Quantifying the Role of Coarse Aggregate Strength on Resistance to Load in HMA for Blended Aggregates

Research Report 0-5268-3

TxDOT Project Number 0-5268

Performed in cooperation with the Texas Department of Transportation & Federal Highway Administration

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16. Abstract

The performance of the new generation of HMA mixtures that rely more on a stone-to-stone contact is greatly influenced by the properties of the aggregate blends such as gradation and strength. As a result, aggregates have a significant and direct effect on the performance of asphalt pavements and it is important to maximize the quality of aggregates to ensure the proper performance of roadways.

The objective of this research is to evaluate the effect of stress concentrations at contact points of single-source and blended coarse aggregates. To achieve this objective, an extensive series of tests to characterize and to evaluate the performance of a number of aggregates were carried out. The laboratory activities were supplemented with micro-mechanical modeling to understand the internal behavior of the mixes. The aggregates were tested at different blends in four mixes.

A number of findings were made based on the aggregate quality, the blending ratios and the type of aggregate blended. Also, the results from Phase I and Phase II were supported both in the tests that are recommended to be included as part of the aggregate characterization and in showing the gap in ranking the aggregates based on current tests. It should be emphasized that these observations are preliminary since the database is rather small. As a result, it is proposed to expand the database with more aggregate sources.

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ACRONYMS

ACV:	Aggregate crushing value
AIMS:	Aggregate Imaging System
AIV:	Aggregate Impact Value
AQMP :	Aggregate Quality Monitoring Program
ASTM:	American Society for Testing Materials.
AV:	Air Void
BRSQC:	Bituminous Rated Source Quality Catalog
CMHB:	Coarse Matrix High Binder
CST-M&P:	Construction Division, Materials and Pavements Section
DEM:	Discrete Element Method
FFRC:	Free-Free Resonant Column
HMA:	Hot Mix Asphalt
HMAC:	Hot Mix Asphalt Concrete
HWTD:	Hamburg Wheel-tracking Device
IDT:	Indirect Tensile Test.
JMF :	Job-mix Formula
LWA:	Light Weight Asphalt
PFC:	Porous Friction Course
PFC2D:	article Flow Code in 2-Dimensions
PMC:	Project Monitoring Committee
QCP:	Quality Control Plan
RAP:	Reclaimed Asphalt Pavement
SAC:	Surface Aggregate Classification
SG:	Specific Gravity
SGC:	Superpave Gyratory Compactor
SMA:	Stone Matrix Asphalt
SP:	Superpave
TGC:	Texas Gyratory Compactor
TTI:	Texas Transportation Institute
TxDOT:	Texas Department of Transportation
VFA:	Voids Filled with Asphalt
VMA:	Voids in Mineral Aggregate

ABSTRACT

The performance of the new generation of HMA mixtures that rely more on a stone-to-stone contact is greatly influenced by the properties of the aggregate blends such as gradation and strength. As a result, aggregates have a significant and direct effect on the performance of asphalt pavements and it is important to maximize the quality of aggregates to ensure the proper performance of roadways.

The objective of this research is to evaluate the effect of stress concentrations at contact points of single-source and blended coarse aggregates. To achieve this objective, an extensive series of tests to characterize and to evaluate the performance of a number of aggregates were carried out. The laboratory activities were supplemented with micro-mechanical modeling to understand the internal behavior of the mixes. The aggregates were tested at different blends in four mixes.

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IMPLEMENTATION STATEMENT

In this report a number of recommendations have been made for aggregate blending. The recommendations are based on the results from two blends.

At this time, the recommendations should be implemented on a number of aggregates to confirm the recommendations, and to adjust the limits and/or criteria. As part of the implementation, a guide should be developed to disseminate to the TxDOT staff.

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CHAPTER ONE - INTRODUCTION

The ever-increasing traffic volumes, including increased truck traffic and higher tire pressures, are putting greater stresses on the asphalt pavements which manifest in the form of pavement distresses such as rutting and fatigue cracking. To address these issues, improvements in the hot asphalt mix (HMA) blends are being implemented. The new generation of asphalt pavements such as Stone Matrix Asphalt (SMA) and Porous Friction Course (PFC) rely on stone-on-stone contact for a stronger coarse aggregate skeleton.

The performance of HMA mixtures is greatly influenced by the properties of the aggregate blends. Gradation and strength have a significant and direct effect on the performance of asphalt pavements. It is important to optimize the quality of aggregates to ensure a proper performance of roadways.

Several methods are available to determine aggregate characteristics, but their relationship to field performance, aggregate structure in HMA, and traffic loading needs to be further investigated and defined. Current laboratory protocols do not correlate well with aggregate abrasion, toughness, and strength requirements during handling, construction, and service. Specifications should ensure that aggregate particles possess the necessary strengths to avoid degradation during handling, construction, and loading due to traffic.

To address these issues, the characteristics of the aggregates have to be considered in a multifaceted way, considering the geological, geotechnical, mix design and construction aspects. These parameters can be input in a micro-mechanical model to predict the performance. The effects of stress concentration at contact points on coarse aggregates and means of reducing them are also of interest. The geological aspects consist of characterizing the hardness and nature of rock masses. The geotechnical aspects are necessary to optimize the gradation, to consider the shape and size of the aggregates in the mix and to assess the strength of the aggregate mass as a whole. A proper HMA mix is needed to ensure the adequate durability, structural capacity and performance after the gradation is optimized. In addition, the blending of these aggregates is of importance and has been used by DOT's such as TxDOT to enhance performance either by increasing the structural capacity of the pavement or increasing its resistance to specific distress.

In general it may be easier to compare the aggregate properties by a specific test and relate the performance to a single parameter. But a given aggregate or performance test may focus on only a specific property of the aggregates or mix. Even though more complicated, an attempt has been made here to assess the aggregate properties by a set of tests and relate the performance to multiple tests to capture the complicated interactions between asphalt and aggregate matrix. The authors feel that this approach is more rigorous; however, tests should be carried out on more aggregate types for final recommendations.

ORGANIZATION

The work presented in this report represents an analytical and experimental investigation to evaluate the effect of stress concentration at contact points on blended coarse aggregates that could cause aggregate fracture. Chapter 2 gives an overview of the research work performed in Phase I and Phase II of this project as documented in Research Reports 0-5268-1 and 0-5268-2. In Chapter 3 the results of the tests on blended aggregates of two blends are presented. Chapter 4 discusses the evaluation of the blends using micro-mechanical models and comparison of the experimental and analytical results. Finally, in Chapter 5, the conclusions and recommendations of this study are presented.

CHAPTER TWO - REVIEW OF PHASE I AND II ACTIVITIES

An extensive literature review documenting aggregate properties that significantly impact HMA performance was detailed in Research Report 0-5268-1 by Alvarado et al. (2007). Some of the conventional and recently developed aggregate tests as well as the significance of aggregate stone-on-stone interaction were described in that report. The readers are referred to Alvarado et al. (2007) so that they can become familiar with the background of this research.

Phase I of this study also focused on the effectiveness of integrating experimental results on quarry rock and aggregates. Numerical analysis to realistically predict the performance of mixes was demonstrated for the first time (see Alvarado et al., 2007). In Phase II, the database of aggregate and mix design was expanded to include a total of six aggregates and four mix designs.

LITERATURE REVIEW

Gradation is a primary concern in HMA design and thus most agencies specify allowable aggregate gradations. Gradation of a HMA influences almost all important properties including stiffness, stability, durability, permeability, workability, fatigue resistance, frictional resistance and resistance to moisture damage. Inappropriate selections of aggregate gradation, aggregate properties, and binder grade, type and content are major contributors to rutting and cracking of asphalt pavements. Strong opinions exist among industry experts as to which gradation type, ranging from fine to coarse to open-graded or stone matrix asphalt gradations, will provide the best performance (Hand et al., 2002). Masad et al. (2003) indicate that the particle geometry of an aggregate can be fully expressed in terms of three independent properties which influence the performance of HMA: shape (or form), angularity (roundness), and surface texture.

Aggregates must be tough and abrasion resistant to resist crushing, degradation, and disintegration when stockpiled, placed with a paver, compacted with rollers, and subjected to traffic loadings (Wu et al., 1998). These properties are especially critical for open- or gap-graded asphalt mixtures where coarse particles are subjected to high contact stresses. Aggregate degradation or breakdown may result in significant loss of pavement life.

Aggregate toughness refers to the property of an aggregate to resist breakdown. Such breakdown can alter the HMA gradation, resulting in a mixture that does not meet the volumetric properties (Prowell et al., 2005). Abrasion refers to the wearing of the aggregates in the pavement structure. Aggregates lacking adequate toughness and abrasion resistance may cause construction and performance problems. In addition, aggregates must also be resistant to breakdown when subjected to wetting and drying or freezing and thawing.

Hardness of a rock is the resistance to deformation when it is loaded. The permanence of aggregates depends on their ability to retain their shape after being subjected to mechanical loads and applied disruptive forces (Oztas et al., 1999). The more strongly the particles in an aggregate are held together, the greater the work that has to be done to break the bonds. The performance of HMA is considered as the combined resistance (shear strength) of the mineral aggregates and bituminous cement. Aggregates must provide support from traffic loads without deforming excessively (Cheung and Dawson, 2002).

The strength of an aggregate may be selected as a key factor in providing a qualitative evaluation of the interior quality of aggregates. The coarse aggregate strength is traditionally estimated indirectly by well known tests such as the Los Angeles abrasion test, the hardness and soundness tests, etc. However, based on Alvarado et al. (2007), the indirect tensile and compressive strengths tests of rock before crushing are preferred.

The Discrete Element Method (DEM) can be effectively used to model the interaction among HMA aggregate particles. Cundall and Hart (1992) summarized the advancements in discrete element codes. The DEM has been mainly utilized as a research tool in many studies in the last few years to study the grain-to-grain contact. This numerical modeling technique has been extensively used in this study.

AGGREGATES AND MIX SELECTION

Six aggregate types (three in Phase I and three in Phase II) were selected from six TxDOT Districts. A total of 21 mixes were used in this study for the six aggregate sources (see Table 2.1). Most of these aggregates are commonly used in TxDOT paving and their performance histories are well known. For each of these aggregates, three mix types were chosen in Phase I: Porous Friction Course (PFC), Superpave-C, and Coarse Matrix High Binder (CMHB-C). In Phase II, a traditional Type D mix was also added. Type-D mixes for the aggregates from Phase I were also studied in Phase II. The same asphalt binder (PG 76-22) was used for all mixes to minimize the impact of the binder properties on the results.

The average gradation curve for each mix type, as illustrated in Figure 2.1, was selected to be in the middle of the gradation band specified by TxDOT. These gradations differ from one another to provide different grain-to-grain contact. The PFC is a coarse, almost uniform-graded mixture with a high percentage by weight of coarse aggregates. It is composed of 89% aggregates larger than a No. 8 sieve. In contrast, Superpave-C is a fine-graded mixture. It consists of 35% coarse aggregates (retained on the No. 8 sieve, hereinafter) and 65% fine aggregates. The CMHB-C mix is a coarse-graded mixture that is composed of 63% coarse aggregates and 37% fine aggregates. The Type-D mix demonstrates a well-graded gradation with 40% coarse aggregates and 60% fine aggregates. Although the gradation needs to be adjusted depending on mix design, this step was taken to make sure that an average estimate of crushing can be obtained for each mix type.

Table 2.1 - Selection of Aggregates and Mixtures

Phase I		Phase II	
Aggregate Type	**Mix Type**	**Aggregate Type**	**Mix Type**
Hard Limestone	CMHB-C Superpave-C PFC Type-D*	Sandstone	CMHB-C Superpave-C PFC Type-D
Granite	CMHB-C Superpave-C PFC Type-D*	Gravel	CMHB-C Superpave-C PFC Type-D
Soft Limestone	CMHB-C Superpave-C PFC Type-D*	Lightweight	CMHB-C Superpave-C PFC Type-D

***- Type-D mix for Phase I aggregates was actually added in Phase II of the project.**

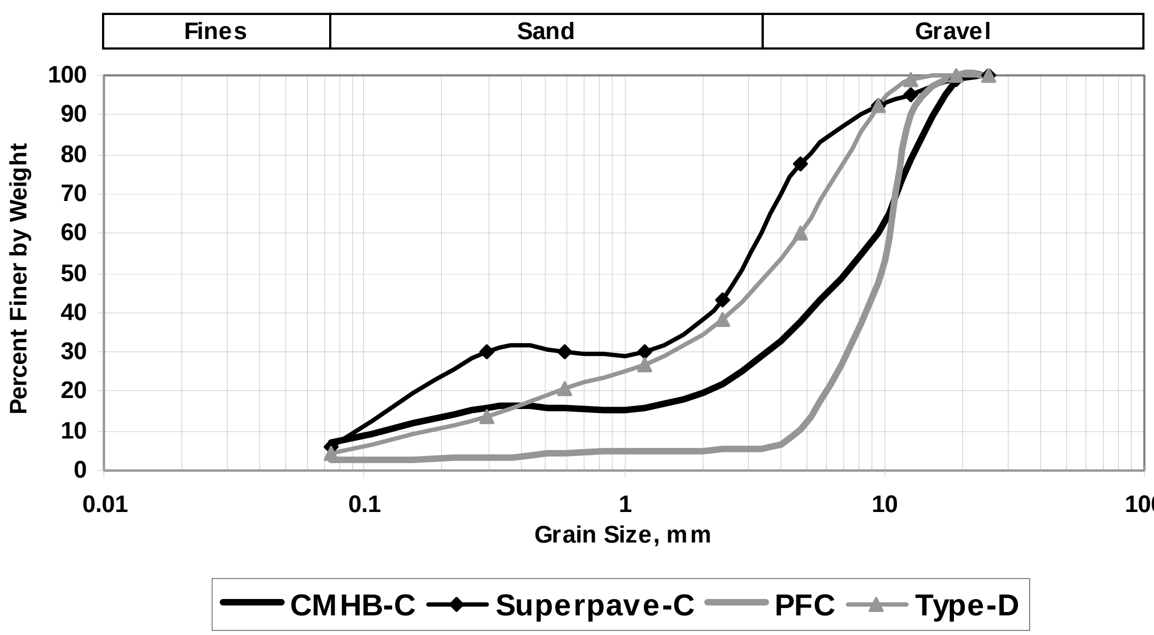


Figure 2.1 - Gradations of Mixes Used in This Study

Since the main focus of this study is to evaluate the effect of stress concentration at contact points on coarse aggregates that could cause aggregate fracture, only coarse aggregates (Retained No. 8) from different sources were used while the fine portion (Passing No. 8) was obtained from one source only.

AGGREGATE CHARACTERIZATION

A comprehensive geological description and petrographic analysis of the aggregates were performed and described thoroughly in Research Reports 0-5268-1 and 0-5268-2. Information regarding the traditional tests currently specified by TxDOT to evaluate the degradation resistance in aggregates, such as the Los Angeles abrasion and Micro-Deval tests, was also gathered. A summary of the results is provided in Table 2.2. The results of the Aggregate Imaging System (AIMS) used to measure the shape characteristics of the aggregates are also provided in Table 2.2. In addition several tests were conducted on the aggregate and rock masses retrieved from the quarries. The test procedures used were presented in Research Report 0-5268-1 and further elaborated upon in Research Report 0-5268-2. Tests carried out on the aggregates include:

- Aggregate Impact Value (AIV) (British Standard 812-Part 112) which provides a measure of the resistance of aggregates to impact.
- Aggregate Crushing Value (ACV) (British Standard 812-Part 110) which provides a measure of the resistance to crushing under gradually applied compressive loads by a compression testing machine.

In addition, rock masses were subjected to the following tests:

- Indirect Tensile test (IDT, similar to Tex-421-A)
- Compressive strength test (similar manner to Tex-418-A)
- Schmidt Hammer (Tex-446-A)
- Free-Free Resonant Column (FFRC) test (Tex-149, draft)
- V-meter Ultrasonic test (Tex-254-F, draft)

Shape characteristic tests were carried out using AIMS before and after Micro-Deval tests to quantify the following items:

- Texture
- Angularity
- Sphericity

Characterization of the aggregate interactions was carried out using the following tests:

- direct shear test (ASTM D3080)
- triaxial compression test (proposed Tex-143)

The results of testing and analysis are categorized in the following three groups:

1. Aggregate properties from tests that may contribute to the identification of point and mass strength,
2. Rock properties of the bulk specimens used to identify the strength and stiffness of rocks before crushing, and
3. Shape and texture properties from the traditional tests commonly carried out by TxDOT for defining the quality of aggregates.

A ranking process as described in the previous reports was developed. This ranking scheme was implemented for the six aggregates. However, the ranking method proposed is flexible enough so that as the number of aggregates tested increases, the ranking can be automatically modified. Table 2.3 shows the final ranking of the aggregates by their rock and aggregate properties. The aggregate ranking was performed based on data from recommended tests. In general, the sandstone and gravel are the best and the soft limestone and lightweight aggregates the worst.

Table 2.2 - Summary Results of Tests to Characterize Aggregates

Source	Test Procedure		Hard Limestone	Granite	Soft Limestone	Sandstone	Gravel	Lightweight Aggregate
TxDOT	Los Angeles Abrasion % Wt. Loss	Tex 410-A	24	38	32	26	19	26
	Mg Soundness Bituminous	Tex 411-A	9	20	29	20	4	7
	Mg Soundness Surface Treatment		8	19	23	19	4	4
	Polish Value	Tex 438-A	20	26	21	35	26	16
	Micro-Deval % Wt. Loss – Bituminous	Tex 461-A	13	13	26	18	4	27
	Acid Insolubility	Tex 612-J	1	91	1	55	81	95
TTI	Micro-Deval %Wt. Loss - Surface Treatment	Tex 461-A	15	9	20	16	2	22
	Texture Before Micro-Deval	AIMS Procedure	193	221	80	265	142	205
	Texture After Micro-Deval		95	187	36	222	108	207
	Angularity Before Micro-Deval		2323	2791	2195	2868	3959	2370
	Angularity After Micro-Deval		1730	2491	1671	1883	2787	1483

*Using HMAC Application Sample Size Fractions

Table 2.3 - Ranking of Aggregates from Selected Tests

a) Rock Tests Only

Aggregate	Summation of Ranks	Qualitative Ranking
Hard Limestone	7	Above Average
Granite	9	Average
Soft Limestone	12	Significantly Below Avg.
Sandstone	8	Above Average

b) Aggregate Tests Only

Aggregate	Summation of Ranks	Qualitative Ranking
Hard Limestone	17	Average
Granite	20	Average
Soft Limestone	23	Below Average
Sandstone	15	Average
Gravel	11	Above Average
LW Aggregate	25	Below Average

c) Traditional Tests Only

Aggregate	Summation of Ranks	Qualitative Ranking
Hard Limestone	8	Average
Granite	11	Average
Soft Limestone	12	Below Average
Sandstone	10	Average
Gravel	6	Above Average
LW Aggregate	9	Average

d) All Selected Tests

Aggregate	Summation of Ranks	Qualitative Ranking
Hard Limestone	32	Above Average
Granite	39	Average
Soft Limestone	48	Below Average
Sandstone	31	Above Average
Gravel	26	Above Average
LW Aggregate	51	Below Average

MIX DESIGN CHARACTERIZATION

The mix designs for the four mix types were developed using Tex-241-F and Tex-205-F. All mixes were designed using the Superpave Gyratory Compactor (SGC) regardless of mix types. The mixing, curing and compaction temperatures were selected as per Tex-241-F. The target air void content for the CMHB-C, Superpave-C and Type D mixes were 4% and for the PFC mixes was 20%. For the PFC mixtures, 1% lime and 0.4% fiber of the total aggregate weight was added, as specified in Tex-241-F. The Job Mix Formula (JMF) for each of the mixes is summarized in Table 2.4 for Phase I mixes and Table 2.5 for the Phase II mixes. Since the lightweight aggregate has a specific gravity less than those of normal weight aggregates, a volumetric approach was used. The two tables of the mix design are presented and discussed in research Report 0-5268-2. The mix designs presented herein are primarily for achieving the goals of this project.

Specimen Preparation of the Mixes

All HMA specimens were prepared using a Pine Instrument Co. Superpave Gyratory Compactor (SGC) with the same compactor parameters; the angle of gyration, vertical pressure, and rotational speed. Two different sets of HMA specimens were prepared for this project at two different compaction efforts. First, the specimens were compacted to achieve a nominal air void content of 7% (20% for PFC), as specified in the TxDOT specifications for performance testing. This generally occurred between 50 and 75 gyrations. Second, another set of lab specimens was compacted to 250 revolutions. Such variation in the compaction effort or number of gyrations was important to evaluate the potential of crushing in the aggregates. The design of Type-D mixes in TxDOT is usually carried out using a Texas Gyratory Compactor (TGC). For uniformity in compaction effort, these mixes were also designed using an SGC in concurrence with the PMC of the project.

The specimens were tested to characterize their performance. After testing, the aggregate breakdown was examined. Specimens compacted to the nominal 7% (or 20% for PFC) air voids and to 250 gyrations were heated and broken down. The asphalt was then burned from the aggregates using an ignition oven according to Tex-236-F, and a sieve analysis was performed on each mix.

Stiffness and Strength of Mixes

A detailed description and results of test methods on the mixes are also documented in Research Report 0-5268-1 and further elaborated on in Research Report 0-5268-2. The following tests were carried out to establish performance:

- Hamburg Wheel Tracking Device Test (Tex-242-F)
- Indirect Tensile Test (Tex-226-F)
- Dynamic Modulus Test (as proposed in NCHRP 9-19)
- Simple Performance Test (a variation of the static creep test, Tex-231-F)
- Ultrasonic Testing of Mixes (Tex-254-F, draft)

The HMA mixes and aggregates were ranked based on certain tests that are proposed in order to assess the quality of the rock and aggregates as well as the performance of HMA mixes. The tests recommended for rock properties are the Schmidt Hammer test, the V-meter seismic modulus test, and the Indirect Tensile test. For the aggregates, the ACV tests are recommended. The four traditional tests recommended are the Los Angeles Abrasion test, Mg Soundness test, and the Micro-Deval test, and AIMS angularity after Micro-Deval. Lastly, the proposed performance tests are the indirect tensile test, V-meter seismic modulus test, and the Hamburg Wheel Tracking Device test.

