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16. Abstract

The primary locally available aggregates in the South Texas districts for highway construction are siliceous river gravels, which typically exhibit a rounded shape. The warm South Texas climate combined with heavy truck traffic aggravates any rutting problems that may occur due to the use of low angularity aggregates in hot mix asphalt (HMA) paving mixtures. The objective of this study was to determine the effect of aggregate angularity and nominal maximum size of siliceous aggregates on performance of selected HMA surface pavement mixtures. The research approach was guided by the realization that engineers can use the results for mixture design, especially for South Texas districts.

Aggregates and mixture designs were obtained from the Corpus Christi, Laredo, and Pharr Districts. The selected aggregates were characterized using image analysis, crushed face count, flat and elongated particles, and Micro-Deval tests. Researchers assessed performance of the HMA based on the simple performance tests and the Hamburg test. Comparison of aggregate properties with mixture performance yielded important information about optimal design of mixtures containing siliceous gravels.

These findings do not support the use of finer South Texas gravel mixtures (Type D and 9.5 mm) with more crushed faces in the coarse aggregate to maximize rutting resistance. In fact, the finer mixes most often demonstrated the least rutting resistance in the simple performance tests. A decrease in nominal maximum aggregate size (NMAS) may adversely affect HMA rutting resistance unless it is offset by improved aggregate shape characteristics. Type C and 12.5-mm materials generally demonstrated the optimum rutting performance in the simple performance tests, however, the fine-graded 12.5-mm mixture performed poorly in the Hamburg test. Cracking resistance of the mixes was not significantly affected by the change in NMAS.

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ANALYSIS OF SOUTH TEXAS AGGREGATES FOR USE IN HOT MIX ASPHALT

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DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Texas Department of Transportation (TxDOT) or Federal Highway Administration (FHWA). This report does not constitute a standard, specification, or regulation. Not intended for construction, bidding, or permit purposes. The engineer in charge of the project was Joe W. Button, P.E. # 40874.

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CHAPTER 1
INTRODUCTION

BACKGROUND

The primary locally available aggregates for highway construction in the Texas Department of Transportation (TxDOT) South Texas districts are siliceous river gravels. Naturally occurring gravel particles occur in various sizes and typically exhibit a rounded or subrounded shaped chert and quartzite aggregates with relatively smooth surface texture and low porosity. Aggregate processors improve the angularity and thus utility of these materials by crushing and sieving to separate them into desired size fractions. Because of the relatively small maximum size of the original coarse aggregates, the larger processed particles tend to have a small number of crushed faces. The smooth and uncrushed faces yield a low coarse aggregate angularity (CAA) value, which, in turn, can cause the hot mix asphalt (HMA) to be more rut susceptible. Coarse aggregates with a smaller top size, on the other hand, can exhibit more crushed faces and higher CAA values. Using an aggregate gradation with a smaller nominal maximum size may increase the CAA values of aggregates, but potentially at the expense of loss in shear strength of the resulting HMA mixture.

The warm South Texas climate combined with heavy truck traffic due partly to the North American Free-Trade Agreement (NAFTA) regulations aggravates any rutting problems that may occur due to the use of the low CAA gravel aggregates in HMA paving mixtures. It is therefore important to TxDOT to investigate whether adopting HMA mixture designs with smaller nominal maximum aggregate size but higher CAA can mitigate the effect of poor CAA associated with siliceous river gravels. This research addressed Task 6 of Project 0-4203, "Strategic Study for Resolving Hot Mix Asphalt Related Issues." This report describes the tests conducted and conclusions drawn from this task.

OBJECTIVE

The primary objective of this research was to determine the effect of CAA and nominal maximum size of siliceous aggregates on performance of selected HMA surface pavement mixtures. The research approach was guided by the realization that the results can be used for mixture design, particularly for South Texas districts where siliceous gravels are the only locally available material. Researchers collaborated with the project director (PD) and South

Texas districts to select the appropriate materials and mixture designs for inclusion in this research. The coarse fractions of the selected aggregates were characterized using image analysis, crushed face count, flat and elongated particles, and Micro-Deval tests. Performance of resulting HMA mixtures was assessed based on simple performance tests and the Hamburg wheel tracking device (HWTD). Comparisons of aggregate properties with mixture performances yielded important information about optimal design of mixtures containing siliceous gravels.

PREVIOUS RELATED TXDOT RESEARCH

Button and Predomo (1989) conducted a field and laboratory study for TxDOT in which one of the objectives was to quantify the influence on resistance to rutting when rounded, smooth, fine (sand-size) aggregate particles are replaced by more textured, angular, and porous particles while other aggregates and the total gradation remained unchanged. They recommended that, to avoid rut-susceptible HMA mixtures for typical dense-graded TxDOT mixtures used before 1991, one should use a maximum of 10 to 15 percent natural sand with rounded particle shapes and smooth surface textures. They pointed out that all natural sands are not created equal and that some exhibit good angularity and/or texture. They recommended the use of Type C mixtures in place of Type D mixtures for surface courses to minimize rutting. Further, they concluded that a triaxial repeated-load test that induces and measures permanent deformation was an effective method for identifying rut susceptibility of HMA mixtures (Perdomo and Button, 1991). Furthermore, they were the first to introduce image analysis for measuring aggregate shape to TxDOT.

