures. Only PG 58-28 did not perform satisfactorily.

Figure 4.2c represents the CT Index obtained from the IDEAL CT Test, mixes with PG 58-28 and 70-28 binders exhibited CT indecies below the acceptance limit of 80.

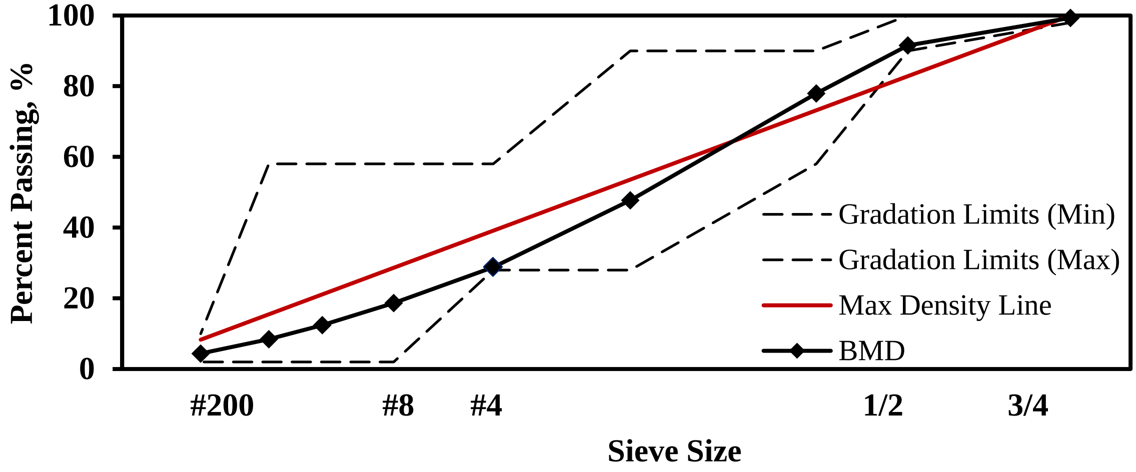


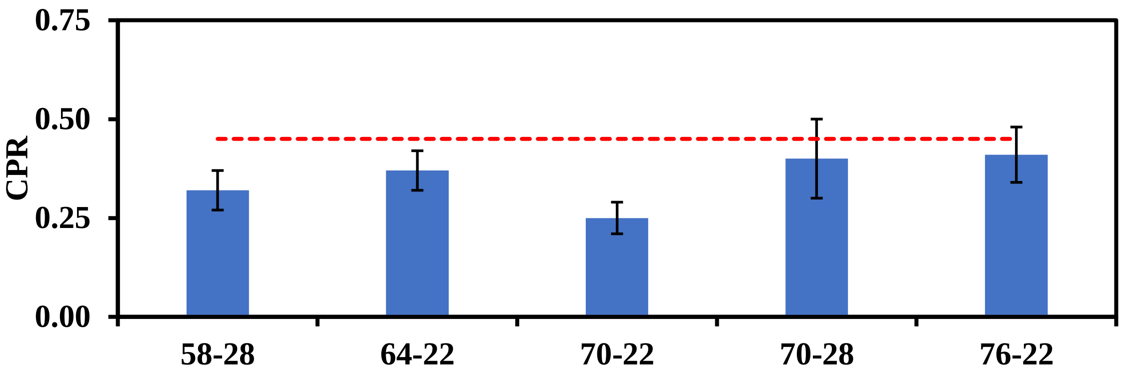
Figure 4.1 - Aggregate Gradation of BMD

Table 4.1 – Mix Design Properties

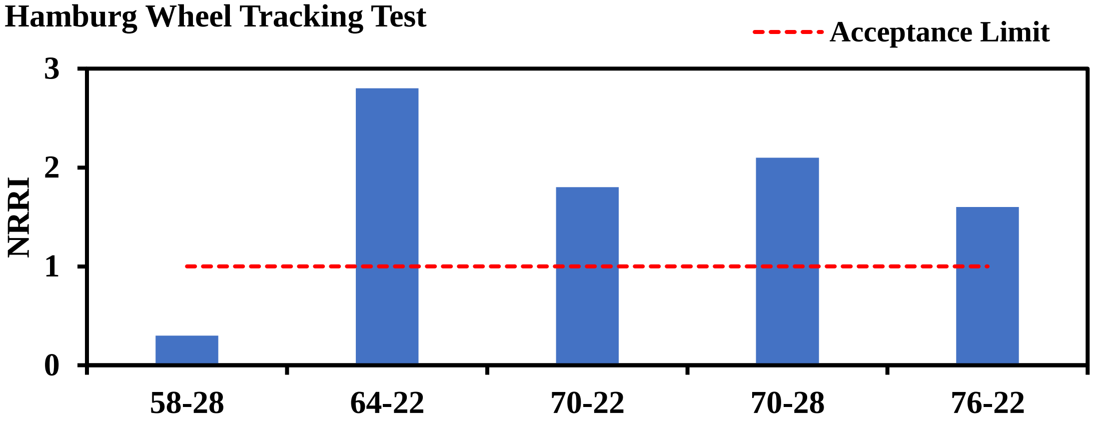
Parameters		**SP C**
Design Parameters	Nominal Maximum Aggregate Size	12.5 mm (1/2”)
	Number of Gyrations	50
	Target Density, %	96
	Aggregate Type	Limestone-Dolomite
Volumetric Properties	Optimum Asphalt Content, %	5.2
	Voids in Mineral Aggregates, %	15.1
	Maximum Specific Gravity	2.468

To analyze the performance of the asphalt mixtures and identify BMDs, the CPR, NRRI and CT Index values are shown in the performance interaction diagram displayed in Figure 4.3. Five mixes are plotted in the green shaded area, demonstrating good cracking resistance and acceptable performance against rutting. The change in the binder PG significantly influenced the rutting properties and CT Index of the mixtures while the cracking performance was similar among the mixtures with different binder PGs. This means the binder PG controls the brittleness and stability properties of the asphalt mixtures.

a) Overlay Test



b) Hamburg Wheel Tracking Test



c) IDEAL CT Test

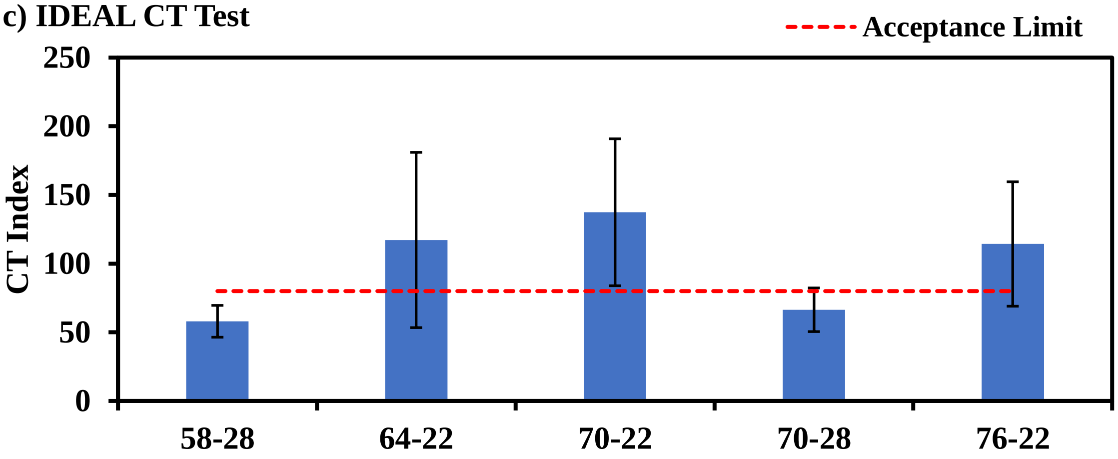


Figure 4.2 – Performance Tests Results from Influence of Binder PG

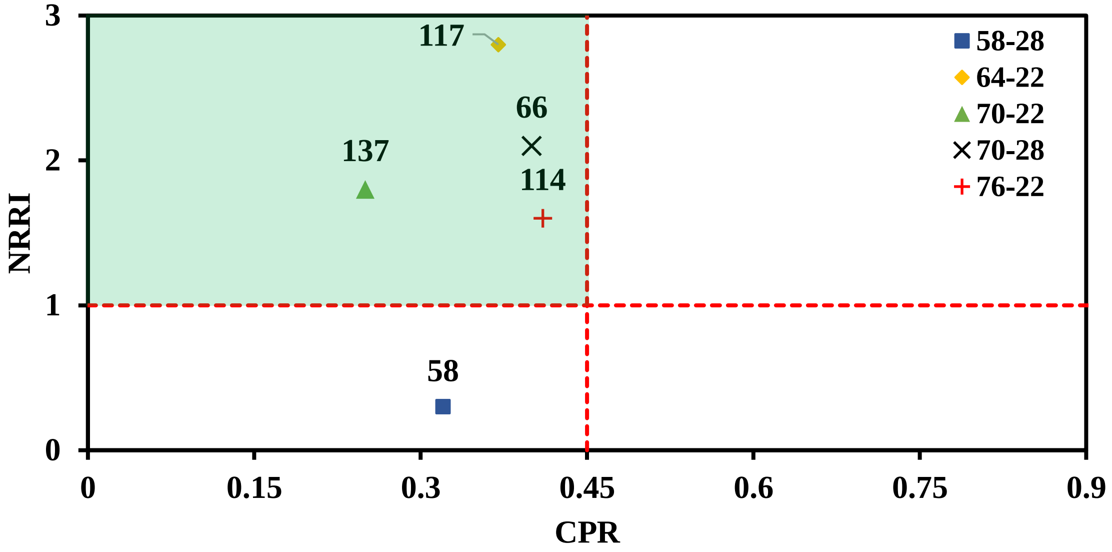


Figure 4.3 - Performance Interaction Diagram: Influence of Binder PG

Table 4.2 summarizes the averages and COV's obtained from the OT, HWT and IDT test results. The variability of the results from the selected performance tests is acceptable with COV values ranging from 11% to 25% for OT test. The variability of the CT Index obtained for these mixtures is between 20% and 54%. For HWT, the number of passes (NP), rut depth (RD), RRI, and NRRI are presented.

4.1.1 Conclusions and Recommendations

1. All mixtures presented acceptable cracking properties with CPR values of no more than 0.41 regardless of the binder's PG.
2. The rutting resistance of the SP C mixtures was improved with a different binder PG from the same source.
3. Changing the PG grade of the asphalt binder might be a solution to improve the rutting and strength properties of mixtures without significantly influencing their cracking potential.

Table 4.2 - Summary of Results

Mix Design	Test Methods	Parameters		Mix Reference				
				58-28	**64-22**	**70-22**	**70-28**	**76-22**
SP C	**IDEAL CT**	**CT Index**	**Average**	58	117	137	66	114
			COV	20%	54%	39%	24%	40%
	OT	**CPR**	**Average**	0.32	0.37	0.25	0.40	0.41
			COV	16%	11%	16%	25%	17%
	HWT	**NP**		6205	20000	20000	20000	20000
		RD, mm		12.8	7.4	7.7	5	4.8
		RRI		3078	14197	13976	16102	16244
		NRRI		0.3	2.8	1.8	2.1	1.6

4.2 Influence of Aggregate Gradation

Although the Superpave specifications provide a wider range of permissible gradations, the current SP mixes yield volumetric and mechanical properties such as dense-graded (DG) mixes. This may occur because selecting the aggregate gradation has been mainly driven by the optimization of the asphalt content to meet a minimum VMA requirement. A study was carried out to investigate the influence that aggregate gradation and binder type might have on the engineering performance of SP and DG mix designs. This information was used to recommend mixtures that conformed to the BMD concept.

4.2.1 Mix Design Characteristics

Utilizing the same mix design information, two different aggregate gradations with a 12.5 mm nominal maximum aggregate size (NMAS) were formulated for a DG C and SP C mix as shown in Figure 4.4. Both mixtures were produced from the same source of a dolomitic-limestone aggregate. The DG C gradation has an aggregate distribution restricted by the narrow lower and

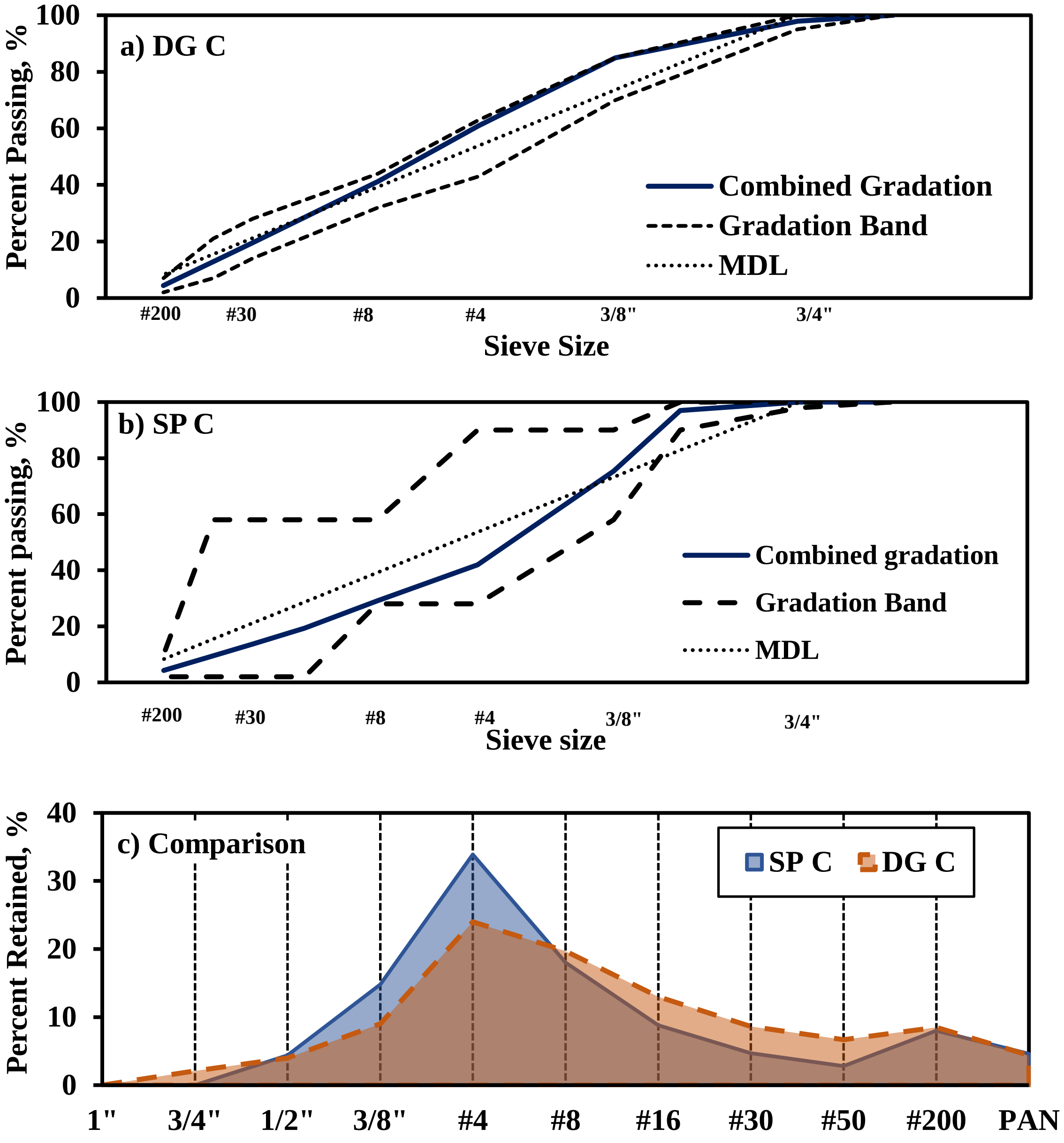


Figure 4.4 - Aggregate gradation for SP C and DG C mix designs

upper bounds, which typically result in a dense combination of aggregates. Using the wider permissible band for the SP C gradation, a coarser skeleton was selected. The distributions of the DG C and SP C aggregate sizes are compared in Figure 4.4c. Typically, the gradation for DG mix contains a small portion of coarse aggregates and large amount of intermediate aggregates and fines. The coarse aggregate content may not be enough to create adequate space to accommodate the intermediate aggregates and fines, and to provide adequate space for the asphalt binder.

Instead, the coarse aggregate skeleton may float in the excessive presence of intermediate aggregates and fines. The aggregate gradation for the SP C mix was formulated to maximize the use of coarse (from ½ in. to #4) aggregates and minimize the content of intermediate (from #8 to #50) aggregates. Increasing the content of coarse aggregates may produce a more stable aggregate skeleton, while adjusting the content of intermediate aggregates may provide adequate space for asphalt binder. The content of fines was kept as similar as possible for consistency.

Asphalt binders from the same source but with three different PGs were also used in this evaluation. The original SP C and DG C mixes were designed with PG70-22 binder. To minimize the influence of compaction method, a Superpave gyratory compactor was utilized to produce the SP C and DG C mixes. The asphalt mixtures were designed to meet a 96% target density at their OAC with 50 gyrations. The other mixtures were produced replacing the binder at the same OAC.

Table 4.3 provides the mix information and properties for the original SP C and DG C mixtures. The DG C mix yielded an OAC of 5.0%, while the SP C mix resulted in an OAC of 5.2%. Both SP C and DG C mixes passed the minimum VMA requirement of 15%.

Table 4.3 - Summary of Mix Design Information and Pavement Material Characteristics

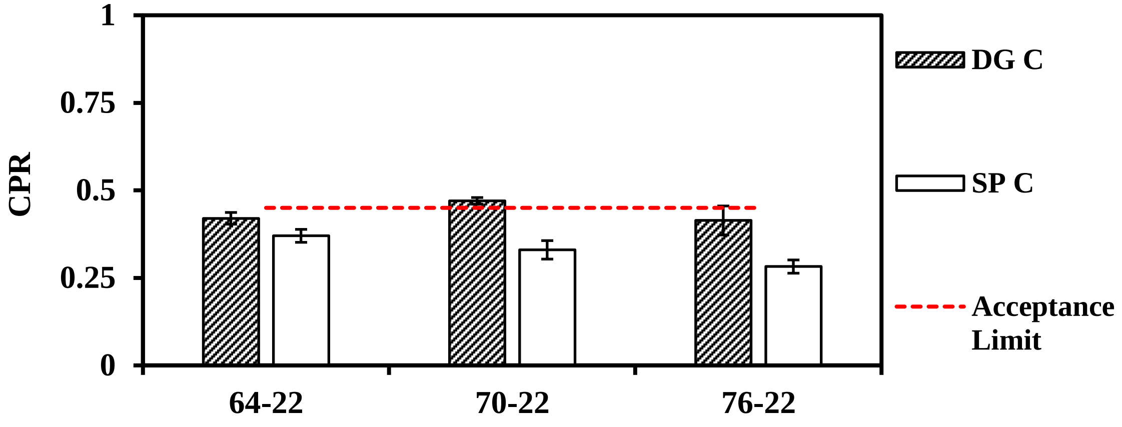
Parameters		**SP C**	**DG C**
Design Parameters	Nominal Maximum Aggregate Size	12.5 mm (1/2”)	12.5 mm (1/2”)
	Number of Gyrations	50	50
	Target Density, %	96	96
	Aggregate Type	Limestone-Dolomite	
Volumetric Properties	Optimum Asphalt Content, %	5.2	5.0
	Voids in Mineral Aggregates, %	15.9	15.4
	Maximum Specific Gravity	2.454	2.467

4.2.2 Results and Discussion of Balanced Mix Design Analysis

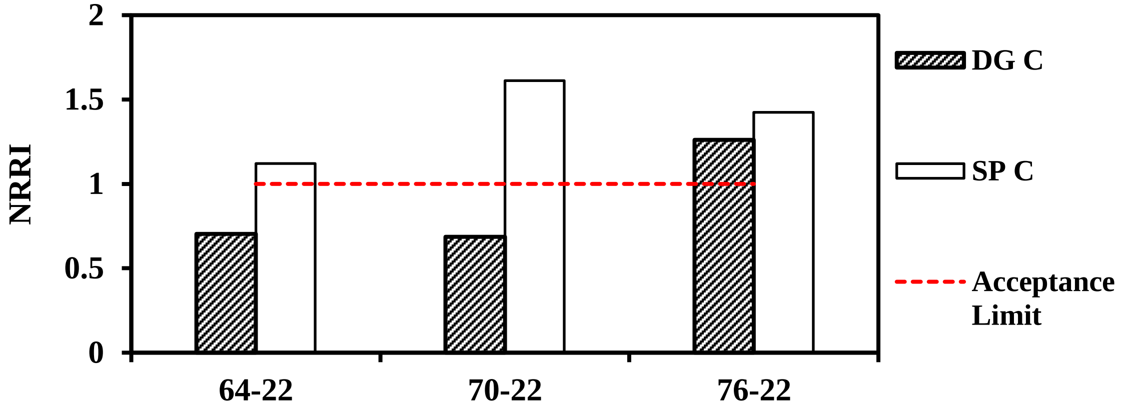
As shown in Figure 4.5, the CPR values for all mixtures, which varied from 0.28 to 0.47, met the acceptance limit of 0.45. The DG C mixtures yielded greater CPR values than the SP C mixtures, indicating that the SP C mixtures are less crack susceptible. The rutting resistance indices (RRIs) from the HWT test results are depicted in Figure 4.5b. The DG C mixture with the PG 64-22 binder did not meet the rutting requirements, while the SP C mixture with the same binder met the rutting requirements. The DG C mixture with PG 70-22 binder did not meet the corresponding rutting requirements, while the SP C mixture with the same binder satisfactorily met the minimum rutting requirements. The mixtures with PG 76-22 binder exhibited satisfactory rutting resistance regardless of the mix type. **¡Error! No se encuentra el origen de la referencia.**c summarizes the CT Index of the mixtures. All DG C mixtures failed to obtain an acceptable CT Index, while all SP C mixtures yielded good CT Index for all PGs.

To identify mixtures with balanced performance, the CPR, NRRI and CT Index values are presented in the performance diagram shown in Figure 4.6. In general, the SP C mixtures exhibited better performance than the DG C mixtures. The CT Index is shown as a data label for a more informed analysis. From Figure 4.6a, only the DG C mixture with PG 76-22 binder can be considered balanced. The DG C mixtures mainly yielded acceptable CPR values but lower than required NRRI values. All three SP C mixtures can be considered balanced as seen in Figure 4.6b. The change in the binder PG significantly impacted the rutting properties and the CT Index of the mixtures while the cracking performance was not as significantly different among the mixtures with different binder PGs.

a) Overlay Test



b) Hamburg Wheel Tracking Test



c) IDEAL CT Test

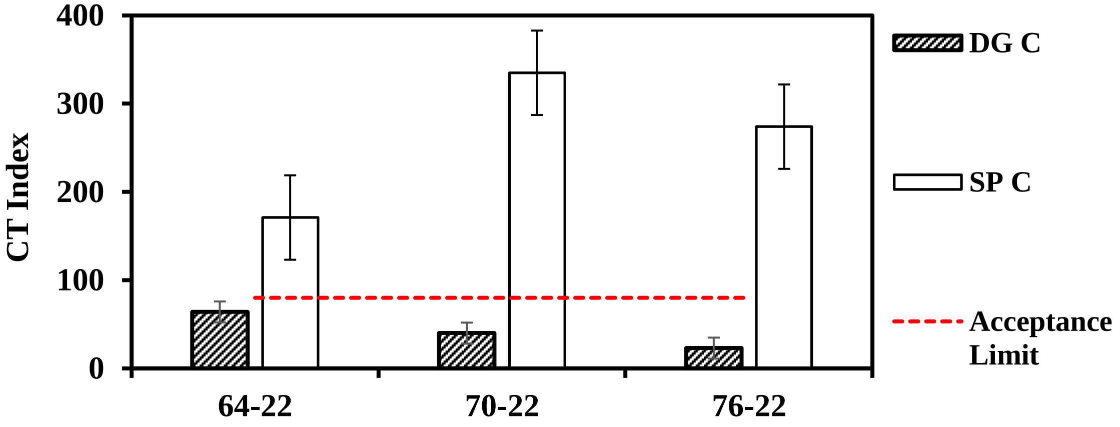


Figure 4.5 - Comparison DG vs SP Results

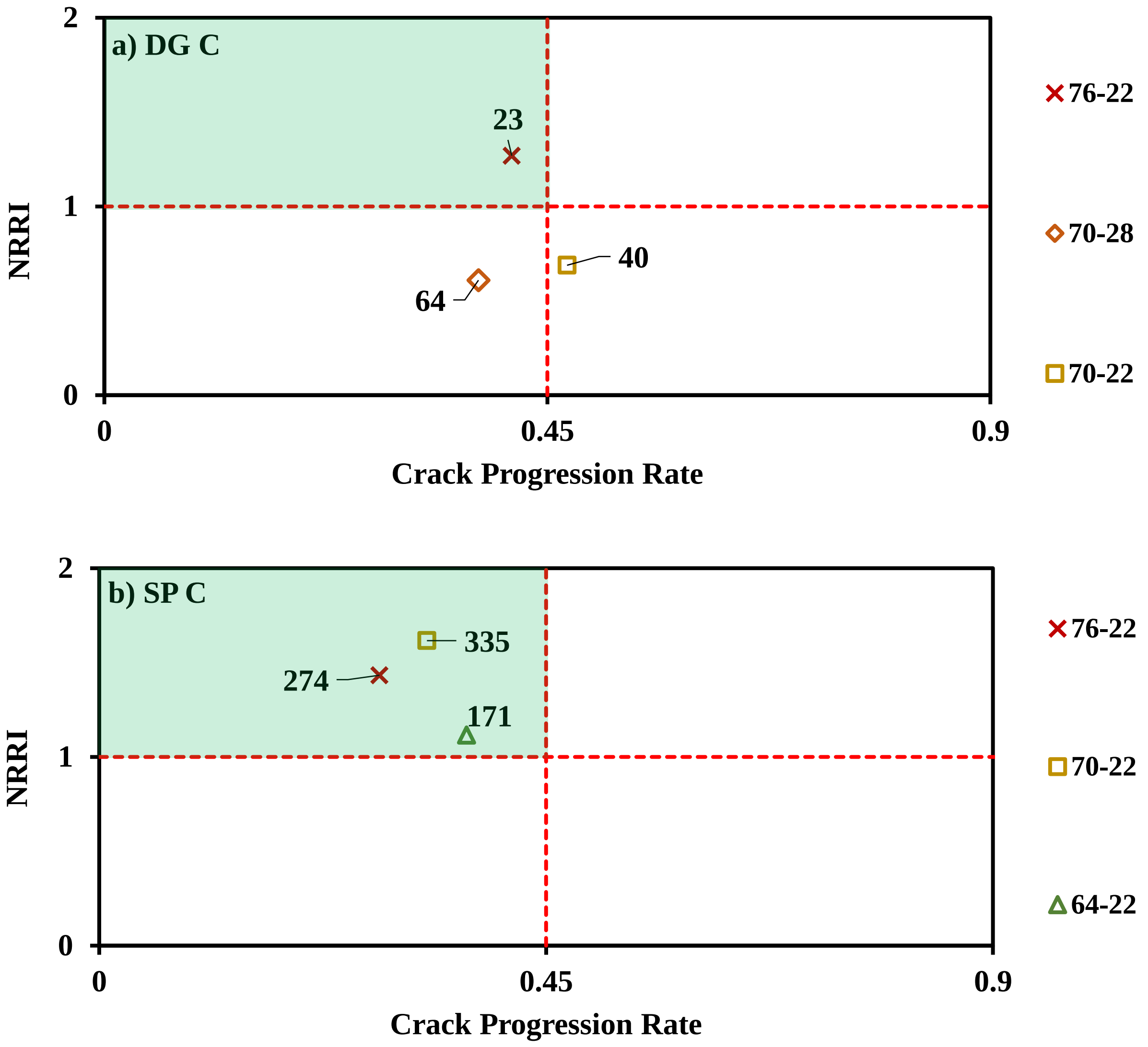


Figure 4.6 - Performance Interaction Diagram: Influence of Aggregate Gradation

Table 4.4 summarizes the averages and coefficients of variation (COV) obtained from the OT, HWT and IDT test results. The variability of the results from the selected performance tests is acceptable with COV values ranging from 1% to 22% for OT test. However, CT Index yields higher variability for the tested samples.

Table 4.4 - Summary of Results from Performance Tests

Mix Design	Test Methods	Parameters		Mix Reference		
				64-22	70-22	76-22
DG C	**IDEAL CT**	**CT Index**	**AVG**	64	40	23
			COV	20%	40%	20%
	OT	**CPR**	**AVG**	0.42	0.47	0.41
			COV	4%	2%	10%
	HWT	**NP**		7,060	10,350	20,000
		RD, mm		12.54	12.56	9.12
		RRI		3574	5232	12819
		NRRI		0.7	0.69	1.27
SP C	**IDEAL CT**	**CT Index**	**AVG**	171	335	274
			COV	17%	38%	29%
	OT	**CPR**	**AVG**	0.37	0.33	0.28
			COV	5%	8%	7%
	HWT	**NP**		11,250	20,000	20,000
		RD, mm		12.5	9.8	7
		RRI		5696	12283	14472
		NRRI		1.12	1.62	1.43

4.2.3 Conclusions and Recommendations

Producing mixtures that can potentially exhibit balanced performance can be achieved by properly formulating the mix design and assessing the engineering properties of the mix with performance tests. The crack progression rate from OT tests, rutting resistance index from HWT tests, and CT Index from IDT tests were utilized to characterize the engineering properties of several DG and SP mixtures produced with binders with different PGs. SP mixes can potentially yield balanced volumetric and mechanical properties if a proper aggregate gradation is selected.

From this study, the following conclusions can be drawn:

1. While all mixtures presented acceptable cracking properties, the SP C mixtures showed better resistance to cracking than the DG mixtures.
2. With the same binder, the rutting resistance of the SP C mixtures was consistently better than those of the DG C mixtures.
3. The SP C mixtures seemed to yield higher CT Index values than the DG C mixtures. However, a definite trend was not observed.