Table 2.4 - Mix Designs Used in Phase I

Property		Hard Limestone				Granite				Soft Limestone			
		CMHB-C	Superpave-C	PFC	Type-D	CMHB-C	Superpave-C	PFC	Type-D	CMHB-C	Superpave-C	PFC	Type-D
Binder Grade		PG 76- 22											
Binder Content,%		4.2	4.0	5.1	5.5	5.3	4.8	6.6	5.1	5.8	5.2	7.1	5.5
Sieve Size, in.	Sieve No.	Percent Passing, %											
1		100	100	100	100	100	100	100	100	100	100	100	100
0.75	(3/4)	99	99	100	100	99	99	100	100	100	100	100	100
0.492	(1/2)	78.5	95	90	99	78.5	95	90	99	84	97.5	91	99.5
0.375	(3/8)	60	92.5	47.5	92.5	60	92.5	47.5	92.5	69.5	92.5	52.5	95
0.187	(No. 4)	37.5	77.5	10.5	60	37.5	77.5	10.5	60	50	76	15.5	70.5
0.0929	(No. 8)	22	43	5.5	38	22	43	5.5	38	36	59	10.5	53.5
0.0469	(No. 16)	16	30	5	27	16	30	5	27	26	41	9.5	38
0.0234	(No. 30)	-	-	4.5	21	-	-	4.5	21	-	-	8.5	29.5
0.0117	(No. 50)	-	-	3.5	13.5	-	-	3.5	13.5	-	-	6.5	19
0.0029	(No. 200)	7	6	2.5	4.5	7	6	2.5	4.5	11.5	8.5	4.5	6.5
Maximum SG		2.554	2.554	2.572	2.756	2.471	2.520	2.469	2.744	2.450	2.515	2.445	2.738
Aggregate Bulk SG		2.696	2.696	2.715	2.710	2.601	2.655	2.526	2.696	2.587	2.653	2.527	2.638
Binder SG		1.02											
AV at N_{design}=100,%		4.0	4.0	20	4	4.0	4.0	20.0	4	4.0	4.0	20.0	4
VMA at N_{design}=100, %		12.7	12.7	27.2	12.9	13.7	13.2	27	15.5	14.3	13.7	28.0	13.9
VFA at N_{design}=100,%		70.2	68.5	26.4	69.8	69.7	69.9	25.8	74.2	72.5	70.9	28.8	72.2
Effective Asphalt Content, %		3.7	3.6	3.7	3.7	4.1	3.9	3.6	4.0	4.5	4.1	4.2	4.2
Dust Proportion		1.7	1.5	0.5	1.2	1.3	1.3	0.4	1.1	1.2	1.2	0.4	1.5

Table 2.5 - Mix Designs Used in Phase II

Property		Sandstone				Gravel				Lightweight Aggregate			
		CMHB-C	Superpave-C	PFC	Type-D	CMHB-C	Superpave-C	PFC	Type-D	CMHB-C	Superpave-C	PFC	Type-D
Binder Grade		PG 76- 22											
Binder Content,%		5.3	4.4	5.5	5.2	5.7	4.6	6.8	4.9	10.4	9.3	11.0	10.0
Sieve Size, in.	**Sieve No.**	**Percent Passing, %**											
1		100	100	100	100	100	100	100	100	100	100	100	100
0.75	**(3/4)**	99	99	100	100	99	99	100	100	100	100	100	100
0.492	**(1/2)**	78.5	95	90	99	78.5	95	90	99	84	97.5	91	99.5
0.375	**(3/8)**	60	92.5	47.5	92.5	60	92.5	47.5	92.5	69.5	92.5	52.5	95
0.187	**(No. 4)**	37.5	77.5	10.5	60	37.5	77.5	10.5	60	50	76	15.5	70.5
0.0929	**(No. 8)**	22	43	5.5	38	22	43	5.5	38	36	59	10.5	53.5
0.0469	**(No. 16)**	16	30	5	27	16	30	5	27	26	41	9.5	38
0.0234	**(No. 30)**	-	-	4.5	21	-	-	4.5	21	-	-	8.5	29.5
0.0117	**(No. 50)**	-	-	3.5	13.5	-	-	3.5	13.5	-	-	6.5	19
0.0029	**(No. 200)**	7	6	2.5	4.5	7	6	2.5	4.5	11.5	8.5	4.5	6.5
Maximum SG		2.430	2.488	2.374	2.450	2.433	2.502	2.376	2.485	1.625	1.879	1.427	1.823
Aggregate Bulk SG		2.585	2.621	2.555	2.608	2.616	2.655	2.594	2.649	1.605	1.914	1.365	1.850
Binder SG		1.02											
AV at N_{design}=100,%		4	4	20	4	4	4	20	4	4	4	20	4
VMA at N_{design}=100, %		14.3	12.9	27.9	14.0	15.7	13.5	31.7	14.2	12.9	16.8	32.8	14.9
VFA at N_{design}=100,%		69.3	69.7	30.7	74.4	74.7	70.8	36.9	71.9	69.6	71.2	20.4	72.8
Effective Asphalt Content, %		4.8	4.2	5.2	4.3	5.1	4.8	5.7	4.9	5.8	6.0	5.0	6.3
Dust Proportion		1.5	1.4	0.5	1.0	1.4	1.3	0.4	0.9	1.2	1.0	0.5	0.7

A series of analysis was carried out with those tests recommended to demonstrate how well they represent the ranking of the aggregates as shown in Table 2.6. For CHMB-C, the gravel ranked first followed by the sandstone (above average), granite was average and the remaining aggregate was ranked lower. For the Superpave-C mix, similar to CMHB-C, gravel and sandstone ranked above average, where hard limestone, granite, and lightweight aggregate (LWA) ranked average and finally soft limestone ranked the lowest. For the PFC mixes, the sandstone, gravel and LWA ranked similarly and above average with the rest ranking below average. For Type-D mixes, gravel, sandstone, and hard limestone were ranked above average with granite and soft limestone as average and finally LWA ranked below average. Overall, gravel and sandstone were the superior aggregate with hard limestone and granite coming in a close second and soft limestone and LWA are the lesser quality aggregate among the group. Important to note that even though granite is known as a superior aggregate based on the current TxDOT classification as compared to hard limestone, the results show that hard limestone was of higher quality.

MICRO-MECHANICAL MODELING

A commercially available DEM code called *Particle Flow Code in 2-Dimensions* (PFC2D) was used to model aggregate and asphalt mix properties under different loading conditions. This code includes a user-friendly graphical interface, linear and non-linear contact models, linear and curvilinear boundary conditions, and different types of bond strength. A summary of the DEM, the calibration results for the aggregate tests, and modeling results of asphalt mixes were presented in the two previous research reports. The conclusions from the DEM modeling can be summarized in the following manner:

- The discrete element model is powerful in modeling the aggregate and mixture tests, as it provides information on the influence of mix design and aggregate properties on resistance to fracture.
- The discrete element model allowed evaluating the internal forces in the HMA mixtures, which cannot be accomplished by the conventional experimental methods.
- The analysis of the internal forces revealed that the PFC mixtures experienced higher stresses than all other mixes. Based on the results, it is recommended that aggregate strength in PFC should be about 25% more than the aggregate strength used in the other mixtures.
- With the exception of the PFC, internal forces were comparable for all other mixtures for a given aggregate type.
- Aggregates were ranked based on the internal force values. This ranking can be used to select the appropriate aggregate type given a mixture design. The soft limestone experienced the highest internal forces as compared to the other aggregates.
- The rate of increase in the internal force with increase in applied loads is an indication of aggregate resistance to breakage. A high increase rate indicates less breakage. PFC mixes experienced the least rate of increase indicating more aggregate breakage when compared with the other mixes.

The model was also successful to a large extent in representing the variability in aggregate properties and the influence of this variability on mixture response.

Table 2.6 - New Ranking of HMA Based on Selected Performance Tests on Specimens Prepared to In-Place Air Voids

a) CMHB-C

Aggregate	Summation of Ranks	Qualitative Ranking
Hard Limestone	11	Below Average
Granite	9	Average
Soft Limestone	11	Below Average
Sandstone	7	Above Average
Gravel	5	Above Average
LW Aggregate	11	Below Average

b) Superpave-C

Aggregate	Summation of Ranks	Qualitative Ranking
Hard Limestone	10	Average
Granite	9	Average
Soft Limestone	11	Below Average
Sandstone	7	Above Average
Gravel	8	Above Average
LW Aggregate	10	Average

c) PFC

Aggregate	Summation of Ranks	Qualitative Ranking
Hard Limestone	7	Below Average
Granite	7	Below Average
Soft Limestone	8	Below Average
Sandstone	5	Above Average
Gravel	5	Above Average
LW Aggregate	4	Above Average

d)Type-D

Aggregate	Summation of Ranks	Qualitative Ranking
Hard Limestone	8	Above Average
Granite	11	Average
Soft Limestone	12	Average
Sandstone	7	Above Average
Gravel	6	Above Average
LW Aggregate	10	Below Average

*** Ranking in the parenthesis are those from when all tests were used in the ranking**

SUMMARY AND CONCLUSIONS FROM PHASE I AND PHASE II

Aggregates have a significant and direct effect on the performance of asphalt pavements and it is important to maximize the quality of aggregates to ensure the proper performance of roadways. It was found that the traditional aggregate test carried out by TxDOT cannot completely characterize the performance of the aggregates.

To evaluate the effect of stress concentrations at contact points on coarse aggregates that could cause aggregate fracture, an extensive series of tests from geological evaluation of quarries and rocks retrieved from them, to rock strength tests, to traditional and new aggregate tests, to geotechnical strength tests were carried out on six aggregates to rank them. To establish the performance of mixes, specimens of four different mix types were prepared and subjected to a number of performance-related tests. The laboratory activities were supplemented with micro-mechanical modeling to understand the internal behavior of the mixes. Through correlation and statistical analyses, the redundant aggregate-related and performance-related tests were identified and the optimum test methods were recommended.

The ranking of aggregates was based on three categories of tests (aggregate properties, rock properties, and shape and texture properties) to further understand the impact of each method. From such ranking, the following conclusions were drawn:

- From the aggregate properties, gravel ranked above average, hard limestone, granite and sandstone ranked average, and soft limestone and the lightweight aggregate ranked below average. Aggregate tests performed after moisture conditioning, indicated that the quality of the hard limestone is negatively impacted and the quality of the lightweight aggregates improves when they become wet.
- From the rock properties, the hard limestone and sandstone ranked above average and granite ranked average. Soft limestone ranked below average. The gravel and lightweight aggregates could not be subjected to rock tests because they are not originated from rock masses.
- As per the traditional shape and texture tests, the gravel ranked above average, the hard limestone, granite, sandstone and lightweight aggregate ranked as average, with once again the soft limestone ranking below average.
- In general, the sandstone and gravel were the best, the hard limestone and granite ranked average, and the soft limestone and lightweight aggregate ranked the worst.

To determine which of the tests are the most representative for the characterization of the aggregates, correlation analysis among the tests was performed. From this analysis, the following observations are provided:

- From the tests characterizing the aggregate point and bulk strength results, the ACV test and its surrogate parameters were found to correlate well with most of the tests. As a result, the ACV test seems to be the most appropriate test for characterizing the aggregates, especially since several parameters can be readily determined from the same test and the cost of implementing this test in Districts owning a concrete compressive test machine would be small.
- The compressive strength obtained using the Schmidt hammer seems to be the most appropriate test for assessing the quality of aggregates from rock masses. This test is not only easier and faster than the compressive strength test, but also eliminates the need for coring the rock and requires minimal training.
- The V-meter seems to be an appropriate tool for estimating the modulus as well as the quality of the aggregates from rock mass in tension. No coring of rock is necessary to perform this test on the rock samples.
- From the traditional tests, the Los Angeles Abrasion test, Mg Soundness test, the Micro-Deval test, and AIMS angularity after Micro-Deval are appropriate.

The same exercise was carried out on the performance tests. For the purpose of this study, the indirect tensile test and the modulus with the V-meter, and Hamburg Wheel Tracking Device seem to be optimal for characterizing the performance of the HMA.

An approach for modeling the response of the HMA mixes was developed in this study. The aggregate properties (stiffness, compressive strength and tensile strength) were determined by matching the model results to experimental measurements conducted on aggregate samples. The model was used to predict the mix response under different loading conditions. The results show that the failure in the soft limestone mixes occurs primarily within the aggregate phase, while the failure in the other mixes occur in the mastic phase. The model was used to investigate the stress or load distributions within the different mixes. The PFC mixes are shown to have more localized high stresses within the aggregates than the Superpave and CMHB mixes. This finding indicates that aggregates with higher resistance to fracture need to be used in PFC mixes.

A database of the information was obtained and a ranking scheme was implemented that can be readily used to rank the aggregates. Based on the average value of each parameter and the coefficient of variation of the test associated with that, parameters for the acceptance limits can be set rationally considering the aggregate sources available to TxDOT.

It should be emphasized that these observations are preliminary since the database is rather small. More aggregate types are needed to be tested to set more definite limits for specifications. As a result, it is proposed to expand the database with more aggregate sources. The new tests, such as the ACV, should be implemented by the TxDOT Construction Division and select Districts to ensure their usefulness for TxDOT.

CHAPTER THREE - EXPERIMENTAL TEST RESULTS OF BLENDED AGGREGATES

TXDOT BLENDING PROCESS

According to TxDOT specifications, coarse aggregate stockpiles must have no more than 20% material passing the No. 8 sieve, and aggregates used should be from sources that are listed in the Bituminous Rated Source Quality Catalog (BRSQC). TxDOT regularly monitors the quality and uniformity of aggregates according to Tex-499-A, “Aggregate Quality Monitoring Program (AQMP).” The AQMP is created to improve the efficiency of TxDOT operations by allowing the Districts to use aggregates from sources qualified through AQMP without project specific testing by the Construction Division, Materials and Pavements Section (CST-M&P).

The BRSQC lists the Aggregate Quality Monitoring Program (AQMP) rated values for bituminous aggregates for several TxDOT test procedures such as:

1. Five-cycle magnesium sulfate soundness (Tex-411-A),
2. Acid insoluble residue (Tex-612-J), and
3. Crushed Faces (Tex-460-A).

Based on above test results, the material is classified as Surface Aggregate Classes A through C as shown in Table 3.1.

Table 3.1 - TxDOT Surface Aggregate Classification (SAC) Criteria

Property	Test Method	Surface Aggregate Classification (SAC)		
		A	B	C
Acid insoluble residue,% min	Tex-612-J	55	---	---
5-cycle Mg, % max	Tex-411-A	25	30	35
Crushed Faces, 2 or more, % min	Tex-460-A	85	85	85

Aggregates from sources that are not listed in the BRSQC can be used only when approved before use. The Districts must perform job control tests to determine specification compliance for those aggregate requirements not covered by the AQMP.

Aside from SAC, other requirements for the coarse aggregates are given in Table 3.2 for different mix types. Tables 3.1 and 3.2 indicate that a Class A aggregate source (ignoring acid

Table 3.2 - Aggregate Quality Requirements Based on TxDOT Specifications

Property	Test Method	Type-D	PFC	CMHB /Superpave-C
SAC	AQMP	As shown on plans		
Deleterious material, %, max	Tex-217-F, Part I	1.5	1.0	1.0
Decantation, %, max	Tex-217-F, Part II	1.5	1.5	1.5
Micro-Deval abrasion, %, max	Tex-461-A	Note[1]	Note[1]	Note[1]
Los Angeles abrasion, %, max	Tex-410-A	40	30	35
Magnesium sulfate soundness, 5 cycle, %, max	Tex-411-A	30	20	25
Coarse aggregate angularity, 2 crushed faces, %, Min	Tex-460-A, Part I	85[2]	95[2]	95[2]
Flat and elongated particles @ 5:1, %, max	Tex-280-F	10	10	10

1. Not used for acceptance purposes. Used by the Engineer as an indicator of the need for further investigation.
2. Only applies to crushed gravel.

insolubility test) is needed for all mixes studied here except for the Type D mix in which a Class B aggregate may be accepted.

The main application of aggregate blending is clearly to enhance the surface properties of the pavement in order to achieve a higher skid resistance. Aggregates with higher surface texture are more desirable. Based on this philosophy, TxDOT permits blending of Class A and Class B aggregates in order to meet requirements for Class A materials. TxDOT specifications require that the blended Class A and B aggregates meet a Class A requirement, and that at least 50% by weight of the material retained on the No. 4 sieve needs to come from the Class A aggregate source.

Even though this blending protocol is clearly not intended for improving the performance of the HMA mixes, nevertheless this is the only guideline available for blending at this time. Blending aggregates with different properties to enhance the performance of asphalt mixtures is also desirable. The performance can be enhanced either by increasing the structural capacity of the pavement, or increasing its resistance to specific distress. For example, more angular aggregates generally tend to produce pavements with less rutting. The focus of this section is to determine whether the current blending process can be also used as a means of improving the performance of HMA mixes. The secondary goal is to explore the feasibility of adding some of the tests found feasible in the previous phases of this study to the current specifications for the purpose of improving the performance.

The classification of the six aggregates is provided in Table 3.3. Four of the six aggregates are Class A, while the hard and soft limestone aggregates are listed as Class B. Based on the results of the research conducted on the individual aggregates it was shown that the current tests used to classify the aggregates may not be sufficient and recommendations were made to use additional tests such as the ACV test for improving the characterization process (see Research

Table 3.3 - Surface Aggregate Classification of Aggregates Used in this Study

Aggregate	Surface Aggregate Classification (SAC)	ACV Value, %
Hard Limestone	B	22 (Marginal)
Granite	A	27 (Marginal)
Soft Limestone	B	32 (Crush Susceptible)
Sandstone	A	18 (High Quality)
Gravel	A	16 (High Quality)
LW Aggregate	A	43 (Crush Susceptible)

Reports 0-5268-1 and 0-5268-2). The ACV for each aggregate is also included in Table 3.3. Based on the ACV values, the quality (crushing potential) of the hard limestone and granite is similar with the granite exhibiting slightly lower quality. On the other hand, based on SAC, the two aggregates are placed in different classes with the hard limestone being perceived as a lower quality aggregate. The results of the aggregate tests also show that the lightweight aggregate exhibits the highest crushing potential among the six aggregates tested; yet it is ranked as Class A according to SAC. These examples clearly demonstrate the need for supplemental aggregate tests for classifying the crushing potential of aggregates.

Based on the interaction with the PMC, two aggregate blends were selected. The first blend consisted of the sandstone and soft limestone. These two aggregates were clearly of different quality based on the research under this project and as specified under the SAC class. This would be the ideal situation in terms of blending a lower quality aggregate with a high quality aggregate.

For the second blend, the granite and hard limestone were used. This would be ideal under the SAC classification since granite was classified as Class A and hard limestone as Class B. As discussed above, the hard limestone is as good a quality or a better aggregate than the granite in terms of strength as reflected in some of tests carried out in this study. This blend would provide a good study to validate or contradict the results from the individual aggregates under this research study. For this blend, despite the SAC recommendation, the hard limestone was considered as the hard aggregate and the granite as the soft aggregate .

The following five blending proportions were used in this study:

a. 100% of the aggregate phase belongs to the hard aggregates
b. 75% of the aggregate phase belongs to the hard aggregates
c. 50% of the aggregate phase belongs to the hard aggregates
d. 25% of the aggregate phase belongs to the hard aggregates
e. 100% of the aggregate phase belongs to the soft aggregates

As for the Phase I and Phase II studies, the following four mix types were considered: CMHB-C (Item 344), PFC (Item 342), Superpave-C (Item 344) and Type-D mix (Items 340/341). The same asphalt binder was used for all mixes to minimize the impact of the binder properties on the study.

RESULTS OF BLENDING ACTIVITY

Tests on the 100% soft and 100% hard aggregates had already been carried out in the previous two phases of the project. Therefore, additional tests were carried out for Items b through d above. The first activity consisted of developing the job mix formula. As such, a total of 24 mix designs were carried out to obtain the optimum asphalt contents.

For each aggregate blend selected the following tests were carried out:

- Aggregate Impact Value (AIV, British Standard 812-Part 112) to provide a measure of the resistance of aggregates to impact.
- Aggregate Crushing Value (ACV, British Standard 812-Part 110) to provide a measure of the resistance to crushing under gradually applied compressive loads by a compression testing machine.

For each mixture, the following tests were carried out to document their strength, modulus and possibly their performance:

- Indirect tensile strength test, Tex-226-F
- V-meter, (Tex-254-F, draft
- Hamburg wheel test, Tex-242-F
- Dynamic modulus test as per NCHRP 10-19 recommendations
- Flow Time test as per NCHRP 10-19 recommendations

ACV and AIV Test Results

The ACV and AIV tests were performed on different proportions of soft/hard aggregates from the two blends to estimate the crushing potential of the aggregates. These tests that were studied under this project were recommended to be used to characterize the aggregates. Two limits based on both the research performed on the six aggregates and the British Standards were used as criteria to characterize the results from the ACV and AIV tests. If the result from either test is less than 20, the aggregate is assumed to be not susceptible to crushing; but if the value is greater than 30, the aggregate is assumed to be susceptible to crushing. Any value between 20 and 30 suggests that the aggregate is marginal.

Figure 3.1a presents the results of the ACV tests for the two blends. The two horizontal lines correspond to the threshold values of 20 and 30 described above. Since tests were performed in triplicate for each blending ratio, the mean as well as the range for one standard deviation are shown for each data point. A linear trend is observed between the ACV and the increase in the proportion of the softer aggregates for both blends. For Blend 1, where aggregates with distinctly different properties are blended, the crushing potential of the aggregate increases as the percentage of soft material increases. For Blend 2 however, where the two aggregates are more similar in crushing potential, the change in ACV is less significant.