Yeggoni et al. (1994) conducted a follow-up study for TxDOT wherein the main objective was evaluating the influence of coarse aggregate shape and surface texture on rut-susceptibility of Type C HMA mixtures. They used three aggregate types (uncrushed and crushed river gravel and crushed limestone) to create eight blends of aggregates with the same fine material, but with various coarse materials ranging from 100 percent uncrushed gravel to 100 percent crushed gravel or limestone. As expected, HMA stability and resistance to permanent deformation consistently increased, as angularity and texture of the coarse aggregate increased. Both static and dynamic creep (unconfined compression) tests exhibited good sensitivity to changes in coarse aggregate surface characteristics. Their work verified that TxDOT's then current specification, requiring that 85 percent of the particles retained on the No. 4 sieve must have two or more crushed faces. This was about optimum for rut resistance and economy. That is, the data using those particular materials repeatedly showed only small or modest changes in static or dynamic creep compliance and other measures of rut resistance when both the gravel and limestone based mixtures transitioned from 85 to 100 percent crushed faces. Moreover, they demonstrated conclusively a strong relationship between coarse aggregate angularity, as measured using image analysis, and resistance to HMA rutting.

Yildirim and Donmez (2002) performed research for TxDOT to study the effect of crushed coarse aggregate content on rutting and stripping performance of HMA. They primarily used the HWTD and the Asphalt Pavement Analyzer (APA) to study 12.5-mm and 19-mm Superpave mixtures containing 50, 85, 95, and 100 percent crushed gravel aggregates (i.e., the given percentage of particles with two or more crushed faces) and either PG 64-22 or PG 76-22 binder. Both the HWTD and the APA showed that the 12.5-mm mix containing either binder with 95 percent crushed aggregates yielded the best performance. The 19-mm mixes yielded inconsistent behavior. The 12.5-mm mix containing PG 76-22 binder showed no difference in performance of the 50, 85, and 95 percent crushed aggregates in the APA, and the 100 percent crushed aggregate mix showed only slightly poorer performance than the other three. In fact, the APA demonstrated almost no difference between any of the mixtures containing 50 and 85 percent crushed aggregate. For the 19-mm mix containing PG 64-22 asphalt, the HWTD indicated the 50 percent crushed mix was better than the 85 percent mix. Overall, the HMA mixtures containing 95 percent crushed aggregate exhibited the best HWTD and APA performance. A close examination of the findings indicates that only one mix/test combination (12.5-mm mix with PG 64-22 on the HWTD) exhibited significantly more wheel passes to failure for the 95 percent crushed mix than for the corresponding 100 percent crushed mix. Subsequent studies show significant variability in the HWTD testing process (including specimen preparation) (Chowdhury et al., 2004) and the APA testing process, particularly when using cylindrical rather than beam specimens (Kandhal and Cooley, 2003). Therefore, it appears that the more practical finding might be that there was no significant difference between the mixtures containing 95 and 100 percent crushed materials.

CHAPTER 2
DESIGN OF THE EXPERIMENT

EXPERIMENT DESIGN

Three main elements comprised the experiment design for this research:

- selection of candidate materials,
- selection of tests for assessing aggregate properties related to shape and angularity, and
- selection of tests for assessing HMA performance.

The candidate materials were selected in cooperation with the PD and three South Texas districts (Corpus Christi, Laredo, and Pharr). Three mixture designs containing materials from the same sources but with different nominal maximum aggregate sizes (NMAS) were selected from each district. The selected mixture designs were either already used in the field or were prepared for potential field application. The mixtures from Corpus Christi and Laredo were designed using the Texas gyratory compactor (TGC) with gradations as per TxDOT specifications. Mixtures from the Pharr district were designed using the Superpave gyratory compactor (SGC) and aggregate gradations meeting the TxDOT Superpave HMA requirements. Researchers selected a total of nine mixtures for this project (Table 2.1).

Since the primary focus of this research was to investigate the effect of aggregate angularity and top size on HMA mixture performance, analysis of the results was restricted to comparisons of mixtures containing aggregates from the same source (i.e., within a given district). The materials selected were, therefore, analyzed in three groups (corresponding to the three districts) with three mixes in each group. Using the same grade of asphalt for all mixes eliminated variability due to asphalt grade. Details about the aggregate gradations and mixture designs are covered later in this chapter.

A series of tests were included in the experiment design to characterize the shape and angularity of the different aggregate types. The percentage of crushed faces and flat and elongated particle tests were included, since these tests are an accepted part of the TxDOT and Superpave design requirements. Additionally, the National Cooperative Highway Research Program (NCHRP) 4-19 study (1998) suggest that engineers could use the Micro-Deval test to estimate the durability of the coarse aggregates. Image analysis of the coarse aggregates was included as one of the tools to characterize aggregate shape and angularity.

Image analysis provides a more objective measure of aggregate shape than manually counting crushed faces. Image analysis provides more useful information to quantitatively characterize the aggregates particularly for use in mathematical models for predicting HMA performance. Table 2.1 summarizes the selected HMA mixtures and tests used to characterize the coarse aggregates.

The last and most important part of the experiment design was to select tests for comparing HMA mixture performance. Since the mixtures containing rounded aggregates are typically more prone to rutting, this form of damage was considered as the key parameter in the selection of laboratory test protocols. The HWTD was selected as a torture test to assess rut susceptibility of the different mixes. The HWTD also identifies stripping or moisture damage during the loading sequence. Based on recent national studies (Witczak et al., 2002; Bhasin et al., 2003) and their recommendations, the dynamic modulus test, flow time, and flow number tests were also included to compare performance of the mixtures related to rutting. These three tests are currently referred to as the simple performance tests. Additionally, the dynamic modulus test can be used to compare relative fatigue performance of the mixtures at lower service temperatures. Table 2.2 summarizes all tests used to compare mixture performance.

Table 2.1. Tests to Examine Coarse Aggregates Properties.

Aggregate Source	HMA Mixture Type	Crushed Faces Tex-460-A	Flat & Elongated Tex-280-A	Micro-Deval AASHTO TP 58-00	Image Analysis of Coarse Aggregates*
Laredo District	Type D	X	X	X	X
	Type C	X	X	X	X
	Type B	X	X	X	X
Pharr District	9.5-mm Superpave	X	X	X	X
	12.5-mm Superpave	X	X	X	X
	19-mm Superpave	X	X	X	X
Corpus Christi District	Type D	X	X	X	X
	Type C	X	X	X	X
	Type B	X	X	X	X

* The automated aggregate imaging system (AIMS) was used.