The following specific observations can be drawn from the results of this study:

a. Comparing SP and DG mixes, the aggregate gradation plays a key role in producing mixtures with acceptable volumetric and mechanical properties. Design specifications for SP mix designs allow to formulate an aggregate gradation that can result on more durable and stable mixtures regardless of the binder type.

b. Changing the PG grade of the asphalt binder might be a solution to improve the rutting and strength properties of mixtures without significantly impacting their cracking potential.

c. Regardless of the mixture type (SP or DG), mixtures designed with PG 76-22 binder satisfactorily met all the performance tests requirements.

4.3 Influence of Recycled Materials

To reduce the use of new mineral aggregates and asphalt binder, the implementation of sustainable measures such as recycling previously-used materials, reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) has been the main alternative. In the current mix-design processes, the recycled materials are being added at percentages that are essentially educated guesses. The main goal of this study is to determine the optimum RAP, and RAS contents in balanced mixes without significantly compromising the quality and performance of the final product. **¡Error! No se encuentra el origen de la referencia.** shows the aggregate gradation used in the study, it was the same for all mixtures. The only parameter affected was the amount of recycled material in the mixture.

4.3.1 Evaluation of Asphalt Mixtures Containing Different Recycle Material Contents

An experiment design that covered a wide range of mixes with different RAP and RAS contents was formulated for this evaluation as sown in

Table **4.5**. Mixes were designed without recycled materials, with only RAP, with only RAS and with a combination of RAP and RAS. Up to 20% RAP and 2% RAS were used. The aggregate gradation was similar for all mixes. The OAC values ranged from 5.1% to 6.0%. One mix with recycled material presented an asphalt binder replacement (ABR) ratio that was greater than the maximum limit of 20%.

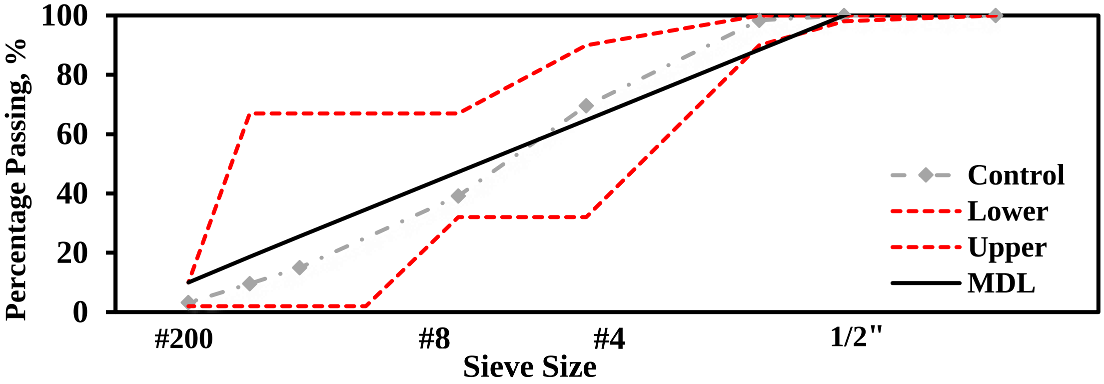


Figure 4.7 - Aggregate Gradation for Influence of Recycled Materials

Table 4.5 – Characteristics of Asphalt Mixtures

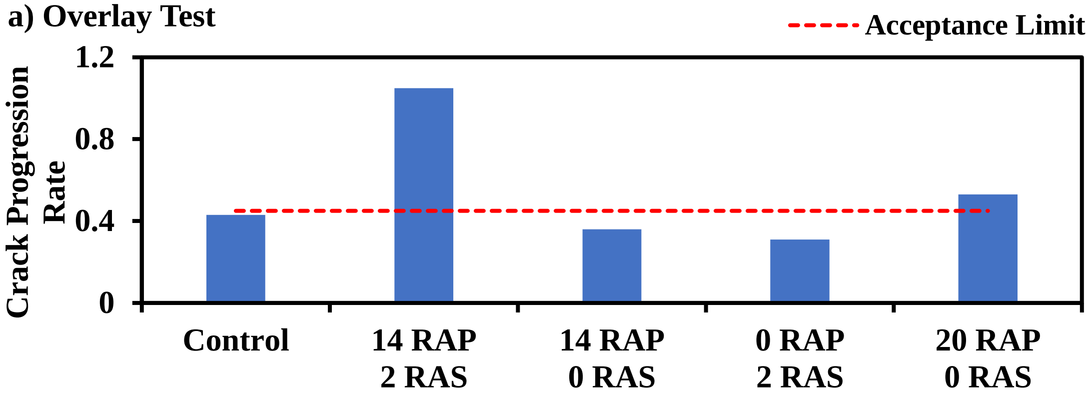
Designation	PG of Binder	OAC, %	RAP, %	RAS, %	ABR, %	VMA, %
CONTROL	64-22	5.1%	0	0	0.0	15.9
14 RAP 2 RAS	64-22	5.3%	14	2	20.8	16.4
14 RAP 0 RAS	64-22	5.7%	14	0	12.3	17.3
0 RAP 2 RAS	64-22	6.0%	0	2	6.7	17.8
20 RAP 0 RAS	64-22	5.4%	20	0	18.5	16.5

4.3.2 Understanding Performance of Asphalt Mixes

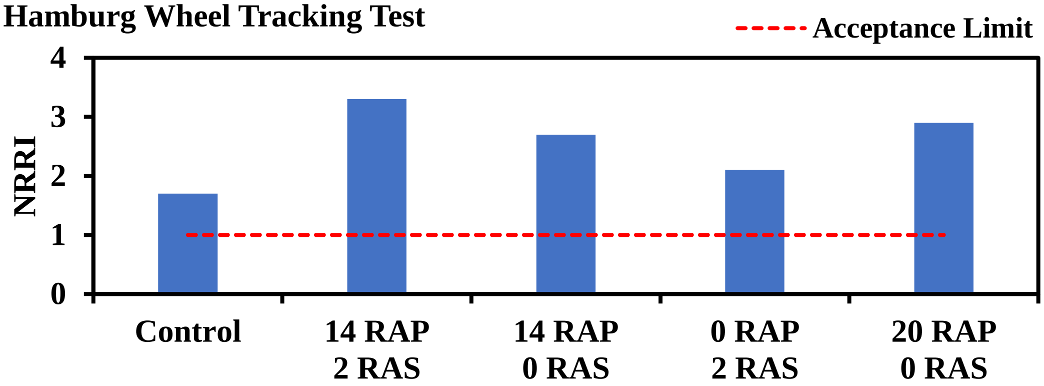
Figure 4.8 displays the results from all three tests performed to asses a mixture performance. The control mixture (0 RAP and 0 RAS) is compared to four other mixtures with different quantities of recycled material. Figure 4.8a displays the results of the overlay test, in which the control mix yields an acceptable CPR less than 0.45, while two other mixtures that included the most recycled materials (14 RAP 2 RAS, and 20 RAP 0 RAS) do not perform adequately in cracking. Figure 4.8b shows the results of HWT, in which all mixtures yield a NRRI greater than the minimum required. For permanent deformation, the mixtures with the best performance are the ones with the most recycled material (14 RAP 2 RAS, and 20 RAP 0 RAS). Figure 4.8c exhibits the results for the IDEAL CT Test, in which two mixtures yielded a CT Index higher than 80, while the others did not meet the minimum required.

The results from the HWT, OT and IDT tests are superimposed on the performance interaction diagram shown in Figure 4.9. A summary of the test results is presented in Table 4.6**.** In general, the mixes performed well in rutting, but failed cracking criterion because the CPR values were too high (mixtures 20 RAP 0 RAS and 14 RAP 2 RAS). The control mix can be classified as balanced mixture although it has a low CT Index. The two mixtures that are not considered BMDs contained the higher amounts of recycled materials.

a) Overlay Test



b) Hamburg Wheel Tracking Test



c) IDEAL CT Test

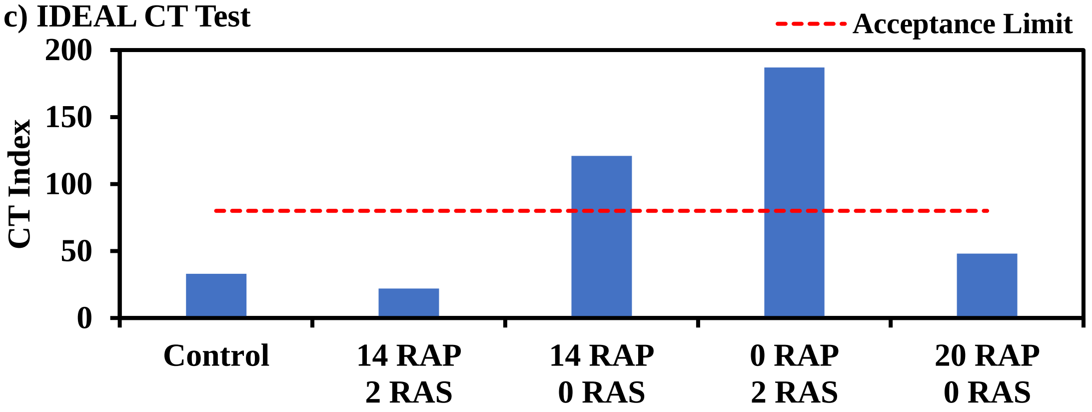


Figure 4.8 - Influence of Recycled Material Results

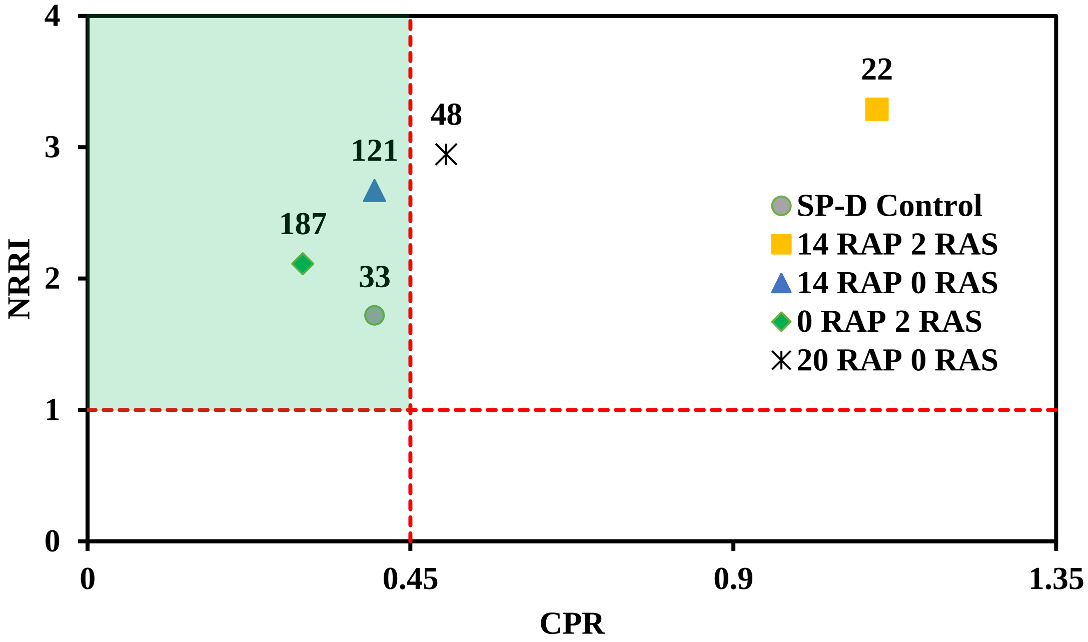


Figure 4.9 - Performance Interaction Diagram for Balanced Asphalt Mixtures

Table 4.6 – Summary of Test Results for Asphalt Mixtures

Performance Parameters			**Control**	**14 RAP 2 RAS**	**14 RAP 0 RAS**	**0 RAP 2 RAS**	**20 RAP 0 RAS**
OT	**CPR**	AVG	0.4	1.1	0.4	0.3	0.5
		COV	4%	15%	7%	2%	5%
IDEAL CT	**CT Index**	AVG	33	22	121	187	48
		COV	88%	27%	11%	14%	38%
HWT	**Number of Passes**		17230	20000	20000	20000	20000
	Ruth Depth, mm		12.5	4.2	8.2	11.8	6.4
	RRI		8737	16709	13567	10732	14961
	NRRI		1.7	3.3	2.7	2.1	2.9

4.3.3 Summary and Conclusions

Mixes designed with different amounts of recycled materials, RAP and RAS, were evaluated as an illustrative example. From this evaluation, the following conclusions can be drawn:

1. The selected cracking performance test method showed acceptable repeatability. The OT test results, based on CPR parameters, presented COV values between 3% and 15%. For HWT four mixtures reached 20,000 passes, with different rut depths. The CT Index exhibited variability between 11% and 88%.
2. A high percentage of recycled materials negatively affected the cracking properties of the mix. The use of an optimal recycled material content seems to help the rutting and stiffness resistance of mixes.
3. Changing the PG grade of the asphalt binder might be a solution to improve the rutting and stiffness properties of AC mixes without significantly impacting their cracking potential.

Chapter 5: Conclusions and Recommendations

Different laboratory testing procedures were evaluated to assess the cracking and permanent deformation of asphalt mixtures. Environmental characterization of asphalt mixtures was investigated through several performance-based test methods. To properly characterize a mixture behavior, the implementation of a performance-based analysis methodology is needed at different stages including the design process, field production and environmental-related characterization. The main objective of this thesis study was to investigate several performance test methods that can be readily used for laboratory characterization of asphalt mixtures throughout a performance-based analysis methodology.

Using the parameters from the OT, HWT and IDEAL CT test methods, the mechanical performance of asphalt mixtures was investigated with a performance-based analysis methodology that accounts for the cracking susceptibility and rutting resistance of asphalt mixtures.

5.1 Conclusions

From this study, the following conclusions were drawn:

1. For this study, the OT is selected as a more rigorous performance test method for the characterization of cracking susceptibility. Offering CPR with an acceptance limit of 0.45 as the best parameter to discriminate between well and bad mixtures.
2. The CPR parameter of the OT is better for characterization of cracking resistance of Superpave mixtures used in Texas, than the Flexibility Index obtained from the SCB I-FIT because of repeatability in tested specimens, and requirements to pass the test.

3. HWT Test is selected over the Flow Number Test as the best performance test method for characterization of rutting resistance because it takes into consideration binder PG used in the asphalt mixture, while being simpler to conduct.
4. Using the CPR parameter from the OT with an acceptance limit of 0.45, NRRI parameter from the HWT with acceptance limit of 1.0, and CT Index from the IDEAL CT tests, an interaction diagram can be developed to assess the cracking susceptibility, rutting resistance, and quality control information of asphalt mixtures, helping to predict a mixture behavior in the field.
5. Although several DOTs use the ITS parameter to characterize a mixture performance, it may not be the best parameter available to delineate between well and poor mixtures because it does not consider the post-peak behavior of the mixture. CT Index was selected in this study as a quality control index to delineate mixtures with a well and poor performance during the production phase.
6. Several cracking indices are available to characterize a mixture quality with the IDT test. The CT Index seems to be the best available index because of repeatability and correlation to the CPR parameter from the OT test. Several other indices such Nflex also present a promising alternative parameter to characterize a mixture's performance.
7. Superpave mixtures seemed to yield better CT Index properties than the Dense-graded mixtures. The quality control parameter of the balanced mix design was met easier following the guidelines of the Superpave rather than a typical mixture design procedure.

8. Aggregate gradation of asphalt mixture was modified to analyze the influence in the behavior through a performance-based analysis methodology. The Superpave mixture design can effectively be modified into a balance mix design, meeting the minimum

performance requirements for cracking and permanent deformation, in comparison to the Dense-graded mixtures.

9. The rutting resistance of the Superpave mixtures was improved with a different binder PG from the same source. Changing the PG grade of the asphalt binder might be a solution to improve the rutting and strength properties of mixtures without significantly impacting their cracking potential.
10. The amount of recycled materials in the mixture such as RAP and RAS was changed, and performance testing showed a high percentage of recycled materials negatively affected the cracking properties of the asphalt mixture, but the use of an optimal recycled material content seems to help the rutting and stiffness resistance of mixes.

5.2 Recommendations

The following recommendations are provided to continue evaluating and implementing the proposed test protocols for balanced mixes:

1. Different conditioning environments should be considered to evaluate a mixture performance under a minor and larger environmental impact, such as different curing times and testing temperatures. To properly characterize a mixture, it should be taken into critical behavior to analyze the performance under negative environments.
2. One of the challenges of this study is to establish reliably the acceptance limits and boundaries for the four quadrants from the balanced performance interaction diagram. A larger testing matrix should be executed to gather more performance data and delineate potential OT, IDT and HWT test results’ thresholds.

3. Guidelines should be established so that the pavement engineer and designer can improve the performance of poor performing mixes. The research team will evaluate different mixes following the selected testing protocol to document the most feasible approaches to improve the performance of mixes.
4. Inclusion of the environmental parameters such as the long-term aging into the performance interaction diagram to understand the mixture's performance in future exposure to different environmental conditions. Guidelines and limits should be investigated under the long-term aging testing procedure of the asphalt mixture, to properly predict to behavior in future years.
5. Investigation and development of different performance indices derived from the load-displacement curves from the IDT to properly characterize a mixture performance with a simple test. To adequately describe the quality of an asphalt mixtures all parameters obtained from the load-displacement curve should be taken into consideration.
6. Substitute different parameters and properties in the mixture design to evaluate the impact on their performance such binder source, and type of aggregate. In order to legitimately identify which parameters should be more consistent and what is limiting the performance of the asphalt mixture in the field.
7. Ranking system should be further developed to characterize a mixture's behavior based on the performance and ranking attained in comparison to other mixtures, to truly understand the characteristics and performance of the asphalt mixture.
8. Implementation of the balanced mix design concept should be established into all types of mixtures, such as Dense-graded mixture to prolong the life span of an asphalt

mixture in the field. Using performance testing to identify possible failure mechanisms and address them before the production phase.

9. The Superpave mixture design guidelines should be implemented more consistently to future mixtures in Texas, since it has proven to be adaptable to the balanced mix design performance testing requirements, while including different quantities of recycled materials.

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Appendix A – Literature Review

Author	Objective and Scope	Key Points
Barman et al. (2018)	This study proposes new procedure to characterize fatigue resistance of asphalt mixtures using the IDT test. A new parameter called Fatigue Index is obtained from the existing testing methodology.	The Superpave volumetric mix design does not consider the inspection of asphalt mixtures based on fatigue resistance. Testing asphalt mixtures based on their rutting and cracking performance is critical. IDT test can be used to describe the fatigue resistance of asphalt mixtures. This paper proposes a parameter known as Fatigue Index
Hamzah et al. (2015)	The paper reviews moisture damage in asphalt mixtures. To evaluate the effects of traffic impact and moisture damage a lab testing procedure and analysis protocol is proposed.	A usual cause of pavement distress causing loss of strength, fatigue damage and permanent deformation is moisture damage, the study recommends a single test cannot be applied to assess moisture damage. Investigation must be conducted on pavement surface and subsurface drainage system for mitigation of moisture damage.
Garcia et al. (2018)	This paper reports on the methodology for characterizing asphalt mixtures with the OT identifying crack propagation represented by the CPR parameter, using more than 250 OT results from ten different mix types	OT test results were assessed with the CPR index to foresee the cracking potential of asphalt mixtures. Utilizing data from more than 350 tests of various mixtures the effectiveness of the proposed cracking methodology was evaluated
Newcomb (2018)	This study included a literature review to review the states of the art practices for asphalt mixture performance testing and BMD. This project created a structure for BMD mixtures for the Minnesota Department of Transportation.	A BMD mixture establishes a maximum asphalt content based on the rutting resistance and a minimum asphalt content based on cracking susceptibility. The performance tests and the BMD method were successful in characterizing the influence of asphalt content on cracking susceptibility and rutting resistance
Huang et al. (2005)	This paper presents a comparison between SCB test results and the IDT test results in characterizing the tensile strength of HMA.	The results from this study revealed that SCB and IDT test results were equivalent for certain parameters indicating the properties of each mixture. SCB test considerably reduces the loading strip induced permanent deformation thus the IDT is more suitable for evaluating tensile strength properties of HMA.

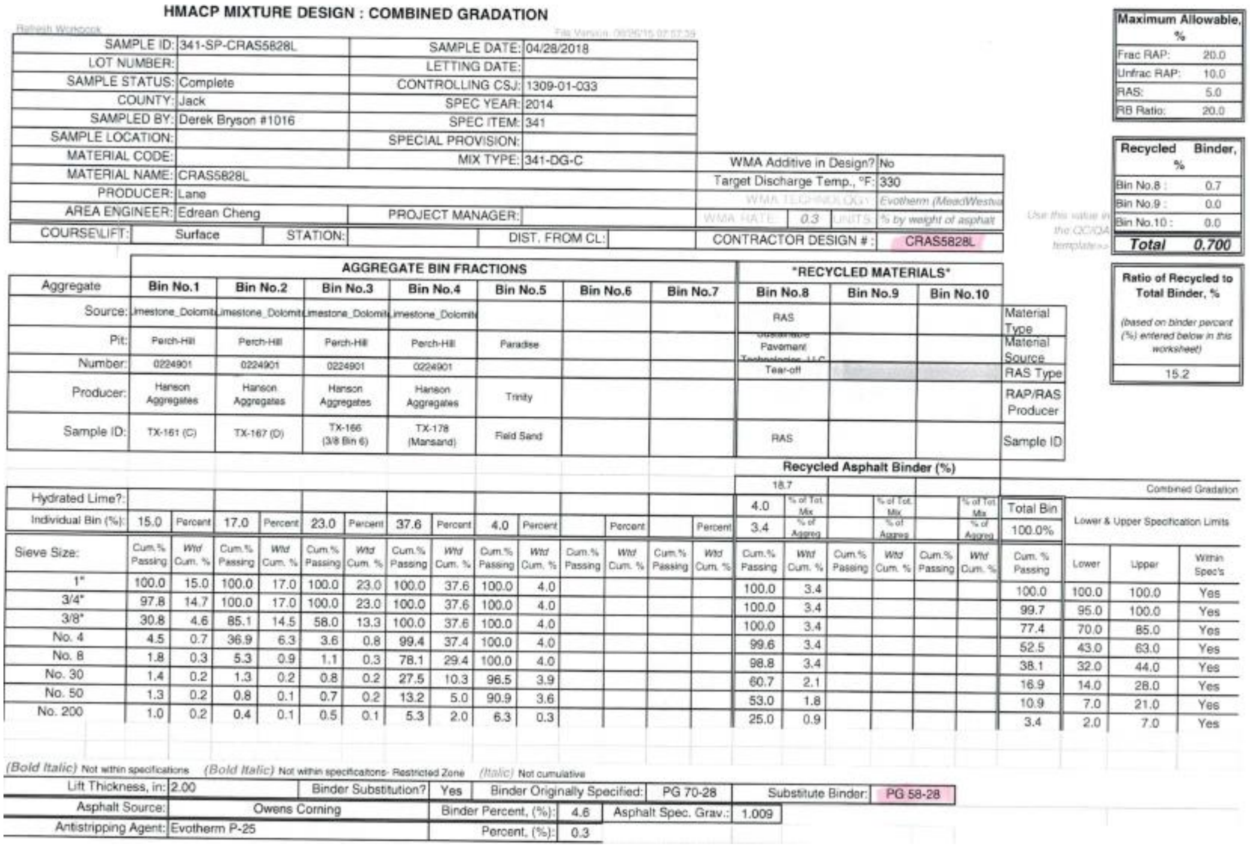
Author	**Objective and Scope**	**Key Points**
Izadi et al. (2018)	The objective was to examine mixtures in aged and unaged conditions to more accurately predict the fatigue life of asphalt mixtures	By identify the fracture energy parameter form the IDT one can predict the aging effects changes in the mechanical properties of the asphalt mixtures. When evaluating aged and unaged results, warm mixtures have a higher fatigue life than hot mixtures.
Aschenbrener (1995)	This paper assesses the most influencing components in the Hamburg wheel tracking tool results.	An outstanding correlation between the HWT test and asphalt mixtures of known field performance was found. The HWT device has the capacity to discriminate between pavements with known field stripping performance. When employing only one testing temperature and increasing the asphalt binder stiffness, the stripping inflection point occurred at a larger number of passes.
Chen and Huang (2007)	The purpose of this study is the evaluation of moisture damage in a dense graded Superpave mixture using IDT test.	Combining IDT and MIST is an effective way to characterize lab measured moisture susceptibility for HMA. Results from IDT indicate change in multiple parameters of the mixtures. Using a combination of freeze thaw cycles and dynamic modulus can also be an efficient to classify the performance of a mixture.
Wu et al. (2005)	Tthis paper reports the examination of the SCB test as a candidate for the fracture resistance characterization of asphalt mixtures. Performing the testing at 25°C in a three-point bending fixture in a MTS system and evaluating the fracture resistance.	SCB tests with a single notch depth, the fracture resistance is observed to be consistent with vertical displacement results, but different from the peak load measurements. Superpave mixtures with higher tensile strengths could be more brittle and less fracture resistant than those with lower tensile strengths.
Roque et al. (1999)	The objective was to develop a complete testing and analysis method to determine fracture parameters using the IDT. The testing system presented the parameters that correspond to a mixture's resistance to cracking.	The procedure developed provided reliable fracture test results that successfully compared with other fracture parameters. Fracture tests performed on Superpave mixtures suggested that the mixture graded on the coarse side of the restricted zone had significantly lower fracture resistance than the mixture graded on the fine side of the restricted zone.

Author	Objective and Scope	Key points
Zhou et al. (2014)	This paper depicts the development and implementation of the OT as a possible cracking test. Cases studies are also presented to compare lab and field results.	The OT is sensitive to asphalt mixture composition and volumetric properties. A balanced HMA mixture design system integrating both rutting and cracking conditions is proposed. Implementing the performance tests at different asphalt contents around the OAC determined based on volumetric design is proposed.
Zhou et al. (2006)	The goal of this project is to develop a HMA mixture design methodology to balance the rutting and cracking requirements HWT and OT devices were employed to evaluate the rutting and cracking resistance of HMA mixtures, respectively.	A methodology of incorporating the OT into the TxDOT mixture design process was developed, and a balanced HMA mixture design protocol considering rutting and cracking resistance requirements was proposed. Several mixtures including Superpave and dense-graded mixtures were utilized to authenticate and validate the balanced HMA mixture design procedure. It was found that aggregate absorption had a considerable influence on cracking and rutting resistance of HMA mixtures.
Harvey and Tsai (1997)	An analysis of the effects of long-term oven aging (LTOA) on initial stiffness and fatigue of asphalt mixtures was performed using two typical California asphalt mixtures which were known to have distinct aging characteristics.	Along with more days of LTOA initial stiffness increased. The combination of higher air-void contents and LTOA occasioned an increased mixture stiffness. The effect of long-term aging on pavement fatigue life depends on asphalt type, aggregate type, pavement, and air-void content. Findings of the study show that increases in stiffness caused by long-term aging, are not always disadvantageous to pavement fatigue performance.
Elseifi et al. (2012)	The objective of this study was to perform a complete assessment of the SCB test to later utilize this test to evaluate a number of asphalt mixtures for cracking failure.	Results of the testing procedure showed that the SCB test results effectively calculated the fracture performance of the evaluated mixes and was able to discriminate between them in terms of cracking resistance. Damage that propagates near the notch is mainly caused by a combination of vertical and horizontal stresses in the specimen. The shear effect was insignificant in the progressing damage in the specimen.

Author	Objective and Scope	Key Points
Brown et al. (2001)	The purpose of this project is to evaluate information on permanent deformation, fatigue cracking, low-temperature cracking, moisture susceptibility, and friction properties, and if applicable recommend performance test(s) that can be implemented to ensure a better performance. Emphasis is placed on permanent deformation	Permanent deformation problems typically appear early in life of a mixture and normally result in the need for major repair while other distresses take much longer to develop. Since the bottom-up fatigue is dominated mainly by the pavement structure there is no way that a mixture test can be used alone to precisely predict fatigue. Moisture susceptibility is a problem causing asphalt binder to strip from the aggregate leading to raveling and disintegration of the mixture. The Hamburg test has also shown to identify mixes that tend to strip
Kaloush et al. (2003)	This paper focuses on recommending a laboratory based simple performance test for permanent deformation evaluation of asphalt mixtures.	The FN sensitivity results showed good consistent indication of the stability of mix as a function of binder content; yet, both confined and unconfined testing showed that relatively larger FN values occurred (higher resistance to rutting) at air voids less than the critical threshold normally accepted in typical mix design.
Airey and Choi (2002)	This paper includes a review of existing testing methods, protocols and techniques for evaluating the moisture sensitivity of asphalt mixture materials. Loose aggregate and compacted asphalt mixture tests have been reviewed and correlated test results with observed field performance.	Most water damage test procedures on compacted mixtures calculate the loss of strength and stiffness of an asphalt mixture due to moisture. The conditioning processes linked with most test methods attempt to simulate field conditions by accelerating the rate of strength loss. An alternative is to expose the samples to a conditioning procedure that does not necessarily replicate field conditions
Zhou et al. (2007)	In this paper, information on the OT reflective cracking is presented first. Then a theoretical assessment was conducted to determine the relationship between crack initiation and crack propagation.	Fatigue cracking is a two-stage process: crack initiation and crack propagation. the OT mainly characterizes crack propagation therefore it can be used for fatigue cracking. The OT is used to ensure satisfactory crack resistance of the designed mixtures. The existing good relationship between crack initiation and crack propagation theoretically, indicates the feasibility of using the OT for fatigue cracking

Author	Objective and Scope	Key Points
Epps et al. (2000)	This study focuses on the cracking performance of asphalt mixtures. The asphalt mixture must endure the effects of air and water, resist permanent deformation, and resist cracking caused by loading and the environment.,	The study indicated that fatigue cracking starts at the bottom or at the top of the asphalt layer, depending on the characteristics of the pavement. The study shows that fatigue cracks start as microcracks (crack initiation phase) that later propagates to form macrocracks (crack propagation phase) as the mixture is subjected to a stress. Changes in properties resulting from the effects of aging and moisture sensitivity further complicate mixture behavior and its evaluation.
Brown et al. (1999)	This study outlines the construction issues that have been detected by contractors working with Superpave mixes. The report provides results of a national performance survey of Superpave mixes.	Superpave mixes inspected provided good performance. Rutting was not observed to be a problem. Cracking seemed to be a major problem in the performance survey. Superpave mixtures segregate. This problem is no bigger nor smaller than conventional mixes. Segregated areas are more difficult to identify due to the amount of coarse aggregate in the mix
Walubita et al. (2012)	The objective of this study is to evaluate the repeatability between laboratories for the OT in a production environment by running duplicate tests, and validate the potential for having alternative tests to identify crack-susceptible mixes.	The OT specimen sitting time between molding and testing should not exceed 5 days. OT specimens having air-void values between 6.5 percent and 7.5 percent gave the most repeatable results. The OT result variability showed improvement in repeatability with decreasing opening displacement, the current practice of 0.025 in. opening displacement was recommended.
Zhou et al. (2005)	The objective of this study is to develop and validate the upgraded overlay tester and related test protocol and to characterize reflective cracking resistance	The test is rapid, and poor samples fail in minutes. It characterizes both crack initiation and crack propagation properties of asphalt mixtures. The overlay tester is repeatable, based on repeatability study results, three replicates are recommended for the overlay tester. Sensitivity studies indicate that the overlay tester provides reasonable test results.