The AIV test indicates the crushing of aggregates under dynamic impact, which is more representative of the compaction of the HMA layer with vibratory compactors. The AIV test results (see Figure 3.1b) are quite similar to those from the ACV tests in that the crushing potential increases linearly with the increase in the percentage of softer aggregates. The exception is the point corresponding to 100% granite for Blend 2, where the AIV is significantly

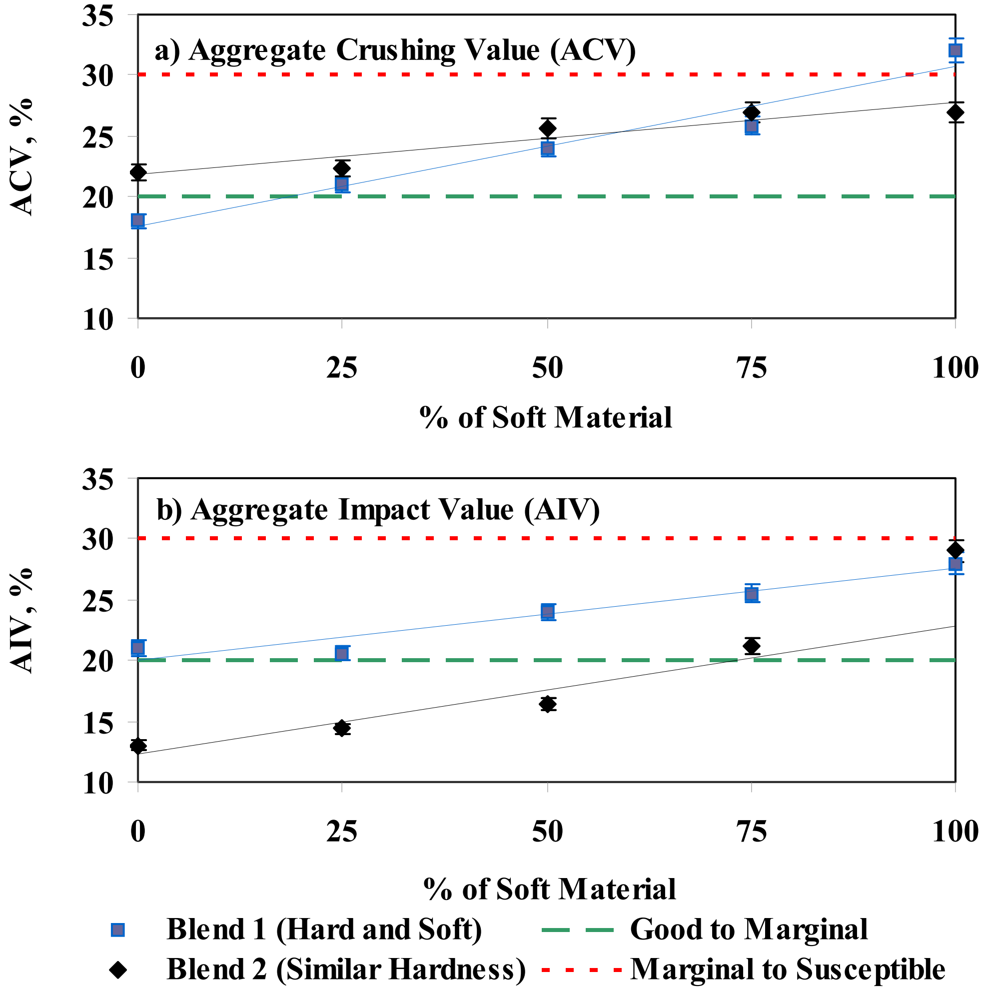


Figure 3.1 - Results of the Aggregate Tests for the Two Blends

greater than what the linear trend suggests. This can be interpreted as the 'cushioning" impact that even a modest amount (25%) of better aggregate (hard limestone) has on reducing the crushing potential of the granite. As indicated in the previous reports, the granite, because of large crystals, crushes more readily than indicated by the classical tests such as LA abrasion.

Based on the AIV results, Blend 1 is marginally susceptible to crushing, whereas Blend 2 is not susceptible to crushing until more than 75% of the softer aggregate is added.

Asphalt Content of Blends

The variations in the asphalt content with the percentage of softer aggregates are shown in Figure 3.2. Forty mix designs, twenty for each blend, was required based on the blending ratios. Sixteen of the mixes were developed in the previous phases of the study. Except for Type-D mixes, the asphalt content increases almost linearly as the percent of soft material increases. The asphalt content is more or less independent of the blending for Type-D mixes. The PFC mixes show a much larger increase (as much as 1.5%) in the asphalt content as the percent of soft material increases.

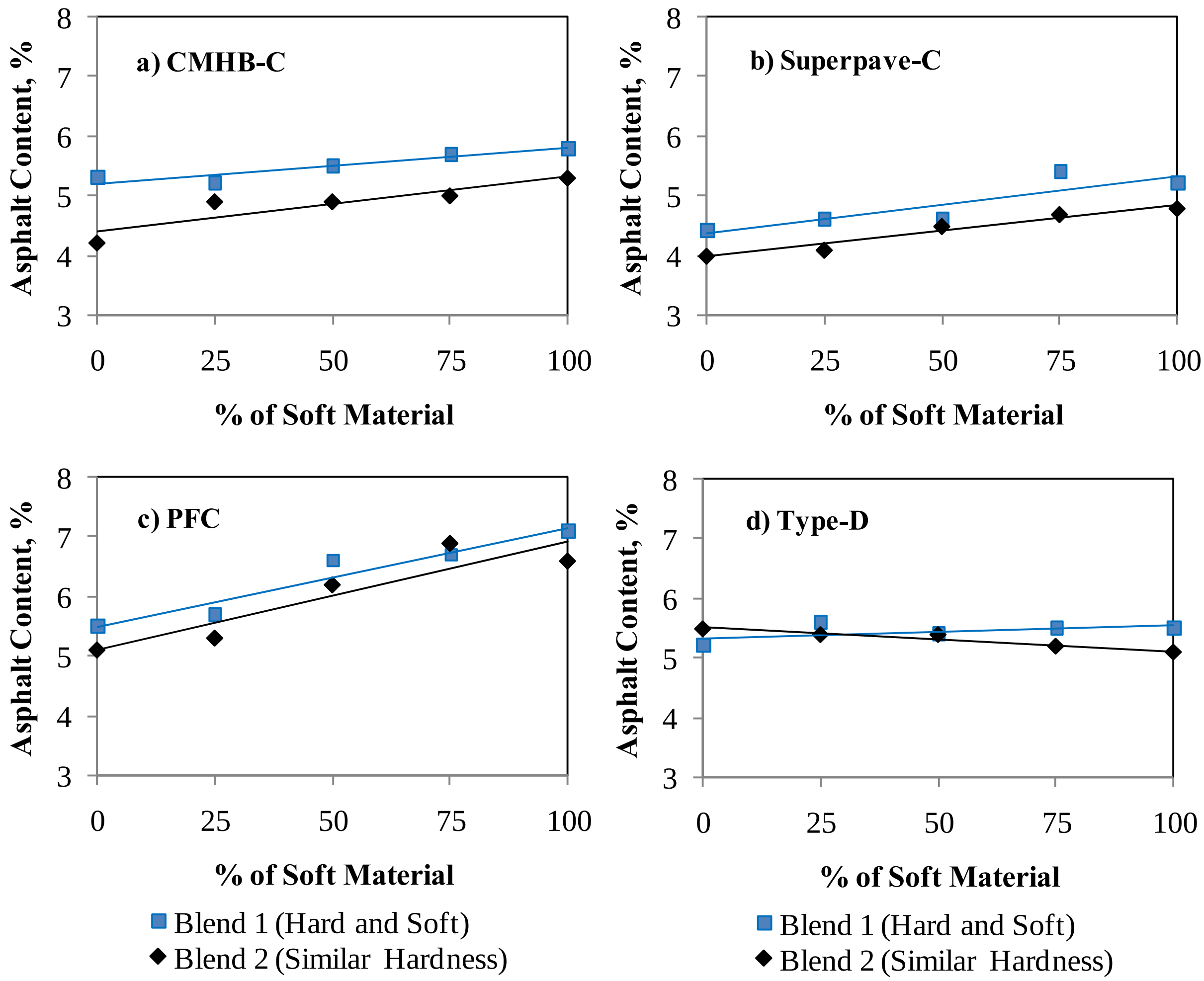


Figure 3.2 - Results of the Asphalt Content for the Two Blends

Since in all the mixes, except Type-D, the better quality aggregates required less asphalt than the lower quality aggregates, one should carefully weigh the economic impact of blending lower quality aggregates in the mix given the very high costs of asphalt binder.

Indirect Tensile Strength Test Results

Indirect tensile strength tests were performed in triplicate for each blending ratio. The variations in the IDT strengths with the blending ratio for the four mix types are shown in Figure 3.3. In general, the impact of blending on the tensile strength of the mixes is small, with a tendency towards lower strength with increase in the softer percentage of softer aggregates. For Blend 1, up to 75% of softer aggregates in the blend do not seem to significantly impact the IDT strengths. However, the mixes with 100% soft limestone tend to provide lower strengths in all but the PFC mix. For Blend 2, the CMHB-C and PFC mixes exhibit similar IDT strengths, whereas the Type-D and Superpave-C mixes exhibit gradual decrease in strength with increase in the granite aggregate content.

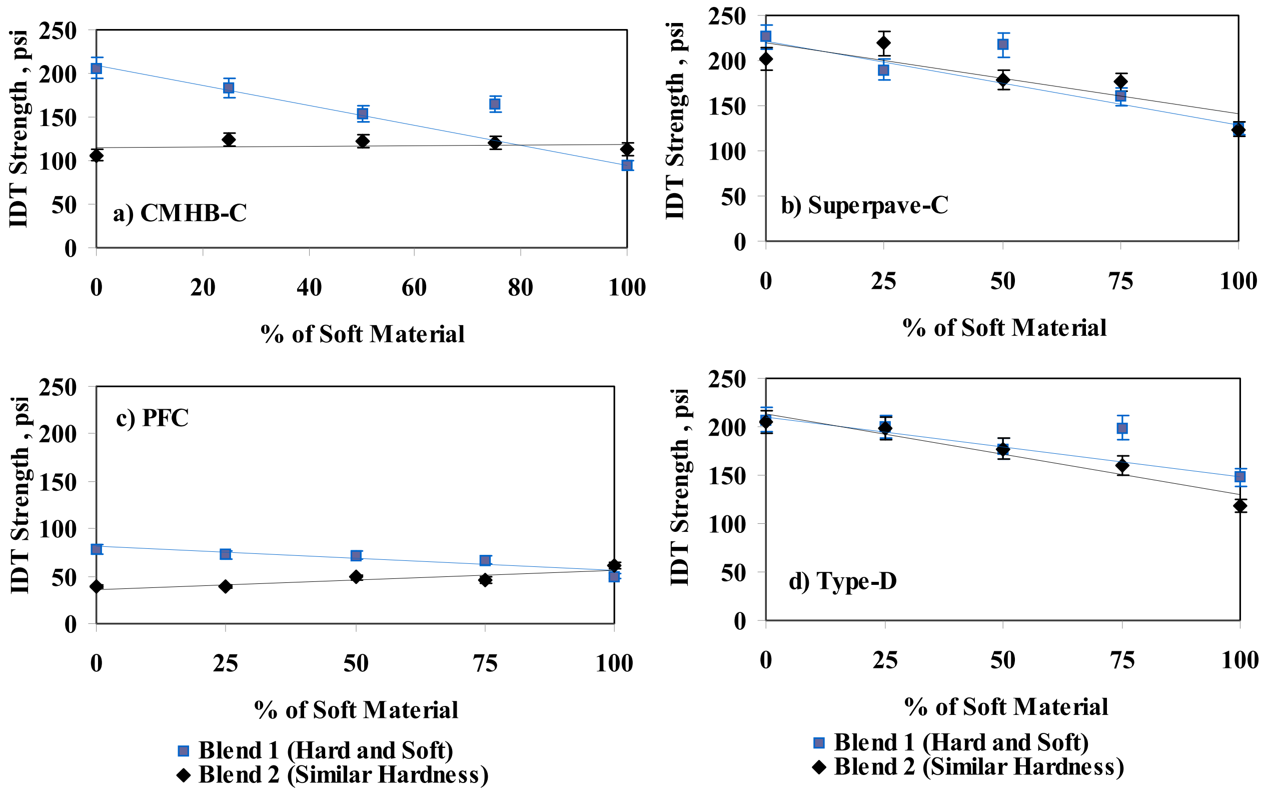


Figure 3.3 - Results of the Indirect Tensile Strength for the Two Blends

Dynamic Modulus Test Results

The dynamic modulus is a significant parameter since it impacts the structural design of pavements more than any other parameter. Dynamic modulus tests were also performed in triplicate for each blending ratio. Similar to the IDT results, both the averages and standard deviation are presented for each blending ratio of the four mixes (see Figure 3.4).

For Blend 1, CMHB-C and PFC show a significant decrease (by a factor of more than 2) in modulus when the proportion of the soft aggregates increases; whereas the moduli of the Superpave-C and Type-D mixes are much less impacted (less than 25%) with the increase in the proportion of the soft aggregates. Given the variability in the test results (as reflected in the error bands in the figures), only the modulus of the 100% soft limestone for the Superpave-C is noticeably lower than the other blends.

For Blend 2, the coarser mixes (CHMB-C and PFC) and Type-D mixes show small change in the modulus with change in the blend proportions. The Superpave-C mixes however show a much larger sensitivity in the modulus when the percent of soft material changes. For this mix type, the average modulus of the specimens with the hard limestone alone is significantly higher than that of the specimens with the granite aggregate alone. Adding between 25% to 75% granite

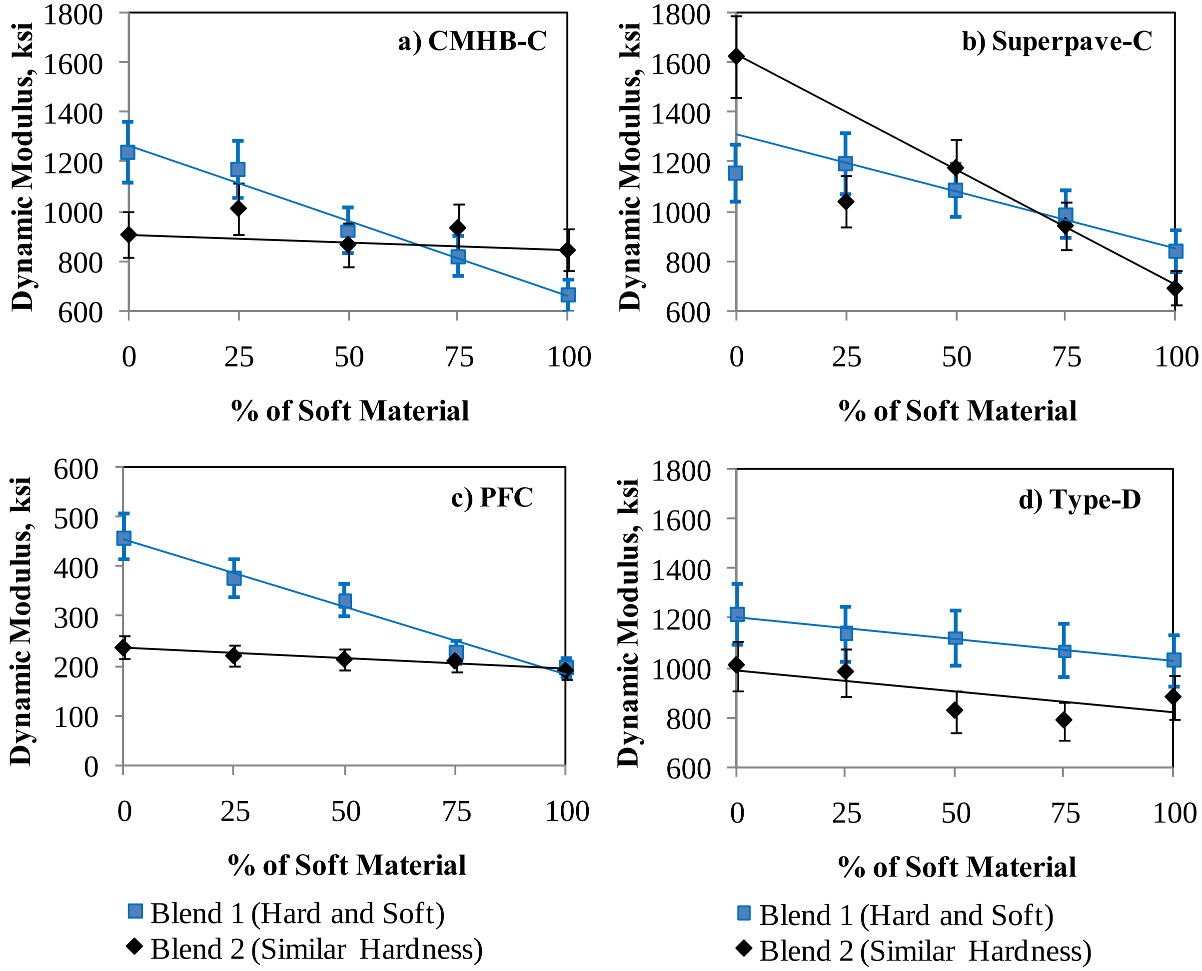


Figure 3.4 - Results of the Dynamic Modulus Tests for the Two Blends

aggregates to the mix significantly but almost similarly reduces the modulus of the mix. This pattern may need further investigation with other similar materials. This case study shows that blending of very soft aggregates with very hard aggregates may not be advisable for the coarser mixes, but may be reasonable for the finer mixes.

Flow Time Test Results

The flow time test is advocated for assessing the rutting potential of the mixes. As shown in Figure 3.5, the flow time test results show the highest variability among the performance tests. The results from the PFC and Type-D mixes for Blend 2 are not shown because specimens prematurely deformed excessively. For Blend 1, the Type-D mixes are most affected by the change in the percentage of soft aggregates, followed by the CMHB-C mixes. The Superpave-C mixes do not show any sign of change in the maximum strain, except for 100% blend of soft limestone. For the PFC mixes, it seems that adding 25% of the soft aggregates (is not shown in Figure 3.5C since all triplicate specimens excessively deformed) and 50% of the soft aggregates is detrimental to the rutting potential of the mix, whereas the addition of 75% of the soft aggregates or even 100% soft aggregate mixes perform better. The reason for this pattern, aside from experimental error, is not known. Due to the high variability of the test method, it is hard to draw significant conclusions from the results of these tests.

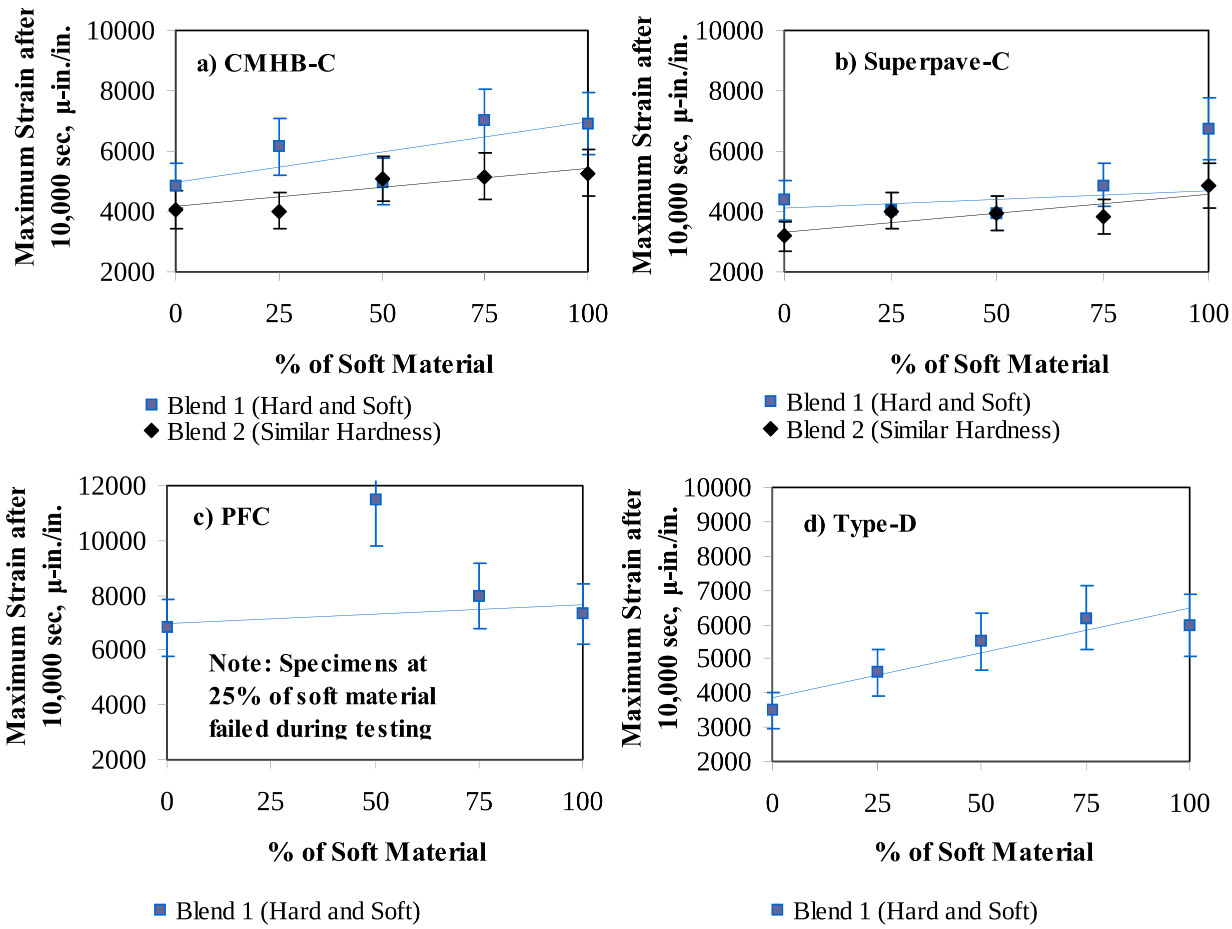


Figure 3.5 - Results of the Flow Time Tests for the Two Blends

Hamburg Wheel Tracking Device Test Results

Figure 3.6 shows the results of the HWTD in terms of the maximum rut depth. As indicated in the previous reports, it was not practical to test the PFC mixes with this test method. For Blend 1, the results from the three mixes tested show a trend towards increase in rutting potential with increasing the percentage of the soft aggregates. For the CMHB-C and Type-D mixes, almost all blends pass the requirements of TxDOT, whereas for the Superpave-C mix even adding 25% of the soft materials will cause excessive rutting as per current specifications.

For Blend 2, the CMHB-C mixes seem not to be impacted by the blending of the two aggregates. For the Superpave-C and the Type-D mixes, the rutting potential decreases as the percentage of the lower quality aggregates increases. This trend seems counterintuitive at first considering that the lower quality aggregate (granite) is much stronger in compression than the hard limestone, but the trend, upon closer observation, is reasonable.