Table 2.2. Experiment Design for Studying HMA Containing South Texas Aggregates.

Mixture Design Source	**HMA Mixture Type**	**Dynamic Modulus**	**Flow Number**	**Flow Time**	**Hamburg Tex-242-F**
Laredo District	Type D	X	X	X	X
	Type C	X	X	X	X
	Type B	X	X	X	X
Pharr District	9.5-mm Superpave	X	X	X	X
	12.5-mm Superpave	X	X	X	X
	19-mm Superpave	X	X	X	X
Corpus Christi District	Type D	X	X	X	X
	Type C	X	X	X	X
	Type B	X	X	X	X

MATERIAL SELECTION

Three HMA mixture designs were selected from each of the Corpus Christi, Laredo, and Pharr districts. The mixture designs from Corpus Christi and Laredo were designed using the TGC (Types B, C, and D) and those from Pharr were designed using the SGC (9.5-mm, 12.5-mm, and 19-mm Superpave). All mix designs for a given district used siliceous gravel aggregates from the same source but, of course, varied the nominal maximum aggregate size. These mixture designs were either existing field mixes or designed in the district with the intention of being used to surface a pavement.

The gradations for all nine mixtures are summarized and plotted along with the maximum density line in Appendix A. The reader should note that, for Corpus Christi and Laredo districts, the Type D mixtures exhibit a notably coarser shaped gradation curve than their two corresponding mixtures. For Pharr, the 12.5-mm mix exhibits a notably finer gradation curve shape than its two corresponding mixtures.

The focus of this research was to evaluate the relative effects of crushed faces and NMAS on mixture performance. It was therefore necessary to control all other sources of variability between the mixes to the maximum extent. One such factor was the asphalt grade, since all mixes were not originally designed using the same PG grade of asphalt. In some cases, the asphalt grade for the original mix designs within the same district differed. Therefore, the researchers in cooperation with the PD decided to use PG 64-22 from Eagle Asphalt for all nine HMA mixtures. Another reason for using PG 64-22 grade asphalt in this laboratory experiment was that it is more sensitive to permanent deformation or rutting tests when compared to PG 70 or PG 76 asphalt. All mixtures were redesigned using the original aggregate gradations by replacing the original asphalt with the PG 64-22 to determine the optimum asphalt content at 4 percent air voids. Redesign was performed using the TGC for the mixes from Laredo and Corpus Christi and the SGC for the mixes from Pharr. Table 2.3 provides a summary of the redesigned optimum asphalt contents for the nine mixture designs.

AGGREGATE CHARACTERIZATION TESTS

Four tests were selected to characterize properties of the aggregates used in the mix designs. These tests are:

- crushed face angularity
- flat and elongated particles
- Micro-Deval test
- image analysis

This section explains the rationale for selecting each of these tests, along with a brief description of the test methods.

Crushed Face Angularity. A crushed face angularity test is used by a large number of state departments of transportation as a routine specification test to evaluate aggregate properties (Kandhal and Mallick, 1997). This test is also included as a part of the consensus properties in the Superpave mixture design procedures.

For this study, the Tex-460-A procedure was adopted to test the aggregates for crushed face angularity. However, representative samples from individual stockpiles were not tested; rather, samples from each size fraction were individually tested, then the values were mathematically combined to obtain estimates for the coarse aggregates in the job mix blend. This procedure relies on visual segregation of aggregates with one crushed face, aggregates with two or more crushed faces, and questionable aggregates that do not fall within either of the previous groups. The percentage of crushed particles is then reported using the following equation:

Percentage of crushed particles = $100\{[N_F + (N_Q/2)]/[(N_F + N_U + N_Q)]\}$

where,

N_F = number of aggregates with two or more crushed faces,
N_U = number of aggregates with none or one crushed face,
N_Q = remaining number of questionable aggregates from the sample.

Although TxDOT includes this method as a part of routine specifications, it is not sensitive enough to distinguish between HMA mixes that use different sources of rounded gravel aggregates. Other techniques such as image analysis, discussed later in this section, were incorporated in the experiment design to address this issue.

Table 2.3. Redesigned Optimum Asphalt Contents for the Nine Mixtures Studied.

Source	HMA Mixture Type	TxDOT Mix Design from District		Design Verification at TTI	
		Asphalt Grade	Optimum Asphalt Content (%)	Asphalt Grade	Optimum Asphalt Content (%)
Laredo District	Type B	PG 76-22	4.5	PG 64-22	4.6
	Type C	PG 76-22	4.5	PG 64-22	4.5
	Type D	PG 76-22 (SBS)	4.9	PG 64-22	5.1
Pharr District	19-mm Superpave	PG 76-22	4.6	PG 64-22	5.3
	12.5-mm Superpave	PG 70-22 (S)	5.3	PG 64-22	5.3
	9.5-mm Superpave	PG 76-22	5.0	PG 64-22	5.1
Corpus Christi District	Type B	PG 76-22 (S)	4.4	PG 64-22	4.6
	Type C	PG 76-22 (S)	4.7	PG 64-22	4.8
	Type D	PG 76-22 (S)	5.1	PG 64-22	4.5

TTI = Texas Transportation Institute

Flat and Elongated Particles. Highway agencies in the United States routinely use flat and elongated particle test as a specification test to control the quality of aggregates (Kandhal and Mallick, 1997) for HMA. Estakhri et al. (2004) found that HMA containing higher quantities of flat and elongated particles yielded slightly higher permanent deformation in HWTD and APA tests; however, the higher permanent deformations were acceptable by typical state agency specifications for the HWTD and APA. Further, they demonstrated that the multiple ratio test can provide much more information about flat and/or elongated particles than the standard caliper (ASTM D 4791 or Tex-141-E).