Appendix B - Mix Designs and Pavement Materials for Laboratory Testing



HMACP MIXTURE DESIGN : COMBINED GRADATION

File Version: 08/26/15 07:57:39

SAMPLE ID:	341-SP-CRAS5828L	SAMPLE DATE:	04/28/2018
LOT NUMBER:		LETTING DATE:	
SAMPLE STATUS:	Complete	CONTROLLING CSJ:	1309-01-033
COUNTY:	Jack	SPEC YEAR:	2014
SAMPLED BY:	Derek Bryson #1016	SPEC ITEM:	341
SAMPLE LOCATION:		SPECIAL PROVISION:	
MATERIAL CODE:		MIX TYPE:	341-DG-C
MATERIAL NAME:	CRAS5828L		
PRODUCER:	Lane		
AREA ENGINEER:	Edrean Cheng	PROJECT MANAGER:	
COURSE\LIFT:	Surface	STATION:	
		DIST. FROM CL:	

WMA Additive in Design?	No		
Target Discharge Temp., °F:	330		
WMA TECHNOLOGY:	Evotherm (MeadWestva		
WMA RATE:	0.3	UNITS:	% by weight of asphalt
CONTRACTOR DESIGN #:	CRAS5828L		

Maximum Allowable, %	
Frac RAP:	20.0
Unfrac RAP:	10.0
RAS:	5.0
RB Ratio:	20.0

Use this value in the QC/QA template>>

Recycled Binder, %	
Bin No.8 :	0.7
Bin No.9 :	0.0
Bin No.10 :	0.0
Total	***0.700***

Ratio of Recycled to Total Binder, %
(based on binder percent (%) entered below in this worksheet)
15.2

AGGREGATE BIN FRACTIONS

Aggregate	Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.5	Bin No.6	Bin No.7
Source:	Limestone_Dolomit	Limestone_Dolomit	Limestone_Dolomit	Limestone_Dolomite			
Pit:	Perch-Hill	Perch-Hill	Perch-Hill	Perch-Hill	Paradise		
Number:	0224901	0224901	0224901	0224901			
Producer:	Hanson Aggregates	Hanson Aggregates	Hanson Aggregates	Hanson Aggregates	Trinity		
Sample ID:	TX-161 (C)	TX-167 (D)	TX-166 (3/8 Bin 6)	TX-178 (Mansand)	Field Sand		

"RECYCLED MATERIALS"

Bin No.8	Bin No.9	Bin No.10	
RAS			Material Type
Sustainable Pavement Technologies LLC			Material Source
Tear-off			RAS Type
			RAP/RAS Producer
RAS			Sample ID

Recycled Asphalt Binder (%)

Bin No.8	Bin No.9	Bin No.10
18.7		

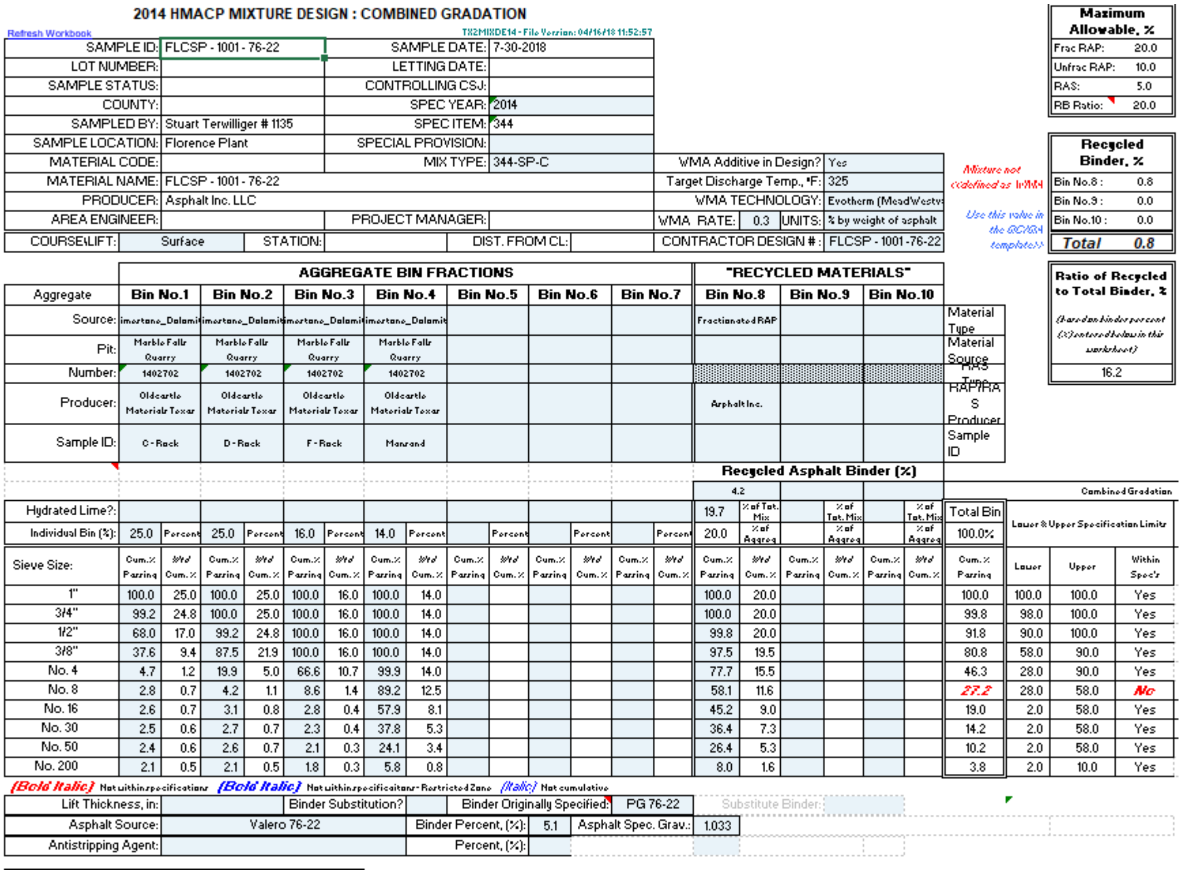
Combined Gradation

Sieve Size:	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		Total Bin	Lower & Upper Specification Limits		
Hydrated Lime?:															4.0	% of Tot. Mix		% of Tot. Mix		% of Tot. Mix				
Individual Bin (%):	15.0	Percent	17.0	Percent	23.0	Percent	37.6	Percent	4.0	Percent		Percent		Percent	3.4	% of Aggreg		% of Aggreg		% of Aggreg	100.0%			
	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum. % Passing	Lower	Upper	Within Spec's
1"	100.0	15.0	100.0	17.0	100.0	23.0	100.0	37.6	100.0	4.0					100.0	3.4					100.0	100.0	100.0	Yes
3/4"	97.8	14.7	100.0	17.0	100.0	23.0	100.0	37.6	100.0	4.0					100.0	3.4					99.7	95.0	100.0	Yes
3/8"	30.8	4.6	85.1	14.5	58.0	13.3	100.0	37.6	100.0	4.0					100.0	3.4					77.4	70.0	85.0	Yes
No. 4	4.5	0.7	36.9	6.3	3.6	0.8	99.4	37.4	100.0	4.0					99.6	3.4					52.5	43.0	63.0	Yes
No. 8	1.8	0.3	5.3	0.9	1.1	0.3	78.1	29.4	100.0	4.0					98.8	3.4					38.1	32.0	44.0	Yes
No. 30	1.4	0.2	1.3	0.2	0.8	0.2	27.5	10.3	96.5	3.9					60.7	2.1					16.9	14.0	28.0	Yes
No. 50	1.3	0.2	0.8	0.1	0.7	0.2	13.2	5.0	90.9	3.6					53.0	1.8					10.9	7.0	21.0	Yes
No. 200	1.0	0.2	0.4	0.1	0.5	0.1	5.3	2.0	6.3	0.3					25.0	0.9					3.4	2.0	7.0	Yes

(Bold Italic) Not within specifications ***(Bold Italic)*** Not within specifications- Restricted Zone *(Italic)* Not cumulative

Lift Thickness, in:	2.00	Binder Substitution?	Yes	Binder Originally Specified:	PG 70-28	Substitute Binder:	PG 58-28
Asphalt Source:	Owens Corning	Binder Percent, (%):	4.6	Asphalt Spec. Grav.:	1.009		
Antistripping Agent:	Evotherm P-25	Percent, (%):	0.3				

Figure 3 - Mix Design 1



2014 HMACP MIXTURE DESIGN : COMBINED GRADATION

Refresh Workbook

TX2MIXDE14 - File Version: 04/16/18 11:52:57

SAMPLE ID:	FLCSP - 1001 - 76-22	SAMPLE DATE:	7-30-2018
LOT NUMBER:		LETTING DATE:	
SAMPLE STATUS:		CONTROLLING CSJ:	
COUNTY:		SPEC YEAR:	2014
SAMPLED BY:	Stuart Terwilliger # 1135	SPEC ITEM:	344
SAMPLE LOCATION:	Florence Plant	SPECIAL PROVISION:	
MATERIAL CODE:		MIX TYPE:	344-SP-C
MATERIAL NAME:	FLCSP - 1001 - 76-22		
PRODUCER:	Asphalt Inc. LLC		
AREA ENGINEER:		PROJECT MANAGER:	

COURSE\LIFT:	Surface	STATION:		DIST. FROM CL:	

WMA Additive in Design?	Yes
Target Discharge Temp., °F:	325
WMA TECHNOLOGY:	Evotherm (MeadWestv
WMA RATE: 0.3 UNITS:	% by weight of asphalt
CONTRACTOR DESIGN # :	FLCSP - 1001 -76-22

Mixture not <<defined as WMA

Use this value in the QC/QA template>>

Maximum Allowable, %	
Frac RAP:	20.0
Unfrac RAP:	10.0
RAS:	5.0
RB Ratio:	20.0

Recycled Binder, %	
Bin No.8 :	0.8
Bin No.9 :	0.0
Bin No.10 :	0.0
Total	**0.8**

Ratio of Recycled to Total Binder, %

(based on binder percent (%) entered below in this worksheet)

16.2

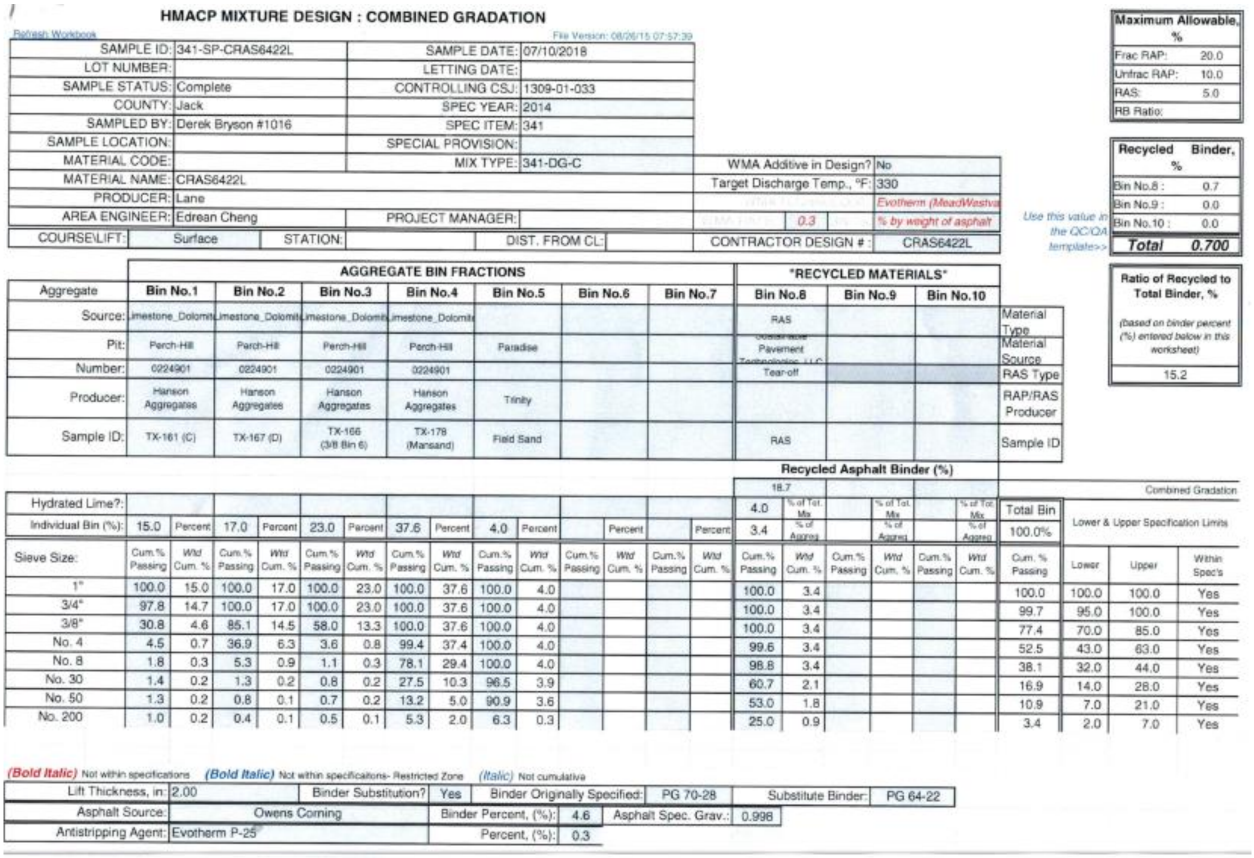
	AGGREGATE BIN FRACTIONS							"RECYCLED MATERIALS"			
Aggregate	Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.5	Bin No.6	Bin No.7	Bin No.8	Bin No.9	Bin No.10	
Source:	imestone_Dolomit	imestone_Dolomit	imestone_Dolomit	imestone_Dolomit				Fractionated RAP			Material Type
Pit:	Marble Falls Quarry	Marble Falls Quarry	Marble Falls Quarry	Marble Falls Quarry							Material Source
Number:	1402702	1402702	1402702	1402702							RAS Type
Producer:	Oldcastle Materials Texas	Oldcastle Materials Texas	Oldcastle Materials Texas	Oldcastle Materials Texas				Asphalt Inc.			RAP/RAS Producer
Sample ID:	C - Rock	D - Rock	F - Rock	Mansand							Sample ID
								Recycled Asphalt Binder (%)			
								4.2			

	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		Combined Gradation			
Hydrated Lime?:															19.7	% of Tot. Mix		% of Tot. Mix		% of Tot. Mix	Total Bin	Lower & Upper Specification Limits		
Individual Bin (%):	25.0	Percent	25.0	Percent	16.0	Percent	14.0	Percent		Percent		Percent		Percent	20.0	% of Aggreg		% of Aggreg		% of Aggreg	100.0%			
Sieve Size:	Cum.% Passing	Wtd Cum.%	Cum.% Passing	Wtd Cum.%	Cum.% Passing	Wtd Cum.%	Cum.% Passing	Wtd Cum.%	Cum.% Passing	Wtd Cum.%	Cum.% Passing	Wtd Cum.%	Cum.% Passing	Wtd Cum.%	Cum.% Passing	Wtd Cum.%	Cum.% Passing	Wtd Cum.%	Cum.% Passing	Wtd Cum.%	Cum.% Passing	Lower	Upper	Within Spec's
1"	100.0	25.0	100.0	25.0	100.0	16.0	100.0	14.0							100.0	20.0					100.0	100.0	100.0	Yes
3/4"	99.2	24.8	100.0	25.0	100.0	16.0	100.0	14.0							100.0	20.0					99.8	98.0	100.0	Yes
1/2"	68.0	17.0	99.2	24.8	100.0	16.0	100.0	14.0							99.8	20.0					91.8	90.0	100.0	Yes
3/8"	37.6	9.4	87.5	21.9	100.0	16.0	100.0	14.0							97.5	19.5					80.8	58.0	90.0	Yes
No. 4	4.7	1.2	19.9	5.0	66.6	10.7	99.9	14.0							77.7	15.5					46.3	28.0	90.0	Yes
No. 8	2.8	0.7	4.2	1.1	8.6	1.4	89.2	12.5							58.1	11.6					***27.2***	28.0	58.0	***No***
No. 16	2.6	0.7	3.1	0.8	2.8	0.4	57.9	8.1							45.2	9.0					19.0	2.0	58.0	Yes
No. 30	2.5	0.6	2.7	0.7	2.3	0.4	37.8	5.3							36.4	7.3					14.2	2.0	58.0	Yes
No. 50	2.4	0.6	2.6	0.7	2.1	0.3	24.1	3.4							26.4	5.3					10.2	2.0	58.0	Yes
No. 200	2.1	0.5	2.1	0.5	1.8	0.3	5.8	0.8							8.0	1.6					3.8	2.0	10.0	Yes

{Bold Italic} Not within specifications ***{Bold Italic}*** Not within specificaitons - Restricted Zone *{Italic}* Not cumulative

Lift Thickness, in:		Binder Substitution?		Binder Originally Specified:	PG 76-22	Substitute Binder:	
Asphalt Source:	Valero 76-22	Binder Percent, (%):	5.1	Asphalt Spec. Grav.:	1.033		
Antistripping Agent:		Percent, (%):					

Figure 4 - Mix Design 2



HMACP MIXTURE DESIGN : COMBINED GRADATION

Refresh Workbook

File Version: 08/26/15 07:57:39

SAMPLE ID:	341-SP-CRAS6422L	SAMPLE DATE:	07/10/2018
LOT NUMBER:		LETTING DATE:	
SAMPLE STATUS:	Complete	CONTROLLING CSJ:	1309-01-033
COUNTY:	Jack	SPEC YEAR:	2014
SAMPLED BY:	Derek Bryson #1016	SPEC ITEM:	341
SAMPLE LOCATION:		SPECIAL PROVISION:	
MATERIAL CODE:		MIX TYPE:	341-DG-C
MATERIAL NAME:	CRAS6422L		
PRODUCER:	Lane		
AREA ENGINEER:	Edrean Cheng	PROJECT MANAGER:	

COURSE\LIFT:	Surface	STATION:		DIST. FROM CL:	

WMA Additive in Design?	No	
Target Discharge Temp., °F:	330	
	Evotherm (MeadWestva	
0.3	% by weight of asphalt	
CONTRACTOR DESIGN # :	CRAS6422L	

Maximum Allowable, %	
Frac RAP:	20.0
Unfrac RAP:	10.0
RAS:	5.0
RB Ratio:	

Use this value in the QC/QA template>>

Recycled Binder, %	
Bin No.8 :	0.7
Bin No.9 :	0.0
Bin No.10 :	0.0
Total	***0.700***

Ratio of Recycled to Total Binder, %
(based on binder percent (%) entered below in this worksheet)
15.2

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:	Limestone_Dolomit	Limestone_Dolomit	Limestone_Dolomit	Limestone_Dolomit				RAS			Material Type
Pit:	Perch-Hill	Perch-Hill	Perch-Hill	Perch-Hill	Paradise			Sustainable Pavement Technologies, LLC			Material Source
Number:	0224901	0224901	0224901	0224901				Tear-off			RAS Type
Producer:	Hanson Aggregates	Hanson Aggregates	Hanson Aggregates	Hanson Aggregates	Trinity						RAP/RAS Producer
Sample ID:	TX-161 (C)	TX-167 (D)	TX-166 (3/8 Bin 6)	TX-178 (Mansand)	Field Sand			RAS			Sample ID

Recycled Asphalt Binder (%)

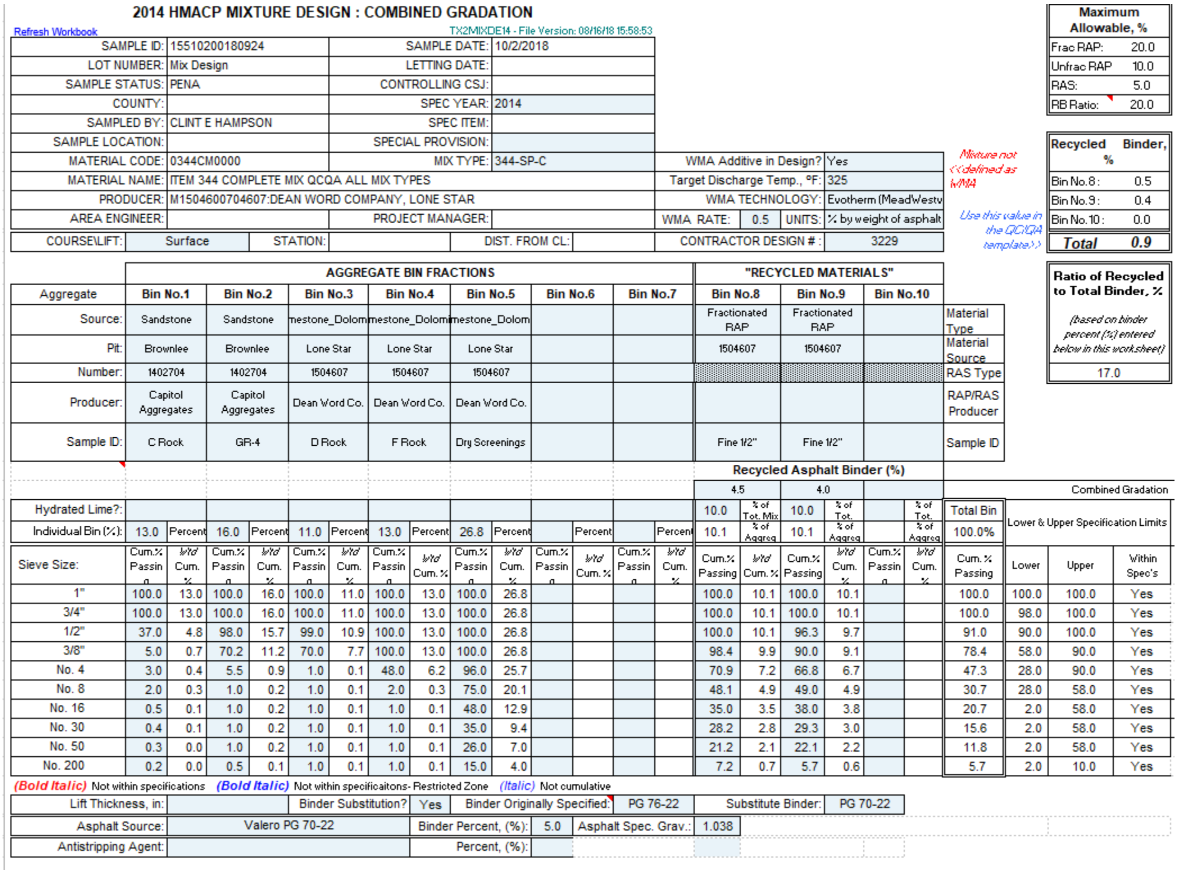
Combined Gradation

	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					
															18.7									
Hydrated Lime?:															4.0	% of Tot. Mix		% of Tot. Mix		% of Tot. Mix	Total Bin	Lower & Upper Specification Limits		
Individual Bin (%):	15.0	Percent	17.0	Percent	23.0	Percent	37.6	Percent	4.0	Percent		Percent		Percent	3.4	% of Aggreg		% of Aggreg		% of Aggreg	100.0%			
Sieve Size:	Cum.% Passing	*Wtd* Cum. %	Cum.% Passing	*Wtd* Cum. %	Cum.% Passing	*Wtd* Cum. %	Cum.% Passing	*Wtd* Cum. %	Cum.% Passing	*Wtd* Cum. %	Cum.% Passing	*Wtd* Cum. %	Cum.% Passing	*Wtd* Cum. %	Cum.% Passing	*Wtd* Cum. %	Cum.% Passing	*Wtd* Cum. %	Cum.% Passing	*Wtd* Cum. %	Cum. % Passing	Lower	Upper	Within Spec's
1"	100.0	15.0	100.0	17.0	100.0	23.0	100.0	37.6	100.0	4.0					100.0	3.4					100.0	100.0	100.0	Yes
3/4"	97.8	14.7	100.0	17.0	100.0	23.0	100.0	37.6	100.0	4.0					100.0	3.4					99.7	95.0	100.0	Yes
3/8"	30.8	4.6	85.1	14.5	58.0	13.3	100.0	37.6	100.0	4.0					100.0	3.4					77.4	70.0	85.0	Yes
No. 4	4.5	0.7	36.9	6.3	3.6	0.8	99.4	37.4	100.0	4.0					99.6	3.4					52.5	43.0	63.0	Yes
No. 8	1.8	0.3	5.3	0.9	1.1	0.3	78.1	29.4	100.0	4.0					98.8	3.4					38.1	32.0	44.0	Yes
No. 30	1.4	0.2	1.3	0.2	0.8	0.2	27.5	10.3	96.5	3.9					60.7	2.1					16.9	14.0	28.0	Yes
No. 50	1.3	0.2	0.8	0.1	0.7	0.2	13.2	5.0	90.9	3.6					53.0	1.8					10.9	7.0	21.0	Yes
No. 200	1.0	0.2	0.4	0.1	0.5	0.1	5.3	2.0	6.3	0.3					25.0	0.9					3.4	2.0	7.0	Yes

(Bold Italic) Not within specifications ***(Bold Italic)*** Not within specifications- Restricted Zone *(Italic)* Not cumulative

Lift Thickness, in:	2.00	Binder Substitution?	Yes	Binder Originally Specified:	PG 70-28	Substitute Binder:	PG 64-22
Asphalt Source:	Owens Corning	Binder Percent, (%):	4.6	Asphalt Spec. Grav.:	0.998		
Antistripping Agent:	Evotherm P-25	Percent, (%):	0.3				

Figure 5 - Mix Design 3



2014 HMACP MIXTURE DESIGN : COMBINED GRADATION

Refresh Workbook

TX2MIXDE14 - File Version: 08/16/18 15:58:53

SAMPLE ID:	15510200180924	SAMPLE DATE:	10/2/2018
LOT NUMBER:	Mix Design	LETTING DATE:	
SAMPLE STATUS:	PENA	CONTROLLING CSJ:	
COUNTY:		SPEC YEAR:	2014
SAMPLED BY:	CLINT E HAMPSON	SPEC ITEM:	
SAMPLE LOCATION:		SPECIAL PROVISION:	
MATERIAL CODE:	0344CM0000	MIX TYPE:	344-SP-C
MATERIAL NAME:	ITEM 344 COMPLETE MIX QCQA ALL MIX TYPES		
PRODUCER:	M1504600704607:DEAN WORD COMPANY, LONE STAR		
AREA ENGINEER:		PROJECT MANAGER:	

WMA Additive in Design?	Yes		
Target Discharge Temp., °F:	325		
WMA TECHNOLOGY:	Evotherm (MeadWestv		
WMA RATE:	0.5	UNITS:	% by weight of asphalt
CONTRACTOR DESIGN # :	3229		

Mixture not <<defined as WMA

Use this value in the QC/QA template>>

COURSE\LIFT:	Surface	STATION:		DIST. FROM CL:	

Maximum Allowable, %	
Frac RAP:	20.0
Unfrac RAP	10.0
RAS:	5.0
RB Ratio:	20.0

Recycled Binder, %	
Bin No.8 :	0.5
Bin No.9 :	0.4
Bin No.10 :	0.0
Total	***0.9***

Ratio of Recycled to Total Binder, %
(based on binder percent (%) entered below in this worksheet)
17.0