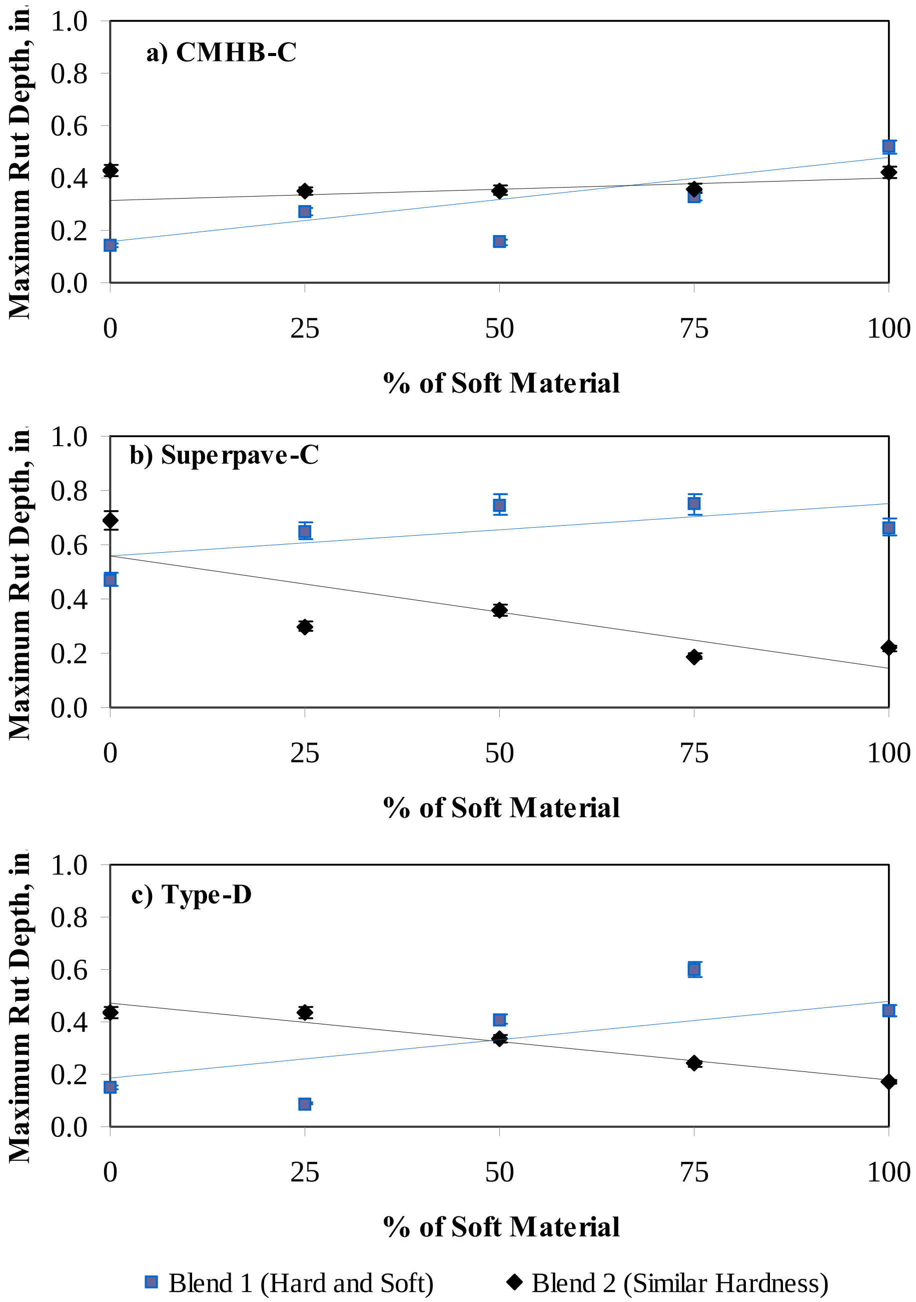


Figure 3.6 - Results of the HWTD Tests for the Two Blends

V-meter Test Results

Figure 3.7 shows the moduli obtained with the V-meter tests. The modulus with a V-meter is more indicative of the stability of the aggregate skeleton than the binder. For Blend 1, the PFC mixes demonstrate the highest rate of decrease in modulus with increase in the percentage of soft aggregates. The other three mixes are marginally impacted by the change in the percentage of the aggregate blend. The moduli of Blend 2 are not significantly impacted by the change in the blend since the two aggregates were more similar than the first blend.

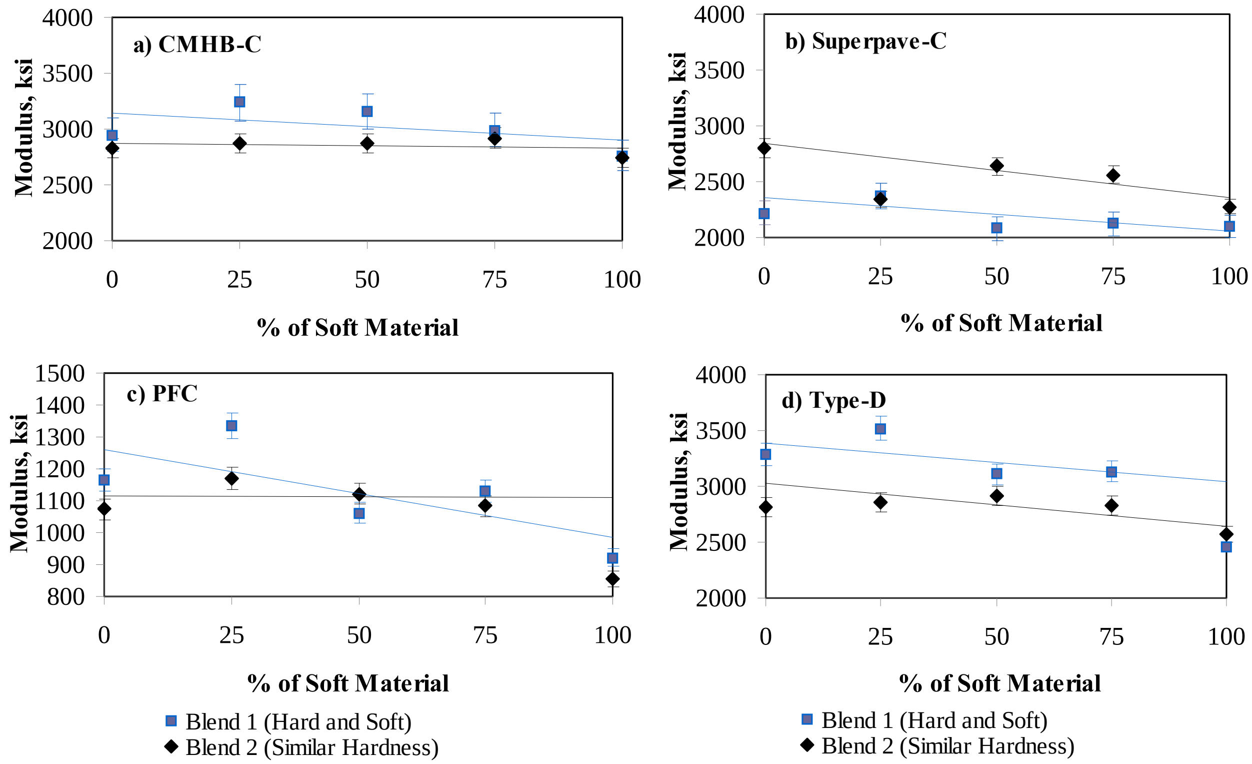


Figure 3.7 - Results of the V-meter Tests for the Two Blends

Summary

The impact of aggregate blending on the performance of four mix types was studied. The results of the blending showed that both the mix type and quality of the aggregate used in the blend may influence the performance.

The results of the ACV and AIV tests are very promising. The aggregate crushing and impact values seem to show a linear trend as the percent of softer material is added. Both these test allow us to further characterize the aggregates and are recommended to be part of the quality catalog that TxDOT uses for evaluating the aggregates. The consistency in the blended results further validated the findings in Phase I and II.

The results for characterizing the performance of the mix presented in this chapter were based on three blending ratios of 25%, 50% and 75%. In almost all tests, a linear trend seems to match the experimental data well. Therefore, one preliminary conclusion is that if the results based on any of the performance indicators are known for the two aggregates to be blended then the performance indicators at any blending ratio can be reasonably estimated by a linear interpolation.

In order to further summarize the results of the experimental analysis and make generalization based on the two blends, the slopes of the lines between the performance indicator and the percentage of soft aggregates in the blends from each test were used. The first assumption made is that the behavior of the blending ratio and any performance indicator is linear. The next step was to use the normalized slopes of the trend lines for comparison purposes. To normalize the slopes for each performance parameter, each slope is divided by the maximum slope obtained for each mix. For example, the slope of the IDT for the CMHB-C Blend 1 is the largest. All the slopes related to the IDT are divided by that slope. Therefore the range of the normalized slopes is from 0 to 1. The same was done for dynamic modulus, V-meter and HWTD results.

Figure 3.8 shows the results of the normalized slopes for each mix. One significant conclusion that can be drawn from these figures is that for the two coarse mixes (CMHB-C and PFC) the slopes are much greater for Blend 1 (very high quality and very low quality aggregates) than for Blend 2 (reasonably similar aggregates). This indicates that for coarse mixes the quality of the two aggregates being blended does matter.

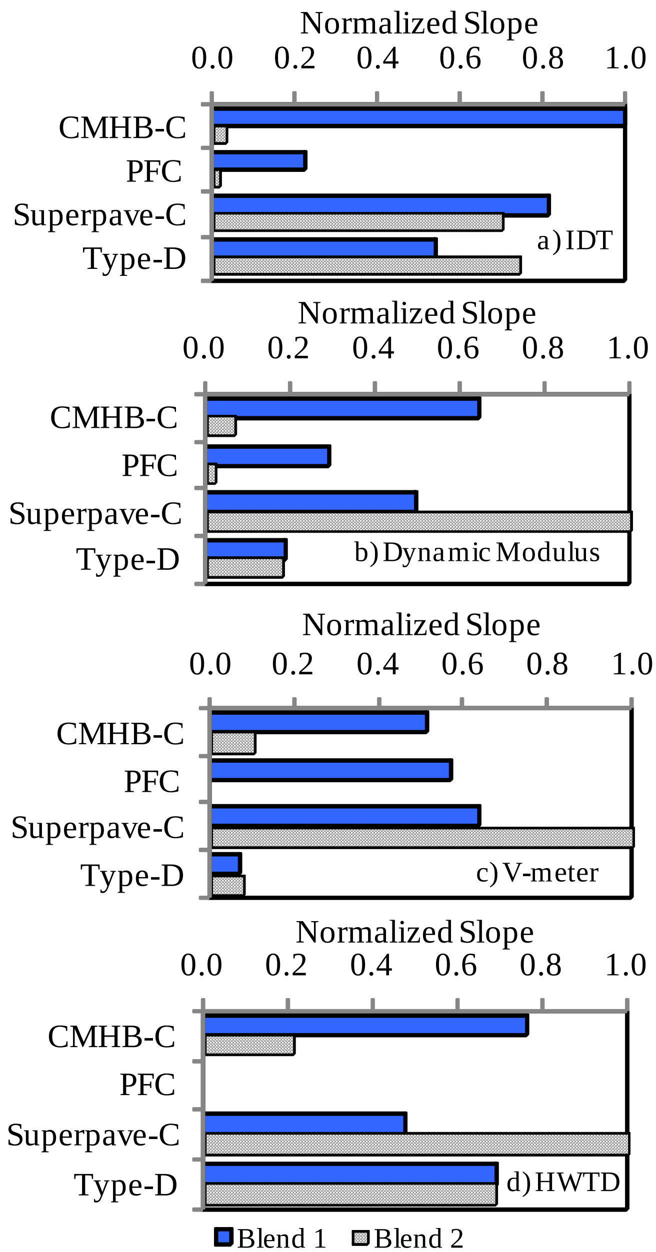


Figure 3.8 - Comparison of Normalized Slopes for Performance Indicators of the Four Mixes

For the two fine mixes (Superpave-C and Type D), it seems that the blending activity is more important than the quality of the two aggregates being blended, since the normalized slopes from the two blends for different performance indicators are either close to one another or the slopes of Blend 2 is greater..

It is important to note that since only two blends were considered and since the inherent variability of some tests is rather high, no definite conclusions can be stated. The numerical analysis presented in the next chapter allows for better recommendation in terms of the blending ratios since it provides more flexibility in increasing the number of blending ratios investigated given the time constraints on this project.

CHAPTER FOUR - AGGREGATE BLEND USING MICRO-MECHANICAL MODELS

This chapter includes the analysis of blending different types of aggregates (soft and hard) within one mix. The blending effects were studied for both the Discrete Element Method (DEM) and experimental laboratory samples. Two blending cases were considered. The two DEM blends were analyzed both on a separate and combined basis. Combining the two blends allowed drawing some conclusions regarding the mix type effects on the blending results. The experimental results were compared to the DEM results directly when it was feasible (the same exact blend), and indirectly for the different blend.

BLENDING PROCEDURE IN DEM

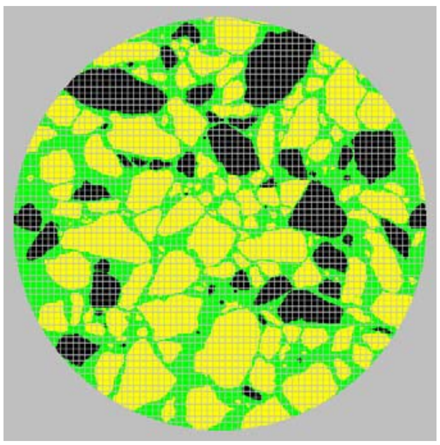
The DEM was used to study the effects of blending on the structural capacity (strength) of pavement through the indirect tensile test, as the DEM models had already been calibrated for this purpose in Phase I of the study. The DEM analysis was conducted for two different blends. The first blend consisted of the hard limestone and soft limestone (Case I), and in the second blend the sandstone was blended with the soft limestone (Case II). As it shows in the name, soft limestone is the soft material in the two blending cases. Based on the DEM study discussed in the previous reports, the ratio of the aggregate strengths is 1.70 for Case I and 2.13 for Case II.

The experimental study, as discussed in Chapter 3, consisted of blending the hard limestone with granite, and the soft limestone with sandstone. The second blend is used to provide direct comparison between the DEM and the laboratory results, while the first one is used to check if the DEM models can predict the blending results based on the aggregates blended strength ratio. Since the laboratory and DEM blends had one blend in common (similar aggregates) and one blend with different aggregates, the notation used for blending for the DEM is different using Case I for the first blend and Case II for the second.

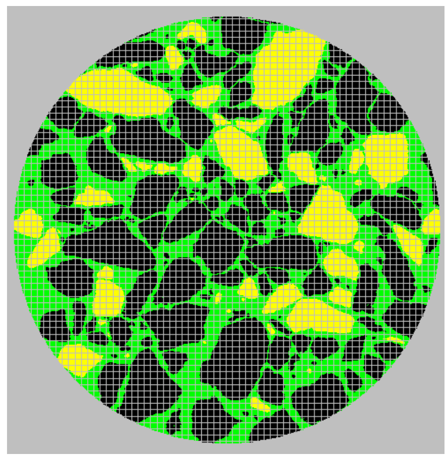
Blending two types of aggregate within one mix in the DEM was done at eleven different blending percentages of soft material ranging from 0 to 100 with an increment of 10. The model simply picked the specific percentage of soft materials randomly from all the aggregate particles within the mix and assigned the soft material properties to them. The hard material properties were assigned to all other aggregates.

Since the aggregate selection process for each experiment was random, the impact of the variability in placement of the soft and hard aggregates was studied by simulating each model multiple times at each percentage. The detailed steps are as follow:

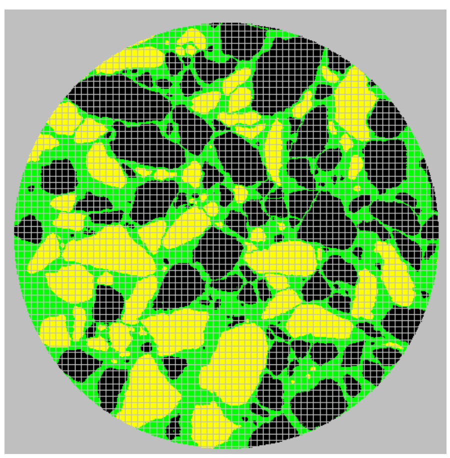
1. Create DEM models with different percentages of two aggregate types. The percentages were applied with 10% increments (hard/soft: 100/0, 90/10, 80/20, 70/30, 60/40, 50/50, 40/60, 30/70, 20/80, 10/90, 0/100). Examples of different blends are shown in Figure 4.1. The aggregate particles in a DEM structure that belong to each aggregate type were selected randomly.
2. For each blending percentage from 90/10 to 10/90, the analysis was conducted nine times (i.e. repeating Step 1 nine different times) representing different random selections of aggregates that belong to each aggregate type. Nine repetitions were considered as a good compromise between the execution time and representativeness of the results. Figure 4.2 shows the six different distributions of soft/hard limestone of a blend that consists of 30% soft limestone and 70% hard limestone. The analysis of different random distribution at the same blend was necessary because the location distribution of soft particles in an asphalt mixture would affect the results of simulating mixture performance.



30% Soft



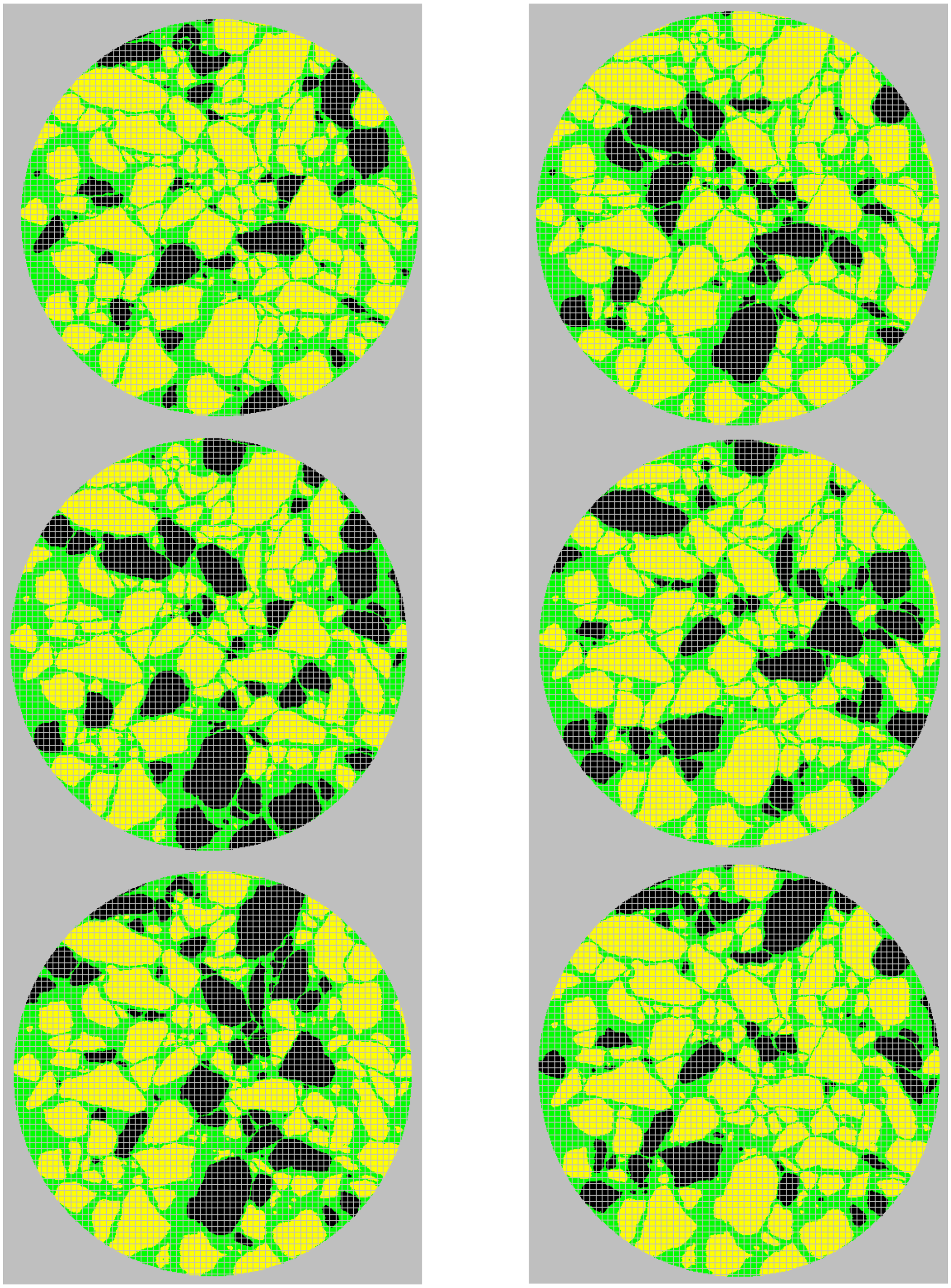
70% Soft



50% Soft

Black Particles: Soft Materials, Yellow Particles: Hard Materials

Figure 4.1 - Different Percentages of Blends of Two Aggregate Types



Black Particles: Soft Materials, Yellow Particles: Hard Materials

Figure 4.2 - Different Random Distributions of 30% of Soft Limestone (70% Hard Limestone).

BLENDING RESULTS

Case I: Soft Limestone and Hard Limestone

The blending procedure described above was done for four different mixes (PFC, CMHB-C, Type-D and Superpave-C). Each blend percentage was repeated nine times representing different location distributions of soft and hard aggregates within the mix. Therefore, the analysis allowed for calculating the mean and the standard deviation of mix strength for each blend percentage. Figure 4.3 summarizes the results for the PFC mix. The error bars represent one standard deviation. Blending 10 to 50% of the soft materials did not seem to affect the strength of the mix; however, for values between 50 and 70% the mix exhibited a drop in the mix strength.

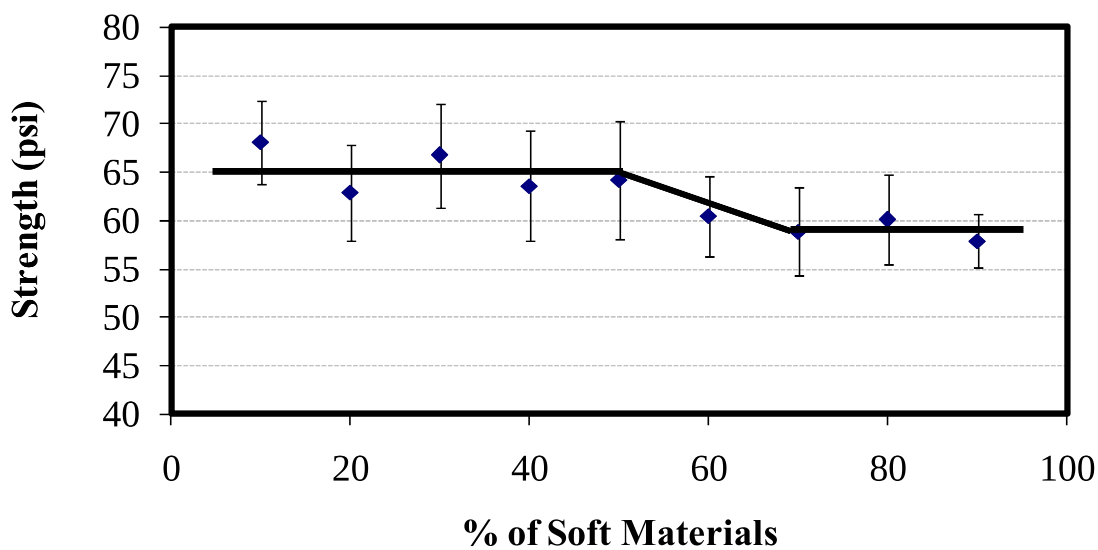


Figure 4.3 - PFC Blending Results (Case I)

The same plots for the CMHB-C, Superpave-C and Type-D mixes are shown in Figures 4.4 through 4.6, respectively. The CMHB-C mixes exhibited higher variability at the same blending percentage as compared to other mixes. As shown in Figure 4.4, the CMHB-C mix strength did not change significantly until the 60% blend, after which the strength decreased with increase in the percentage of soft materials. The trend for the Type-D mixes, as shown in Figure 4.5, is similar to the PFC mixes except that the strengths were constant up to 30% blend of soft aggregates. Between 30% to about 80% of soft aggregates, the strength decreased with the increase in the percentage of soft aggregates. Strength reached a constant value after 80% of soft limestone.