Project NCHRP 4-19 (Kandhal and Parker, 1998) reported that none of the rutting or fatigue models that the researchers used demonstrated good correlations with flat *and* elongated aggregates; however, the percentage of flat *or* elongated particles did correlate with permanent deformation and cracking. They further stated that the test for flat *and* elongated particles measures neither flat particles nor elongated particles; it simply measures the ratio between the length and thickness of particles. Furthermore, they recommended that agencies switch from flat *and* elongated particles to flat *or* elongated particles.

For this project, the Tex-141-E procedure was adopted to characterize flat and elongated aggregate particles. This procedure estimates the percentage of particles with an aspect ratio greater than 1:3. The percentage of flat and elongated particles was not used as a basis for correlating mixture properties with flat and elongated particle content. However, it was important to estimate this quantity, as it could be an additional source of variability in the mixtures selected. In other words, the main purpose of the Tex-141-E test, as used herein, was to control aggregate properties with respect to flat and elongated particle content.

Micro-Deval Test. Kandhal and Parker (1998) identified the Micro-Deval test as a useful test to predict the durability of HMA as it can account for aggregate degradation. They concluded that the Micro-Deval and magnesium sulfate soundness tests, when used together, were able to separate good and fair aggregates from poor aggregates.

This test was conducted in accordance with Tex-461-A. The Micro-Deval apparatus subjects wet aggregates to abrasion with about 5000 grams of steel balls for about 105 minutes at 100 rpm. The degraded material (passing No.16 or 1.18-mm sieve) is removed after the test and the percent loss is reported. Higher loss of material indicates lower abrasion resistance and vice-versa. One of the purposes of this test is to estimate the influence of NMAS on abrasion resistance.

Image Analysis. The percentage crushed face test provides limited information about the aggregate shapes in the mixture. This subjective test is limited to reporting only one or two or more crushed faces and is based on visual inspection of aggregates. Further, the crushed face count does not provide any other quantitative measure relating to the aggregate shape or angularity. Image analysis of aggregate particles has proven to be a very useful tool for this research, as it is capable of providing detailed quantitative information about aggregate shape and angularity. Image analysis used exactly the same aggregates samples as in the crushed face count (Tex-460-A).

The Automated Aggregate Imaging System (AIMS) was used herein for image analysis. AIMS was designed to quantitatively measure the entire distribution of different aggregate shapes and angularities for coarse aggregates (Masad, 2003; Fletcher et al., 2003; Chandan et al., 2004). The two most important parameters from the AIMS used in this research are the shape parameter and angularity. The shape parameter or sphericity of an aggregate particle is defined by the following equation:

$$\text{Sphericity} = \sqrt[3]{\frac{d_s d_i}{d_l^2}},$$

where,
d_s is the smallest axis of the aggregate,
d_i is the intermediate axis of the aggregate, and
d_l is the longest axis of the aggregate.

Based on three-dimensional analysis, AIMS provides percentage distribution of particles with different sphericities ranging from one, indicating a perfect sphere to approximately zero, indicating a completely flat and elongated element. Figure 2.1 shows a typical distribution of sphericity. Earlier research (Masad, 2003; Fletcher et al., 2003; Chandan et al., 2004) recommends different threshold values of sphericity to distinguish between high, medium, and low sphericity and flat and elongated particles. Their recommended threshold values were used in this project and are defined in Figure 2.1. Other important information available from the image analysis is aggregate particle angularity.

AIMS uses two methods for analyzing angularity: radius method and gradient method. Results from both methods show similar trends and distributions. For the purpose of this project, the radius method was selected to quantify angularity. Figure 2.2 shows a typical distribution of different aggregate angularities.

PERFORMANCE TESTS

The aim of this project was to estimate the impact of maximum size and angularity of aggregate on hot mix asphalt performance. Most experts agree that the performance characteristic which is most affected by the presence of rounded particles in HMA is resistance to permanent deformation. Based on this, the tests selected to evaluate performance of these HMAs containing South Texas gravels were:

- dynamic modulus tests over a range of five temperatures and six frequencies to assess rut resistance at high temperature and fatigue resistance at low temperature,
- flow time or static creep test at high temperature and stress level to assess rut resistance,
- flow number or dynamic creep test at high temperature and stress level to assess rut resistance, and
- Hamburg wheel tracking test to assess rut resistance and susceptibility of the mixes to water damage.

The above-mentioned simple performance tests and the HWTD torture test can be used effectively to characterize HMA mixture performance. The following section includes a brief description of each of these tests. The dynamic modulus, flow time, and flow number tests were performed using the IPC UTM-25 machine (Figure 2.3). The HWTD test was conducted using a device manufactured by Precision Machine Works (PMW) as shown in (Figure 2.4).