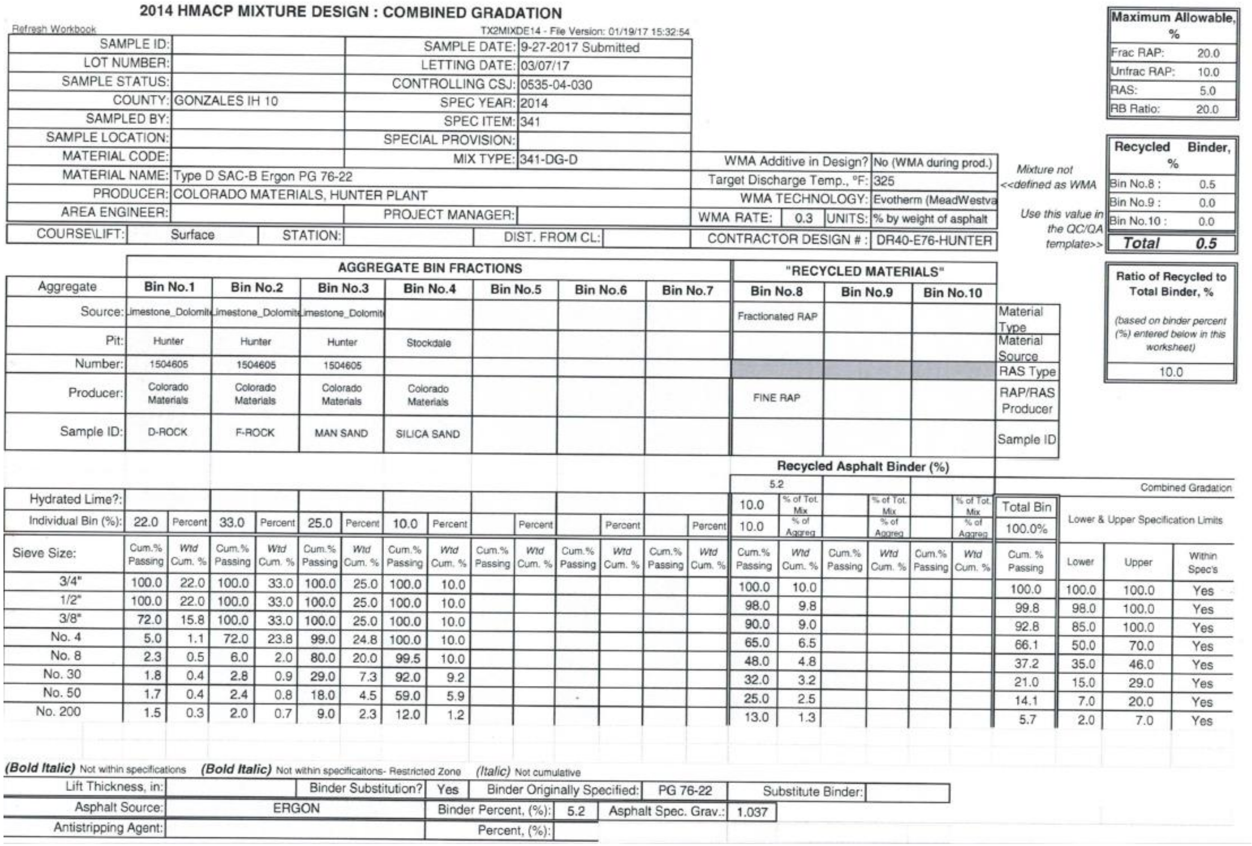
	AGGREGATE BIN FRACTIONS							"RECYCLED MATERIALS"			
Aggregate	Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.5	Bin No.6	Bin No.7	Bin No.8	Bin No.9	Bin No.10	
Source:	Sandstone	Sandstone	mestone_Dolom	mestone_Dolom	mestone_Dolom			Fractionated RAP	Fractionated RAP		Material Type
Pit:	Brownlee	Brownlee	Lone Star	Lone Star	Lone Star			1504607	1504607		Material Source
Number:	1402704	1402704	1504607	1504607	1504607						RAS Type
Producer:	Capitol Aggregates	Capitol Aggregates	Dean Word Co.	Dean Word Co.	Dean Word Co.						RAP/RAS Producer
Sample ID:	C Rock	GR-4	D Rock	F Rock	Dry Screenings			Fine 1/2"	Fine 1/2"		Sample ID

	Bin No.1		Bin No.2		Bin No.3		Bin No.4		Bin No.5		Bin No.6		Bin No.7		Recycled Asphalt Binder (%)						Combined Gradation			
															4.5		4.0							
Hydrated Lime?:															10.0	% of Tot. Mix	10.0	% of Tot.		% of Tot.	Total Bin	Lower & Upper Specification Limits		
Individual Bin (%):	13.0	Percent	16.0	Percent	11.0	Percent	13.0	Percent	26.8	Percent		Percent		Percent	10.1	% of Aggreg	10.1	% of Aggreg		% of Aggreg	100.0%			
Sieve Size:	Cum.% Passing	Wt'd Cum. %	Cum.% Passing	Wt'd Cum. %	Cum.% Passing	Wt'd Cum. %	Cum.% Passing	Wt'd Cum. %	Cum.% Passing	Wt'd Cum. %	Cum.% Passing	Wt'd Cum. %	Cum.% Passing	Wt'd Cum. %	Cum.% Passing	Wt'd Cum. %	Cum.% Passing	Wt'd Cum. %	Cum.% Passing	Wt'd Cum. %	Cum. % Passing	Lower	Upper	Within Spec's
1"	100.0	13.0	100.0	16.0	100.0	11.0	100.0	13.0	100.0	26.8					100.0	10.1	100.0	10.1			100.0	100.0	100.0	Yes
3/4"	100.0	13.0	100.0	16.0	100.0	11.0	100.0	13.0	100.0	26.8					100.0	10.1	100.0	10.1			100.0	98.0	100.0	Yes
1/2"	37.0	4.8	98.0	15.7	99.0	10.9	100.0	13.0	100.0	26.8					100.0	10.1	96.3	9.7			91.0	90.0	100.0	Yes
3/8"	5.0	0.7	70.2	11.2	70.0	7.7	100.0	13.0	100.0	26.8					98.4	9.9	90.0	9.1			78.4	58.0	90.0	Yes
No. 4	3.0	0.4	5.5	0.9	1.0	0.1	48.0	6.2	96.0	25.7					70.9	7.2	66.8	6.7			47.3	28.0	90.0	Yes
No. 8	2.0	0.3	1.0	0.2	1.0	0.1	2.0	0.3	75.0	20.1					48.1	4.9	49.0	4.9			30.7	28.0	58.0	Yes
No. 16	0.5	0.1	1.0	0.2	1.0	0.1	1.0	0.1	48.0	12.9					35.0	3.5	38.0	3.8			20.7	2.0	58.0	Yes
No. 30	0.4	0.1	1.0	0.2	1.0	0.1	1.0	0.1	35.0	9.4					28.2	2.8	29.3	3.0			15.6	2.0	58.0	Yes
No. 50	0.3	0.0	1.0	0.2	1.0	0.1	1.0	0.1	26.0	7.0					21.2	2.1	22.1	2.2			11.8	2.0	58.0	Yes
No. 200	0.2	0.0	0.5	0.1	1.0	0.1	1.0	0.1	15.0	4.0					7.2	0.7	5.7	0.6			5.7	2.0	10.0	Yes

(Bold Italic) Not within specifications ***(Bold Italic)*** Not within specificaitons- Restricted Zone *(Italic)* Not cumulative

Lift Thickness, in:		Binder Substitution?	Yes	Binder Originally Specified:	PG 76-22	Substitute Binder:	PG 70-22
Asphalt Source:	Valero PG 70-22	Binder Percent, (%):	5.0	Asphalt Spec. Grav.:	1.038		
Antistripping Agent:		Percent, (%):					

Figure 6 - Mix Design 4



2014 HMACP MIXTURE DESIGN : COMBINED GRADATION

Refresh Workbook

TX2MIXDE14 - File Version: 01/19/17 15:32:54

SAMPLE ID:		SAMPLE DATE:	9-27-2017 Submitted
LOT NUMBER:		LETTING DATE:	03/07/17
SAMPLE STATUS:		CONTROLLING CSJ:	0535-04-030
COUNTY:	GONZALES IH 10	SPEC YEAR:	2014
SAMPLED BY:		SPEC ITEM:	341
SAMPLE LOCATION:		SPECIAL PROVISION:	
MATERIAL CODE:		MIX TYPE:	341-DG-D
MATERIAL NAME:	Type D SAC-B Ergon PG 76-22		
PRODUCER:	COLORADO MATERIALS, HUNTER PLANT		
AREA ENGINEER:		PROJECT MANAGER:	
COURSE\LIFT:	Surface	STATION:	
DIST. FROM CL:			

WMA Additive in Design?	No (WMA during prod.)
Target Discharge Temp., °F:	325
WMA TECHNOLOGY:	Evotherm (MeadWestva
WMA RATE: 0.3	UNITS: % by weight of asphalt
CONTRACTOR DESIGN # :	DR40-E76-HUNTER

Mixture not
<<defined as WMA

Use this value in the QC/QA template>>

Maximum Allowable, %	
Frac RAP:	20.0
Unfrac RAP:	10.0
RAS:	5.0
RB Ratio:	20.0

Recycled Binder, %	
Bin No.8 :	0.5
Bin No.9 :	0.0
Bin No.10 :	0.0
Total	***0.5***

Ratio of Recycled to Total Binder, %

(based on binder percent (%) entered below in this worksheet)

10.0

	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:	Limestone_Dolomit	Limestone_Dolomit	Limestone_Dolomit					Fractionated RAP			Material Type
Pit:	Hunter	Hunter	Hunter	Stockdale							Material Source
Number:	1504605	1504605	1504605								RAS Type
Producer:	Colorado Materials	Colorado Materials	Colorado Materials	Colorado Materials				FINE RAP			RAP/RAS Producer
Sample ID:	D-ROCK	F-ROCK	MAN SAND	SILICA SAND							Sample ID

	Bin No.1		Bin No.2		Bin No.3		Bin No.4		Bin No.5		Bin No.6		Bin No.7	
Hydrated Lime?:														
Individual Bin (%):	22.0	Percent	33.0	Percent	25.0	Percent	10.0	Percent		Percent		Percent		Percent
Sieve Size:	Cum.% Passing	*Wtd Cum. %*	Cum.% Passing	*Wtd Cum. %*	Cum.% Passing	*Wtd Cum. %*	Cum.% Passing	*Wtd Cum. %*	Cum.% Passing	*Wtd Cum. %*	Cum.% Passing	*Wtd Cum. %*	Cum.% Passing	*Wtd Cum. %*
3/4"	100.0	22.0	100.0	33.0	100.0	25.0	100.0	10.0						
1/2"	100.0	22.0	100.0	33.0	100.0	25.0	100.0	10.0						
3/8"	72.0	15.8	100.0	33.0	100.0	25.0	100.0	10.0						
No. 4	5.0	1.1	72.0	23.8	99.0	24.8	100.0	10.0						
No. 8	2.3	0.5	6.0	2.0	80.0	20.0	99.5	10.0						
No. 30	1.8	0.4	2.8	0.9	29.0	7.3	92.0	9.2						
No. 50	1.7	0.4	2.4	0.8	18.0	4.5	59.0	5.9						
No. 200	1.5	0.3	2.0	0.7	9.0	2.3	12.0	1.2						

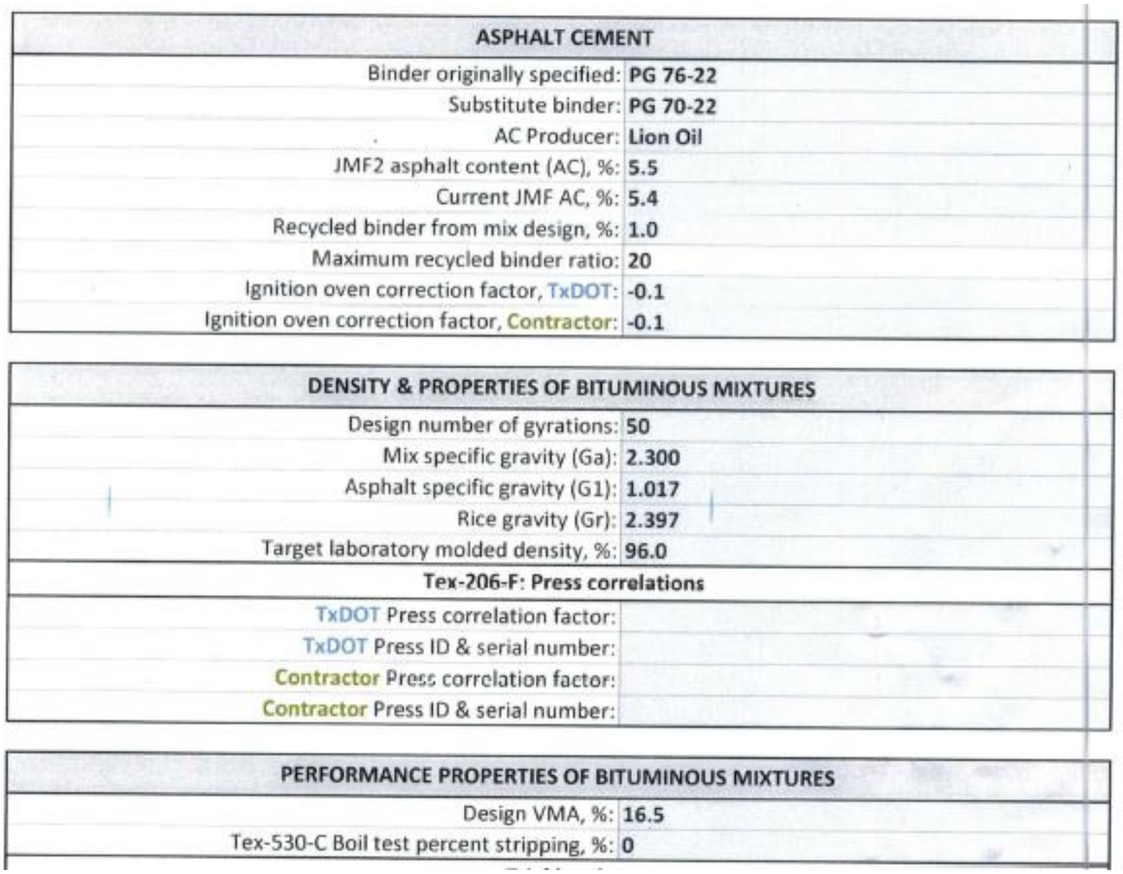
Recycled Asphalt Binder (%)

	Bin No.8		Bin No.9		Bin No.10		Combined Gradation			
	5.2									
	10.0	% of Tot. Mix		% of Tot. Mix		% of Tot. Mix	Total Bin	Lower & Upper Specification Limits		
	10.0	% of Aggreg		% of Aggreg		% of Aggreg	100.0%			
Sieve Size:	Cum.% Passing	*Wtd Cum. %*	Cum.% Passing	*Wtd Cum. %*	Cum.% Passing	*Wtd Cum. %*	Cum. % Passing	Lower	Upper	Within Spec's
3/4"	100.0	10.0					100.0	100.0	100.0	Yes
1/2"	98.0	9.8					99.8	98.0	100.0	Yes
3/8"	90.0	9.0					92.8	85.0	100.0	Yes
No. 4	65.0	6.5					66.1	50.0	70.0	Yes
No. 8	48.0	4.8					37.2	35.0	46.0	Yes
No. 30	32.0	3.2					21.0	15.0	29.0	Yes
No. 50	25.0	2.5					14.1	7.0	20.0	Yes
No. 200	13.0	1.3					5.7	2.0	7.0	Yes

(Bold Italic) Not within specifications ***(Bold Italic)*** Not within specificaitons- Restricted Zone *(Italic)* Not cumulative

Lift Thickness, in:		Binder Substitution?	Yes	Binder Originally Specified:	PG 76-22	Substitute Binder:	
Asphalt Source:	ERGON	Binder Percent, (%):	5.2	Asphalt Spec. Grav.:	1.037		
Antistripping Agent:		Percent, (%):					

Figure 7 - Mix Design 5

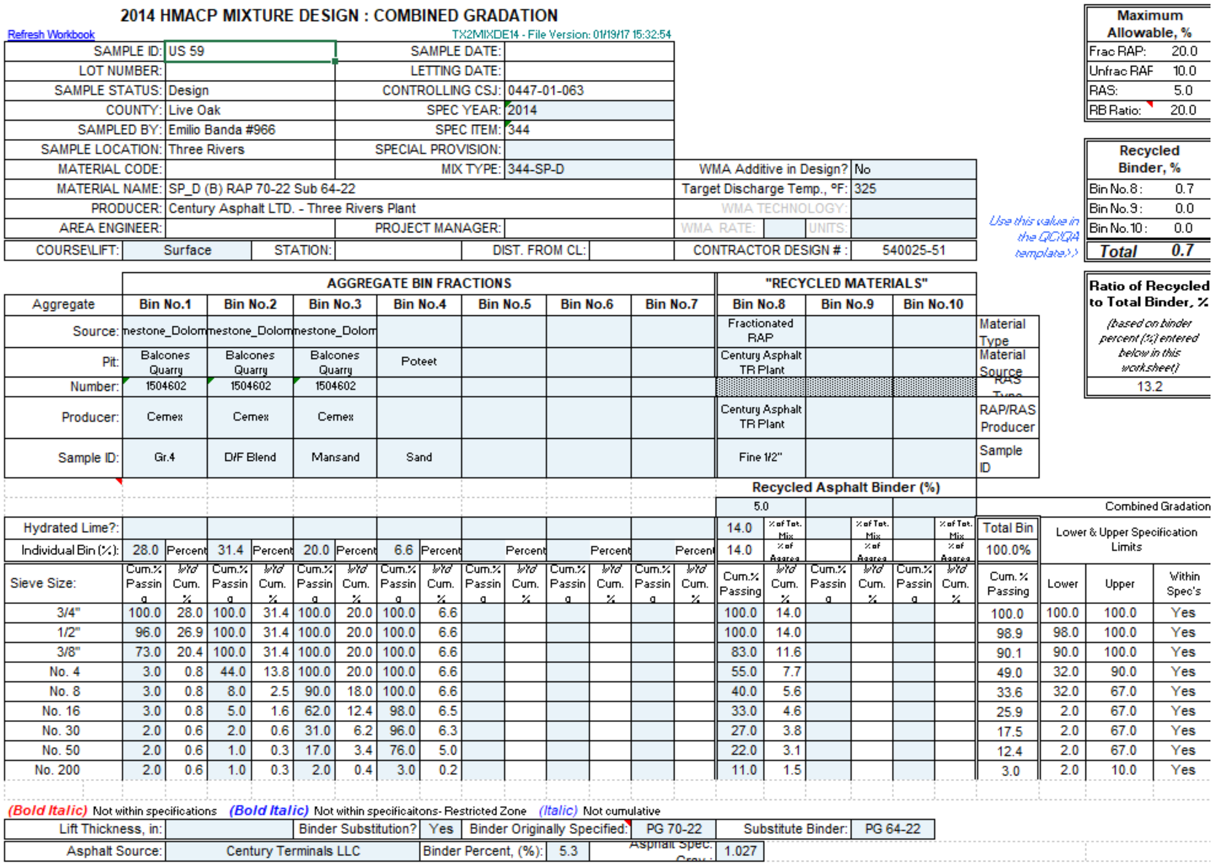


ASPHALT CEMENT	
Binder originally specified:	PG 76-22
Substitute binder:	PG 70-22
AC Producer:	Lion Oil
JMF2 asphalt content (AC), %:	5.5
Current JMF AC, %:	5.4
Recycled binder from mix design, %:	1.0
Maximum recycled binder ratio:	20
Ignition oven correction factor, TxDOT:	-0.1
Ignition oven correction factor, Contractor:	-0.1

DENSITY & PROPERTIES OF BITUMINOUS MIXTURES	
Design number of gyrations:	50
Mix specific gravity (Ga):	2.300
Asphalt specific gravity (G1):	1.017
Rice gravity (Gr):	2.397
Target laboratory molded density, %:	96.0
Tex-206-F: Press correlations	
TxDOT Press correlation factor:	
TxDOT Press ID & serial number:	
Contractor Press correlation factor:	
Contractor Press ID & serial number:	

PERFORMANCE PROPERTIES OF BITUMINOUS MIXTURES	
Design VMA, %:	16.5
Tex-530-C Boil test percent stripping, %:	0

Figure 8 - Mix Design 6



2014 HMACP MIXTURE DESIGN : COMBINED GRADATION

Refresh Workbook

TX2MIXDE14 - File Version: 01/19/17 15:32:54

SAMPLE ID:	US 59	SAMPLE DATE:	
LOT NUMBER:		LETTING DATE:	
SAMPLE STATUS:	Design	CONTROLLING CSJ:	0447-01-063
COUNTY:	Live Oak	SPEC YEAR:	2014
SAMPLED BY:	Emilio Banda #966	SPEC ITEM:	344
SAMPLE LOCATION:	Three Rivers	SPECIAL PROVISION:	
MATERIAL CODE:		MIX TYPE:	344-SP-D
MATERIAL NAME:	SP_D (B) RAP 70-22 Sub 64-22		
PRODUCER:	Century Asphalt LTD. - Three Rivers Plant		
AREA ENGINEER:		PROJECT MANAGER:	

WMA Additive in Design?	No		
Target Discharge Temp., °F:	325		
WMA TECHNOLOGY:			
WMA RATE:		UNITS:	

COURSE\LIFT:	Surface	STATION:		DIST. FROM CL:	
CONTRACTOR DESIGN # :	540025-51				

Maximum Allowable, %	
Frac RAP:	20.0
Unfrac RAF	10.0
RAS:	5.0
RB Ratio:	20.0

Use this value in the QC/QA template>>

Recycled Binder, %	
Bin No. 8 :	0.7
Bin No. 9 :	0.0
Bin No. 10 :	0.0
Total	***0.7***

Ratio of Recycled to Total Binder, % *(based on binder percent (%) entered below in this worksheet)*
13.2

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:	nestone_Dolom	nestone_Dolom	nestone_Dolom					Fractionated RAP			Material Type
Pit:	Balcones Quarry	Balcones Quarry	Balcones Quarry	Poteet				Century Asphalt TR Plant			Material Source
Number:	1504602	1504602	1504602								RAS Type
Producer:	Cemex	Cemex	Cemex					Century Asphalt TR Plant			RAP/RAS Producer
Sample ID:	Gr.4	D/F Blend	Mansand	Sand				Fine 1/2"			Sample ID

Recycled Asphalt Binder (%)

Bin No.8	Bin No.9	Bin No.10
5.0		

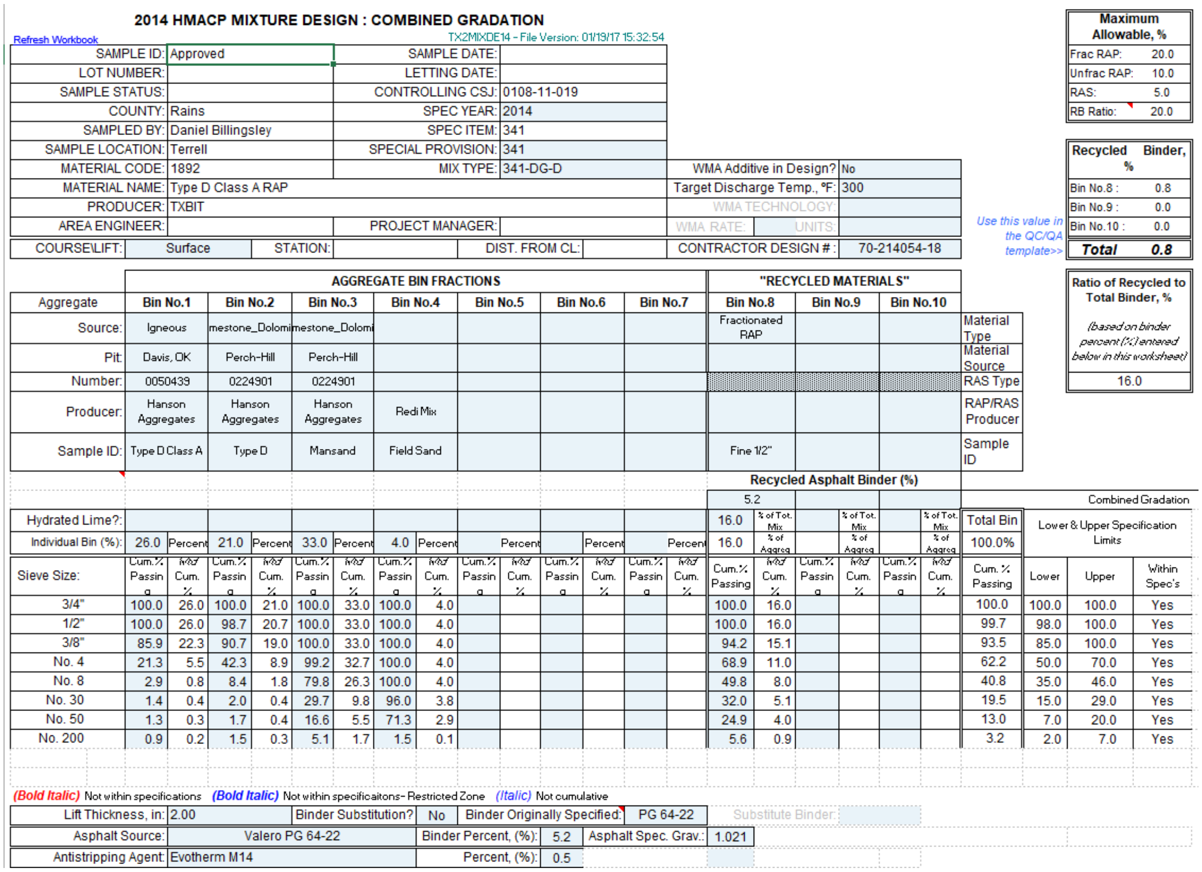
Combined Gradation

	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		Total Bin	Lower & Upper Specification Limits		
Hydrated Lime?:															14.0	% of Tot. Mix		% of Tot. Mix		% of Tot. Mix				
Individual Bin (%):	28.0	Percent	31.4	Percent	20.0	Percent	6.6	Percent		Percent		Percent		Percent	14.0	% of Aggreg		% of Aggreg		% of Aggreg	100.0%			
Sieve Size:	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum. % Passing	Lower	Upper	Within Spec's
3/4"	100.0	28.0	100.0	31.4	100.0	20.0	100.0	6.6							100.0	14.0					100.0	100.0	100.0	Yes
1/2"	96.0	26.9	100.0	31.4	100.0	20.0	100.0	6.6							100.0	14.0					98.9	98.0	100.0	Yes
3/8"	73.0	20.4	100.0	31.4	100.0	20.0	100.0	6.6							83.0	11.6					90.1	90.0	100.0	Yes
No. 4	3.0	0.8	44.0	13.8	100.0	20.0	100.0	6.6							55.0	7.7					49.0	32.0	90.0	Yes
No. 8	3.0	0.8	8.0	2.5	90.0	18.0	100.0	6.6							40.0	5.6					33.6	32.0	67.0	Yes
No. 16	3.0	0.8	5.0	1.6	62.0	12.4	98.0	6.5							33.0	4.6					25.9	2.0	67.0	Yes
No. 30	2.0	0.6	2.0	0.6	31.0	6.2	96.0	6.3							27.0	3.8					17.5	2.0	67.0	Yes
No. 50	2.0	0.6	1.0	0.3	17.0	3.4	76.0	5.0							22.0	3.1					12.4	2.0	67.0	Yes
No. 200	2.0	0.6	1.0	0.3	2.0	0.4	3.0	0.2							11.0	1.5					3.0	2.0	10.0	Yes

(Bold Italic) Not within specifications ***(Bold Italic)*** Not within specificaitons- Restricted Zone *(Italic)* Not cumulative

Lift Thickness, in:		Binder Substitution?	Yes	Binder Originally Specified:	PG 70-22	Substitute Binder:	PG 64-22
Asphalt Source:	Century Terminals LLC	Binder Percent, (%):	5.3	Asphalt Spec. Grav.:	1.027		

Figure 9 - Mix Design 7



2014 HMACP MIXTURE DESIGN : COMBINED GRADATION

Refresh Workbook

TX2MIXDE14 - File Version: 01/19/17 15:32:54

SAMPLE ID:	Approved	SAMPLE DATE:	
LOT NUMBER:		LETTING DATE:	
SAMPLE STATUS:		CONTROLLING CSJ:	0108-11-019
COUNTY:	Rains	SPEC YEAR:	2014
SAMPLED BY:	Daniel Billingsley	SPEC ITEM:	341
SAMPLE LOCATION:	Terrell	SPECIAL PROVISION:	341
MATERIAL CODE:	1892	MIX TYPE:	341-DG-D
MATERIAL NAME:	Type D Class A RAP		
PRODUCER:	TXBIT		
AREA ENGINEER:		PROJECT MANAGER:	

COURSE\LIFT:	Surface	STATION:		DIST. FROM CL:	

WMA Additive in Design?	No
Target Discharge Temp., °F:	300
WMA TECHNOLOGY:	
WMA RATE:	UNITS:
CONTRACTOR DESIGN # :	70-214054-18

Maximum Allowable, %	
Frac RAP:	20.0
Unfrac RAP:	10.0
RAS:	5.0
RB Ratio:	20.0

Recycled Binder, %	
Bin No.8 :	0.8
Bin No.9 :	0.0
Bin No.10 :	0.0
Total	**0.8**

Use this value in the QC/QA template>>

Ratio of Recycled to Total Binder, %

(based on binder percent (%) entered below in this worksheet)

16.0

AGGREGATE BIN FRACTIONS

Aggregate	**Bin No.1**	**Bin No.2**	**Bin No.3**	**Bin No.4**	**Bin No.5**	**Bin No.6**	**Bin No.7**
Source:	Igneous	mestone_Dolomi	mestone_Dolomi				
Pit:	Davis, OK	Perch-Hill	Perch-Hill				
Number:	0050439	0224901	0224901				
Producer:	Hanson Aggregates	Hanson Aggregates	Hanson Aggregates	Redi Mix			
Sample ID:	Type D Class A	Type D	Mansand	Field Sand			
Hydrated Lime?:							
Individual Bin (%):	26.0 Percent	21.0 Percent	33.0 Percent	4.0 Percent	Percent	Percent	Percent

"RECYCLED MATERIALS"

Bin No.8	**Bin No.9**	**Bin No.10**	
Fractionated RAP			Material Type
			Material Source
			RAS Type
			RAP/RAS Producer
Fine 1/2"			Sample ID

Recycled Asphalt Binder (%)

Bin No.8		Bin No.9		Bin No.10	
5.2					
16.0	% of Tot. Mix		% of Tot. Mix		% of Tot. Mix
16.0	% of Aggreg		% of Aggreg		% of Aggreg