Figure 4.6 summarizes the Superpave-C mix results. The variability in the strength of the Superpave-C mix is rather small as judged by the length of the error bars. A linear decrease in the strength with the increase in the soft material percentage best described the behavior of this mix.

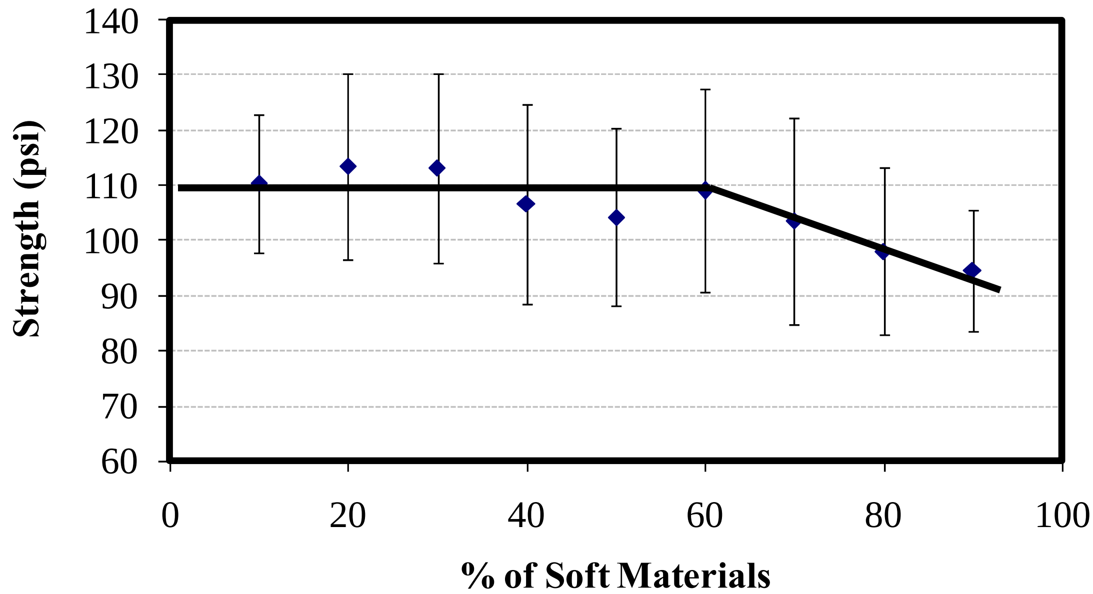


Figure 4.4 - CMHB-C Blending Results (Case I)

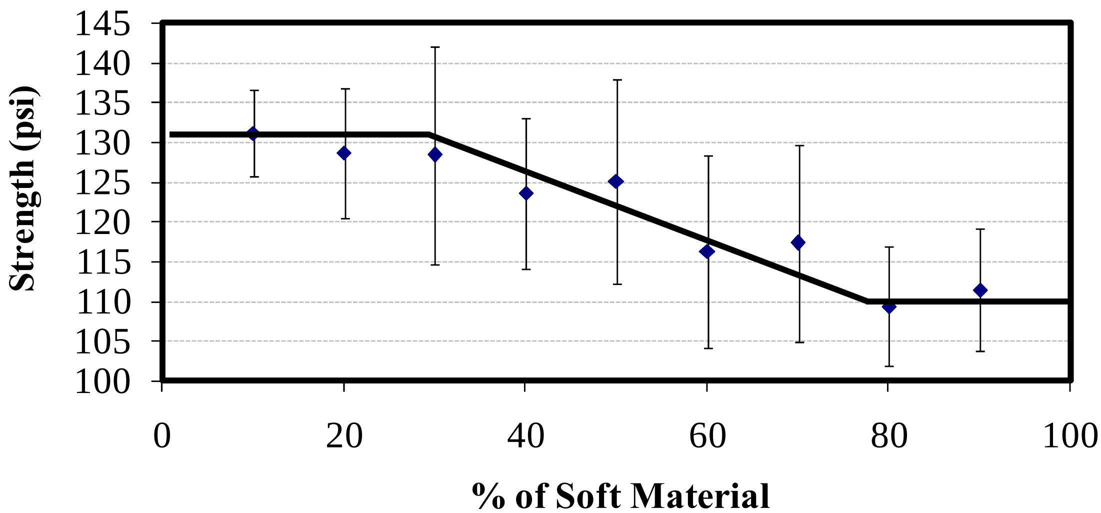


Figure 4.5 - Type-D Blending Results (Case I)

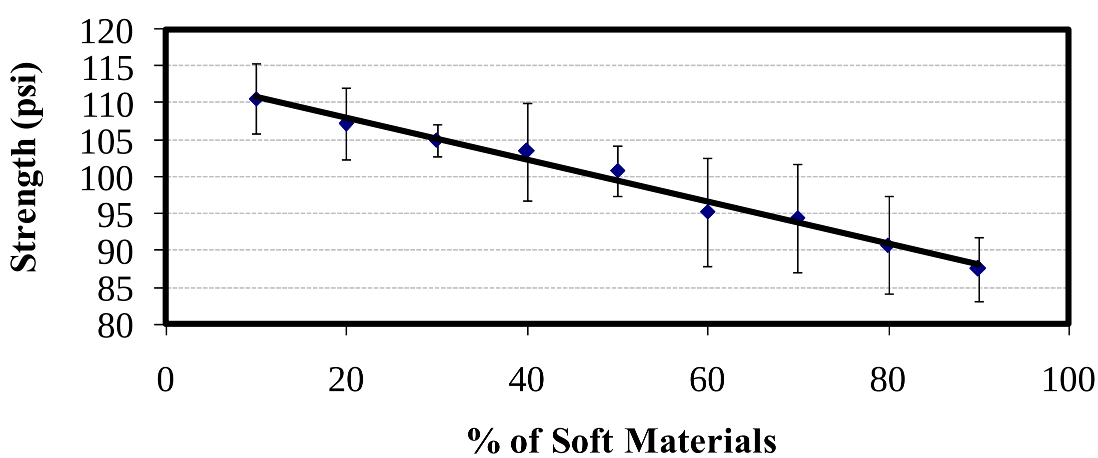
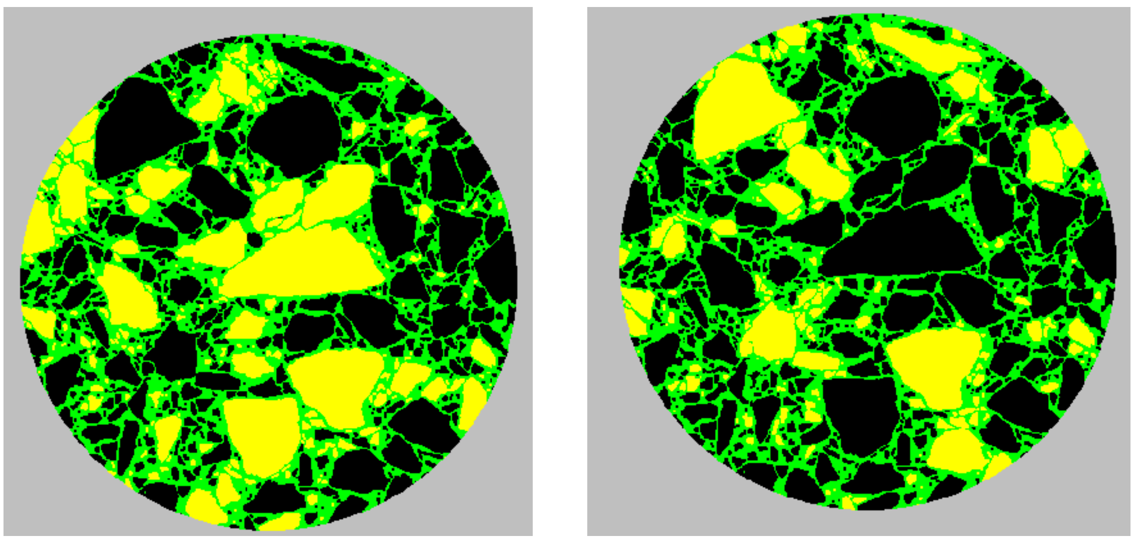


Figure 4.6 - Superpave-C Blending Results (Case I)

The random distributions of the soft and hard aggregates for the same blend percentage revealed interesting information about the effect of mixture segregation on performance. Consider the two cases shown in Figure 4.7 for two specimens with 70% soft limestone. The specimen in Figure 4.7a provided a tensile strength of 139 psi while the specimen in Figure 4.7b had a tensile strength of 82 psi. The difference in the tensile strength can be attributed to the location of soft and hard limestone in a specimen. The maximum tensile stress in the indirect tension test is normally in the center of the specimen. In Figure 4.7a, the center of the specimen has mostly hard limestone with high tensile strength; while the center of the specimen in Figure 4.7b has mostly soft limestone with low tensile strength. These results demonstrate the significance of segregation on mixture response. The error bars shown in Figures 4.3 to 4.6 indicate that the Superpave-C mixture is the least sensitive to segregation (smallest error bars) compared with the other mixtures.



a) Highest Strength b) Lowest Strength

Black Particles: Soft Materials, Yellow Particles: Hard Materials

Figure 4.7 - Different Mix Strengths at Same Blending Percentage

Case II: Sandstone and Soft Limestone

The same procedure discussed for Case I was repeated. Figure 4.8 summarizes the results for the PFC mix. Blending 10 to 40% of the soft materials did not seem to affect the strength of the mix; however, for the blending percentages between 40 and 70% the mix exhibited a drop in its strength. The trend for the PFC is the same in the two cases (hard limestone with soft limestone, sandstone and soft limestone); however, the drop in the strength started at 40% for Case II while it started at 50% for Case I. This can be attributed to the fact that there is a larger difference in strength in the two aggregates used in Case II compared with the aggregates used in Case I.

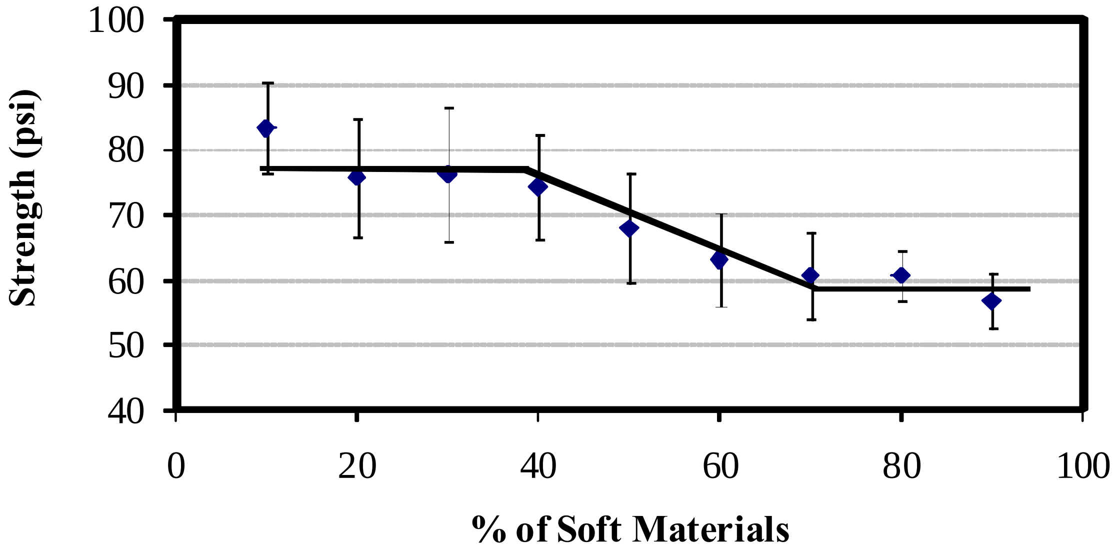


Figure 4.8 - PFC Blending Results (Case II)

Figures 4.9 through 4.11 summarize the Case II results for the CMHB-C, Type-D, and Superpave-C mixes. For the CMHB-C mix, blending 10% to around 40% of the soft materials did not seem to affect the strength of the mix; however, further addition of soft materials resulted in a drop in the mix strengths. This drop stopped after the 70% soft limestone blending point. The behaviors of the CMHB-C in Case II (Figure 4.9) and Case I (Figure 4.4) are different. This indicates that the mix response to blending could depend not only on the percentages but also on the type of materials blended.

The trend for the Type-D mixes, as shown in Figure 4.10, is similar to the Superpave-C mix. The Superpave-C mix results are summarized in Figure 4.11. The effect of blending on the Superpave-C mix is a linear decrease in the mix strength with the increase in the soft material percentage; similar to Case I. This trend is different between Case I and Case II. This supports the assumption that the mix behavior will not only depend on the blending percentages but also the type of material blended.

Comparison of Case I and Case II Results

For a better understanding of the differences between the Case I and Case II results, Figure 4.12 was generated for the four mixes to compare the impact of blending on the mixes. For all four mixes, the Case II strengths are greater than the Case I strengths. This was expected as sandstone used in Case II has a higher strength than the hard limestone used in Case I.

For the PFC and CMHB-C mixes, the curves for both cases almost meet at about 70% of soft limestone indicating that this aggregate dominates the performance at a percentage higher than 70% regardless of the strength of the harder aggregate. For these mixtures, the use of 30% of harder material or less does not contribute to improving performance.

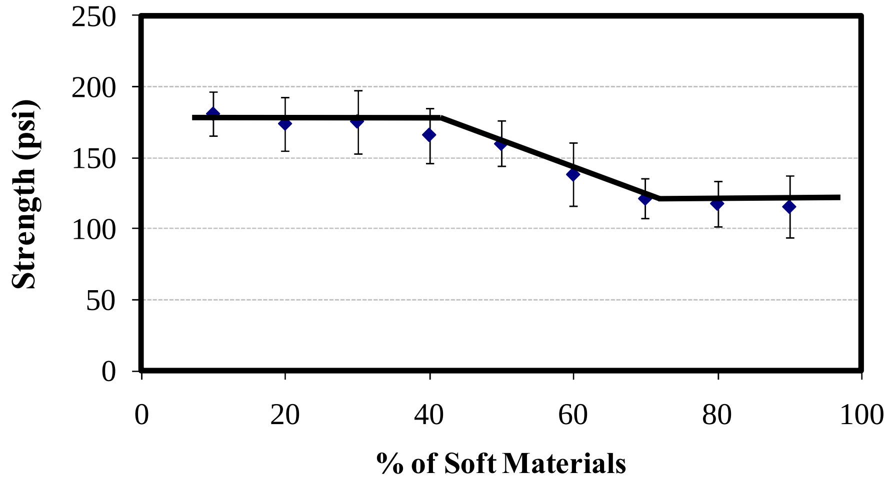


Figure 4.9 - CMHB-C Blending Results (Case II)

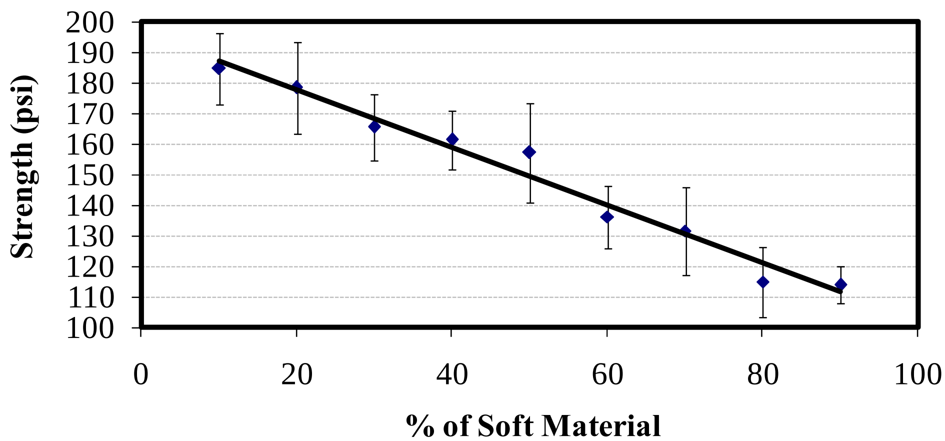


Figure 4.10 - Type-D Blending Results (Case II)

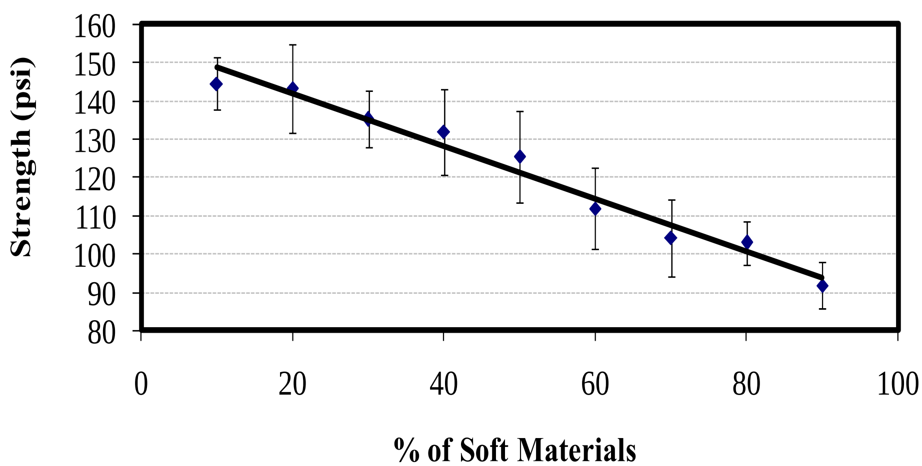
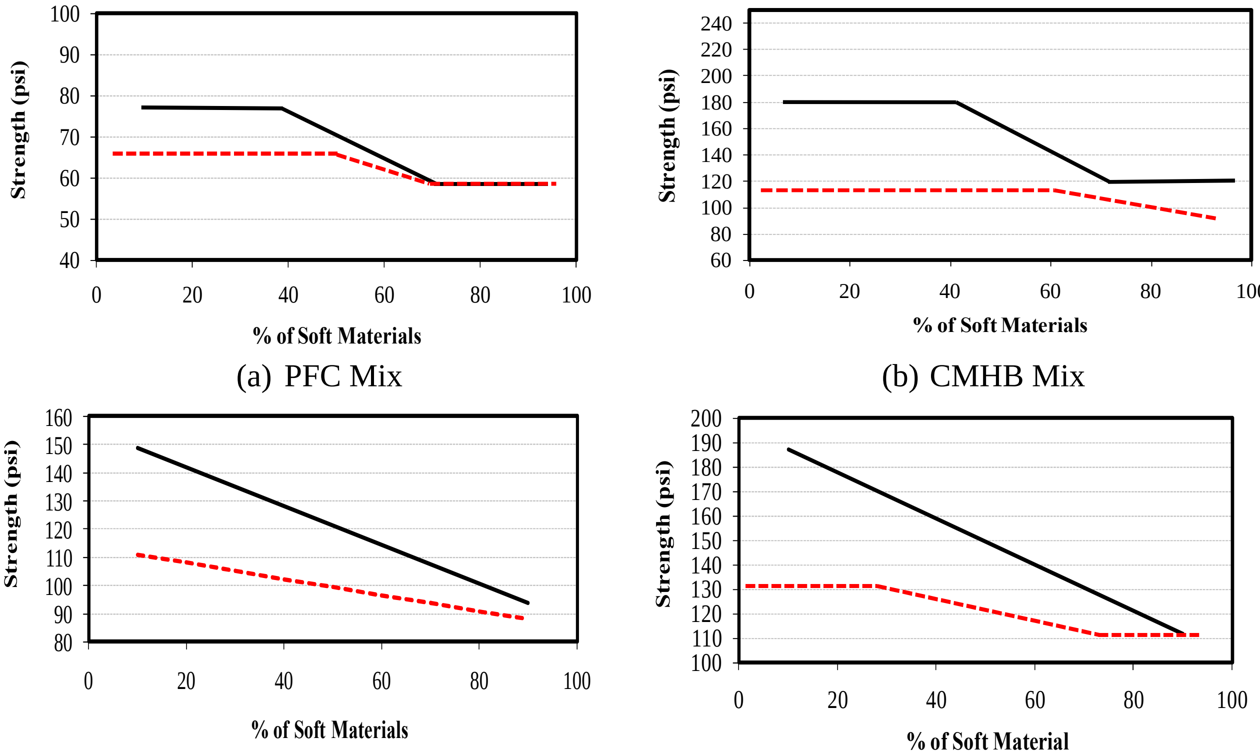


Figure 4.11 - Superpave-C Blending Results (Case II)



(a) PFC Mix

(b) CMHB Mix

(c) Superpave Mix

(d) Type-D Mix

Case I .... Case II ————

Figure 4.12 - Case I and II Blending Trend Results

The Superpave-C mix curves are both linear indicating that this mixture did not tolerate blending of soft aggregate as the CMHB-C and PFC mixes did. Finally, the Type-D curves coincide at the 90% point. This means that an addition of hard aggregate more than 10% would improve the mixture strength.

Table 4.1 summarizes the expected reduction in mixture strength given a specific percentage of soft aggregate and the ratio of the two aggregates used in the mixtures. The ratio of the two aggregates strength was calculated based on the bonding strength used in the DEM model. For Case I, the ratio of the hard limestone to the soft limestone is 1.70, while for Case II, the ratio of the sandstone to the soft limestone is 2.13. On the other hand, the reduction in the strength is calculated as the strength of the mixture with 100% hard aggregate minus the strength of the blend (at the specific blending ratio) divided by the strength of the mixture with 100% hard aggregate (reported as percentage).

Comparing the different mixes for the two blending cases in Table 4.1, the Superpave-C mix and the Type-D mix showed almost identical reduction percentages at the same soft material percentages. This can be seen visually in Figures 4.13 and 4.14 where the points in both figures almost fall along the equality lines.