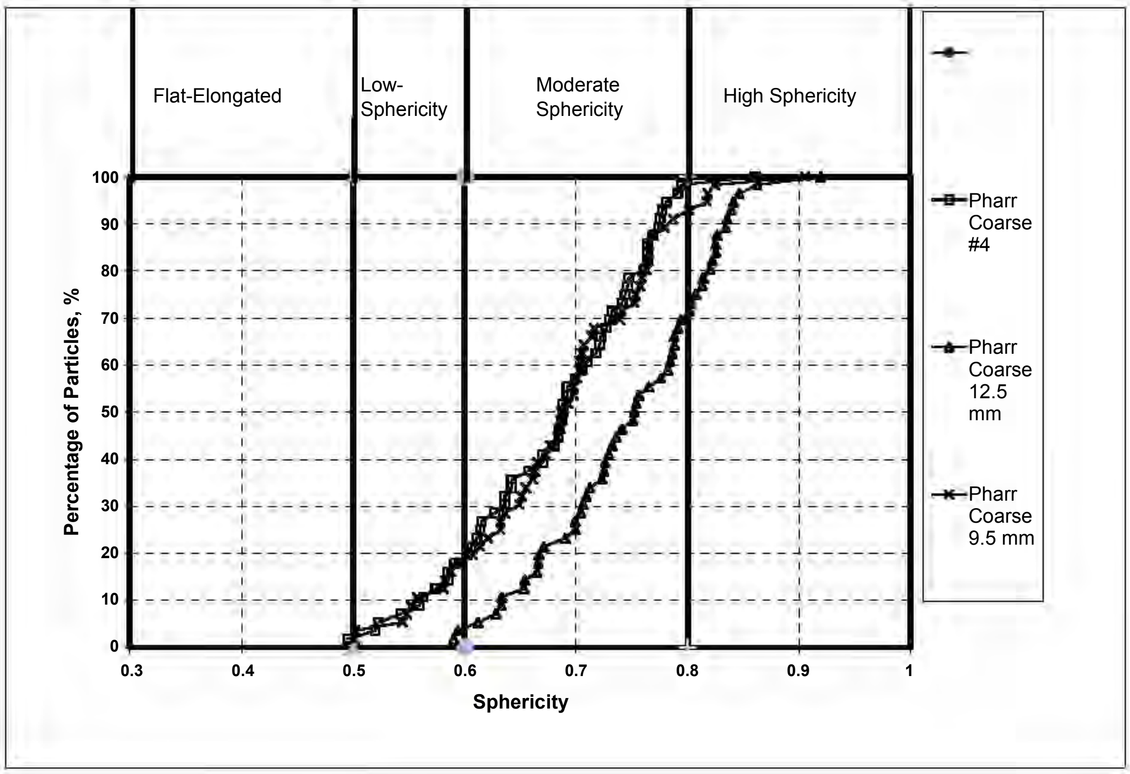


Figure 2.1. Typical Sphericity Distribution for Coarse Aggregates from AIMS.

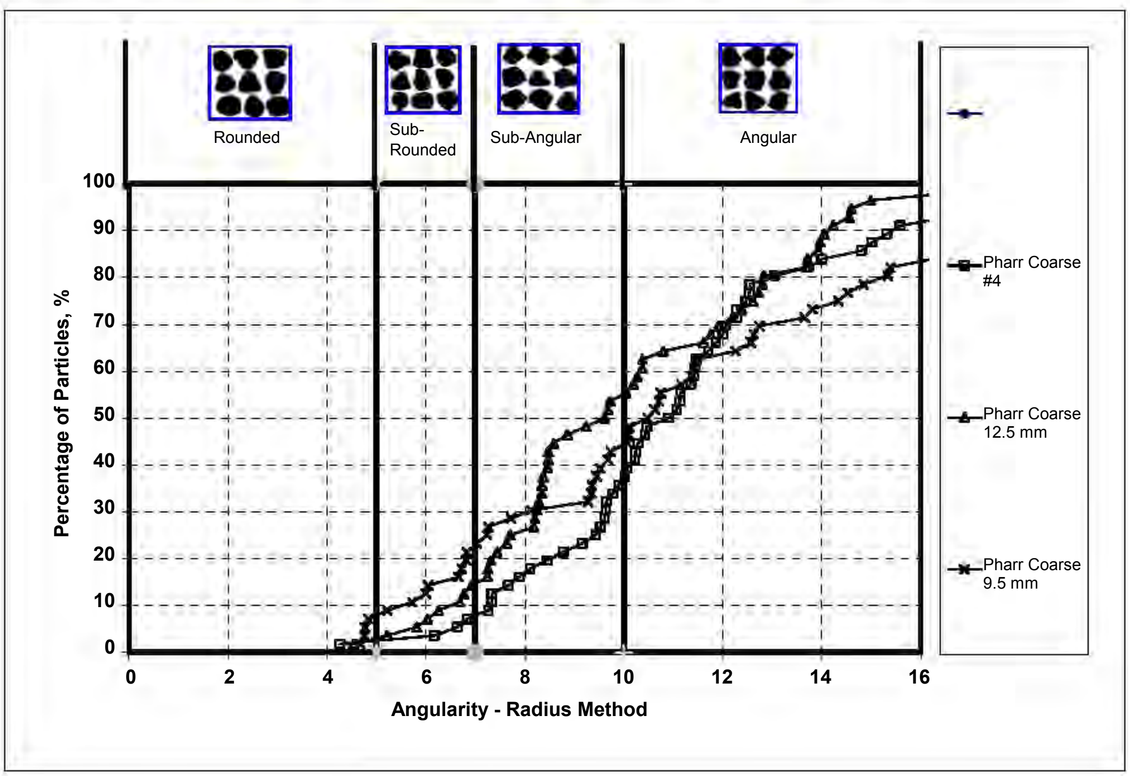


Figure 2.2. Typical Angularity Distribution of Particles from AIMS.

Figure 2.3. UTM Machine Used for Simple Performance Tests.

Figure 2.4. Hamburg Wheel Tracking Device.

Dynamic Modulus Test. The dynamic modulus test is typically performed over a range of different temperatures by applying sinusoidal loading at different frequencies to a confined or unconfined specimen. The typical parameters derived from this test are complex modulus (E*) and phase angle (ϕ). E* is a function of the storage modulus (E′) and loss modulus (E″). Typically, the magnitude of the complex modulus is represented as:

$$|E^*| = \frac{\sigma_0}{\varepsilon_0}$$

where,
σ_0 = axial stress and
ε_0 = axial strain.

Phase angle can be used to assess the storage and loss moduli.