Sieve Size:	Bin No.1 Cum.% Passing	Bin No.1 Wtd Cum. %	Bin No.2 Cum.% Passing	Bin No.2 Wtd Cum. %	Bin No.3 Cum.% Passing	Bin No.3 Wtd Cum. %	Bin No.4 Cum.% Passing	Bin No.4 Wtd Cum. %	Bin No.5 Cum.% Passing	Bin No.5 Wtd Cum. %	Bin No.6 Cum.% Passing	Bin No.6 Wtd Cum. %	Bin No.7 Cum.% Passing	Bin No.7 Wtd Cum. %
3/4"	100.0	26.0	100.0	21.0	100.0	33.0	100.0	4.0						
1/2"	100.0	26.0	98.7	20.7	100.0	33.0	100.0	4.0						
3/8"	85.9	22.3	90.7	19.0	100.0	33.0	100.0	4.0						
No. 4	21.3	5.5	42.3	8.9	99.2	32.7	100.0	4.0						
No. 8	2.9	0.8	8.4	1.8	79.8	26.3	100.0	4.0						
No. 30	1.4	0.4	2.0	0.4	29.7	9.8	96.0	3.8						
No. 50	1.3	0.3	1.7	0.4	16.6	5.5	71.3	2.9						
No. 200	0.9	0.2	1.5	0.3	5.1	1.7	1.5	0.1						

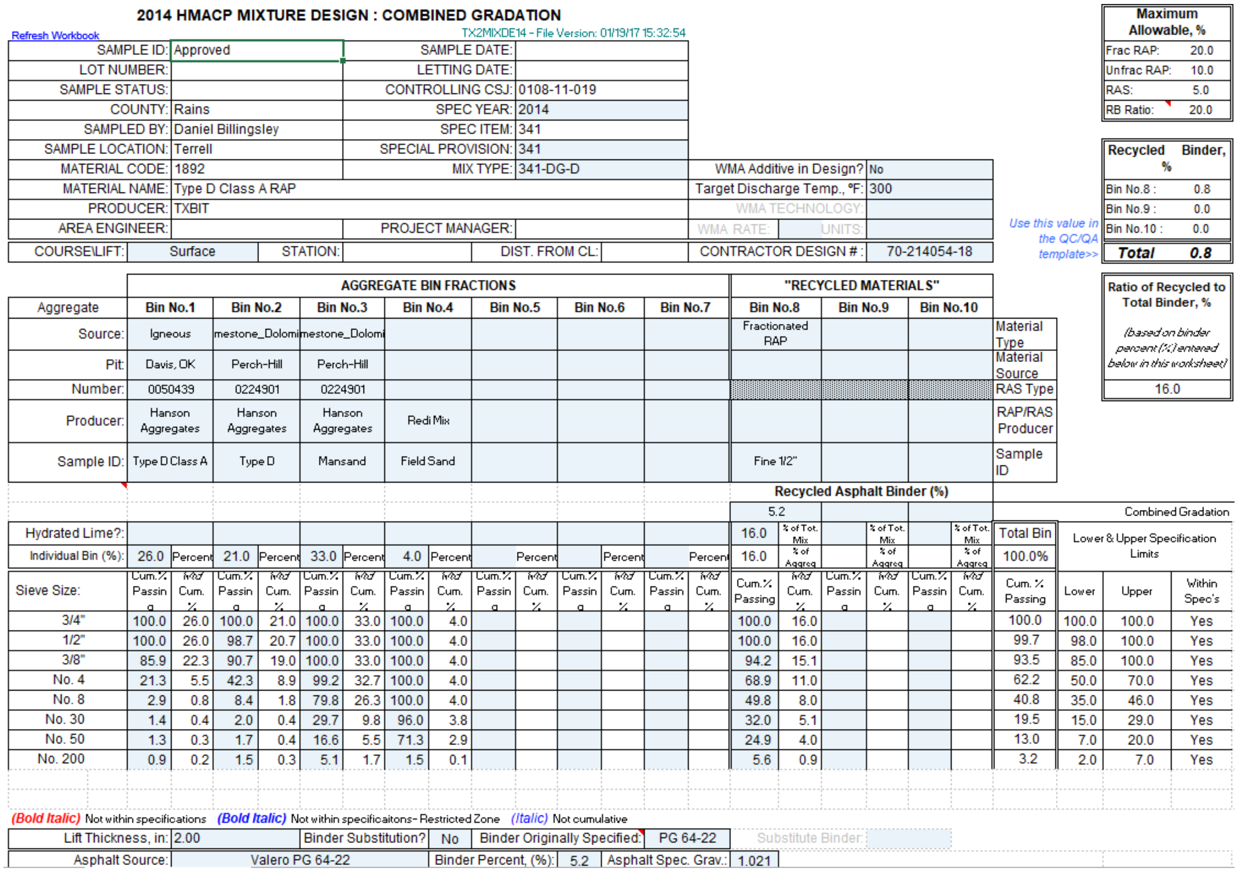
Combined Gradation

Sieve Size:	Bin No.8 Cum.% Passing	Bin No.8 Wtd Cum. %	Bin No.9 Cum.% Passing	Bin No.9 Wtd Cum. %	Bin No.10 Cum.% Passing	Bin No.10 Wtd Cum. %	Total Bin 100.0% Cum. % Passing	Lower & Upper Specification Limits Lower	Upper	Within Spec's
3/4"	100.0	16.0					100.0	100.0	100.0	Yes
1/2"	100.0	16.0					99.7	98.0	100.0	Yes
3/8"	94.2	15.1					93.5	85.0	100.0	Yes
No. 4	68.9	11.0					62.2	50.0	70.0	Yes
No. 8	49.8	8.0					40.8	35.0	46.0	Yes
No. 30	32.0	5.1					19.5	15.0	29.0	Yes
No. 50	24.9	4.0					13.0	7.0	20.0	Yes
No. 200	5.6	0.9					3.2	2.0	7.0	Yes

(Bold Italic) Not within specifications ***(Bold Italic)*** Not within specificaitons- Restricted Zone *(Italic)* Not cumulative

Lift Thickness, in:	2.00	Binder Substitution?	No	Binder Originally Specified:	PG 64-22	Substitute Binder:	
Asphalt Source:	Valero PG 64-22	Binder Percent, (%):	5.2	Asphalt Spec. Grav.:	1.021		
Antistripping Agent:	Evotherm M14	Percent, (%):	0.5				

Figure 10 - Mix Design 8



2014 HMACP MIXTURE DESIGN : COMBINED GRADATION

Refresh Workbook

TX2MIXDE14 - File Version: 01/19/17 15:32:54

SAMPLE ID:	Approved	SAMPLE DATE:	
LOT NUMBER:		LETTING DATE:	
SAMPLE STATUS:		CONTROLLING CSJ:	0108-11-019
COUNTY:	Rains	SPEC YEAR:	2014
SAMPLED BY:	Daniel Billingsley	SPEC ITEM:	341
SAMPLE LOCATION:	Terrell	SPECIAL PROVISION:	341
MATERIAL CODE:	1892	MIX TYPE:	341-DG-D
MATERIAL NAME:	Type D Class A RAP		
PRODUCER:	TXBIT		
AREA ENGINEER:		PROJECT MANAGER:	

WMA Additive in Design?	No
Target Discharge Temp., °F:	300
WMA TECHNOLOGY:	
WMA RATE: UNITS:	

COURSE\LIFT:	Surface	STATION:		DIST. FROM CL:		CONTRACTOR DESIGN # :	70-214054-18

Maximum Allowable, %	
Frac RAP:	20.0
Unfrac RAP:	10.0
RAS:	5.0
RB Ratio:	20.0

Recycled Binder, %	
Bin No.8 :	0.8
Bin No.9 :	0.0
Bin No.10 :	0.0
Total	***0.8***

Use this value in the QC/QA template>>

Ratio of Recycled to Total Binder, % *(based on binder percent (%) entered below in this worksheet)*
16.0

	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	mestone_Dolomi	mestone_Dolomi					Fractionated RAP			Material Type
Pit:	Davis, OK	Perch-Hill	Perch-Hill								Material Source
Number:	0050439	0224901	0224901								RAS Type
Producer:	Hanson Aggregates	Hanson Aggregates	Hanson Aggregates	Redi Mix							RAP/RAS Producer
Sample ID:	Type D Class A	Type D	Mansand	Field Sand				Fine 1/2"			Sample ID

Recycled Asphalt Binder (%): Bin No.8: 5.2

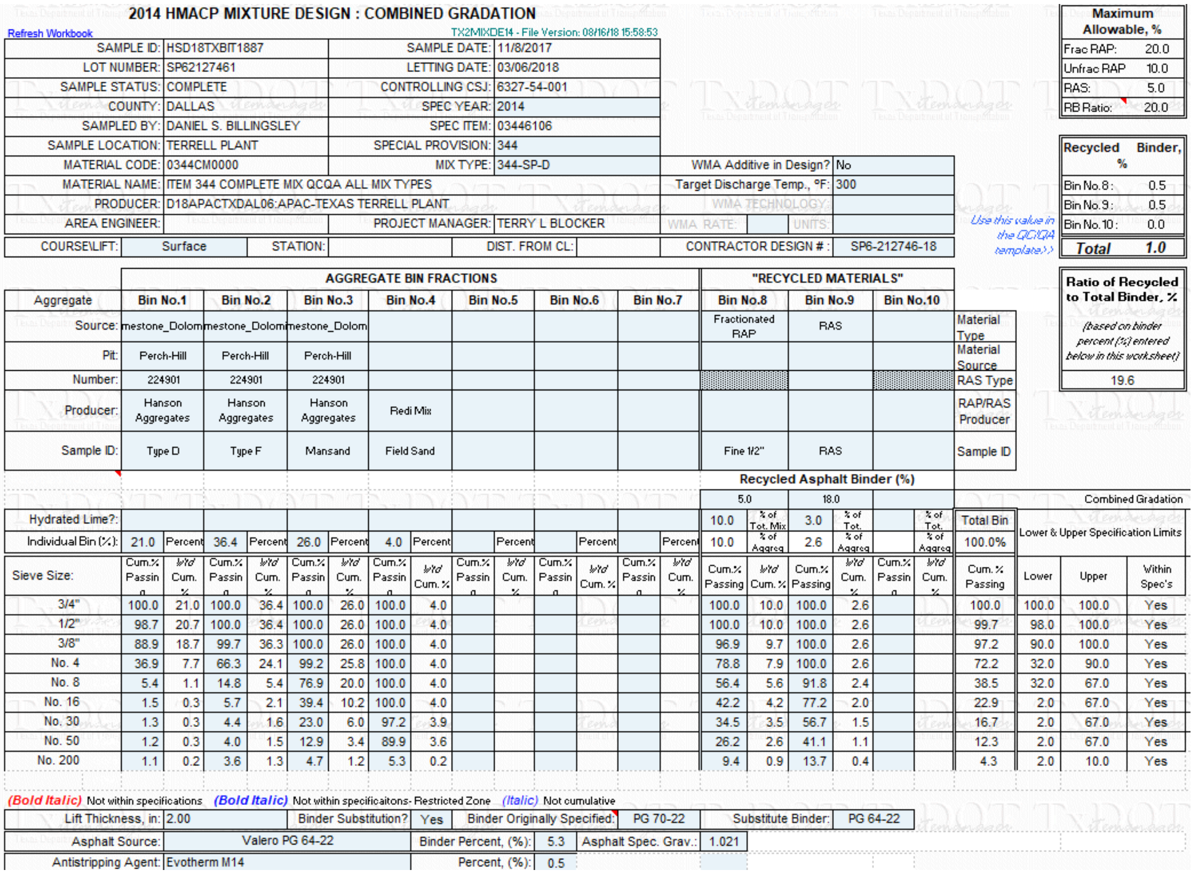
Combined Gradation

	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					
Hydrated Lime?:															16.0	% of Tot. Mix		% of Tot. Mix		% of Tot. Mix	Total Bin	Lower & Upper Specification Limits		
Individual Bin (%):	26.0	Percent	21.0	Percent	33.0	Percent	4.0	Percent		Percent		Percent		Percent	16.0	% of Aggreg		% of Aggreg		% of Aggreg	100.0%			
Sieve Size:	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum. % Passing	Lower	Upper	Within Spec's
3/4"	100.0	26.0	100.0	21.0	100.0	33.0	100.0	4.0							100.0	16.0					100.0	100.0	100.0	Yes
1/2"	100.0	26.0	98.7	20.7	100.0	33.0	100.0	4.0							100.0	16.0					99.7	98.0	100.0	Yes
3/8"	85.9	22.3	90.7	19.0	100.0	33.0	100.0	4.0							94.2	15.1					93.5	85.0	100.0	Yes
No. 4	21.3	5.5	42.3	8.9	99.2	32.7	100.0	4.0							68.9	11.0					62.2	50.0	70.0	Yes
No. 8	2.9	0.8	8.4	1.8	79.8	26.3	100.0	4.0							49.8	8.0					40.8	35.0	46.0	Yes
No. 30	1.4	0.4	2.0	0.4	29.7	9.8	96.0	3.8							32.0	5.1					19.5	15.0	29.0	Yes
No. 50	1.3	0.3	1.7	0.4	16.6	5.5	71.3	2.9							24.9	4.0					13.0	7.0	20.0	Yes
No. 200	0.9	0.2	1.5	0.3	5.1	1.7	1.5	0.1							5.6	0.9					3.2	2.0	7.0	Yes

(Bold Italic) Not within specifications ***(Bold Italic)*** Not within specificaitons- Restricted Zone *(Italic)* Not cumulative

Lift Thickness, in:	2.00	Binder Substitution?	No	Binder Originally Specified:	PG 64-22	Substitute Binder:	
Asphalt Source:	Valero PG 64-22	Binder Percent, (%):	5.2	Asphalt Spec. Grav.:	1.021		

Figure 11 - Mix Design 9



2014 HMACP MIXTURE DESIGN : COMBINED GRADATION

Refresh Workbook

TX2MIXDE14 - File Version: 08/16/18 15:58:53

SAMPLE ID:	HSD18TXBIT1887	SAMPLE DATE:	11/8/2017
LOT NUMBER:	SP62127461	LETTING DATE:	03/06/2018
SAMPLE STATUS:	COMPLETE	CONTROLLING CSJ:	6327-54-001
COUNTY:	DALLAS	SPEC YEAR:	2014
SAMPLED BY:	DANIEL S. BILLINGSLEY	SPEC ITEM:	03446106
SAMPLE LOCATION:	TERRELL PLANT	SPECIAL PROVISION:	344
MATERIAL CODE:	0344CM0000	MIX TYPE:	344-SP-D
MATERIAL NAME:	ITEM 344 COMPLETE MIX QCQA ALL MIX TYPES		
PRODUCER:	D18APACTXDAL06:APAC-TEXAS TERRELL PLANT		
AREA ENGINEER:		PROJECT MANAGER:	TERRY L BLOCKER

WMA Additive in Design?	No
Target Discharge Temp., °F:	300
WMA TECHNOLOGY:	
WMA RATE:	UNITS:

COURSE\LIFT:	Surface	STATION:		DIST. FROM CL:		CONTRACTOR DESIGN # :	SP6-212746-18

Maximum Allowable, %	
Frac RAP:	20.0
Unfrac RAP	10.0
RAS:	5.0
RB Ratio:	20.0

Use this value in the QC/QA template>>

Recycled Binder, %	
Bin No. 8 :	0.5
Bin No. 9 :	0.5
Bin No. 10 :	0.0
Total	***1.0***

Ratio of Recycled to Total Binder, %

(based on binder percent (%) entered below in this worksheet)

19.6

	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:	mestone_Dolom	mestone_Dolom	mestone_Dolom					Fractionated RAP	RAS		Material Type
Pit:	Perch-Hill	Perch-Hill	Perch-Hill								Material Source
Number:	224901	224901	224901					▨		▨	RAS Type
Producer:	Hanson Aggregates	Hanson Aggregates	Hanson Aggregates	Redi Mix							RAP/RAS Producer
Sample ID:	Type D	Type F	Mansand	Field Sand				Fine 1/2"	RAS		Sample ID

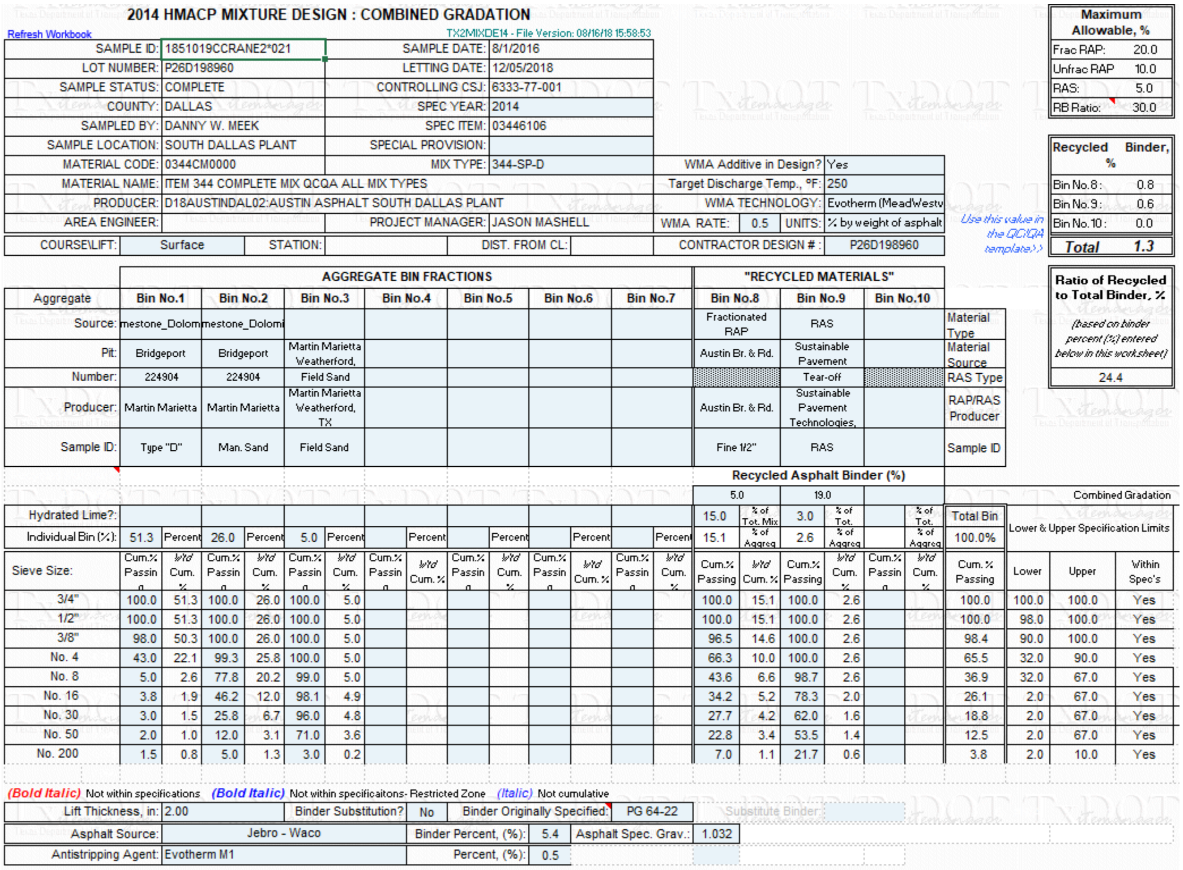
Hydrated Lime?:															
Individual Bin (%):	21.0	Percent	36.4	Percent	26.0	Percent	4.0	Percent		Percent		Percent		Percent	
Sieve Size:	Cum.% Passin	Wt'd Cum. %	Cum.% Passin	Wt'd Cum. %	Cum.% Passin	Wt'd Cum. %	Cum.% Passin	Wt'd Cum. %	Cum.% Passin	Wt'd Cum. %	Cum.% Passin	Wt'd Cum. %	Cum.% Passin	Wt'd Cum. %	
3/4"	100.0	21.0	100.0	36.4	100.0	26.0	100.0	4.0							
1/2"	98.7	20.7	100.0	36.4	100.0	26.0	100.0	4.0							
3/8"	88.9	18.7	99.7	36.3	100.0	26.0	100.0	4.0							
No. 4	36.9	7.7	66.3	24.1	99.2	25.8	100.0	4.0							
No. 8	5.4	1.1	14.8	5.4	76.9	20.0	100.0	4.0							
No. 16	1.5	0.3	5.7	2.1	39.4	10.2	100.0	4.0							
No. 30	1.3	0.3	4.4	1.6	23.0	6.0	97.2	3.9							
No. 50	1.2	0.3	4.0	1.5	12.9	3.4	89.9	3.6							
No. 200	1.1	0.2	3.6	1.3	4.7	1.2	5.3	0.2							

	Recycled Asphalt Binder (%)						Combined Gradation			
	5.0		18.0							
Hydrated Lime?:	10.0	% of Tot. Mix	3.0	% of Tot.		% of Tot.	Total Bin	Lower & Upper Specification Limits		
Individual Bin (%):	10.0	% of Aggreg	2.6	% of Aggreg		% of Aggreg	100.0%			
Sieve Size:	Cum.% Passing	Wt'd Cum. %	Cum.% Passing	Wt'd Cum. %	Cum.% Passin	Wt'd Cum. %	Cum. % Passing	Lower	Upper	Within Spec's
3/4"	100.0	10.0	100.0	2.6			100.0	100.0	100.0	Yes
1/2"	100.0	10.0	100.0	2.6			99.7	98.0	100.0	Yes
3/8"	96.9	9.7	100.0	2.6			97.2	90.0	100.0	Yes
No. 4	78.8	7.9	100.0	2.6			72.2	32.0	90.0	Yes
No. 8	56.4	5.6	91.8	2.4			38.5	32.0	67.0	Yes
No. 16	42.2	4.2	77.2	2.0			22.9	2.0	67.0	Yes
No. 30	34.5	3.5	56.7	1.5			16.7	2.0	67.0	Yes
No. 50	26.2	2.6	41.1	1.1			12.3	2.0	67.0	Yes
No. 200	9.4	0.9	13.7	0.4			4.3	2.0	10.0	Yes

(Bold Italic) Not within specifications ***(Bold Italic)*** Not within specificaitons- Restricted Zone *(Italic)* Not cumulative

Lift Thickness, in:	2.00	Binder Substitution?	Yes	Binder Originally Specified:	PG 70-22	Substitute Binder:	PG 64-22
Asphalt Source:	Valero PG 64-22	Binder Percent, (%):	5.3	Asphalt Spec. Grav.:	1.021		
Antistripping Agent:	Evotherm M14	Percent, (%):	0.5				

Figure 12 - Mix Design 10



2014 HMACP MIXTURE DESIGN : COMBINED GRADATION

Refresh Workbook

TX2MIXDE14 - File Version: 08/16/18 15:58:53

SAMPLE ID:	1851019CCRANE2*021	SAMPLE DATE:	8/1/2016		
LOT NUMBER:	P26D198960	LETTING DATE:	12/05/2018		
SAMPLE STATUS:	COMPLETE	CONTROLLING CSJ:	6333-77-001		
COUNTY:	DALLAS	SPEC YEAR:	2014		
SAMPLED BY:	DANNY W. MEEK	SPEC ITEM:	03446106		
SAMPLE LOCATION:	SOUTH DALLAS PLANT	SPECIAL PROVISION:			
MATERIAL CODE:	0344CM0000	MIX TYPE:	344-SP-D	WMA Additive in Design?	Yes
MATERIAL NAME:	ITEM 344 COMPLETE MIX QCQA ALL MIX TYPES			Target Discharge Temp., °F:	250
PRODUCER:	D18AUSTINDAL02:AUSTIN ASPHALT SOUTH DALLAS PLANT			WMA TECHNOLOGY:	Evotherm (MeadWestv
AREA ENGINEER:		PROJECT MANAGER:	JASON MASHELL	WMA RATE: 0.5 UNITS:	% by weight of asphalt
COURSE\LIFT: Surface	STATION:		DIST. FROM CL:	CONTRACTOR DESIGN # :	P26D198960

Use this value in the QC/QA template>>

Maximum Allowable, %	
Frac RAP:	20.0
Unfrac RAP	10.0
RAS:	5.0
RB Ratio:	30.0

Recycled Binder, %	
Bin No. 8 :	0.8
Bin No. 9 :	0.6
Bin No. 10 :	0.0
Total	***1.3***

Ratio of Recycled to Total Binder, % *(based on binder percent (%) entered below in this worksheet)*
24.4

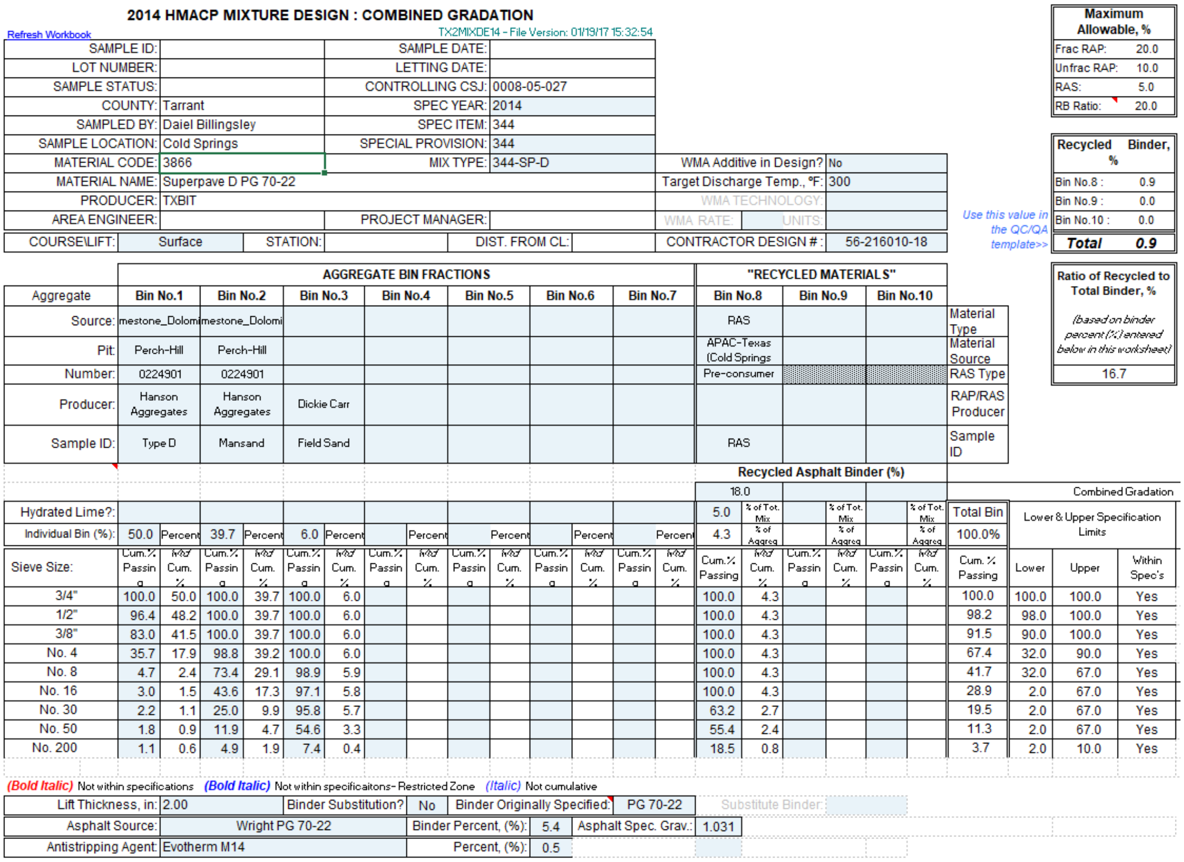
	AGGREGATE BIN FRACTIONS							"RECYCLED MATERIALS"			
Aggregate	Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.5	Bin No.6	Bin No.7	Bin No.8	Bin No.9	Bin No.10	
Source:	mestone_Dolom	mestone_Dolomi						Fractionated RAP	RAS		Material Type
Pit:	Bridgeport	Bridgeport	Martin Marietta Weatherford,					Austin Br. & Rd.	Sustainable Pavement		Material Source
Number:	224904	224904	Field Sand						Tear-off		RAS Type
Producer:	Martin Marietta	Martin Marietta	Martin Marietta Weatherford, TX					Austin Br. & Rd.	Sustainable Pavement Technologies,		RAP/RAS Producer
Sample ID:	Type "D"	Man. Sand	Field Sand					Fine 1/2"	RAS		Sample ID

	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		Combined Gradation			
Recycled Asphalt Binder (%)															5.0		19.0							
Hydrated Lime?:															15.0	% of Tot. Mix	3.0	% of Tot.		% of Tot.	Total Bin	Lower & Upper Specification Limits		
Individual Bin (%):	51.3	Percent	26.0	Percent	5.0	Percent		Percent		Percent		Percent		Percent	15.1	% of Aggreg	2.6	% of Aggreg		% of Aggreg	100.0%			
Sieve Size:	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum. % Passing	Lower	Upper	Within Spec's
3/4"	100.0	51.3	100.0	26.0	100.0	5.0									100.0	15.1	100.0	2.6			100.0	100.0	100.0	Yes
1/2"	100.0	51.3	100.0	26.0	100.0	5.0									100.0	15.1	100.0	2.6			100.0	98.0	100.0	Yes
3/8"	98.0	50.3	100.0	26.0	100.0	5.0									96.5	14.6	100.0	2.6			98.4	90.0	100.0	Yes
No. 4	43.0	22.1	99.3	25.8	100.0	5.0									66.3	10.0	100.0	2.6			65.5	32.0	90.0	Yes
No. 8	5.0	2.6	77.8	20.2	99.0	5.0									43.6	6.6	98.7	2.6			36.9	32.0	67.0	Yes
No. 16	3.8	1.9	46.2	12.0	98.1	4.9									34.2	5.2	78.3	2.0			26.1	2.0	67.0	Yes
No. 30	3.0	1.5	25.8	6.7	96.0	4.8									27.7	4.2	62.0	1.6			18.8	2.0	67.0	Yes
No. 50	2.0	1.0	12.0	3.1	71.0	3.6									22.8	3.4	53.5	1.4			12.5	2.0	67.0	Yes
No. 200	1.5	0.8	5.0	1.3	3.0	0.2									7.0	1.1	21.7	0.6			3.8	2.0	10.0	Yes

(Bold Italic) Not within specifications ***(Bold Italic)*** Not within specificaitons- Restricted Zone *(Italic)* Not cumulative

Lift Thickness, in:	2.00	Binder Substitution?	No	Binder Originally Specified:	PG 64-22	Substitute Binder:	
Asphalt Source:	Jebro - Waco	Binder Percent, (%):	5.4	Asphalt Spec. Grav.:	1.032		
Antistripping Agent:	Evotherm M1	Percent, (%):	0.5				