Table 4.1 - Influence of Blending on Mixture Strength

Percentage of Soft Aggregate	Aggregate Strength Ratio (Hard/Soft)	Percentage Reduction in Strength Relative to Hard Aggregate Strength			
		PFC	CMHB-C	Superpave -C	Type-D
20%	Case I: 1.70	16	19	11	11
	Case II: 2.13	19	15	13	12
40%	Case I: 1.70	15	24	14	15
	Case II: 2.13	21	19	21	20
60%	Case I: 1.70	20	22	21	20
	Case II: 2.13	33	32	33	33
80%	Case I: 1.70	20	30	24	25
	Case II: 2.13	35	42	38	43

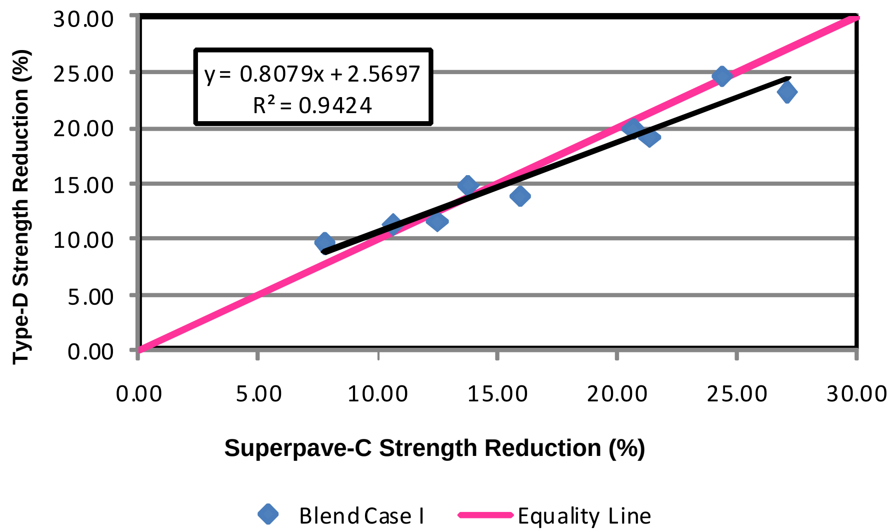


Figure 4.13 - Superpave-C vs. Type-D Strength Reduction (Case I)

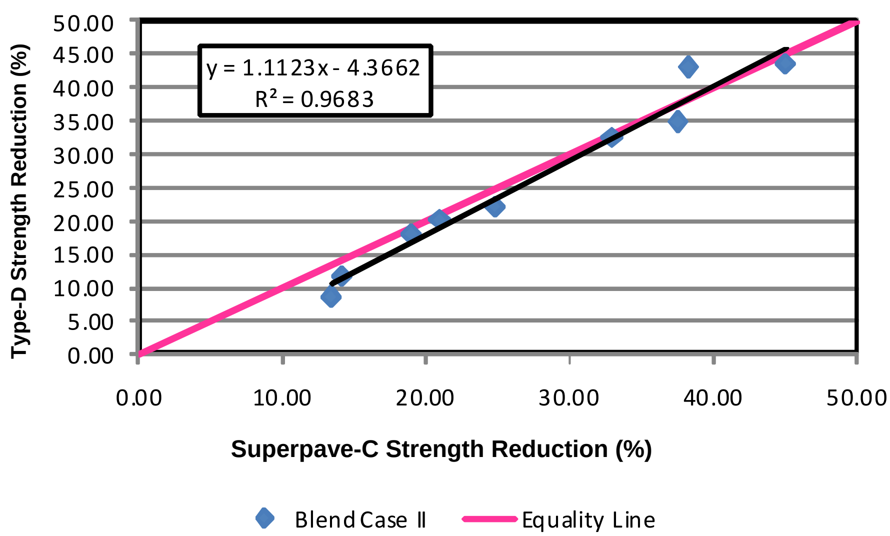
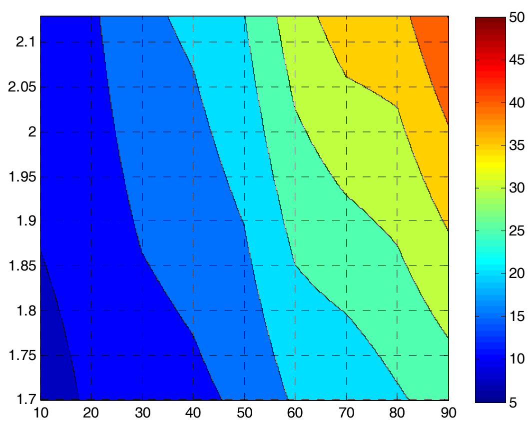


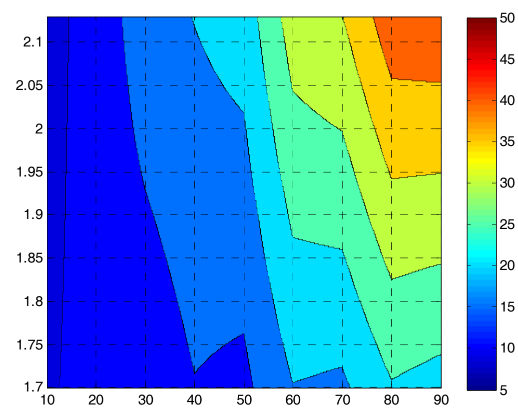
Figure 4.14 - Superpave-C vs. Type-D Strength Reduction (Case II)

In order to generalize the results of the two different blends, contour plots for the different mixes were generated. Such plots can be used to predict the change in the mix strength at the different blending percentages for different aggregate strength ratios (hard/soft). Since the two blends covered the strength ratios between 1.70 and 2.13, the contour can only cover this range of strength ratio. Figure 4.15 shows these contour representations of the strength reduction in the different mixes due to blending (increasing percentage of soft material). The x-axis represents the soft material percentage, and the y-axis represents the ratio between the hard and the soft material strength. The color indicates the percent loss in the mix strength. The y-axis, as expected, ranged between 1.70 and 2.13. This plot will allow the prediction for any of the four mixes behavior for blends with aggregate ratios in this range.

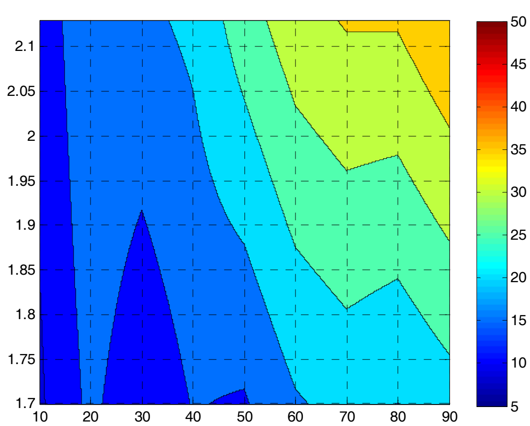
For all the different mixes, the higher proportions of the soft aggregates introduced less tolerance to adding soft materials when compared to smaller proportions, as higher percentages of reduction in rate and magnitude of strength occurs at smaller percentages of soft materials. It is easy to see how the Superpave-C and Type-D followed almost the same exact trends; the surface plots are nearly identical. This further supports the observation that the two mixes had a similar behavior when soft materials were added (in the two blending cases) drawn from Figures 4.13 and 4.14 and Table 4.1.



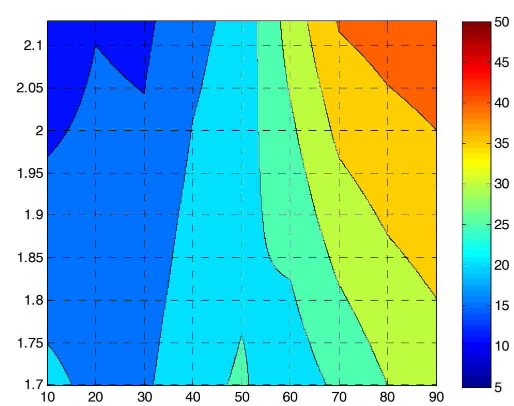
(a) Superpave-C



(b) Type-D



(c) PFC



(d) CMHB-C

Figure 4.15 - Blending Results (Contour Representation)

Comparison to Experimental Laboratory Results

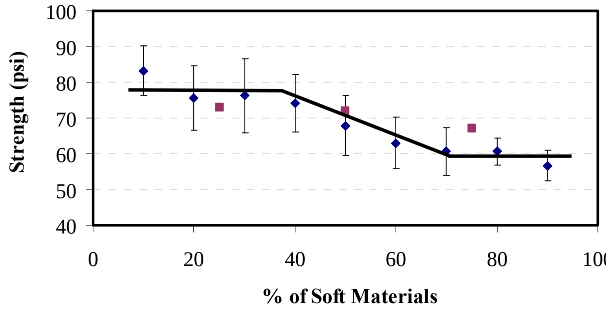
Experimental laboratory tests for blending were limited to 25, 50, and 75% as it was not feasible to study the full spectrum as in the DEM. Table 4.2 summarizes the results from the laboratory blending. The expected trend is a reduction in strength with increase in the soft material percentage. However, due to the expected variability in the laboratory testing, and the limited number of replicates (maximum of three) some points did not follow this trend. For instance, for the soft limestone-sandstone blend, the Superpave-C mix had a 215 psi strength at the 50% soft material level. This is an increase in the strength from the 25% soft material case. Irregular cases for the soft limestone-sandstone blend are designated with an (*).

Table 4.2 - Laboratory Blending Results

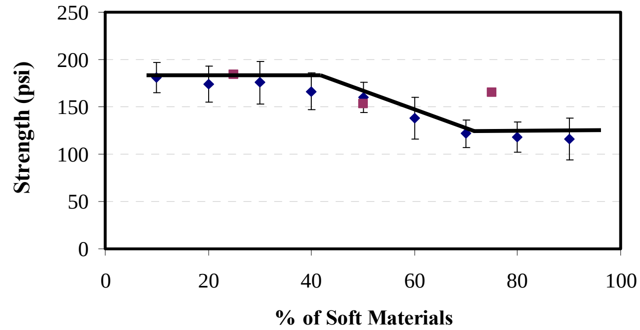
Blend	Percent of Soft Materials	Mix Strength (psi)			
		CMHB-C	Superpave-C	PFC	Type-D
Soft Limestone/ Sandstone Blend	0%	206	226	78	207
	25%	184	190	73	200
	50%	153	217*	72	177
	75%	165*	160	67	199*
	100%	94	125	50	148
Hard Limestone/ Granite Blend	0%	106	202	39	205
	25%	124	219	39	198
	50%	122	179	48.5	177
	75%	120	176	46	160
	100%	113	124	61	118

Since the soft limestone-sandstone blend is common between the experimental and the DEM analysis, their results are compared in Figure 4.16. However, since the DEM results are based on the calibration of the different mixes for single aggregate experimental results, it was necessary to assure that the results from 0 and 100% soft limestone are similar for the experimental and the DEM results. A deviation might be expected, and is accepted, when comparing the single aggregate results, but this deviation might cause the blending results to disagree. The CMHB-C and PFC results were almost identical to the DEM at the 0 and 100% percentages of soft limestone, and so no modification was needed. A multiplication factor was needed for the Type-D and Superpave-C mixes in order to bring the 0 and 100% laboratory results closer to the DEM results. The same factor was used for all the blending percentages within the same mix. The DEM results and the experimental results compare very well and almost identical excluding the experimental values with an * in Table 4.2.

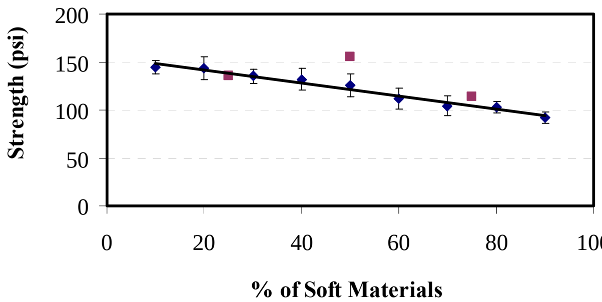
The other experimental case consisted of blending the hard limestone and granite. Since the granite is significantly stronger than the soft limestone, a one-to-one comparison is not possible. The strength ratio of granite to hard limestone is 1.36. This ratio is smaller than the two cases for DEM analysis, and thus the contour plots cannot be used in this case. Any other blend with aggregate strength ratio in the range of 1.70 and 2.13 could be compared to the DEM analysis indirectly using the contour plots in Figure 4.15. Since the strength ratio between the hard limestone and granite is small, small changes in strengths are anticipated as reflected in Chapter 3.



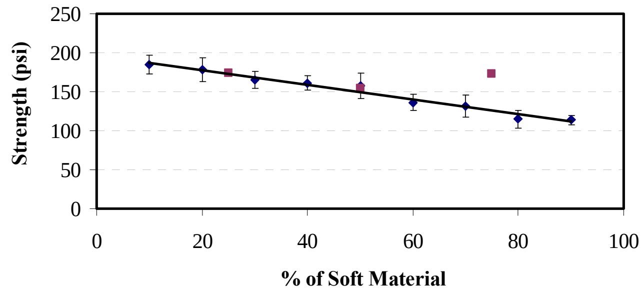
(a) PFC



(b) CMHB-C



(c) Superpave-C



(d) Type-D

Figure 4.16 - Experimental Blending Results Compared to DEM

Due to the current limitations of the DEM software, it is not possible to model the other performance indicators of the materials such as modulus and rutting potential.

SUMMARY

The impact of aggregate blending on the strength of the mixes using DEM was studied. The analysis showed that, similar to the experimental results, both the mix type and strength of aggregates used in the blend influence the performance of the mix with change in blending. The following guidelines can be developed for blending:

- The impact of blending on the indirect tensile strength of mixes is small to moderate based on the DEM analysis. The impact was more pronounced on the DEM analysis than the laboratory tests. Superpave-C and Type-D mixes are more sensitive to blending soft aggregates than open-graded (PFC) and gap-graded (CMHB-C) mixtures.
- The PFC and CMHB-C mixtures can accommodate about 40% of soft limestone without decreasing strength. This percentage could vary depending on aggregate strength but it is the minimum value that was obtained from the analysis conducted in this study.
- There is almost no benefit of using 30% or less of hard limestone or sandstone when the remaining aggregate is soft limestone.

The DEM results were compared to an actual experimental laboratory results, and they match well. However the experimental results revealed that there might be a minimum aggregate strength ratio for blending to be useful; the results available showed that a ratio of 1.4 showed insignificant change in strength; on the other hand, a ratio of 1.70 showed significant change in indirect tensile strengths with the different soft materials percentages. Based on the data available it might be recommended that a minimum strength ratio of 1.70 is needed in order for the hard material to improve the strength of the mix.

CHAPTER FIVE - SUMMARY AND CONCLUSIONS

The performance of the new generation of HMA mixtures relying on a stone-on-stone contact is influenced by the properties of the aggregate blends such as gradation and strength. As a result, aggregates have a significant and direct effect on the performance of asphalt pavements and it is important to optimize the quality of aggregates to ensure the proper performance of roadways.

The objective of this research was to evaluate the effect of stress concentrations at contact points on coarse aggregates that could cause aggregate fracture. To achieve the objective, a three phase study was conducted. In Phase I and Phase II, an extensive series of tests from geological evaluation of quarries and rocks retrieved from them, to rock strength tests, to traditional and new aggregate tests, to geotechnical strength tests were carried out on six aggregates to rank them. To establish the performance of mixes, specimens of four different mix types were prepared and subjected to a number of performance-related tests. The laboratory activities were supplemented with micro-mechanical modeling to understand the internal behavior of the mixes. Through correlation and statistical analyses, the redundant aggregate-related and performance-related tests were identified and the optimum test methods were recommended. Based on these activities, several tests for characterizing and ranking aggregates and mixes were proposed.

From the tests characterizing the aggregate strength, the ACV test and its surrogate parameters were found to correlate well with most of the tests. As a result, the ACV test seems to be the most appropriate test for characterizing the aggregates, especially since several parameters can be readily determined from the same test and the cost of implementing this test in Districts owning a concrete compressive test machine would be insignificant. The AIV test was also proven to be useful for this purpose.

One of the requirements of the project was to extend the quality control of aggregates to quarry rock masses before crushing. Both tensile and compressive strengths of the quarry rock mass seem to contribute to the quality of the aggregates. The compressive strength obtained using the Schmidt hammer seems to be appropriate for characterizing the rock mass. This test is not only easier and faster than the compressive strength test, but also eliminates the need for coring the rock and requires minimal training. Even though the Schmidt hammer test protocol (Tex-446-A) is developed for concrete, Alvarado et al. (2007) showed that the process is quite reliable for rock masses as well.

The V-meter seems to be an appropriate tool for estimating the modulus as well as the quality of the aggregates in tension. These tests can be carried out either on rock cores extracted from the quarry rock mass or alternatively can be performed on the rock mass with smooth faces as reflected in Appendix D

From the traditional tests, the Los Angeles Abrasion test, Mg Soundness test, the Micro-Deval test, and AIMS angularity after Micro-Deval are appropriate.

In Phase III of this study, the aggregate blending was studied. Two blends were studied experimentally and two based on micro-mechanical models. One blend was similar in both activities.

Considering experimental errors, a linear trend seems to match the change in the performance of the mixes with the increase in the percentage of softer materials. Therefore, one conclusion is that if the results based on any of the performance indicators are known for the 100% blends of soft and hard aggregates, then the performance indicators at any blending ratio can be estimated reasonably well.

The AIV and ACV seem to increase as the percent of soft material increases. This shows that as the percent of soft material increases, the material becomes more susceptible to crushing. The results also support the recommendation based on the results of the individual aggregates.

The results indicate that the asphalt content is a function of the quality of aggregate in the mix. As the percentage of lower quality (and perhaps more absorbent) aggregates increases, the asphalt demand increases. This matter should be factored into the decision on blending of aggregates.

Performance tests such as the IDT which measures strength, dynamic modulus and V-meter which are measures of modulus, and HWTD which measures rutting potential all seem to indicate that aggregate gradation plays a part in blending. In mixes where the gradation is coarse, such as the open-and gap-graded mixes, the aggregate hardness is reflected in the strength of the mix. When blending aggregates with similar hardness, the strength of the mix does not vary as compared to blending a soft with a hard aggregate. When the hardness of the two blends varies, the strength of the mix varies as well.

In the dense graded mixes, Superpave-C and Type-D, the strength of the mix does not seem to be as sensitive to the hardness of the aggregates, but it is sensitive to the blending ratios.

The DEM analyses, in general, validates the results of the indirect tensile strength tests performed experimentally. The variation in tensile strength with change in blending is small for most mixes. The DEM results are more sensitive to the blending ratios as compared to the experimental results.

Based on the indirect tensile test results as a performance indicator, the PFC and CMHB-C mixtures can accommodate about 40% of soft aggregates without decreasing strength. This percentage could vary depending on aggregate strength but it is the minimum value that was obtained from the analysis conducted in this study.

There is almost no benefit of blending 30% or less of the hard aggregates.

RECOMMENDATIONS

A guideline for using the findings of this study for trial basis is included in Appendix A. It should be emphasized that these observations are preliminary since the database is rather small.

In general it may be easier to compare the aggregate properties by a specific test and relate the performance to a single parameter. But a given aggregate or performance test may focus on only a specific property of the aggregates or mix. Even though more complicated, an attempt has been made here to assess the aggregate properties by a set of tests and relate the performance to multiple tests to capture the complicated interactions between asphalt and aggregate matrix. The authors feel that this approach is more rigorous. As a result, it is proposed to expand the database with more aggregate sources.

REFERENCE

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APPENDIX A - GUIDELINES FOR THE DEVELOPMENT OF HMA DESIGNS TO MINIMIZE AGGREGATE FRACTURE.

ITEM 341 (Modified)
DENSE-GRADED HOT-MIX ASPHALT (QC/QA)

341.1. Description. Construct a pavement layer composed of a compacted, dense-graded mixture of aggregate and asphalt binder mixed hot in a mixing plant.

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

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

A. Aggregate. Furnish aggregates from sources that conform to the requirements shown in Table 1, and as specified in this Section, unless otherwise shown on the plans. Provide aggregate stockpiles that meet the definition in this Section for either a coarse aggregate or fine aggregate. When reclaimed asphalt pavement (RAP) is allowed by plan note, provide RAP stockpiles in accordance with this Section.
Aggregate from RAP is not required to meet Table 1 requirements unless otherwise shown on the plans. Supply mechanically crushed gravel or stone aggregates that meet the definitions in Tex-100-E. The Engineer will designate the plant or the quarry as the sampling location. Samples must be from materials produced for the project. The Engineer will establish the surface aggregate classification (SAC) and perform Los Angeles abrasion, magnesium sulfate soundness, and Micro-Deval tests. Perform all other aggregate quality tests listed in Table 1. Document all test results on the mixture design report. The Engineer may perform tests on independent or split samples to verify Contractor test results. Stockpile aggregates for each source and type separately. Determine aggregate gradations for mixture design and production testing based on the washed sieve analysis given in Tex-200-F, Part II. Do not add material to an approved stockpile from sources that do not meet the aggregate quality requirements of the Department's *Bituminous Rated Source Quality Catalog* (BRSQC) unless otherwise approved.

1. **Coarse Aggregate**. Coarse aggregate stockpiles must have no more than 20% material passing the No. 8 sieve. Provide aggregates from sources listed in the BRSQC. Provide aggregate from nonlisted sources only when tested by the Engineer and approved before use. Allow 30 calendar days for the Engineer to sample, test, and report results for nonlisted sources.

   Provide coarse aggregate with at least the minimum SAC as shown on the plans. SAC requirements apply only to aggregates used on the surface of travel lanes, unless otherwise shown on the plans.

   The SAC for sources on the Department's Aggregate Quality Monitoring Program (AQMP) is listed in the BRSQC.

   Class B aggregate meeting all other requirements in Table 1 may be blended with a Class A aggregate in order to meet requirements for Class A materials. When blending Class A and B aggregates to meet a Class A requirement, ensure that at least 50% by weight of the material retained on the No. 4 sieve comes from the Class A aggregate source. Blend by volume if the bulk specific gravities of the Class A and B aggregates differ by more than 0.300. When blending, do not use Class C or D aggregates. For blending purposes, coarse aggregate from RAP will be considered as Class B aggregate.

2. RAP. No Changes to this Section
3. Fine Aggregate. No Changes to this Section

Table 1
Aggregate Quality Requirements

Property	Test Method	Requirement
Coarse Aggregate		
SAC	AQMP	As shown on plans
Deleterious material, %, max	Tex-217-F, Part I	1.5
Decantation, %, max	Tex-217-F, Part II	1.5
Micro-Deval abrasion, %, max	Tex-461-A	Note 1
Los Angeles abrasion, %, max	Tex-410-A	40
Magnesium sulfate soundness, 5 cycles, %, max	Tex-411-A	30
Coarse aggregate angularity, 2 crushed faces, %, Min	Tex 460-A, Part I	85[2]
Flat and elongated particles @ 5:1, %, max	Tex-280-F	10
Aggregate Crushing Value (ACV), %, Max	Tex-1XX-E	30 (Note 1)
Aggregate Impact Value (AIV), %, Max	Tex-1XX-E	30 (Note 1)
Schmidt Hammer, psi, Min	Tex-446-A	10000 (Note 1)
Ultrasonic test (V-meter), ksi, Min	Tex-254-F,draft	8000 (Note 1)
Fine Aggregate		
Linear shrinkage, %, Max	Tex-107-E	3
Combined Aggregate[3]		
Sand equivalent, %, Min	Tex-203-F	45

1. Not used for acceptance purposes. Used by the Engineer as an indicator of the need for further investigation.
2. Only applies to crushed gravel.
3. Aggregates, without mineral filler, RAP, or additives, combined as used in the job-mix formula (JMF).