In this task, tests were conducted in accordance with recommendations from NCHRP Project 1-37A, "Draft Test Method for Dynamic Modulus Test," at 25, 10, 5, 1, 0.5, and 0.1 Hz; and 14, 40, 70, 100 and 130°F (Wizczak et al., 2002). The stress level for measuring dynamic modulus was chosen in order to achieve the measured resilient strain within a range of 50 to 150 microstrain. Each test was performed in order of lowest to highest temperature and highest to lowest frequency of loading at each temperature to minimize specimen damage.

The data generated were used for plotting a master curve using the sigmoidal curve fitting function as Pellinen (2002) demonstrates. The sigmoidal function used is shown below:

$$\log(|E^*|) = \delta + \frac{\alpha}{1 + e^{\beta - \gamma \log(\xi)}}$$

where,
|E*| = dynamic modulus,
ξ = reduced frequency,
δ = minimum modulus value,
α = span of modulus values,
β = shape parameter, and
γ = shape parameter.

Parameters from the dynamic modulus test that were used for evaluation in this project are:

- $E^*/\sin \phi$ at 1 Hz and 130°F to compare the rutting potential. The researchers selected these test parameters based on previous research by Witczak et al. (2002) and Bhasin et al. (2003).
- $E^* \sin \phi$ at 10 Hz and 14°F to compare the cracking potential of the different mixes, which is based on previous work by Witczak et al. (2002).

Flow Time (Static Creep). NCHRP Project 9-19 (Witczak et al., 2002) recommended the flow time test as one of the tests to measure the fundamental properties of HMA related to rutting performance. The aim of this test is to measure the visco-elastic response of an HMA specimen under a static stress. This test can be performed in a confined or unconfined condition. The total compliance at any given point in time is calculated as the ratio of the measured strain to the applied stress.

Kaloush and Witczak (2002) described three basic zones in a typical plot of the compliance versus time curve on a log-log scale, i.e., primary, secondary, and tertiary. The primary zone is where the strain rate decreases sharply under static load and tends to stabilize reaching the secondary zone. In the secondary zone, the strain rate remains almost constant under the applied static load and starts increasing in the tertiary zone. Figure 2.5 shows these three zones. Since the applied stress level is constant, the rate of change of compliance corresponds to the strain rate. A graph of rate of change of compliance versus loading time on a log-log scale (Figure 2.6) clearly shows the point of minimal rate of change, which corresponds to the starting point of the tertiary zone. The time corresponding to the start of the tertiary zone is referred to as the flow time. Based on the above description, flow time can therefore be considered as the time when the rate of change of compliance is the lowest.

Typically, the total compliance, $D(t)$, in the secondary zone at any given time, can be expressed as a power function as follows:

$D(t) = at^m$,

where,

a and m = regression constants, and

t = time.

The regression constants are obtained by plotting compliance versus time on a log-log scale in the secondary zone.

The above expression on a log-log scale can be rewritten as:

$\log D(t) = m \log(t) + \log(a)$,

where,

m = slope of the curve on a log-log scale, and

log(a) = intercept.

In the present study, the static creep test was conducted at only one temperature of 130°F. All HMA specimens were tested at this temperature in order to provide a uniform basis for comparison.

A stress level of 20 psi was selected for the test. This stress level was selected based on trial tests conducted on representative specimens in order to ensure that most of the specimens would exhibit tertiary flow within a reasonable testing time.

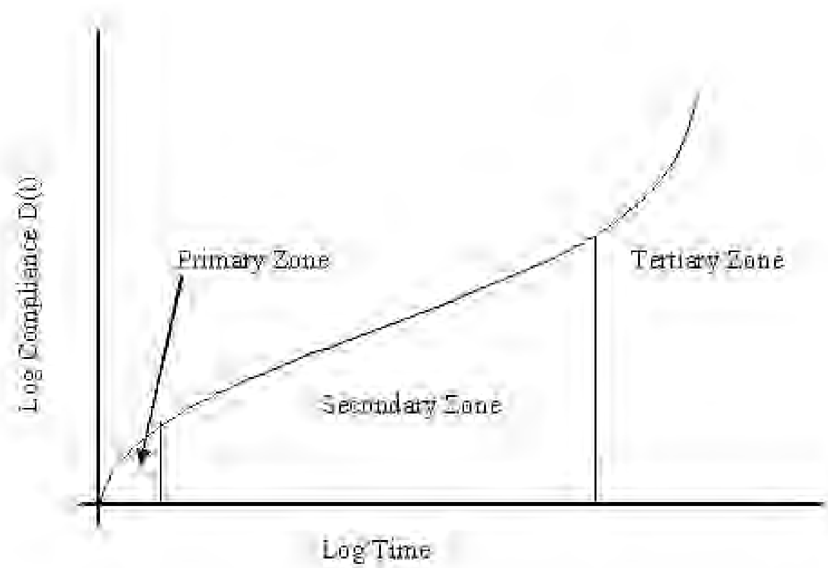


Figure 2.5. Compliance versus Time Curve on a log-log Scale.

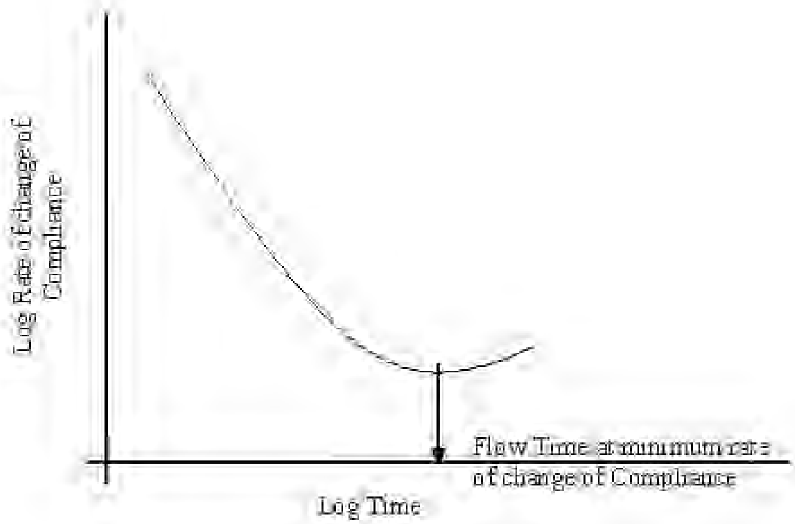


Figure 2.6. Rate of Change of Compliance versus Time on log-log Scale.