Figure 13 - Mix Design 11



2014 HMACP MIXTURE DESIGN : COMBINED GRADATION

Refresh Workbook

TX2MIXDE14 - File Version: 01/19/17 15:32:54

SAMPLE ID:		SAMPLE DATE:	
LOT NUMBER:		LETTING DATE:	
SAMPLE STATUS:		CONTROLLING CSJ:	0008-05-027
COUNTY:	Tarrant	SPEC YEAR:	2014
SAMPLED BY:	Daiel Billingsley	SPEC ITEM:	344
SAMPLE LOCATION:	Cold Springs	SPECIAL PROVISION:	344
MATERIAL CODE:	3866	MIX TYPE:	344-SP-D
MATERIAL NAME:	Superpave D PG 70-22		
PRODUCER:	TXBIT		
AREA ENGINEER:		PROJECT MANAGER:	

COURSE\LIFT:	Surface	STATION:		DIST. FROM CL:	

WMA Additive in Design?	No
Target Discharge Temp., °F:	300
WMA TECHNOLOGY:	
WMA RATE:	UNITS:
CONTRACTOR DESIGN # :	56-216010-18

Maximum Allowable, %	
Frac RAP:	20.0
Unfrac RAP:	10.0
RAS:	5.0
RB Ratio:	20.0

Recycled Binder, %	
Bin No.8 :	0.9
Bin No.9 :	0.0
Bin No.10 :	0.0
Total	***0.9***

Use this value in the QC/QA template>>

Ratio of Recycled to Total Binder, %
(based on binder percent (%) entered below in this worksheet)
16.7

	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:	mestone_Dolomi	mestone_Dolomi						RAS			Material Type
Pit:	Perch-Hill	Perch-Hill						APAC-Texas (Cold Springs			Material Source
Number:	0224901	0224901						Pre-consumer	▨	▨	RAS Type
Producer:	Hanson Aggregates	Hanson Aggregates	Dickie Carr								RAP/RAS Producer
Sample ID:	Type D	Mansand	Field Sand					RAS			Sample ID

Recycled Asphalt Binder (%): 18.0

Combined Gradation

	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		Total Bin	Lower & Upper Specification Limits		
Hydrated Lime?:															5.0	% of Tot. Mix		% of Tot. Mix		% of Tot. Mix				
Individual Bin (%):	50.0	Percent	39.7	Percent	6.0	Percent		Percent		Percent		Percent		Percent	4.3	% of Aggreg		% of Aggreg		% of Aggreg	100.0%			
Sieve Size:	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum. % Passing	Lower	Upper	Within Spec's
3/4"	100.0	50.0	100.0	39.7	100.0	6.0									100.0	4.3					100.0	100.0	100.0	Yes
1/2"	96.4	48.2	100.0	39.7	100.0	6.0									100.0	4.3					98.2	98.0	100.0	Yes
3/8"	83.0	41.5	100.0	39.7	100.0	6.0									100.0	4.3					91.5	90.0	100.0	Yes
No. 4	35.7	17.9	98.8	39.2	100.0	6.0									100.0	4.3					67.4	32.0	90.0	Yes
No. 8	4.7	2.4	73.4	29.1	98.9	5.9									100.0	4.3					41.7	32.0	67.0	Yes
No. 16	3.0	1.5	43.6	17.3	97.1	5.8									100.0	4.3					28.9	2.0	67.0	Yes
No. 30	2.2	1.1	25.0	9.9	95.8	5.7									63.2	2.7					19.5	2.0	67.0	Yes
No. 50	1.8	0.9	11.9	4.7	54.6	3.3									55.4	2.4					11.3	2.0	67.0	Yes
No. 200	1.1	0.6	4.9	1.9	7.4	0.4									18.5	0.8					3.7	2.0	10.0	Yes

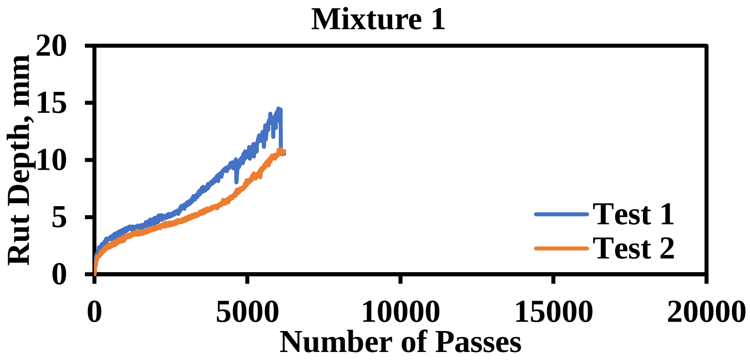
(Bold Italic) Not within specifications ***(Bold Italic)*** Not within specificaitons- Restricted Zone *(Italic)* Not cumulative

Lift Thickness, in:	2.00	Binder Substitution?	No	Binder Originally Specified:	PG 70-22	Substitute Binder:	
Asphalt Source:	Wright PG 70-22	Binder Percent, (%):	5.4	Asphalt Spec. Grav.:	1.031		
Antistripping Agent:	Evotherm M14	Percent, (%):	0.5				

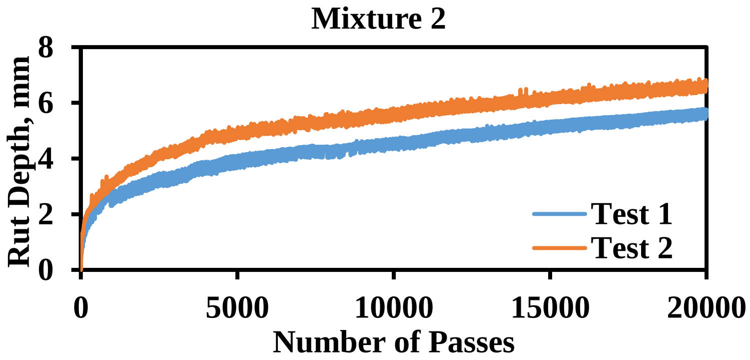
Figure 14 - Mix Design 12

Appendix C- Laboratory Results

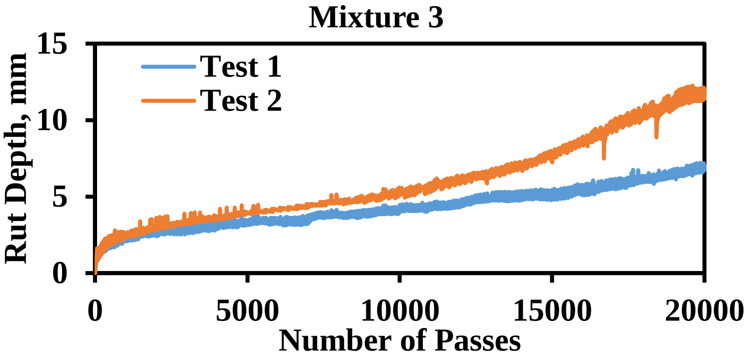
Hamburg Wheel Tracking Test Results



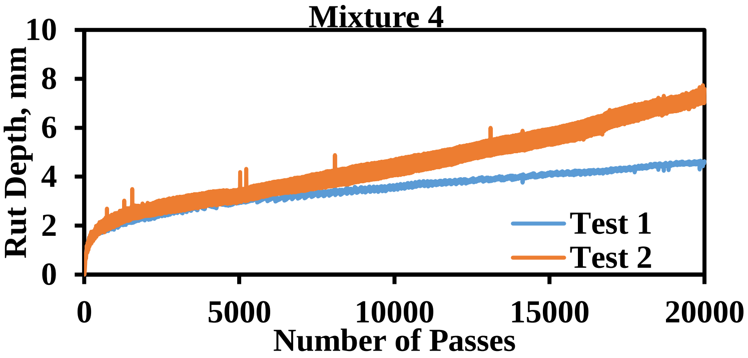
Rutting Properties	Left	Right	Average
Rut Depth (Mid Point), mm	13.0	12.6	12.8
Number of Cycles	5580	6830	6205
RRI	2722	3434	3078
Normalized RRI	0.4	0.5	0.4



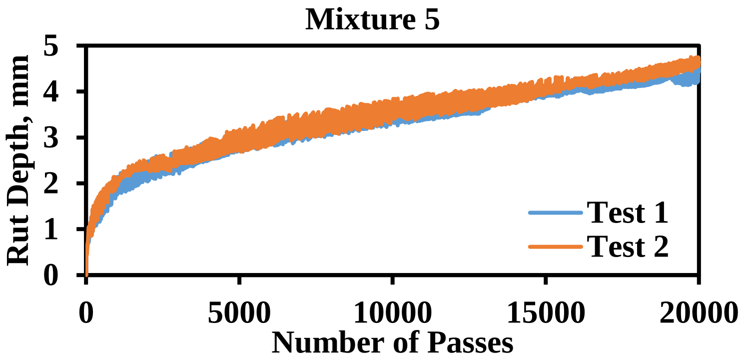
Rutting Properties	Left	Right	Average
Rut Depth (Mid Point), mm	5.8	6.9	6.3
Number of Cycles	20000	20000	20000
RRI	15449	14598	15024
Normalized RRI	1.5	1.4	1.5



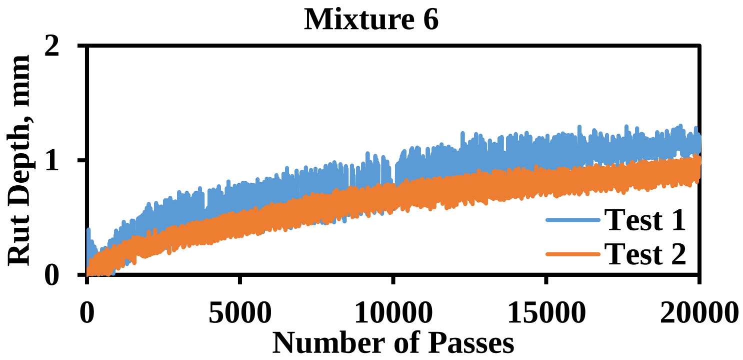
Rutting Properties	Left	Right	Average
Rut Depth (Mid Point), mm	7.2	12.3	9.7
Number of Cycles	20000	20000	20000
RRI	14323	10346	12335
Normalized RRI	1.9	1.4	1.6



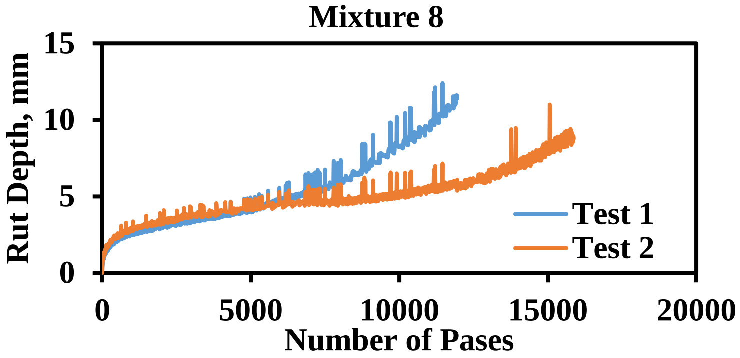
Rutting Properties	Left	Right	Average
Rut Depth (Mid Point), mm	5.1	8.1	6.6
Number of Cycles	20000	20000	20000
RRI	16000	13661	14831
Normalized RRI	1.6	1.3	1.5



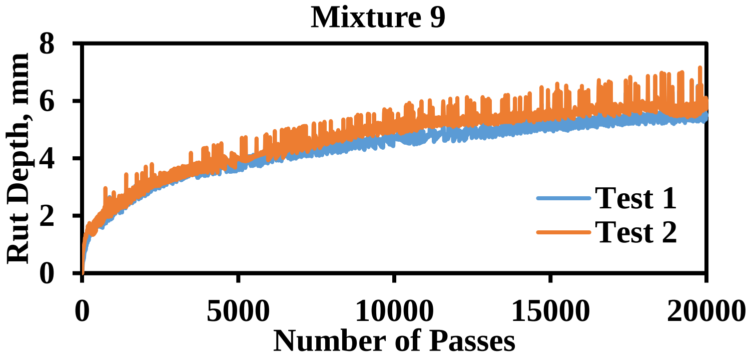
Rutting Properties	Left	Right	Average
Rut Depth (Mid Point), mm	4.6	4.8	4.7
Number of Cycles	20000	20000	20000
RRI	16417	16260	16339
Normalized RRI	1.6	1.6	1.6



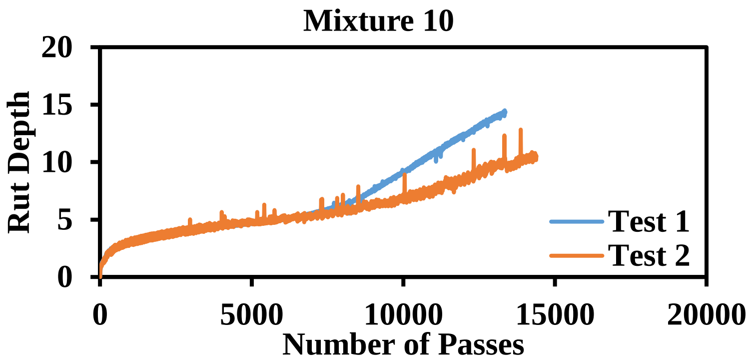
Rutting Properties	Left	Right	Average
Rut Depth (Mid Point), mm	1.3	1.0	1.2
Number of Cycles	20000	20000	20000
RRI	18976	19181	19079
Normalized RRI	1.9	1.9	1.9



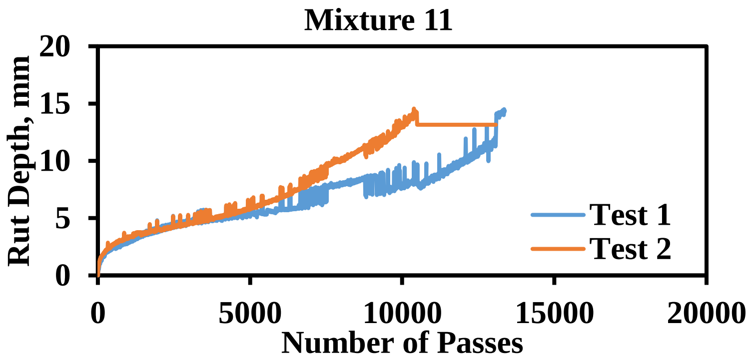
Rutting Properties	Left	Right	Average
Rut Depth (Mid Point), mm	12.7	12.7	12.7
Number of Cycles	11100	14850	12975
RRI	5572	7443	6507
Normalized RRI	1.1	1.5	1.3



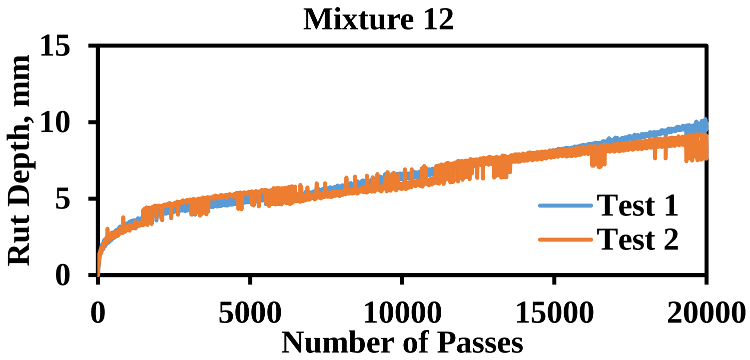
Rutting Properties	Left	Right	Average
Rut Depth (Mid Point), mm	6.6	7.2	6.9
Number of Cycles	20000	20000	20000
RRI	14811	14362	14587
Normalized RRI	2.9	2.8	2.9



Rutting Properties	Left	Right	Average
Rut Depth (Mid Point), mm	12.6	12.6	12.6
Number of Cycles	18120	18320	18220
RRI	9167	9254	9210
Normalized RRI	1.2	1.2	1.2

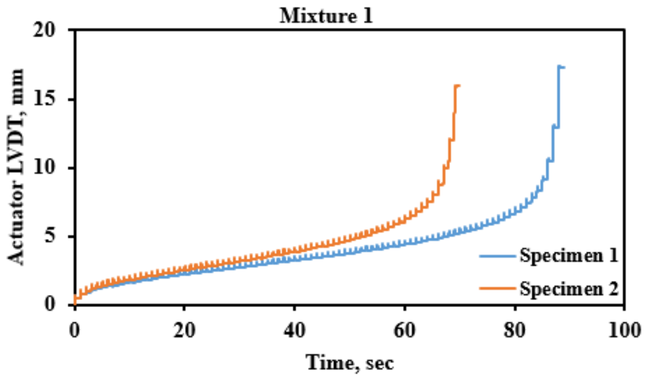


Rutting Properties	Left	Right	Average
Rut Depth (Mid Point), mm	13.1	12.6	12.9
Number of Cycles	13079	9530	11305
RRI	6313	4810	5561
Normalized RRI	1.2	0.9	1.1

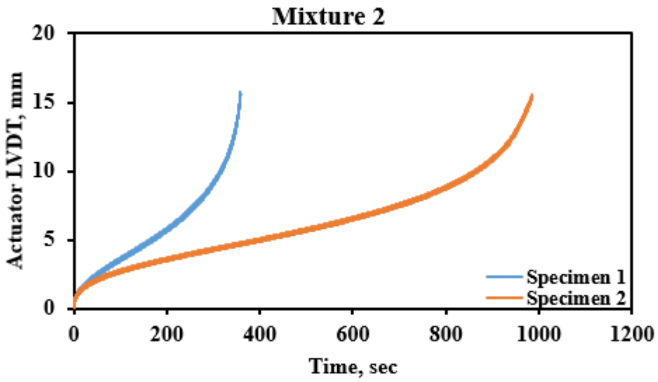


Rutting Properties	Left	Right	Average
Rut Depth (Mid Point), mm	10.2	9.2	9.7
Number of Cycles	20000	20000	20000
RRI	11969	12740	12354
Normalized RRI	1.6	1.7	1.6

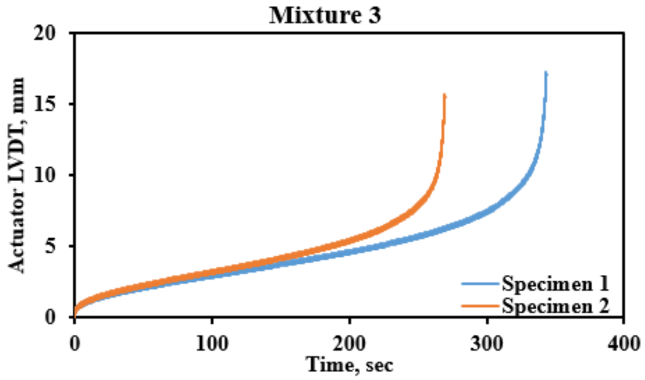
Flow Number Results



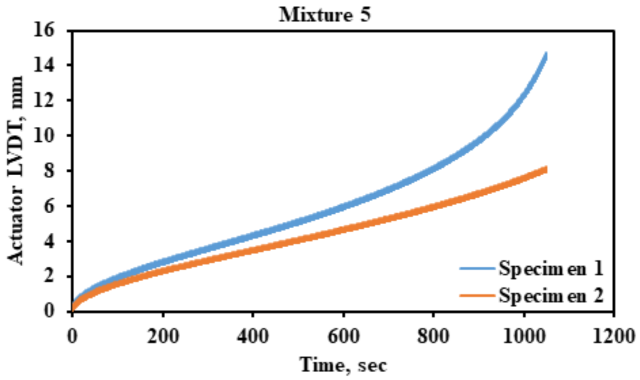
	Cycles	Resilient Microstrain	Resilient Deformation	Flow Point	Microstrain at Flow Point
Specimen 1	89	314	0.047	32	16437
Specimen 2	70	2	0	26	16963
Average	79.5	158	0.0235	29	16700



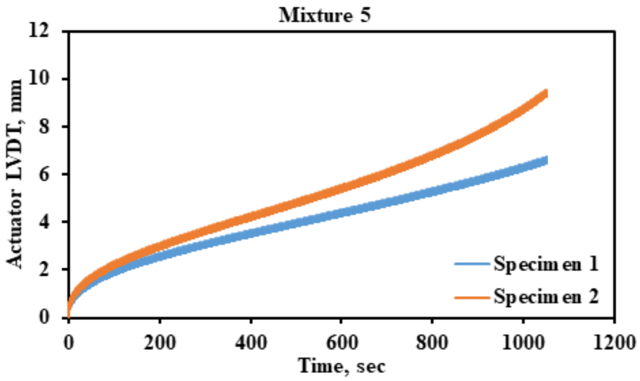
	Cycles	Resilient Microstrain	Resilient Deformation	Flow Point	Microstrain at Flow Point
Specimen 1	1183	1679	0.252	395	29968
Specimen 2	986	1671	0.251	315	26885
Average	1084.5	1675	0.2515	355	28427



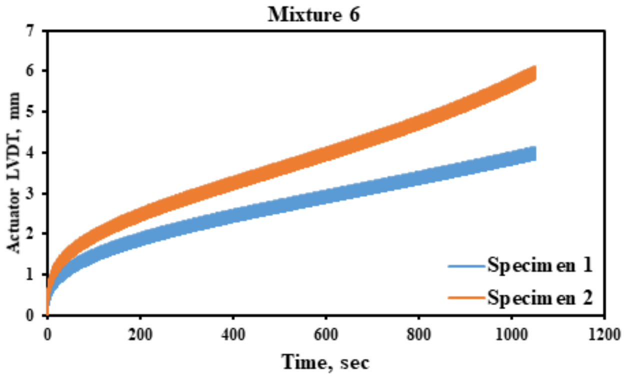
	Cycles	Resilient Microstrain	Resilient Deformation	Flow Point	Microstrain at Flow Point
Specimen 1	344	1034	0.155	100	16854
Specimen 2	270	1149	0.172	92	17763
Average	307	1091.5	0.1635	96	17308.5



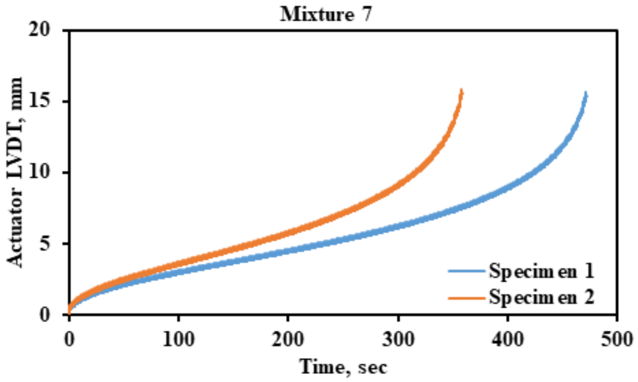
	Cycles	Resilient Microstrain	Resilient Deformation	Flow Point	Microstrain at Flow Point
Specimen 1	1060	1683	0.252	301	22401
Specimen 2	1397	1607	0.241	475	24798
Average	1228.5	1645	0.2465	388	23599.5



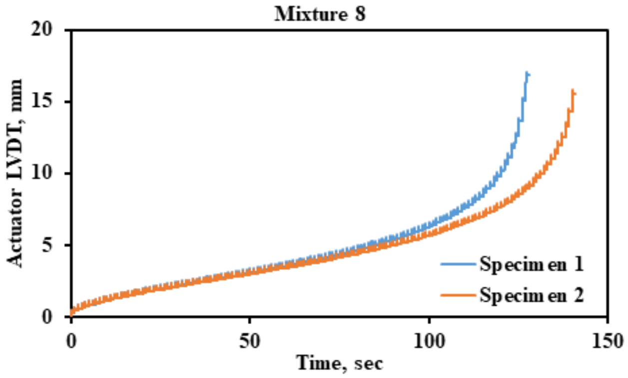
	Cycles	Resilient Microstrain	Resilient Deformation	Flow Point	Microstrain at Flow Point
Specimen 1	1623	1903	0.285	507	24579
Specimen 2	1238	2059	0.309	415	26622
Average	1430.5	1981	0.297	461	25601



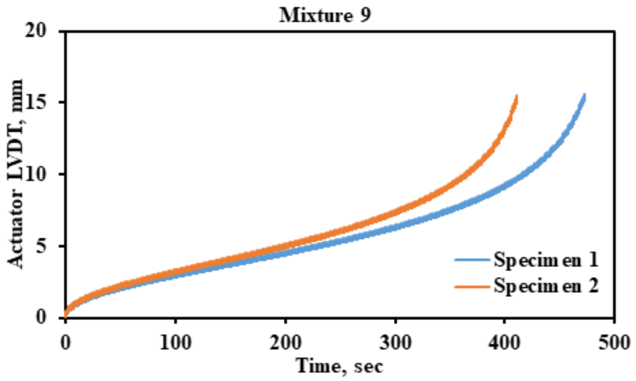
	Cycles	Resilient Microstrain	Resilient Deformation	Flow Point	Microstrain at Flow Point
Specimen 1	2213	2392	0.359	765	19868
Specimen 2	1454	2403	0.36	516	21803
Average	1833.5	2397.5	0.3595	640.5	20836



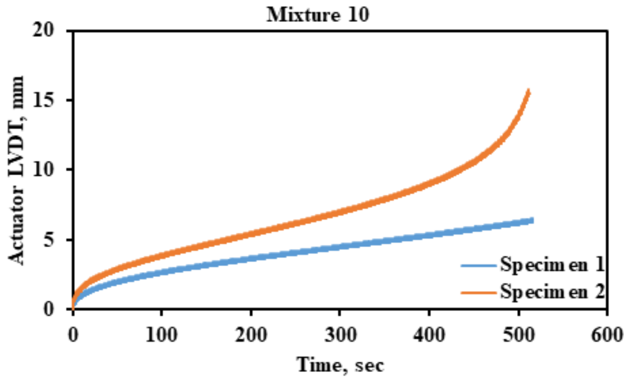
	Cycles	Resilient Microstrain	Resilient Deformation	Flow Point	Microstrain at Flow Point
Specimen 1	472	1642	0.246	159	23663
Specimen 2	359	1616	0.242	122	24583
Average	415.5	1629	0.244	140.5	24123



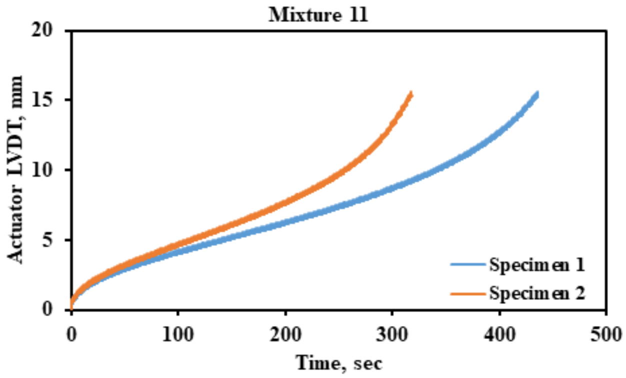
	Cycles	Resilient Microstrain	Resilient Deformation	Flow Point	Microstrain at Flow Point
Specimen 1	128	1263	0.19	41	16605
Specimen 2	141	1458	0.219	44	17046
Average	134.5	1360.5	0.2045	42.5	16825.5



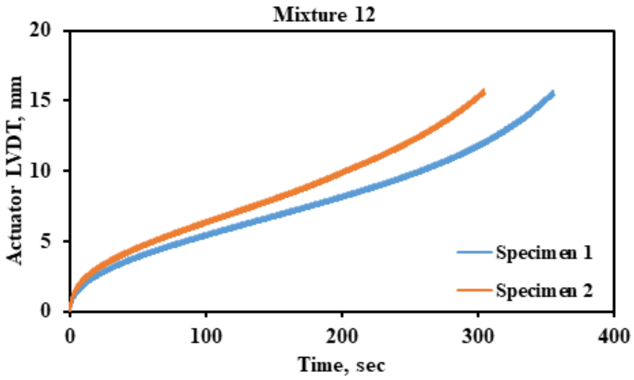
	Cycles	Resilient Microstrain	Resilient Deformation	Flow Point	Microstrain at Flow Point
Specimen 1	473	1795	0.269	147	22617
Specimen 2	411	1736	0.26	140	24111
Average	442	1765.5	0.2645	143.5	23364



	Cycles	Resilient Microstrain	Resilient Deformation	Flow Point	Microstrain at Flow Point
Specimen 1	516	1703	0.256	320	29009
Specimen 2	512	1859	0.279	201	33216
Average	514	1781	0.2675	260.5	31112.5

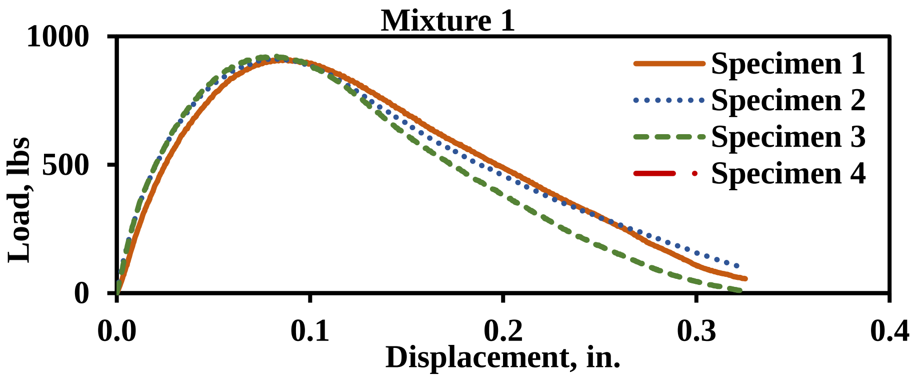


	Cycles	Resilient Microstrain	Resilient Deformation	Flow Point	Microstrain at Flow Point
Specimen 1	436	1794	0.269	152	32409
Specimen 2	318	1667	0.25	108	30116
Average	377	1730.5	0.2595	130	31262.5