B. Mineral Filler. No Changes to this Section
C. Baghouse Fines. No Changes to this Section
D. Asphalt Binder. No Changes to this Section
E. Tack Coat. No Changes to this Section
F. Additives. No Changes to this Section

341.3. Equipment. No Changes to this Section

341.4. Construction. Produce, haul, place, and compact the specified paving mixture. Schedule and participate in a prepaving meeting with the Engineer as required in the Quality Control Plan (QCP).

A. Certification. Personnel certified by the Department-approved hot-mix asphalt certification program must conduct all mixture designs, sampling, and testing in accordance with Table 4. Supply the Engineer with a list of certified personnel and copies of their current certificates before beginning production and when personnel changes are made.

Provide a mixture design that is developed and signed by a Level II certified specialist. Provide a Level IA certified specialist at the plant during production operations. Provide a Level IB certified specialist to conduct placement tests.

Table 4
Test Methods, Test Responsibility, and Minimum Certification Levels

1. Aggregate Testing	**Test Method**	**Contractor**	**Engineer**	**Level**
Sampling	Tex-400-A	√	√	IA
Dry sieve	Tex-200-F, Part I	√	√	IA
Washed sieve	Tex-200-F, Part II	√	√	IA
Deleterious material	Tex-217-F, Part I	√	√	II
Decantation	Tex-217-F, Part II	√	√	II
Los Angeles abrasion	Tex-410-A		√	
Magnesium sulfate soundness	Tex-411-A		√	
Micro-Deval abrasion	Tex-461-A		√	
Aggregate Crushing Value	Tex-1XX-E	√	√	
Aggregate Impact Value	Tex-1XX-E	√	√	
Schmidt Hammer, psi, Min	Tex-446-A	√	√	
Ultrasonic test (V-meter), ksi, Min	Tex-254-F,draft	√	√	
Coarse aggregate angularity	Tex-460-A	√	√	II
Flat and elongated particles	Tex-280-F	√	√	II
Linear shrinkage	Tex-107-E	√	√	II
Sand equivalent	Tex-203-F	√	√	II
Organic impurities	Tex-408-A	√	√	II
2. Mix Design & Verification	**Test Method**	**Contractor**	**Engineer**	**Level**
No Changes to this Section				
3. Production Testing	**Test Method**	**Contractor**	**Engineer**	**Level**
No Changes to this Section				
4. Placement Testing	**Test Method**	**Contractor**	**Engineer**	**Level**
No Changes to this Section				

B. Reporting. No Changes to this Section
C. QCP. No Changes to this Section
D. Mixture Design. No Changes to this Section
E. Production Operations. No Changes to this Section
F. Hauling Operations. No Changes to this Section
G. Placement Operations. No Changes to this Section
H. Compaction. No Changes to this Section
I. Acceptance Plan. No Changes to this Section

342.5. Measurement. No Changes to this Section

342.6. Payment. No Changes to this Section

ITEM 342 (Modified)
PERMEABLE FRICTION COURSE (PFC)

342.1. Description. Construct a surface course composed of a compacted permeable mixture of aggregate, asphalt binder, and additives mixed hot in a mixing plant.

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

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

A. Aggregate. Furnish aggregates from sources that conform to the requirements shown in Table 1, and as specified in this Section, unless otherwise shown on the plans. Provide aggregate stockpiles that meet the definition in this Section for coarse aggregate. Do not use fine aggregate or reclaimed asphalt pavement (RAP) in PFC mixtures. Supply mechanically crushed gravel or stone aggregates that meet the definitions in Tex-100-E. The Engineer will designate the plant or the quarry as the sampling location. Samples must be from materials produced for the project. The Engineer will establish the surface aggregate classification (SAC) and perform Los Angeles abrasion, magnesium sulfate soundness, and Micro-Deval tests. Perform all other aggregate quality tests listed in Table 1. Document all test results on the mixture design report. The Engineer may perform tests on independent or split samples to verify Contractor test results. Stockpile aggregates for each source and type separately. Determine aggregate gradations for mixture design and production testing based on the washed sieve analysis given in Tex-200-F, Part II. Do not add material to an approved stockpile from sources that do not meet the aggregate quality requirements of the Department's *Bituminous Rated Source Quality Catalog* (BRSQC) unless otherwise approved.

1. Coarse Aggregate. Coarse aggregate stockpiles must have no more than 20% material passing the No. 8 sieve. Provide aggregates from sources listed in the BRSQC. Provide aggregate from nonlisted sources only when tested by the Engineer and approved before use. Allow 30 calendar days for the Engineer to sample, test, and report results for nonlisted sources.

Provide coarse aggregate with at least the minimum SAC as shown on the plans. SAC requirements only apply to aggregates used on the surface of travel lanes, unless otherwise shown on the plans. The SAC for sources on the Department's Aggregate Quality Monitoring Program (AQMP) is listed in the BRSQC.

Class B aggregate, meeting all other requirements in Table 1, may be blended with a Class A aggregate in order to meet requirements for Class A materials. When blending Class A and B aggregates to meet a Class A requirement, ensure that at least 50% by weight of the material retained on the No. 4 sieve comes from the Class A aggregate source. Blend by volume if the bulk specific gravities of the Class A and B aggregates differ by more than 0.300. When blending, do not use Class C or D aggregates.

Table 1
Aggregate Quality Requirements

Property	Test Method	Requirement
Coarse Aggregate		
SAC	AQMP	As shown on plans
Deleterious material, %, max	Tex-217-F, Part I	1.0
Decantation, %, max	Tex-217-F, Part II	1.5
Micro-Deval abrasion, %, max	Tex-461-A	Note 1
Los Angeles abrasion, %, max	Tex-410-A	30
Magnesium sulfate soundness, 5 cycles, %, max	Tex-411-A	20
Coarse aggregate angularity, 2 crushed faces, %, Min	Tex 460-A, Part I	95[2]
Flat and elongated particles @ 5:1, %, max	Tex-280-F	10
Aggregate Crushing Value (ACV), %, Max	Tex-1XX-E	30
Aggregate Impact Value (AIV), %, Max	Tex-1XX-E	30
Schmidt Hammer, psi, Min	Tex-446-A	10000
Ultrasonic test (V-meter), ksi, Min	Tex-254-F,draft	8000

1. Not used for acceptance purposes. Used by the Engineer as an indicator of the need for further investigation.
2. Only applies to crushed gravel.

2. RAP. No Changes to this Section

B. Baghouse Fines. No Changes to this Section
C. Asphalt Binder. No Changes to this Section
D. Additives. No Changes to this Section

342.3. Equipment. No Changes to this Section

342.4. Construction. Produce, haul, place, and compact the specified paving mixture. When shown on the plans, schedule and participate in a prepaving meeting with the Engineer as required in the Quality Control Plan (QCP).

A. Certification. Personnel certified by the Department-approved hot-mix asphalt certification program must conduct all mixture designs, sampling, and testing in accordance with Table 2. In addition to meeting the certification requirements in Table 2, all Level II certified specialists must successfully complete an approved Superpave training course. Supply the Engineer with a list of certified personnel and copies of their current certificates before beginning production and when personnel changes are made. Provide a mixture design that is developed and signed by a Level II certified specialist. Provide a Level IA certified specialist at the plant during production operations. Provide a Level IB certified specialist to conduct placement tests.

Table 2
Test Methods, Test Responsibility, and Minimum Certification Levels

1. Aggregate Testing	Test Method	Contractor	Engineer	Level
Sampling	Tex-400-A	√	√	IA
Dry sieve	Tex-200-F, Part I	√	√	IA
Washed sieve	Tex-200-F, Part II	√	√	IA
Deleterious material	Tex-217-F, Part I	√	√	II
Decantation	Tex-217-F, Part II	√	√	II
Los Angeles abrasion	Tex-410-A		√	
Magnesium sulfate soundness	Tex-411-A		√	
Micro-Deval abrasion	Tex-461-A		√	
Aggregate Crushing Value	Tex-1XX-E		√	
Aggregate Impact Value	Tex-1XX-E		√	
Schmidt Hammer, psi, Min	Tex-446-A		√	
Ultrasonic test (V-meter), ksi, Min	Tex-254-F,draft		√	
Coarse aggregate angularity	Tex-460-A	√	√	II
Flat and elongated particles	Tex-280-F	√	√	II
2. Mix Design & Verification	**Test Method**	**Contractor**	**Engineer**	**Level**
No Changes to this Section				
3. Production Testing	**Test Method**	**Contractor**	**Engineer**	**Level**
No Changes to this Section				
4. Placement Testing	**Test Method**	**Contractor**	**Engineer**	**Level**
No Changes to this Section				

B. Reporting. No Changes to this Section
C. QCP. No Changes to this Section
D. Mixture Design. No Changes to this Section
E. Production Operations. No Changes to this Section
F. Hauling Operations. No Changes to this Section
G. Placement Operations. No Changes to this Section
H. Compaction. No Changes to this Section
I. Acceptance Plan. No Changes to this Section

342.5. Measurement. No Changes to this Section

342.6. Payment. No Changes to this Section

ITEM 344 (Modified)
PERFORMANCE-DESIGNED MIXTURES

344.1. Description. Construct a pavement layer composed of a compacted performance-designed mixture of aggregate and asphalt binder mixed hot in a mixing plant. Performance-designed mixtures are defined as either Superpave (SP) or coarse-matrix high-binder (CMHB) mixtures.

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

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

A. Aggregate. Furnish aggregates from sources that conform to the requirements shown in Table 1, and as specified in this Section, unless otherwise shown on the plans. Provide aggregate stockpiles that meet the definition in this Section for either a coarse aggregate or fine aggregate. When reclaimed asphalt pavement (RAP) is allowed by plan note, provide RAP stockpiles in accordance with this Section.
Aggregate from RAP is not required to meet Table 1 requirements unless otherwise shown on the plans. Supply mechanically crushed gravel or stone aggregates that meet the definitions in Tex-100-E. The Engineer will designate the plant or the quarry as the sampling location. Samples must be from materials produced for the project. The Engineer will establish the surface aggregate classification (SAC) and perform Los Angeles abrasion, magnesium sulfate soundness, and Micro-Deval tests. Perform all other aggregate quality tests listed in Table 1.

Document all test results on the mixture design report. The Engineer may perform tests on independent or split samples to verify Contractor test results. Stockpile aggregates for each source and type separately. Determine aggregate gradations for mixture design and production testing based on the washed sieve analysis given in Tex-200-F, Part II. Do not add material to an approved stockpile from sources that do not meet the aggregate quality requirements of the Department's *Bituminous Rated Source Quality Catalog* (BRSQC) unless otherwise approved.

1. **Coarse Aggregate**. Coarse aggregate stockpiles must have no more than 20% material passing the No. 8 sieve. Provide aggregates from sources listed in the BRSQC. Provide aggregate from nonlisted sources only when tested by the Engineer and approved before use. Allow 30 calendar days for the Engineer to sample, test, and report results for nonlisted sources.

   Provide coarse aggregate with at least the minimum SAC shown on the plans. SAC requirements apply only to aggregates used on the surface of travel lanes, unless otherwise shown on the plans. The SAC for sources on the Department's Aggregate Quality Monitoring Program (AQMP) is listed in the BRSQC.

   Class B aggregate meeting all other requirements in Table 1 may be blended with a Class A aggregate in order to meet requirements for Class A materials. When blending Class A and B aggregates to meet a Class A requirement, ensure that at least 50% by weight of the material retained on the No. 4 sieve comes from the Class A aggregate source. Blend by volume if the bulk specific gravities of the Class A and B aggregates differ by more than 0.300. When blending, do not use Class C or D aggregates. For blending purposes, coarse aggregate from RAP will be considered as Class B aggregate.

2. RAP. No Changes to this Section
3. Fine Aggregate. No Changes to this Section

Table 1
Aggregate Quality Requirements

Property	Test Method	Requirement
Coarse Aggregate		
SAC	AQMP	As shown on plans
Deleterious material, %, max	Tex-217-F, Part I	1.0
Decantation, %, max	Tex-217-F, Part II	1.5
Micro-Deval abrasion, %, max	Tex-461-A	Note 1
Los Angeles abrasion, %, max	Tex-410-A	35
Magnesium sulfate soundness, 5 cycles, %, max	Tex-411-A	25
Coarse aggregate angularity, 2 crushed faces, %, Min	Tex 460-A, Part I	95[2]
Flat and elongated particles @ 5:1, %, max	Tex-280-F	10
Aggregate Crushing Value (ACV), %, Max	Tex-1XX-E	30 (Note 1)
Aggregate Impact Value (AIV), %, Max	Tex-1XX-E	30 (Note 1)
Schmidt Hammer, psi, Min	Tex-446-A	10000 (Note 1)
Ultrasonic test (V-meter), ksi, Min	Tex-254-F,draft	8000 (Note 1)
Fine Aggregate		
Linear shrinkage, %, Max	Tex-107-E	3
Combined Aggregate[3]		
Sand equivalent, %, Min	Tex-203-F	45

1. Not used for acceptance purposes. Used by the Engineer as an indicator of the need for further investigation.
2. Only applies to crushed gravel.
3. Aggregates, without mineral filler, RAP, or additives, combined as used in the job-mix formula (JMF).

B. Mineral Filler. No Changes to this Section
C. Baghouse Fines. No Changes to this Section
D. Asphalt Binder. No Changes to this Section
E. Tack Coat. No Changes to this Section
F. Additives. No Changes to this Section

344.3. Equipment. No Changes to this Section

344.4. Construction. Produce, haul, place, and compact the specified paving mixture. Schedule and participate in a prepaving meeting with the Engineer as required in the Quality Control Plan (QCP).

A. Certification. Personnel certified by the Department-approved hot-mix asphalt certification program must conduct all mixture designs, sampling, and testing in accordance with Table 4. In addition to meeting the certification requirements in Table 4, all Level II certified specialists must successfully complete an approved SP training course.

Supply the Engineer with a list of certified personnel and copies of their current certificates before beginning production and when personnel changes are made. Provide a mixture design that is developed and signed by a Level II certified specialist. Provide a Level IA certified specialist at the plant during production operations. Provide a Level IB certified specialist to conduct placement tests.

Table 4
Test Methods, Test Responsibility, and Minimum Certification Levels

1. Aggregate Testing	**Test Method**	**Contractor**	**Engineer**	**Level**
Sampling	Tex-400-A	√	√	IA
Dry sieve	Tex-200-F, Part I	√	√	IA
Washed sieve	Tex-200-F, Part II	√	√	IA
Deleterious material	Tex-217-F, Part I	√	√	II
Decantation	Tex-217-F, Part II	√	√	II
Los Angeles abrasion	Tex-410-A		√	
Magnesium sulfate soundness	Tex-411-A		√	
Micro-Deval abrasion	Tex-461-A		√	
Aggregate Crushing Value	Tex-1XX-E		√	
Aggregate Impact Value	Tex-1XX-E		√	
Schmidt Hammer, psi, Min	Tex-446-A		√	
Ultrasonic test (V-meter), ksi, Min	Tex-254-F,draft		√	
Coarse aggregate angularity	Tex-460-A	√	√	II
Flat and elongated particles	Tex-280-F	√	√	II
Linear shrinkage	Tex-107-E	√	√	II
Sand equivalent	Tex-203-F	√	√	II
Organic impurities	Tex-408-A	√	√	II
2. Mix Design & Verification	**Test Method**	**Contractor**	**Engineer**	**Level**
No Changes to this Section				
3. Production Testing	**Test Method**	**Contractor**	**Engineer**	**Level**
No Changes to this Section				
4. Placement Testing	**Test Method**	**Contractor**	**Engineer**	**Level**
No Changes to this Section				

B. Reporting. No Changes to this Section
C. QCP. No Changes to this Section
D. Mixture Design. No Changes to this Section
E. Production Operations. No Changes to this Section
F. Hauling Operations. No Changes to this Section
G. Placement Operations. No Changes to this Section
H. Compaction. No Changes to this Section
I. Acceptance Plan. No Changes to this Section

344.5. Measurement. No Changes to this Section

344.6. Payment. No Changes to this Section

APPENDIX B - AGGREGATE CRUSHING VALUE (ACV)

Tex-1xx-E, Aggregate Crushing Value

Contents:

Section 1

Overview

The aggregate crushing value (ACV) is a method that gives a relative measure of the resistance of an aggregate to crushing under a gradually applied compressive load. In this test an aggregate specimen is compacted in a standardized manner into a steel cylinder fitted with a freely moving plunger. The specimen is then subjected to a standard loading applied through the plunger. This action crushes the aggregate to a degree which is dependent on the crushing resistance of the material. This degree is assessed by a sieving test on the crushed aggregate and is taken as a measure of the aggregate crushing value (ACV).

The method is applicable to aggregates passing the 1/2 in. (12.7 mm) sieve and retained on the 3/8 in. (9.5 mm) sieve.

A specimen is compacted in a standardized manner into a fitted steel cylinder.

Units of Measurement

The values given in parentheses (if provided) are not standard and may not be exact mathematical conversions. Use each system of units separately. Combining values from the two systems may result in nonconformance with the standard.

Section 2 Definitions

The following terms and definitions are referenced in this test method.

Section 3
Apparatus

The following apparatus is required:

- *A steel cylinder*, open-ended, of nominal 6 in. (150 mm) internal diameter with plunger and base plate of the general form and dimensions shown in Figure 1 and given in Table 1.
- *A tamping rod*, made out of straight iron or steel bar of circular cross section, 0.63 ± 0.04 in (16 ± 1 mm) diameter and 23.5 ± 0.2 in (600 ± 5 mm) long, with both ends hemispherical.
- *A balance*, of at least 6.6 lb (3 kg) capacity, readable and accurate to 0.01 lb (1 g).
- *Square-hole perforated-plate sieves*, of sizes 1/2 in. (12.7 mm) sieve, a 3/8 in. (9.5 mm), a #4 (4.76 mm), a #40 (0.42 mm), and a #200 (0.074 mm) sieve.
- *A well-ventilated oven* thermostatically controlled at a temperature of 230 ± 10 °F (105 ± 5 °C).
- *A compression testing machine*, capable of applying any force up to 112 kips (500 kN) and which can be operated to give a uniform rate of loading so that this force is reached in 10 min. (a machine that can record the load and deformation is preferred).
- *A cylindrical metal measure,* for measuring the samples, of sufficient rigidity to retain its form under rough usage and having an internal diameter of 4.5 ± 0.04 in. (115 ± 1 mm) and an internal depth of 7 ± .05 in. (180 ± 1 mm).
- *A rubber mallet.*
- *A metal tray,* of known mass large enough to contain 6.6 lb (3 kg) of aggregate.
- *A brush,* with stiff bristles.

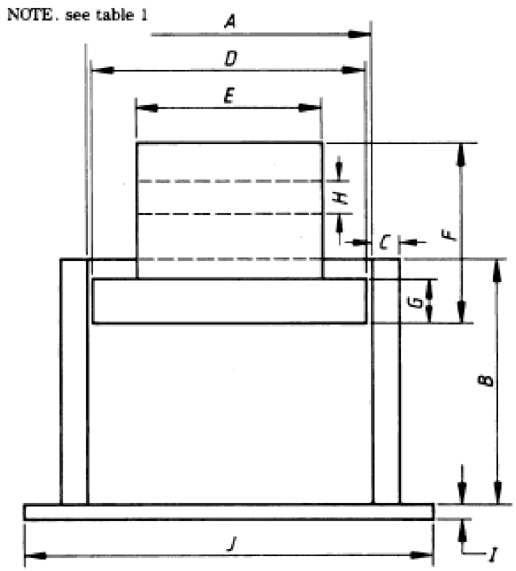


Figure 1 — Outline form of cylinder and plunger apparatus for the aggregate crushing value

Table 1 — Principal Dimensions of Cylinder and Plunger Apparatus

Component	Dimensions (see Figure 1)	Nominal 6in (150 mm) internal diameter of cylinder in	mm
Cylinder	Internal diameter, *A*	6.1 ± 0.02	154 ± 0.5
	Internal depth, *B*	5.0 to 5.5	125 to 140
	Minimum wall thickness, *C*	6.3	16.0
Plunger	Diameter of piston, *D*	5.9 ± 0.02	152 ± 0.5
	Diameter of stem, *E*	< 3.7 to ≤ *D*	< 95 to ≤ *D*
	Overall length of piston plus stem, *F*	4.0 to 4.5	100 to 115
	Minimum depth of piston, *G*	not less than 1.0	not less than 25.0
	Diameter of hole, *H*	0.75 ± 0.004	20.0 ± 0.1
Base Plate	Minimum thickness, *I*	0.4	10.0
	Length of each side of square, *J*	8.0 to 9.0	200 to 230

Section 4

Preparation of Specimen

- Produce a sample of sufficient mass to acquire three specimens of 1/2 in. (12.7 mm) and 3/8 in. (9.5 mm) size fraction.
  NOTE: A single specimen is that quantity of material required to fill the cylinder
- Thoroughly sieve the entire sample on the 1/2 in. (12.7 mm) and 3/8 in. (9.5 mm) sieves to remove the oversize and undersize fractions. Divide the resulting 1/2 in. (12.7 mm) and 3/8 in. (9.5 mm) size fractions to produce three specimens each of mass such that the depth of the material in the cylinder is approximately 4 in. (100 mm) after tamping (see note 1).
  NOTE 1: The appropriate quantity of aggregate may be found conveniently by filling the cylindrical measure in three layers of approximately equal depth. Tamp each layer 25 times, from a height of approximately 2 in. (50 mm) above the surface of the aggregate, with the rounded end of the tamping rod. Level off using the tamping rod as a straightedge.
  NOTE 2: Mechanical sieving should only be used for aggregates which do not degrade under this action.
- Dry the specimens by heating at a temperature of 230 ± 10 °F (105 ± 5 °C) for a period of not more than 4 hours. Cool to room temperature and record the mass of material comprising the specimens before testing.

Section 5
Procedure

This part explains the steps followed to perform the aggregate crushing value test.