The parameters used for comparing rutting performance of the mixes include:

- flow time value, which corresponds to the start of the tertiary flow or the time at which the rate of change of compliance is minimum, and
- slope parameter: m.

Flow Number (Dynamic Creep). The flow number test was used to compare relative rutting performance of the HMA mixtures. This test is different from the static test in that it involves application of a specific stress level in a dynamic form and it provides for periodic recovery of the specimen. The stress is typically applied in a sinusoidal (i.e., haversine) waveform with a wavelength of 0.1 seconds followed by a rest or dwell period of 0.9 seconds. Each load cycle is composed of stress application followed by a rest period with no load. The flow number test was performed at 130°F using a peak load of 20 psi.

Permanent strain data from the test were recorded and plotted against the number of load cycles. A typical plot is similar to that in the static creep test with a primary, secondary, and tertiary zone. Permanent strain is expressed as a power function in terms of the number of cycles as follows:

$\varepsilon_p = aN^b$

where,

a and b = regression constants, and

N = number of load cycles.

On a log-log scale, the equation is:

$\log \varepsilon_p = \log a + b \log N$

The intercept and slope on the log-log plot of plastic strain versus number of load cycles thus represents log a and b, respectively. In this study, the following parameters are used to compare rutting performance of the mixtures tested:

- flow number, and
- slope parameter 'b'.

Hamburg Wheel Tracking Device. In the HWTD test, a 8.0-inch diameter and 1.85-inch wide steel wheel loaded with 158 pounds oscillates over two adjacent SGC-compacted specimens 2.5 inches in height and submerged in water at 122°F. Permanent deformation of each specimen is recorded with reference to the number of passes of the loaded wheel. Mixtures showing excessive susceptibility to moisture damage tend to undergo stripping and may exhibit a sudden increase in the slope of a plot of rut depth versus the number of passes after a certain number of cycles. If a mixture exhibits stripping, then the final deformation value cannot be used directly for comparison of permanent deformation characteristics of other tests. Figure 2.7 shows a description of typical HWTD results.

For HMA containing PG 64-22 asphalt, TxDOT specifications require that the HWTD rut depth be less than 0.5 inch at 10,000 passes. In this experiment, the HWTD test was used to compare rut depths at 10,000 cycles and to identify any mixtures that were susceptible to water damage.

SPECIMEN PREPARATION AND CONDITIONING FOR HMA TESTS

For the dynamic modulus, flow time, and flow number tests, the specimens were 4 inches in diameter and 6 inches in height with a gauge length of 4 inches. Technicians prepared these specimens by coring and sawing the ends of 6-inch diameter and 7-inch height specimens, which were compacted using an SGC. Air voids in the cored and finished specimen were maintained between 6 and 8 percent. Two replicates with three linear variable differential transformers (LVDTs) glued on each specimen were used for each of these tests in accordance with recommendations from Witczak et al. (2002).

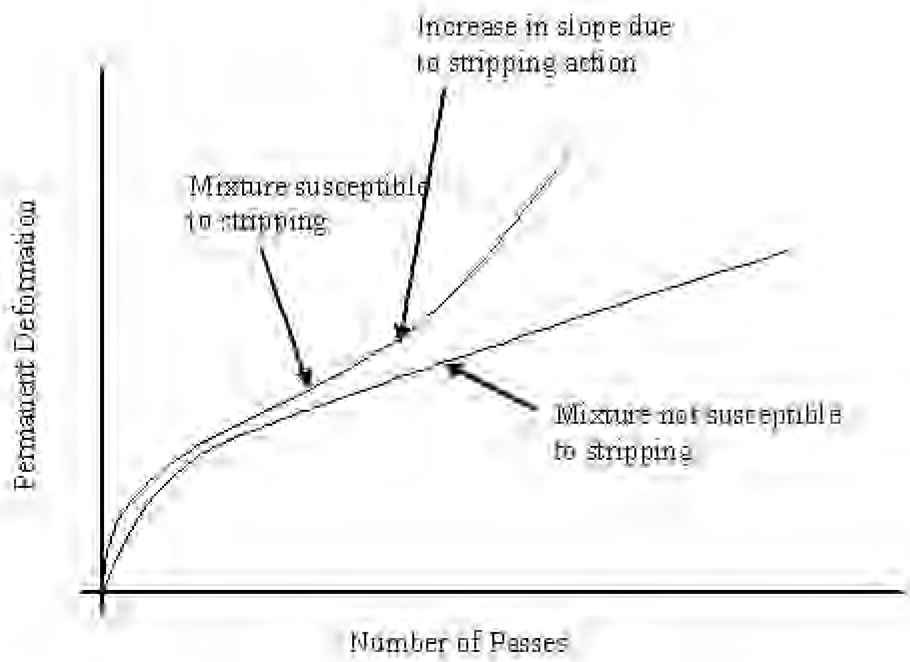


Figure 2.7. Typical Hamburg Wheel Tracking Results.