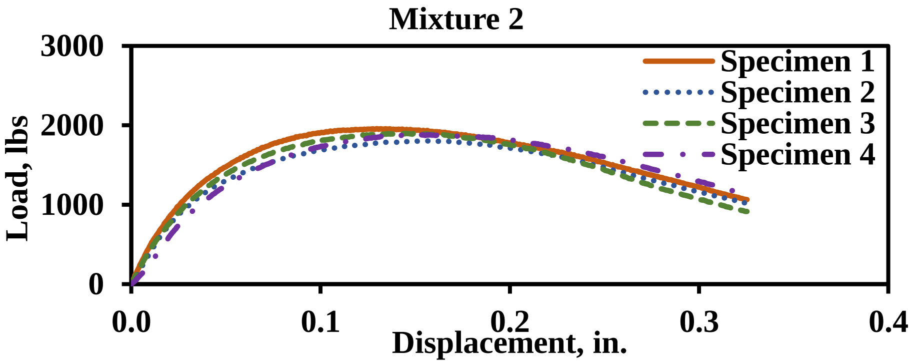


	Cycles	Resilient Microstrain	Resilient Deformation	Flow Point	Microstrain at Flow Point
Specimen 1	356	1790	0.268	144	41084
Specimen 2	305	1713	0.257	122	43572
Average	330.5	1751.5	0.2625	133	42328

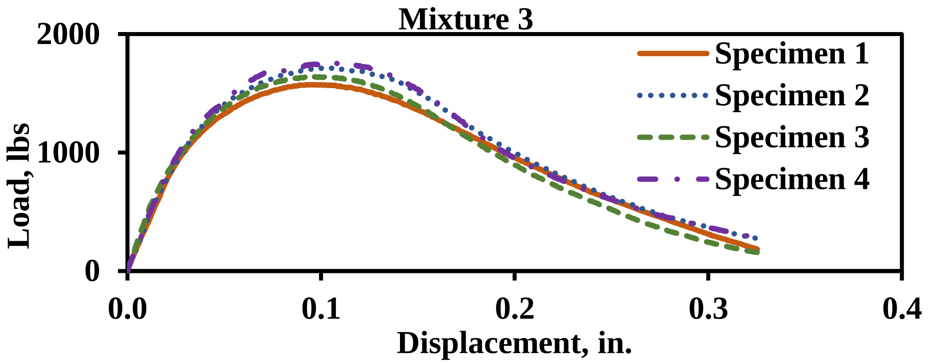
Indirect Tension Test Results



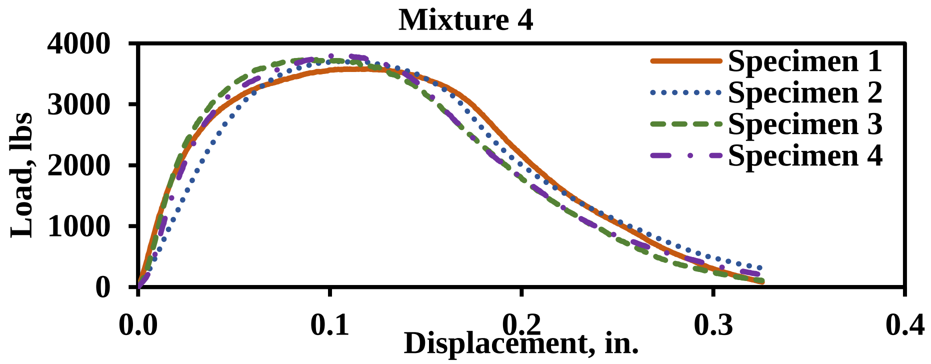
Parameter	Max Load, lbs	Tensile Strength, psi	Critical Fracture Energy, in.-lbs/in.2	Total Energy	Slope After Peak, lbs/in.	CT Index
Average	927	39	3.8	11.4	0.005	58.2
Std Dev	20	1	0.4	0.9	0.001	11.6
COV	2%	2%	10%	8%	11%	20%



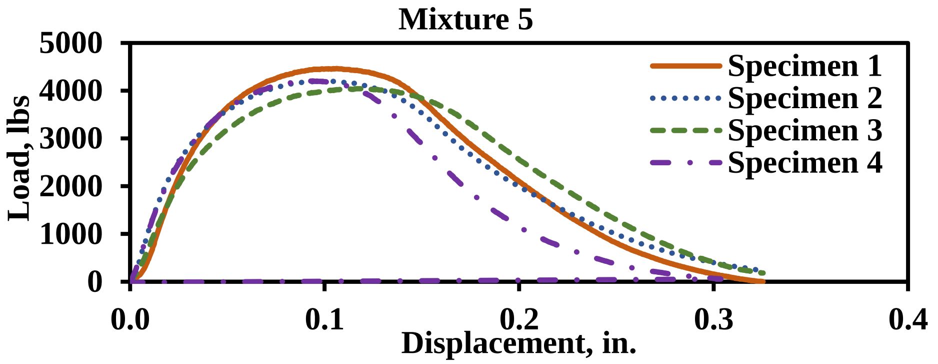
Parameter	Max Load, lbs	Tensile Strength, psi	Critical Fracture Energy, in.-lbs/in.2	Total Energy	Slope After Peak, lbs/in.	CT Index
Average	1885	80	13.7	38.1	0.006	264.2
Std Dev	55	2	0.6	1.3	0.001	36.2
COV	0	0	0.0	0.0	0.097	0.1



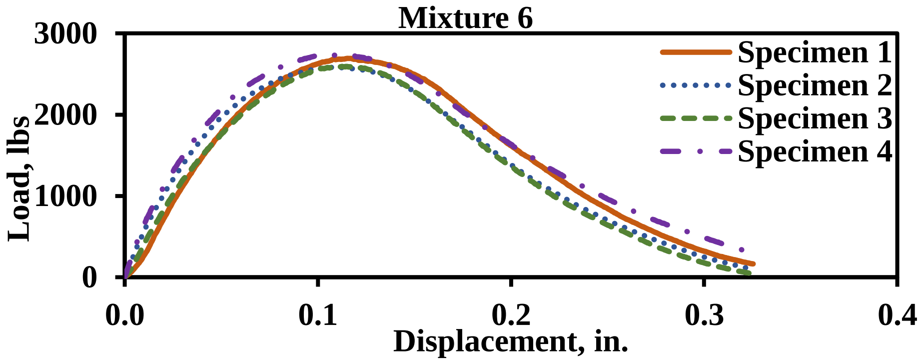
Parameter	Max Load, lbs	Tensile Strength, psi	Critical Fracture Energy, in.-lbs/in.2	Total Energy	Slope After Peak, lbs/in.	CT Index
Average	1670	71	8.2	22.4	0.010	61.9
Std Dev	69	3	0.8	1.1	0.001	8.0
COV	4%	4%	9%	5%	14%	13%



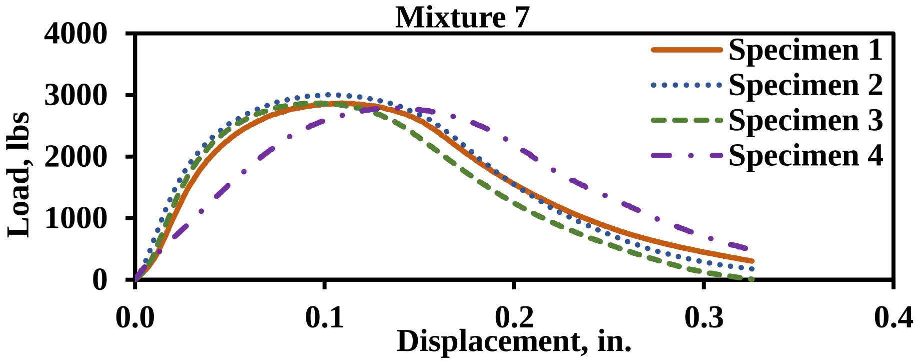
Parameter	Max Load, lbs	Tensile Strength, psi	Critical Fracture Energy, in.-lbs/in.2	Total Energy	Slope After Peak, lbs/in.	CT Index
Average	3709	157	19.0	46.0	0.031	41.8
Std Dev	78	3	2.3	0.8	0.002	2.6
COV	2%	2%	12%	2%	6%	6%



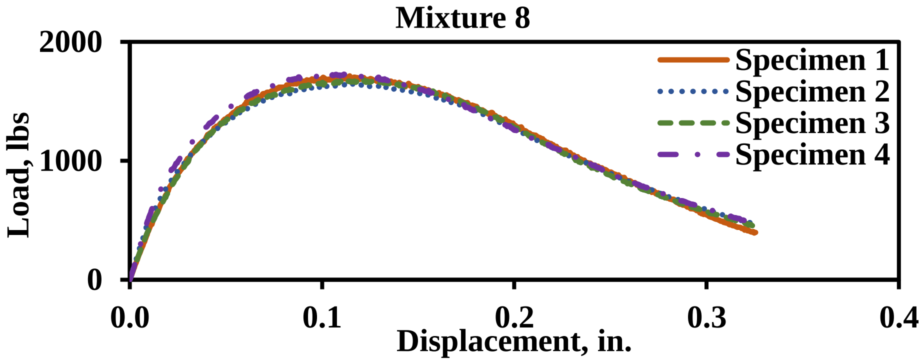
Parameter	Max Load, lbs	Tensile Strength, psi	Critical Fracture Energy, in.-lbs/in.2	Total Energy	Slope After Peak, lbs/in.	CT Index
Average	4228	179	21.5	49.3	0.036	38.8
Std Dev	151	6	1.8	3.8	0.004	10.4
COV	4%	4%	8%	8%	12%	27%



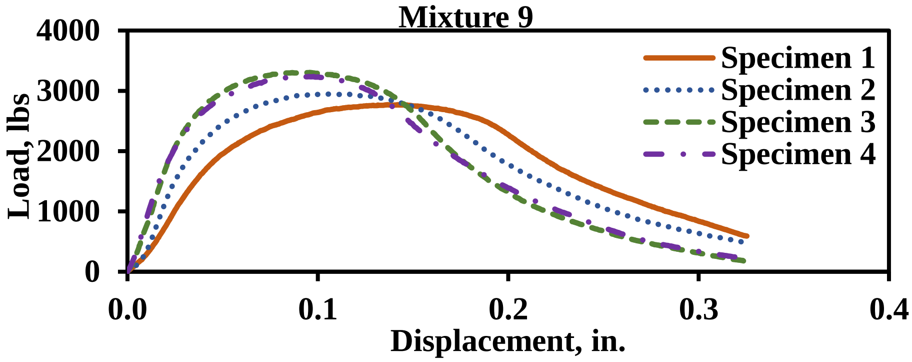
Parameter	Max Load, lbs	Tensile Strength, psi	Critical Fracture Energy, in.-lbs/in.2	Total Energy	Slope After Peak, lbs/in.	CT Index
Average	2651	113	13.4	32.4	0.018	51.1
Std Dev	66	3	0.7	2.2	0.001	6.5
COV	3%	3%	5%	7%	5%	13%



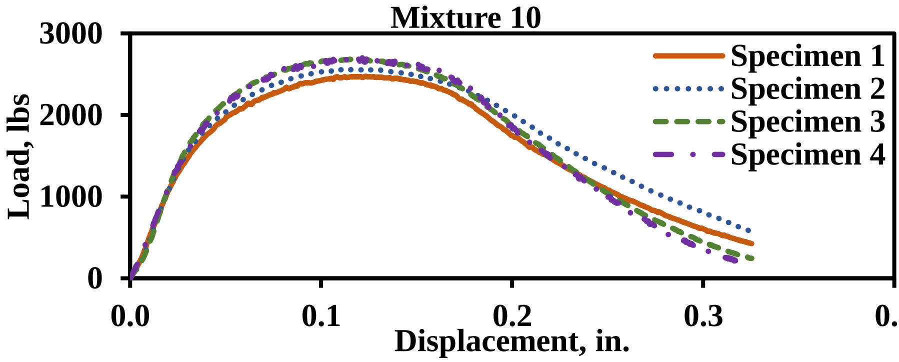
Parameter	Max Load, lbs	Tensile Strength, psi	Critical Fracture Energy, in.-lbs/in.2	Total Energy	Slope After Peak, lbs/in.	CT Index
Average	2882	122	14.8	36.3	0.022	48.9
Std Dev	79	3	1.5	2.3	0.002	11.7
COV	3%	3%	10%	6%	8%	24%



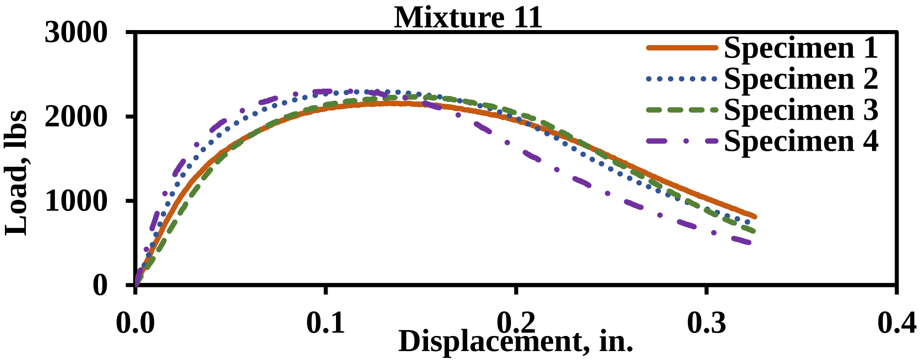
Parameter	Max Load, lbs	Tensile Strength, psi	Critical Fracture Energy, in.-lbs/in.2	Total Energy	Slope After Peak, lbs/in.	CT Index
Average	1692	72	9.8	27.2	0.008	114.6
Std Dev	31	1	0.3	0.5	0.000	4.5
COV	2%	2%	3%	2%	3%	4%



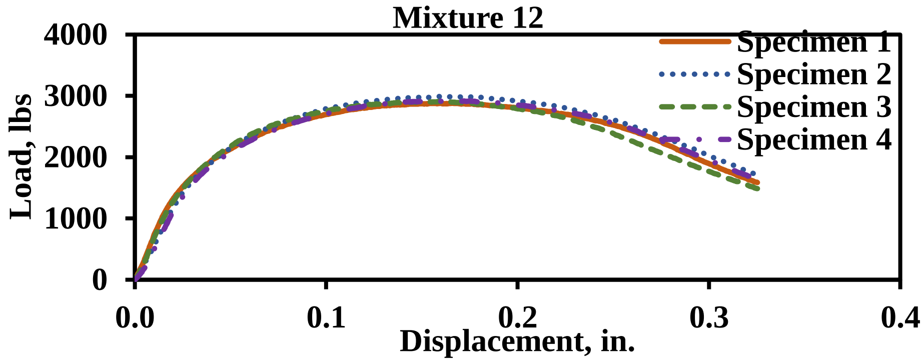
Parameter	Max Load, lbs	Tensile Strength, psi	Critical Fracture Energy, in.-lbs/in.2	Total Energy	Slope After Peak, lbs/in.	CT Index
Average	3066	130	15.8	40.0	0.025	48.5
Std Dev	217	9	1.3	1.4	0.004	14.4
COV	7%	7%	8%	3%	15%	30%



Parameter	Max Load, lbs	Tensile Strength, psi	Critical Fracture Energy, in.-lbs/in.2	Total Energy	Slope After Peak, lbs/in.	CT Index
Average	2606	111	15.6	37.3	0.017	72.4
Std Dev	92	4	0.5	1.4	0.002	14.4
COV	4%	4%	3%	4%	13%	20%

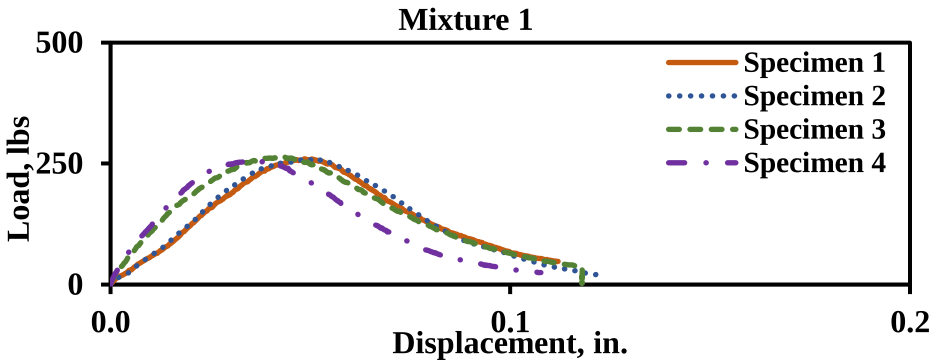


Parameter	Max Load, lbs	Tensile Strength, psi	Critical Fracture Energy, in.-lbs/in.2	Total Energy	Slope After Peak, lbs/in.	CT Index
Average	2249	95	14.3	37.9	0.012	122.2
Std Dev	59	2	1.2	1.6	0.001	26.3
COV	3%	3%	8%	4%	11%	22%

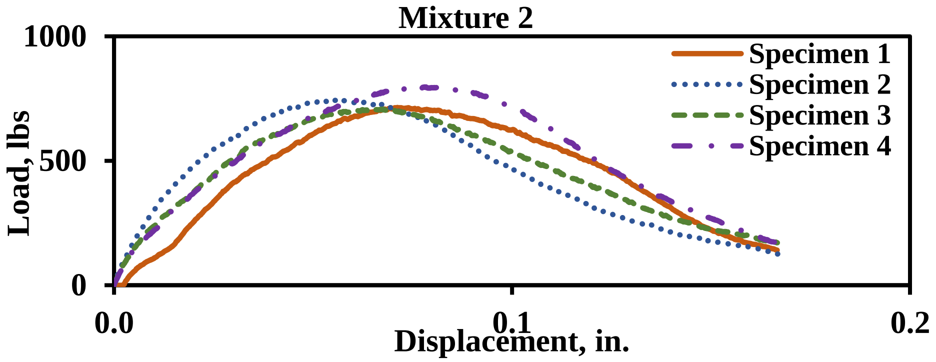


Parameter	Max Load, lbs	Tensile Strength, psi	Critical Fracture Energy, in.-lbs/in.2	Total Energy	Slope After Peak, lbs/in.	CT Index
Average	2927	124	24.7	59.8	0.013	221.9
Std Dev	43	2	0.7	1.1	0.000	12.7
COV	1%	1%	3%	2%	4%	6%

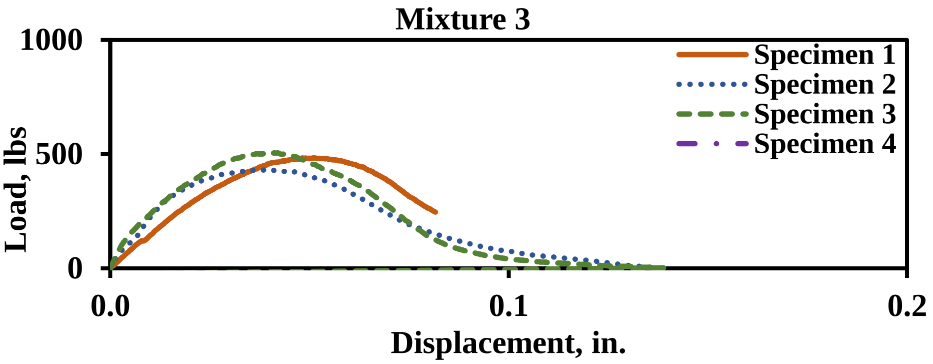
Semi-Circular Bending Test I-FIT Results



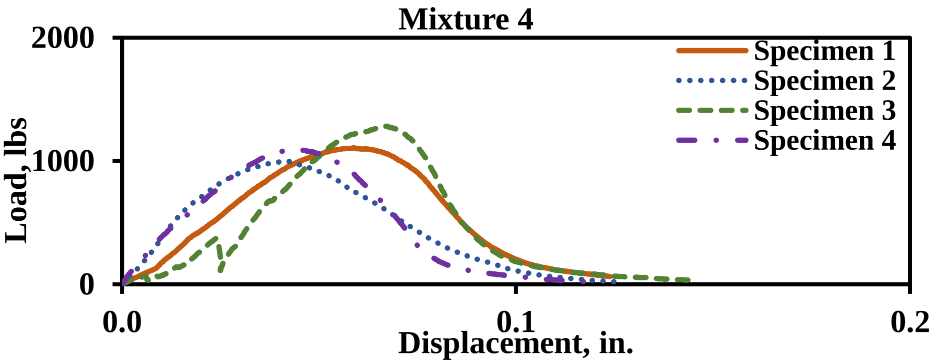
Parameter	Max Load, lbs	Critical Fracture Energy, in.-lbs/in.2	Total Energy	Slope After Peak, lbs/in.	FI 2
Average	260	1.5	3.3	0.005	6.5
Std Dev	3	0.2	0.23	0.000	0.9
COV	1%	10%	7%	7%	14%



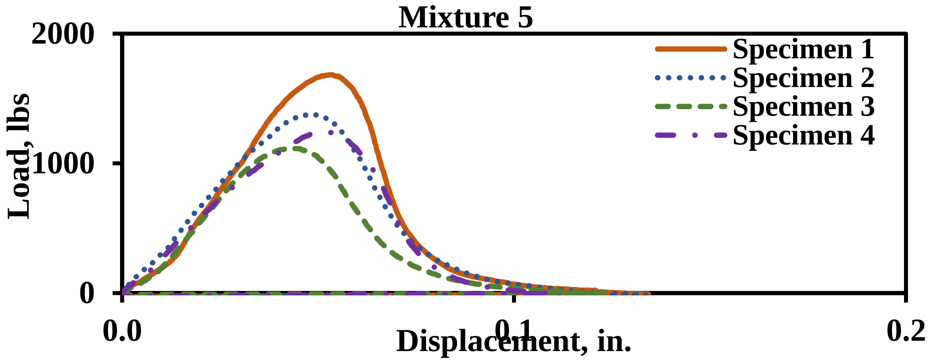
Parameter	Max Load, lbs	Critical Fracture Energy, in.-lbs/in.2	Total Energy	Slope After Peak, lbs/in.	FI 2
Average	741	7.2	17.2	0.008	21.6
Std Dev	36	1.3	1.1	0.002	3.4
COV	5%	18%	6%	19%	16%



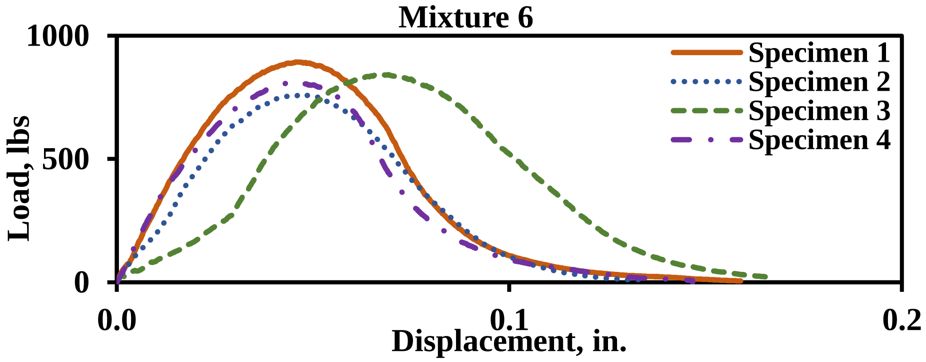
Parameter	Max Load, lbs	Critical Fracture Energy, in.-lbs/in.2	Total Energy	Slope After Peak, lbs/in.	FI 2
Average	474	2.9	6.5	0.010	6.4
Std Dev	31	0.4	0.5	0.001	0.3
COV	7%	13%	8%	13%	5%



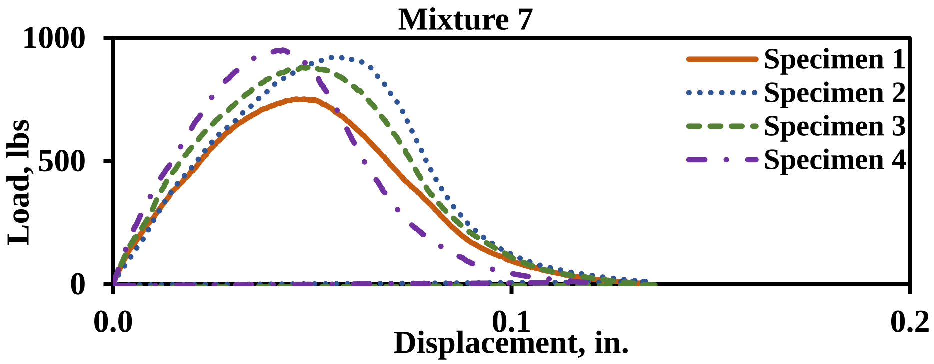
Parameter	Max Load, lbs	Critical Fracture Energy, in.-lbs/in.2	Total Energy	Slope After Peak, lbs/in.	FI 2
Average	1119	7.1	13.4	0.035	4.4
Std Dev	103	1.1	1.0	0.013	1.4
COV	19%	15%	7%	38%	33%



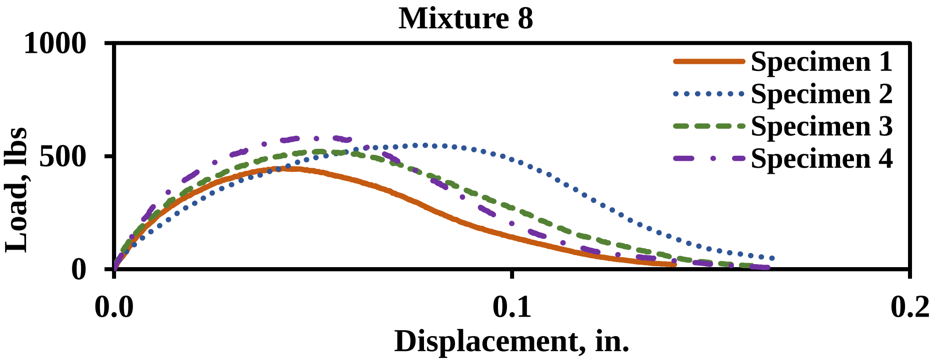
Parameter	Max Load, lbs	Critical Fracture Energy, in.-lbs/in.2	Total Energy	Slope After Peak, lbs/in.	FI 2
Average	1355	7.7	13.3	0.060	2.3
Std Dev	211	1.5	2.0	0.20	0.5
COV	16%	19%	15%	33%	20%



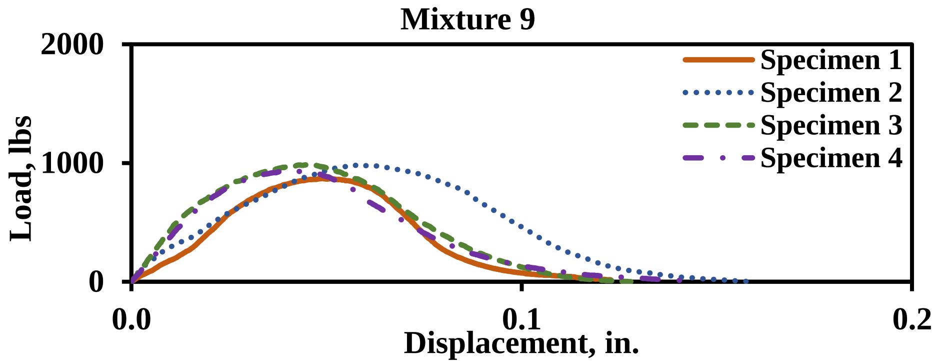
Parameter	Max Load, lbs	Critical Fracture Energy, in.-lbs/in.2	Total Energy	Slope After Peak, lbs/in.	FI 2
Average	826	5.3	11.3	0.020	5.9
Std Dev	48	0.5	1.4	0.005	1.7
COV	6%	10%	13%	24%	29%



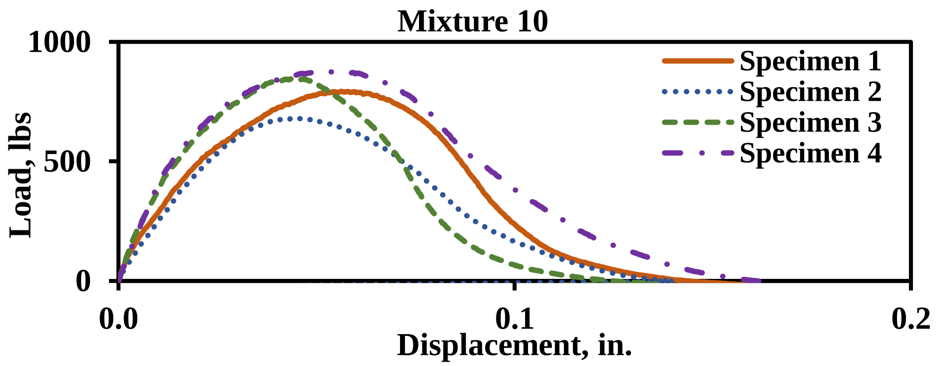
Parameter	Max Load, lbs	Critical Fracture Energy, in.-lbs/in.2	Total Energy	Slope After Peak, lbs/in.	FI 2
Average	877	5.9	11.0	0.024	4.8
Std Dev	76	0.7	0.9	0.005	0.9
COV	9%	11%	8%	21%	18%



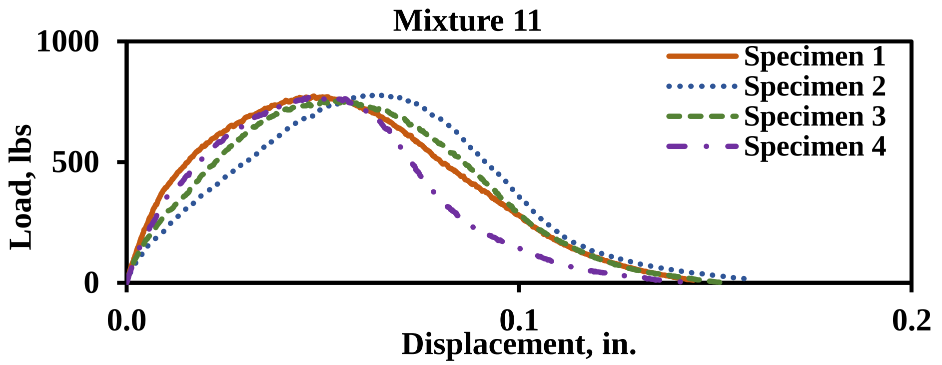
Parameter	Max Load, lbs	Critical Fracture Energy, in.-lbs/in.2	Total Energy	Slope After Peak, lbs/in.	FI 2
Average	525	4.6	9.6	0.008	11.9
Std Dev	51	1.3	1.7	0.001	1.7
COV	10%	18%	18%	16%	14%