Step	Action
1	Place the cylinder of the test apparatus in position on the base plate and add the specimen in three layers of approximately equal depth, each layer being subjected to 25 strokes from the tamping rod distributed evenly over the surface of the layer and dropping from a height approximately 2 in. (50 mm) above the surface of the aggregate. Carefully level the surface of the aggregate and insert the plunger so that it rests horizontally on this surface. Take care to ensure that the plunger does not jam in the cylinder.
2	Place the apparatus, with the specimen prepared as described in **Section 4** and plunger in position, between the platens of the testing machine and load it at as uniform a rate as possible (see note) so that the required force of 90 kips (400 kN) is reached in 10 min ± 30 s. NOTE: When, during the early stages of the test, there is a significant deformation, it may not be possible to maintain the required loading rate and variations in the loading rate may occur especially at the beginning of the test. These variations should be kept to a minimum with the principal object of completing the test in the overall time of 10 min ± 30 s.
3	Record and save time, loading, and deformation of progress of the test.
4	Release the load and remove the crushed material by holding the cylinder over a clean tray of known mass and hammering on the outside of the cylinder with the rubber mallet until the particles are sufficiently disturbed to enable the mass of the specimen to fall freely on to the tray. NOTE: If this fails to remove the compacted aggregate other methods may be used but take care not to cause further crushing of the particles. Transfer any particles adhering to the inside of the cylinder, to the base plate and the underside of the plunger, to the tray by means of a stiff bristle brush. Weigh the tray and the aggregate and determine the mass of aggregate used ($M1$) to the nearest gram.
5	Sieve the specimen on the tray with the #4 (4.76 mm), #40 (0.42 mm), and #200 (0.074 mm) sieves until no further significant amount passes during a further period of 1 min. Weigh and record the masses of the fractions passing and retained on the sieve to the nearest gram. If the total mass of the individual fractions differs from the initial mass by more than 0.05 lb (25 g), discard the result and repeat the complete procedure using a new specimen. NOTE 1: In all of the procedures described in Steps 3 and 5 take care to avoid loss of fines and overloading the sieves. NOTE 2: Mechanical sieving should only be used for aggregates which do not degrade under its action.
5	Repeat the whole procedure described in Steps 1 to 5 with a second and third test specimen.

Section 6

Calculations

- Calculate the aggregate crushing value (ACV) expressed as a percentage to the first decimal place, of the mass of fines formed to the total mass of the specimen from the following equation:

$$ACV = \frac{M_2}{M_1} \times 100\%$$

where

M_1 is the mass of the specimen (in g);
M_2 is the mass of the material passing the #4 (4.76 mm) sieve (in g).

- Calculate the aggregate passing the #4 (4.76 mm) and retained on the #40 (0.42 mm) sieve, ACV4, expressed as a percentage to the first decimal place, of the mass of fines formed to the total mass of the specimen from the following equation:

$$ACV4 = \frac{M_3}{M_1} \times 100\%$$

where

M_3 is the mass of the material passing the #4 (4.76 mm) and retained on #40 (0.42 mm) sieve (in g).

- Calculate the aggregate passing the #40 (0.42 mm) and retained on the #200 (0.074 mm) sieve, ACV40, expressed as a percentage to the first decimal place, of the mass of fines formed to the total mass of the specimen from the following equation:

$$ACV40 = \frac{M_4}{M_1} \times 100\%$$

where

M_4 is the mass of the material passing the #40 (0.42 mm) and retained on #200 (0.074 mm) sieve (in g).

- Calculate the aggregate passing the #200 (0.074 mm) sieve, ACV200, expressed as a percentage to the first decimal place, of the mass of fines formed to the total mass of the specimen from the following equation:

$$ACV200 = \frac{M_5}{M_1} \times 100\%$$

where

M_5 is the mass of the material passing the #200 (0.074 mm) sieve (in g).

- Calculate the mean of the three results to the nearest whole number for each ACV, ACV4, ACV40 and ACV200 test. Report the mean as the aggregate crushing value, unless the individual results differ by more than 0.1 times the mean value. In this case, repeat the test on a fourth specimen and calculate the median of the four results to the nearest whole number, and report the median as the aggregate crushing value.
  NOTE: The median of four results is calculated by excluding the highest and the lowest result and calculating the mean of the two middle results.

- Quantify the behavior under loading by using the data recorded during the test (if available)
  - Plot the stress-strain curve as shown in Figure 2.
  - Fit two straight lines to the stress-strain curve as shown in Figure 2.
  - Calculate the compacting modulus by using two point on the straight line covering the initial part of the stress strain curve, using the following equation:

$$Compacting\ Modulus = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1}$$

where

σ_1 is the stress for the first point chosen (in psi)
σ_2 is the stress for the second point chosen (in psi)
ε_1 is the strain for the first point chosen (in in./in.)
ε_2 is the strain for the second point chosen (in in./in.)

  - Calculate the crushing modulus by using two point on the straight line covering the final part of the stress strain curve, using the following equation:
  -

$$Crushing\ Modulus = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1}$$

where

σ_1 is the stress for the first point chosen (in psi)
σ_2 is the stress for the second point chosen (in psi)
ε_1 is the strain for the first point chosen (in in./in.)
ε_2 is the strain for the second point chosen (in in./in.)

  - Find the maximum compacting stress and strain from the stress-strain curve at the intersection of the two straight line as shown in Figure 2.

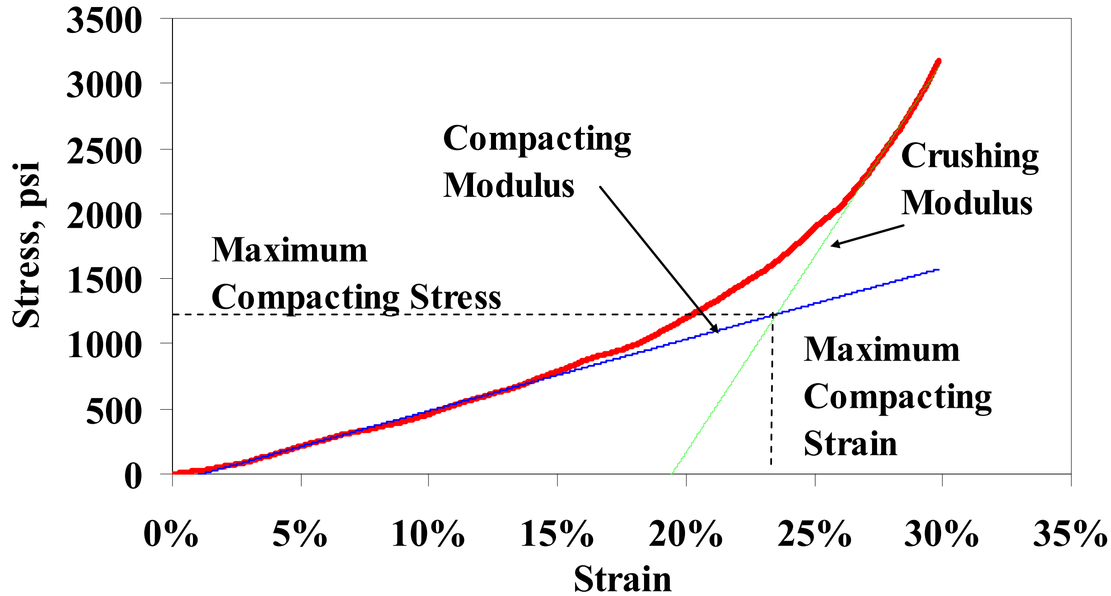


Figure 2 - Typical Results for the ACV Test

Section 7
Report

The report shall contain the following information:

- Material description of sample;
- The aggregate crushing value (ACV) of the aggregate;
- Parameters ACV4, ACV40 and ACV200
- Stress-strain curve and two lines fitted to it;
- Maximum compacting stress value;
- Maximum compacting strain value;
- Compacting modulus value;
- Crushing modulus value;

APPENDIX C - AGGREGATE IMPACT VALUE (AIV)

Tex-1xx-E, Aggregate Impact Value (AIV)

Contents:

Section 1

Overview

This specification describes methods for the determination of the aggregate impact value (AIV) which gives a relative measure of the resistance of an aggregate to sudden shock or impact.

Two procedures are described, one in which the aggregate is tested in a dry condition, and the other in a soaked condition.

The methods are applicable to aggregates passing at 1/2 in. (12.7 mm) sieve and retained on a 3/8 in. (9.5 mm) sieve.

A specimen is compacted, in a standardized manner, into an open steel cup. The specimen is then subjected to a number of standard impacts from a drop weight. This action breaks the aggregate to a degree which is dependent on the impact resistance of the material. This degree is assessed by a sieving test on the impacted specimen and is taken as the aggregate impact value (AIV).

Units of Measurement

The values given in parentheses (if provided) are not standard and may not be exact mathematical conversions. Use each system of units separately. Combining values from the two systems may result in nonconformance with the standard.

Section 2 Definitions

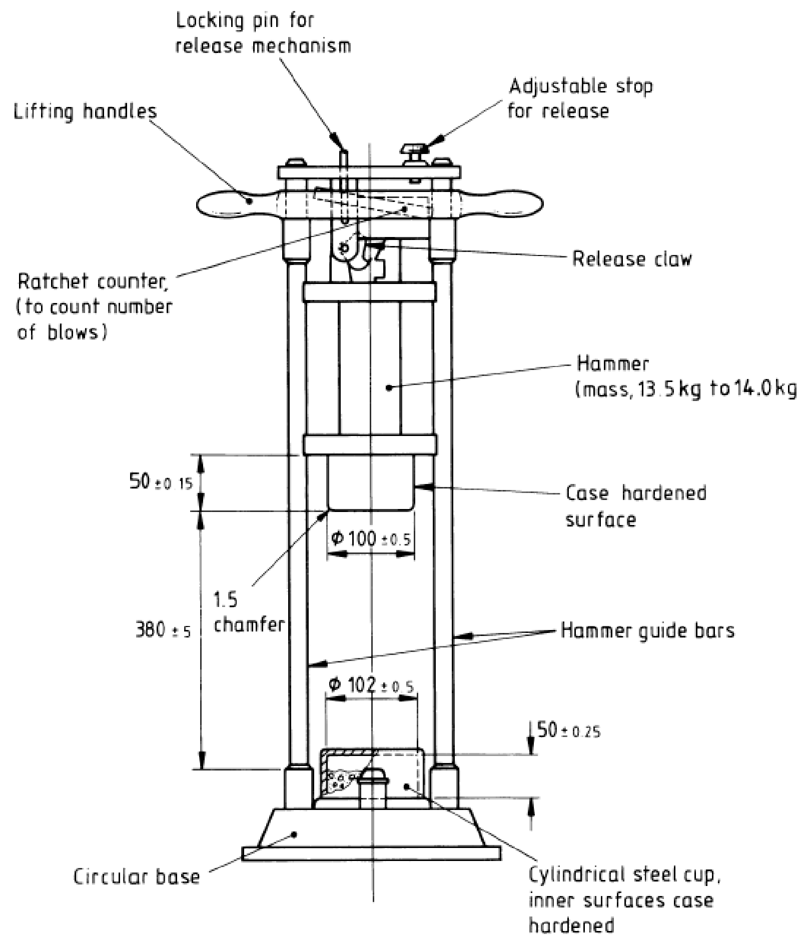
The following terms and definitions are referenced in this test method.

Section 3
Apparatus

The following apparatus is required:

- The machine shall be of the general form shown, have a total mass of between 99 lb (45 kg) and 132 lb (60 kg) and shall comprise the parts described in **Figure 1**.
- A circular metal base, with a mass of 50 lb (22.7 kg), with a plane lower surface of not less than 8 in. (200 mm) diameter and shall be supported on a level and plane concrete or stone block floor at least 18in. (450mm) thick. The machine shall be prevented from rocking either by fixing it to the block or floor or by supporting it on a level and plane metal plate cast into the surface of the block or floor.
- A cylindrical steel cup, having an internal diameter of 4.02 ± 0.02 in. (102 ± 0.5mm) and an internal depth of 2 ± 0.01 in. (50.8 ± 0.25 mm). The walls shall be not less than 0.25 in. (6.35 mm) thick and the inner surfaces shall be case hardened. The cup shall be rigidly fastened at the centre of the base and be easily removed for emptying.
- A metal hammer, with a mass of 30 lb (13.6 kg), the lower end of which shall be cylindrical in shape, 3.94 ± 0.02 in. (100 ± 0.5 mm) diameter and 2 ± 0.01 in. (50 ± 0.25 mm) long, with a 0.5 in. (1.5 mm) chamfer at the lower edge, and case hardened. The hammer shall slide freely between vertical guides so arranged that the lower (cylindrical) part of the hammer is above and concentric with the cup.
- Means for raising the hammer and allowing it to fall freely between the vertical guides from a height of 15 ± 0.2 in. (380 ± 5 mm) on to the sample in the cup, and means for adjusting the height of fall within 0.2 in. (5 mm).
- Means for supporting the hammer, whilst fastening or removing the cup.
  NOTE: Some means for automatically recording the number of blows is desirable.
- Square-hole perforated-plate sieves, of sizes 1/2 in. (12.7 mm) sieve, a 3/8 in. (9.5 mm), a #4 (4.76 mm), a #40 (0.42 mm), and a #200 (0.074 mm) sieve.
- A tamping rod, made out of straight iron or steel bar of circular cross section, 0.63 ± 0.04 in. (16 ± 1 mm) diameter and 23.5 ± 0.2 in. (600 ± 5 mm) long, with both ends hemispherical.
- A balance, of capacity not less than 1 lb (500 g) readable to 0.01 lb (0.1 g).
- A well-ventilated oven thermostatically controlled at a temperature of 230 ± 10 °F (105 ± 5 °C).
- A rubber mallet.
- A metal tray, of known mass large enough to contain 2.2 lb (1 kg) of aggregate.
- A brush, with stiff bristles.
- Additional items for testing aggregates in a soaked condition
  - Drying cloths or absorbent paper, for the surface-drying of the aggregate after it has been soaked in water, e.g. two hand-towels of a size not less than 29.5 in. × 17.7 in. (750 mm × 450 mm) or rolls of absorbent paper of suitable size and absorbency.

- One or more wire-mesh baskets, having apertures not larger than 0.25 in. (6.5 mm) or a perforated container of convenient size with hangers for lifting purposes.
- A stout watertight container, in which the basket(s) may be immersed.
- A supply of clean water, of drinking quality.



All linear dimensions are in millimetres.

Figure 1 — Aggregate impact test machine

Section 4

Preparation of Specimen

For test specimens in a dry condition

- Produce a sample of sufficient mass to acquire three specimens of 1/2 in. (12.7 mm) and 3/8 in. (9.5 mm) size fraction.

- Thoroughly sieve the entire sample on the 1/2 in. (12.7 mm) and 3/8 in. (9.5 mm) sieves to remove the oversize and undersize fraction. Divide the resulting 1/2 in. (12.7 mm) and 3/8 in. (9.5 mm) size fractions to produce three specimens each of sufficient mass to fill the container.

- Dry the specimens by heating at a temperature of 230 ± 10 °F (105 ± 5 °C) for a period of not more than 4 h. Cool to room temperature before testing.

- Fill the cup to overflowing with the aggregate comprising the specimen by means of a scoop. Tamp the aggregate with 25 blows of the rounded end of the tamping rod, each blow being given by allowing the tamping rod to fall freely from a height of about 2 in. (50 mm) above the surface of the aggregate and the blows being evenly distributed over the surface. Remove the surplus aggregate by rolling the tamping rod across, and in contact with, the top of the container. Remove by hand any aggregate which impedes its progress and fill any obvious depressions with added aggregate. Record the net mass of aggregate in the cup and use the same mass for the subsequent specimens.

For test specimens in a soaked condition

- Prepare the sample using the procedure described for dry **condition** except that the sample is tested in the as-received condition and not oven-dried. Place each specimen in the wire basket and immerse it in the water in the container with a cover of at least 50 mm (2 in.) of water above the top of the basket. Immediately after immersion remove the entrapped air from the specimen by lifting the basket 1 in. (25 mm) above the base of the container and allowing it to drop 25 times at a rate of about once a second. Keep the basket and aggregate completely immersed during the operation and for a subsequent period of 24 ± 2 h and maintain the water temperature at 70 ± 4 °F (20 ± 5 °C).

- After soaking, remove the specimen from the basket and blot the free water from the surface with the absorbent cloths. Carry out the completion of preparation and testing immediately after this operation.

Section 5
Procedure

This part explains the steps followed to perform the aggregate impact value test.

Dry Condition	
Step	Action
1	Rest the impact machine, without wedging or packing, upon the level plate, block or floor, so that it is rigid and the hammer guide columns are vertical. Before fixing the cup to the impact machine, place the specimen in the cup and then compact by 25 strokes of the tamping rod as discussed above. With the minimum of disturbance to the specimen, fix the cup firmly in position on the base of the machine. Adjust the height of the hammer so that its lower face is 15 ± 0.2 in. (380 ± 5 mm) above the upper surface of the aggregate in the cup and then allow it to fall freely on to the aggregate. Subject the specimen to a total of 25 such blows. NOTE: No adjustment for hammer height is required after the first blow.
2	Remove the crushed aggregate by holding the cup over a clean tray and hammering on the outside with the rubber mallet until the particles are sufficiently disturbed to enable the mass of the specimen to fall freely on to the tray. NOTE 1: If this fails to remove the compacted aggregate other methods should be used but take care not to cause further crushing of the particles. Transfer fine particles adhering to the inside of the cup and the underside of the hammer to the tray by means of the stiff bristle brush. Weigh the tray and the aggregate and record the mass of aggregate used (M_1) to the nearest 0.01 lb (0.1 g).
3	Sieve the entire specimen on the tray with the #4 (4.76 mm), #40 (0.42 mm), and #200 (0.074 mm) sieves until no further significant amount passes during a further period of 1 min. Weigh and record the masses of the fractions passing and retained on the sieve to the nearest 0.01 lb (0.1 g), and if the total mass differs from the initial mass by more than 0.02 lb (2 g), discard the result and test a further specimen.
4	Repeat the procedure as described in **Steps 1** to **3** inclusive using a second specimen of the same mass as the first specimen.

Soaked Condition	
Step	Action
1	Follow the test procedure described in dry condition.
2	Remove the crushed specimen from the cup and dry it in the oven at a temperature of 230 ± 10 °F (105 ± 5 °C) either to constant mass or for a minimum period of 12 hrs. Allow the dried material to cool and weigh to the nearest gram and record the mass of the specimen (M_1). Complete the procedure as described in **Step 2 for dry condition**, starting at the stage where the specimen is sieved on the #4 (4.76 mm), #40 (0.42 mm), and #200 (0.074 mm) sieves.

Section 6

Calculations

- Calculate the aggregate impact value (AIV) expressed as a percentage to the first decimal place, of the mass of fines formed to the total mass of the specimen from the following equation:

$$AIV = \frac{M_2}{M_1} \times 100$$

where

M_1 is the mass of the specimen (in g);
M_2 is the mass of the material passing the #4 (4.76 mm) sieve (in g).

- Calculate the aggregate passing the #4 (4.76 mm) and retained on the #40 (0.42 mm) sieve expressed as a percentage to the first decimal place, of the mass of fines formed to the total mass of the specimen from the following equation:

$$AIV4 = \frac{M_3}{M_1} \times 100\%$$

where

M_3 is the mass of the material passing the #4 (4.76 mm) and retained on #40 (0.42 mm) sieve (in g).

- Calculate the aggregate passing the #40 (0.42 mm) and retained on the #200 (0.074 mm) sieve expressed as a percentage to the first decimal place, of the mass of fines formed to the total mass of the specimen from the following equation:

$$AIV40 = \frac{M_4}{M_1} \times 100\%$$

where

M_4 is the mass of the material passing the #40 (0.42 mm) and retained on #200 (0.074 mm) sieve (in g).

- Calculate the aggregate passing the #200 (0.074 mm) sieve expressed as a percentage to the first decimal place, of the mass of fines formed to the total mass of the specimen from the following equation:

$$AIV200 = \frac{M_5}{M_1} \times 100\%$$

where

M_5 is the mass of the material passing the #200 (0.074 mm) sieve (in g).

- Calculate the mean of the two values from the above equations to the nearest whole number. Report the mean as the aggregate impact value, unless the individual results differ by more than 0.2 times the mean value. In this case repeat the on two further specimens, calculate the median of the four results to the nearest whole number, and report the median as the aggregate impact value.

  NOTE: The median of four results is calculated by excluding the highest and the lowest result and calculating the mean of the two middle results.

Section 7

Report

The report shall contain the following information:

- Material description of sample;
- Conditions under sample was tested, i.e. dry or soaked condition;
- Number of blows;
- The aggregate impact value (AIV) of the dry aggregate;
- The aggregate impact value (AIV) of the aggregate under soaked conditions;
- Parameters AIV4, AIV40 and AIV200

APPENDIX D – V-METER ULTRASONIC TEST (TEX-254-F)

Tex-1xx-E, DETERMINING MODULUS OF ROCK SPECIMENS WITH ULTRASONIC PULSE VELOCITY METHOD

Contents:

Section 1
Overview

This test method provides a procedure to determine the seismic modulus by means of the ultrasonic pulse velocity method. This method determines the velocity of propagation of ultrasonic energy pulse, through the material.

Units of Measurement

The values given in parentheses (if provided) are not standard and may not be exact mathematical conversions. Use each system of units separately. Combining values from the two systems may result in nonconformance with the standard.

Section 2 Definitions

The following terms and definitions are referenced in this test method.

Section 3
Apparatus

The following apparatus is required:

- The ultrasonic device consists of a pulse generator and a timing circuit, coupled with piezo-electric transmitting and receiving transducers.
- A balance with a capacity of 35 lbs (15 kg), accurate and readable to 0.001 lbs (0.5 g) or 0.1% of the test mass, whichever is greater.
- Equipment to measure dimensions of specimen, accurate to 0.004 in. (0.1 mm).

Section 4
Preparation of Specimen

Prepare specimens by either coring the rock specimens or polishing the surface.

Section 5
Procedure

Calibration

Calibration of the device shall be verified prior to use on a project using a synthetic specimen provided with the device. If the measured modulus of the calibration specimen differs by more than 2% from established values, the manufacture shall be contacted.

Test Procedure

This part explains the steps followed to perform the test.

Step	Action
1	Measure the diameter and height and mass of each specimen. Note: The average of three diameter and height measurements is recommended.
2	Place dampening pads on both transducers with grease to ensure full contact between the transducers and specimen as discussed in the manual provided with the device.
3	Place the transducers on the specimen. Apply firm pressure to the specimen with the transducers as discussed in the manual provided with the device.
4	Make sure that the travel time exhibited is stable. Note the travel time and repeat step 3 for the next specimen. Note: In order to take a more representative wave travel-time, take an average of four readings by changing the location of the transmitter and receiver.

Section 6
Calculations

- The modulus, E_V, is calculated from:

$$E_V = \frac{WH}{(\pi R^2 t_v^2)} x \frac{(1+v)(1-2v)}{(1-v)}$$

where H is the height of the specimen in in. (mm), W is the mass in lbs (Kg), R is the radius of the specimen, t_v in in. (mm) is the average travel time in microseconds, and ν is the Poisson's ratio.

Section 7
Report

The report shall contain the following information:

- Seismic modulus in ksi (MPa)