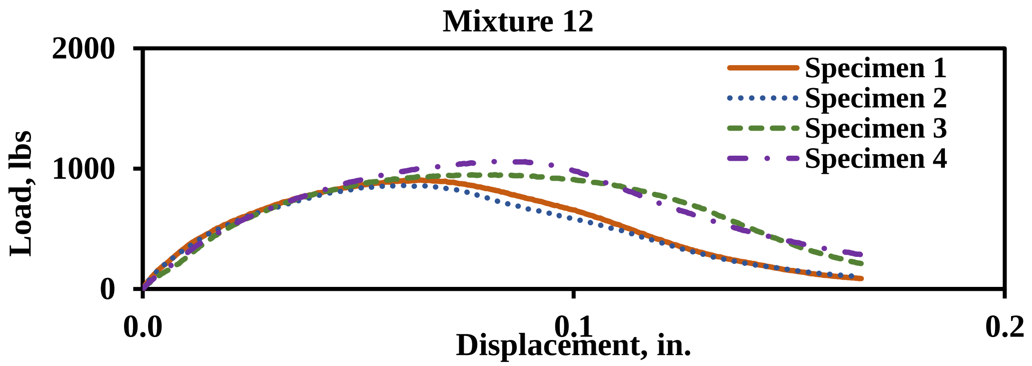
Parameter	Max Load, lbs	Critical Fracture Energy, in.-lbs/in.2	Total Energy	Slope After Peak, lbs/in.	FI 2
Average	942	6.0	12.9	0.023	6.1
Std Dev	47	1.1	2.1	0.004	2.1
COV	5%	18%	16%	18%	34%



Parameter	Max Load, lbs	Critical Fracture Energy, in.-lbs/in.2	Total Energy	Slope After Peak, lbs/in.	FI 2
Average	800	5.9	12.3	0.016	7.9
Std Dev	74	1.1	2.2	0.002	1.1
COV	9%	18%	18%	15%	13%



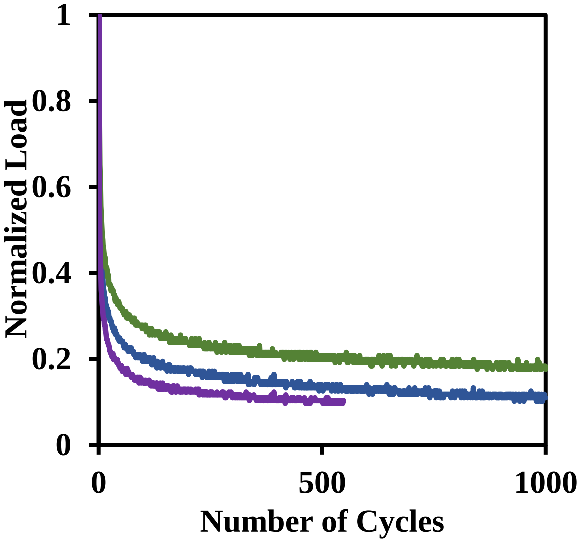
Parameter	Max Load, lbs	Critical Fracture Energy, in.-lbs/in.2	Total Energy	Slope After Peak, lbs/in.	FI 2
Average	769	5.9	12.2	0.016	8.3
Std Dev	10	0.4	0.8	0.003	2.0
COV	1%	6%	65	22%	24%

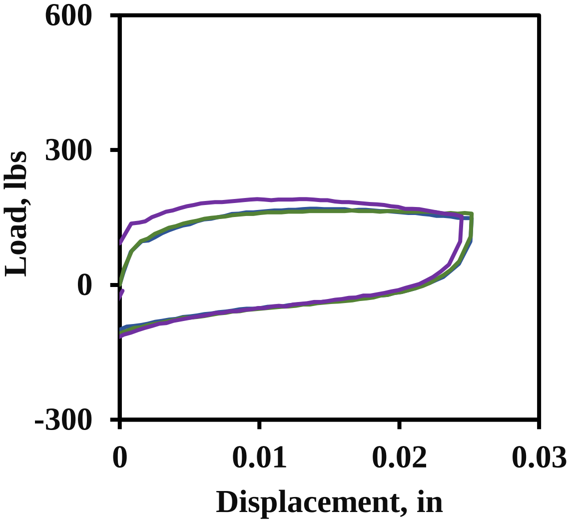


Parameter	Max Load, lbs	Critical Fracture Energy, in.-lbs/in.2	Total Energy	Slope After Peak, lbs/in.	FI 2
Average	944	10.3	22.3	0.011	21.0
Std Dev	74	2.	3.5	0.002	1.0
COV	8%	20%	16%	18%	5%

Overlay Test Results

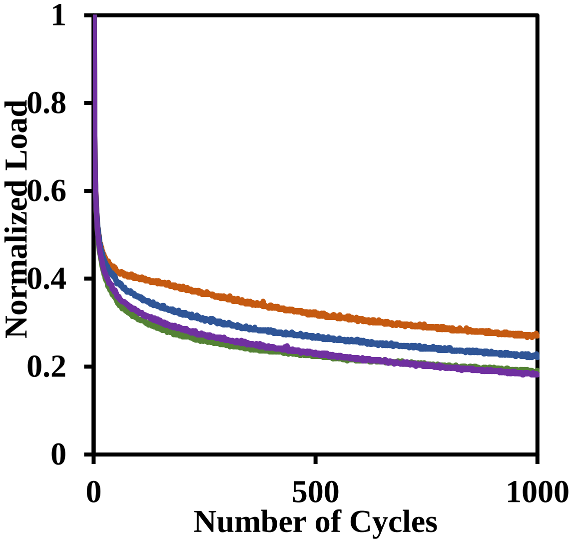
Mixture 1

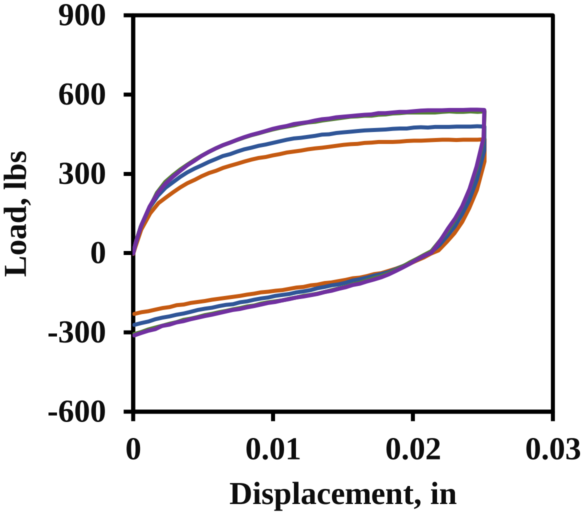




Parameter	Max Load, lbs	Critical Fracture Energy, in.-lbs/in.^{2}	Crack Progression Rate	Number of Cycles to Failure
Average	175.3	0.43	0.32	849.33
Std Dev	11.1	0.07	0.05	213.07
COV	6%	15%	16%	25%

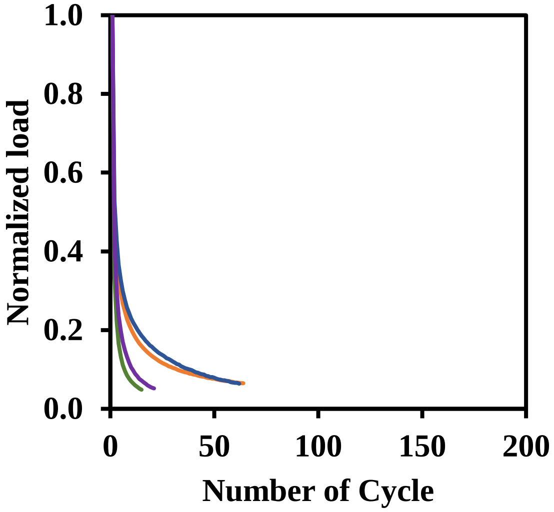
Mixture 2

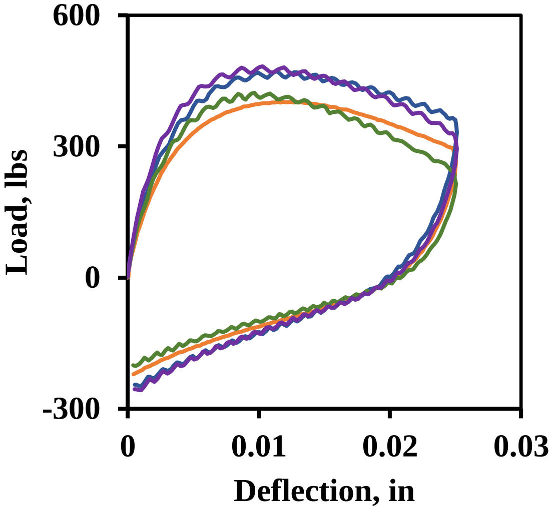




Parameter	Max Load, lbs	Critical Fracture Energy, in.-lbs/in.^{2}	Crack Progression Rate	Number of Cycles to Failure
Average	497.5	2.18	0.22	1000.00
Std Dev	45.5	0.14	0.02	0.00
COV	9%	6%	10%	0%

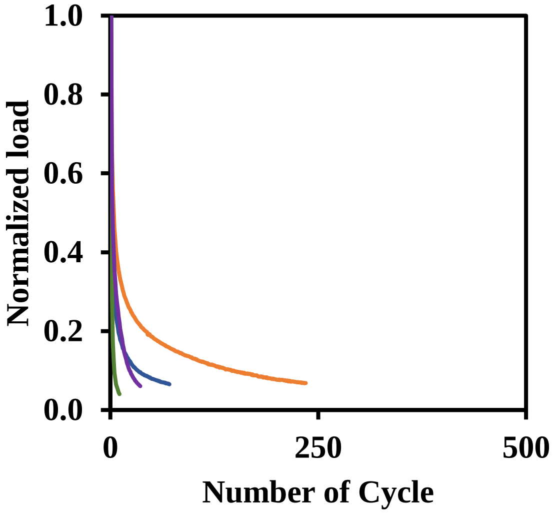
Mixture 3

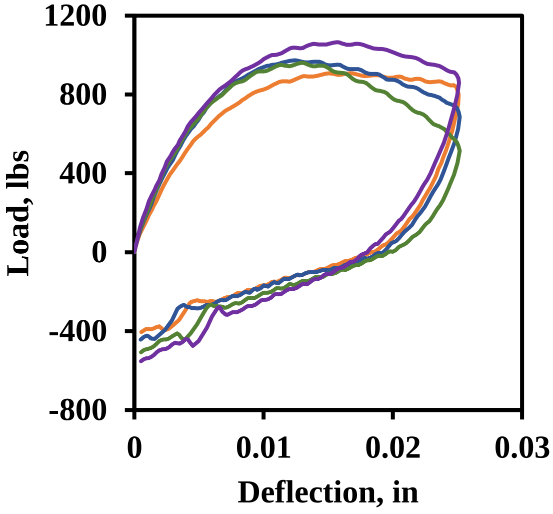




Parameter	Max Load, lbs	Critical Fracture Energy, in.-lbs/in.^{2}	Crack Progression Rate	Number of Cycles to Failure
Average	445.1	0.83	0.87	40.50
Std Dev	33.5	0.09	0.22	22.61
COV	8%	11%	26%	56%

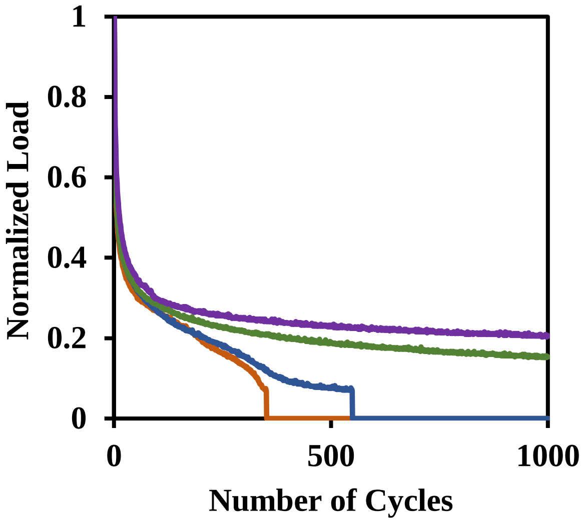
Mixture 4

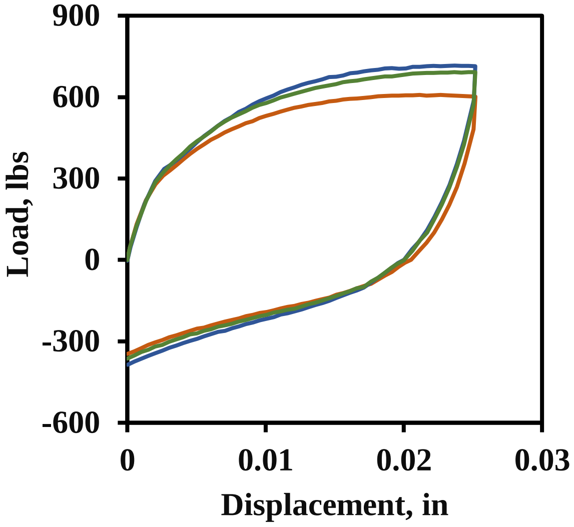




Parameter	Max Load, lbs	Critical Fracture Energy, in.-lbs/in.^{2}	Crack Progression Rate	Number of Cycles to Failure
Average	982.4	2.38	0.61	114.00
Std Dev	64.5	0.36	0.11	86.74
COV	7%	15%	18%	76%

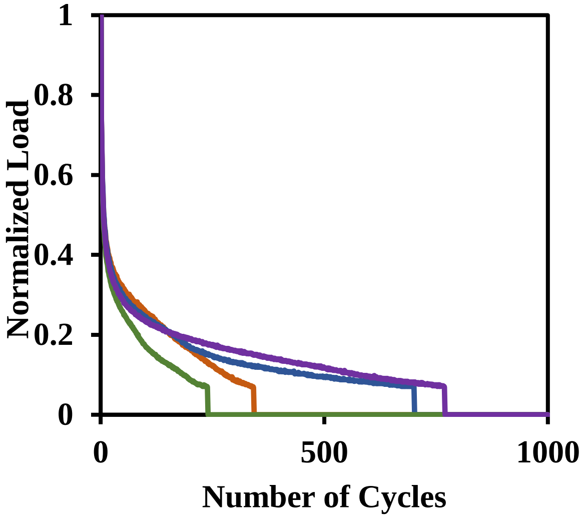
Mixture 5

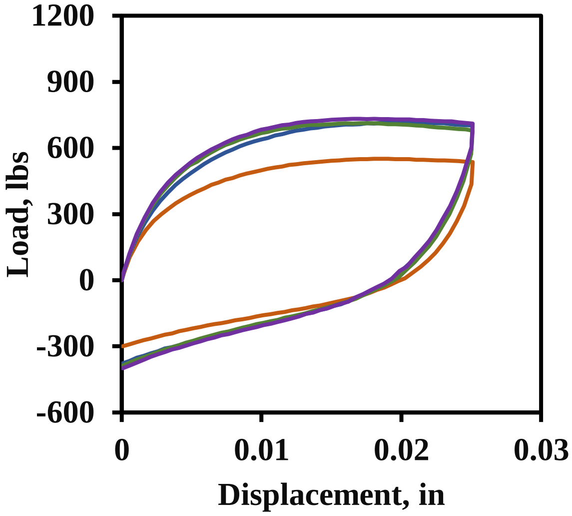




Parameter	Max Load, lbs	Critical Fracture Energy, in.-lbs/in.^{2}	Crack Progression Rate	Number of Cycles to Failure
Average	661.4	2.61	0.30	725.00
Std Dev	44.2	0.31	0.05	283.77
COV	7%	12%	15%	39%

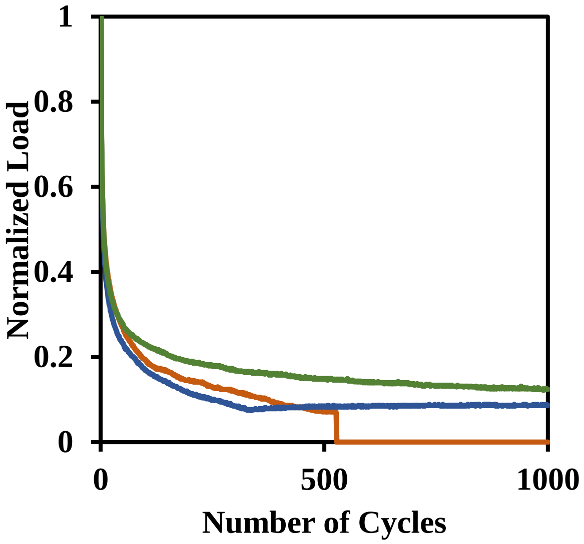
Mixture 6

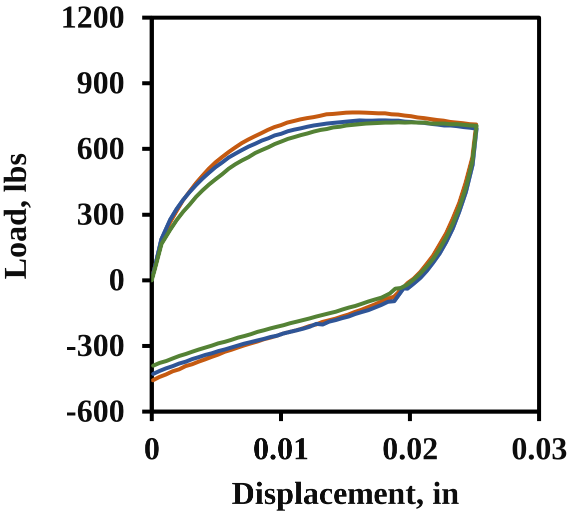




Parameter	Max Load, lbs	Critical Fracture Energy, in.-lbs/in.^{2}	Crack Progression Rate	Number of Cycles to Failure
Average	678.1	2.13	0.37	512.75
Std Dev	73.8	0.35	0.03	226.49
COV	11%	17%	7%	44%

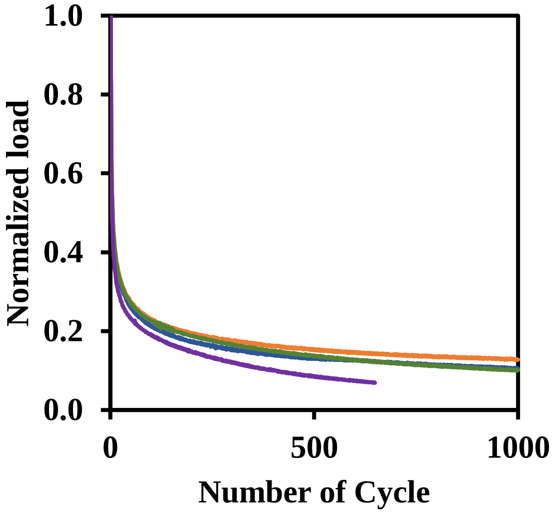
Mixture 7

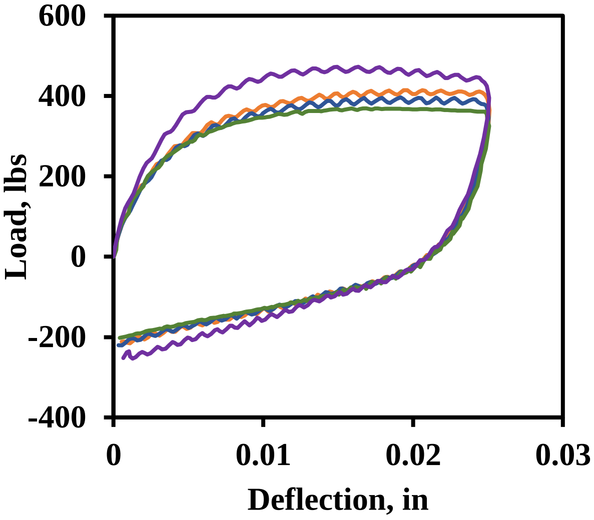




Parameter	Max Load, lbs	Critical Fracture Energy, in.-lbs/in.^{2}	Crack Progression Rate	Number of Cycles to Failure
Average	739.6	2.12	0.36	842.33
Std Dev	19.5	0.16	0.04	222.97
COV	3%	8%	10%	26%

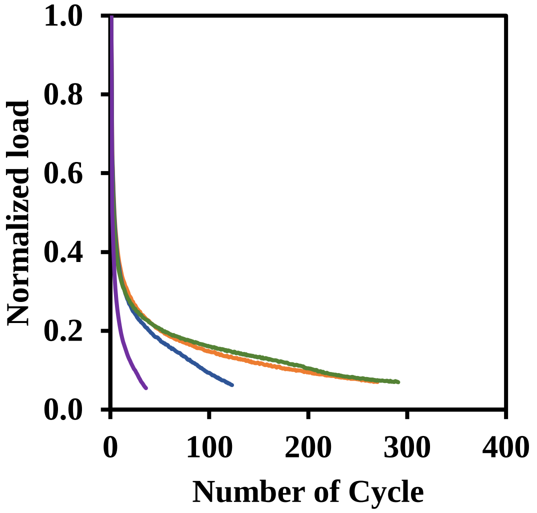
Mixture 8

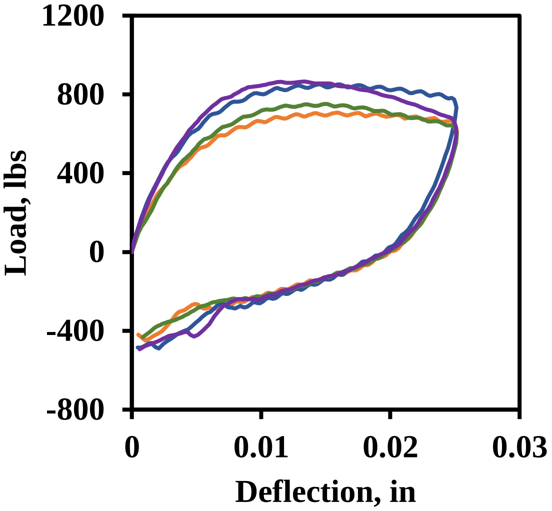




Parameter	Max Load, lbs	Critical Fracture Energy, in.-lbs/in.^{2}	Crack Progression Rate	Number of Cycles to Failure
Average	413.4	1.34	0.33	912.25
Std Dev	37.9	0.15	0.03	151.99
COV	9%	11%	9%	17%

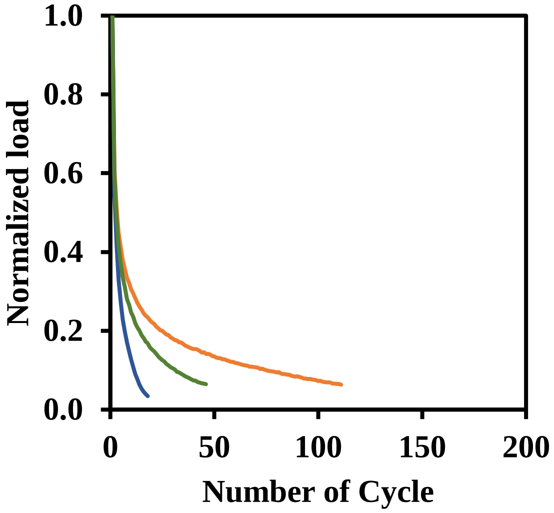
Mixture 9

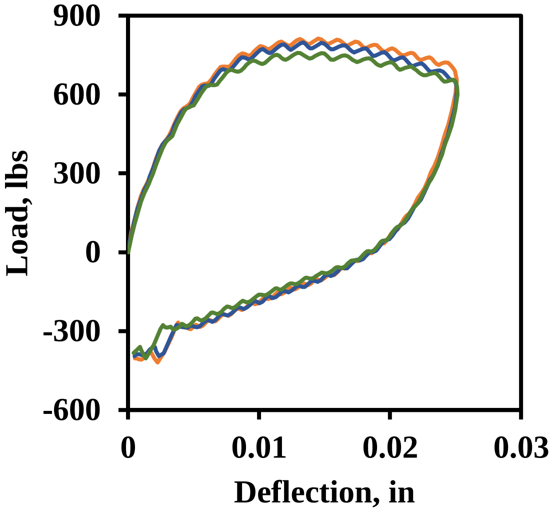




Parameter	Max Load, lbs	Critical Fracture Energy, in.-lbs/in.^{2}	Crack Progression Rate	Number of Cycles to Failure
Average	770.6	1.95	0.45	228.00
Std Dev	60.3	0.09	0.03	74.74
COV	8%	5%	6%	33%

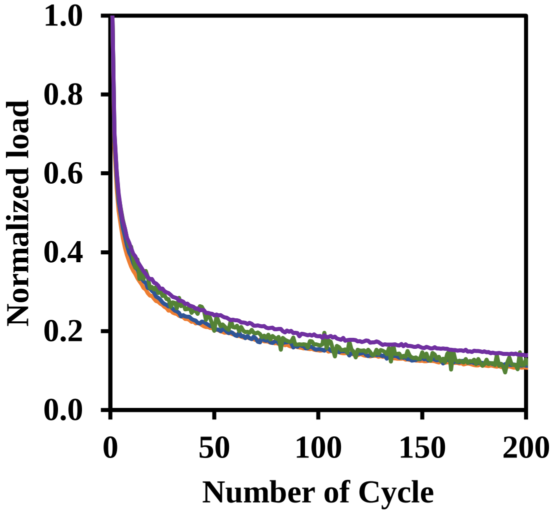
Mixture 10

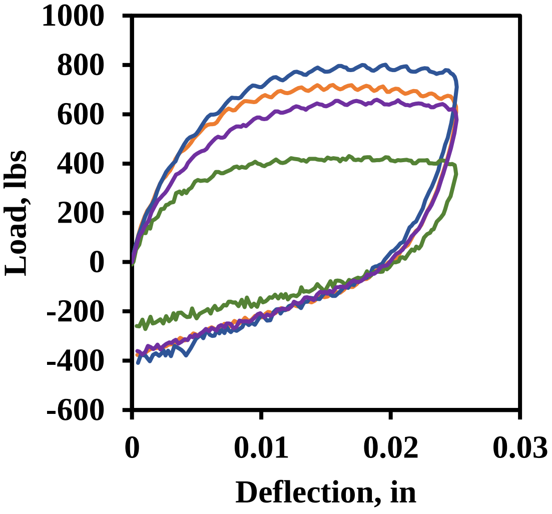




Parameter	Max Load, lbs	Critical Fracture Energy, in.-lbs/in.^{2}	Crack Progression Rate	Number of Cycles to Failure
Average	789.9	1.78	0.72	58.33
Std Dev	23.0	0.16	0.19	38.96
COV	3%	9%	26%	67%

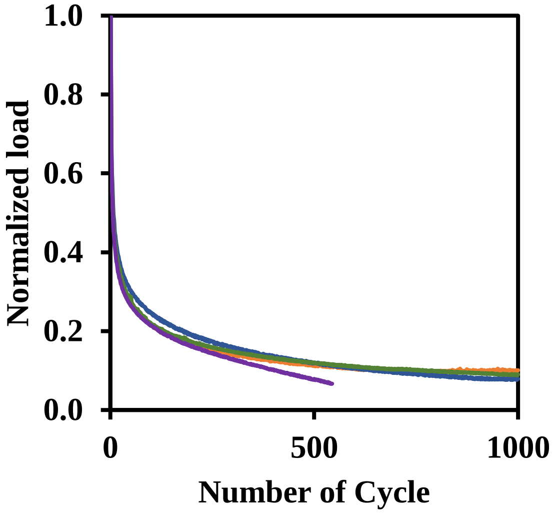
Mixture 11

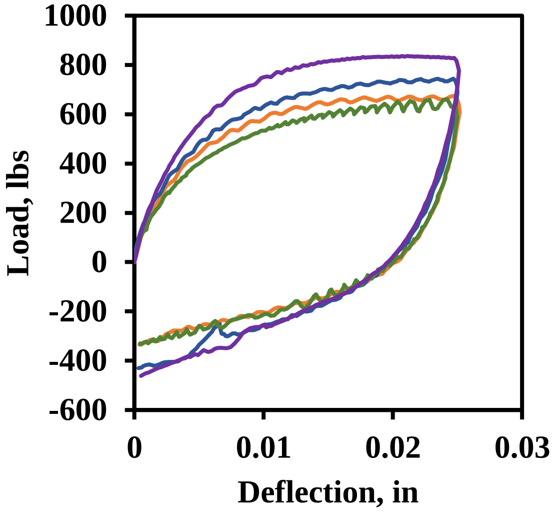




Parameter	Max Load, lbs	Critical Fracture Energy, in.-lbs/in.^{2}	Crack Progression Rate	Number of Cycles to Failure
Average	652.3	2.00	0.41	376.50
Std Dev	137.7	0.52	0.02	134.09
COV	21%	26%	4%	36%

Mixture 12





Parameter	Max Load, lbs	Critical Fracture Energy, in.-lbs/in.^{2}	Crack Progression Rate	Number of Cycles to Failure
Average	729.0	3.04	0.35	886.00
Std Dev	69.8	0.20	0.01	197.45
COV	10%	7%	3%	22%

Vita

Elias Castillo is a native of El Paso, Texas, was born and raised in the border community. The first son of Jesus Castillo and Laura Solis, he graduated from Cathedral High School in 2014. He then followed to enroll in the Civil Engineering program at The University of Texas at El Paso (UTEP) where he received his Bachelor's in Civil Engineering in 2018, and enrolled into the Civil Engineering Master's program thereafter.

Elias Castillo was involved in flexible pavement performance research at UTEP during his undergraduate studies, later expanding his research in the Balance Mix Design of asphalt mixtures. He worked at the Center for Transportation Infrastructure Systems (CTIS) under the mentorship of Dr. Soheil Nazarian and Dr. Imad Abdallah. His professional aspirations are to improve and contribute to innovation of our transportation infrastructure and pavement engineering.