The dynamic modulus test was performed at five different temperatures. For each test temperature, the HMA specimens were conditioned to ensure that the core temperature of the specimen had reached the desired test temperature. This was accomplished using a dummy specimen in the environmental chamber with a thermocouple near its center. Care was taken to avoid prolonged heating of specimens at higher test temperatures. Similar specimen conditioning procedures were followed for flow number and flow time.

For all HWTD tests, specimens were prepared in accordance with Tex-242-F. Cylindrical specimens were compacted using the SGC to 7 ± 0.5 percent air voids.

CHAPTER 3
TEST RESULTS

RESULTS FOR AGGREGATE PROPERTIES

Table 3.1 shows results obtained from the flat and elongated particles and Micro-Deval tests on the coarse gravel aggregates. As mentioned previously, the flat and elongated particles and Micro-Deval tests were designed to ensure that the aggregates in HMA meet the durability criteria. Percentage crushed particles and data from AIMS (sphericity and angularity) were intended to provide quantitative information about aggregate shape that can be used for direct correlations with the HMA mixture properties. These tests were conducted separately on each size fraction of the material.

Table 3.1. Results from Micro-Deval and Flat and Elongated Tests on Coarse Gravel Particles.

District	Aggregate Size	Avg. % loss in Micro-Deval test	Flat and Elongated Particles, % > 1:3
Laredo	Galo Pit Type B	3.52	7
	Galo Pit Type C	3.61	7
	Galo Pit Grade 4	3.59	6
Pharr	Grade 3	3.21	5
	Grade 4	3.66	6
	Grade 6	4.51	5
Corpus Christi	7/8" – 1/2"	2.31	5
	3/4" – 1/2"	3.36	6
	1/2" – 1/4"	2.41	7

Table 3.2 shows results from the crushed face count tests for each size fraction tested from each of the three districts. These tests were performed by a technician and again by one of the authors because there was concern that most of these aggregates did not meet the TxDOT criteria (85 percent with two or more crushed faces). NCHRP Project 4-30A, a study of test methods to measure aggregate shape, found that a similar laboratory protocol (ASTM D 5821) for determining percentage of particles with two or more fractured faces yielded by far the highest coefficient of variation (1s percent for reproducibility = 115 percent) of several protocols evaluated (Masad et al., 2004). Other coarse aggregate test protocols included AASHTO TP 56 (uncompacted void content of coarse aggregates) and ASTM D 5821 (percentage of particles with zero, one, and questionable fractured faces). Since TxDOT had likely approved these aggregates, these unexpected data are attributed to the high between-laboratory variability of the test.

Table 3.2. Percentage Crushed Faces.

District	Size Fraction	Crushed Particles, %
Laredo	1" - 5/8"	70
	5/8" - 3/8"	79
	3/8" - No. 4	88
Corpus Christi	1" - 7/8"	75
	7/8" - 5/8"	82
	5/8" - 3/8"	80
	3/8" - No. 4	89
Pharr	19 mm - 12.5 mm	70
	12.5 mm - 9.5 mm	69
	9.5 mm - No. 4	85

This experiment used AIMS to obtain the sphericity distribution for the different size fractions of coarse aggregates from each district. The aggregates were divided into the following four groups based on this distribution:

- high sphericity (sphericity between 0.8 and 1.0),
- medium sphericity (between 0.8 and 0.6),
- low sphericity (sphericity between 0.6 and 0.5), and
- flat and elongated (sphericity less than 0.5).

Table 3.3 summarizes the percentage of aggregates in each of these groups for each size fraction. To quantify the change in spherical particles in a HMA mix with a change in NMAS, percentage of aggregates with high sphericity was considered as a reasonable shape parameter.

Table 3.3. Sphericity Distribution of Aggregates Determined Using AIMS.

District	Size Fraction	Flat and Elongated, %	Low Sphericity, %	Medium Sphericity, %	High Sphericity, %	Total, %
Laredo	1" - 5/8"	1.8	7.1	67.9	23.2	100
	5/8" - 3/8"	0	10.7	69.6	19.7	100
	3/8" - No. 4	3.5	9	75	12.5	100
Corpus Christi	1" - 7/8"	3.5	0	59	37.5	100
	7/8" - 5/8"	0	1.8	76.8	21.4	100
	5/8" - 3/8"	0	12.5	75	12.5	100
	3/8" - No. 4	3.6	21.4	66.1	8.9	100
Pharr	19 mm - 12.5 mm	0	3.6	66.1	30.3	100
	12.5 mm - 9.5 mm	0	17.8	73.2	9	100
	9.5 mm - No. 4	1.8	16.1	80.3	1.8	100

Distribution of angularity was also measured with AIMS using the radius method. The aggregates were divided into the following four groups based on this distribution:

- rounded (radius parameter less than 5),
- sub rounded (radius parameter between 5 and 7),

- sub angular (radius parameter between 7 and 10), and
- angular (radius parameter greater than 10).

Table 3.4 summarizes the percentage of aggregates in each of these groups for each size fraction. To quantify the change in particle angularity in an HMA mix with a change in NMAS, the percentage of rounded aggregates and percentage of rounded + subrounded aggregates were considered as two reasonable parameters.

Table 3.4. Angularity Distribution of Aggregates Determined Using AIMS.

District	Size Fraction	Angular, %	Sub Angular, %	Sub Rounded, %	Rounded, %	Total, %
Laredo	1" - 5/8"	32.1	35.8	16.0	16.1	100
	5/8" - 3/8"	33.9	32.2	24.9	9	100
	3/8" - No. 4	58.9	25.0	16.1	0	100
Corpus Christi	1" - 7/8"	41.1	32.1	21.4	5.4	100
	7/8" - 5/8"	46.4	32.1	16.1	5.4	100
	5/8" - 3/8"	53.6	33.9	12.5	0	100
	3/8" - No. 4	53.6	35.7	8.9	1.8	100
Pharr	19 mm – 12.5 mm	46.4	39.2	12.5	1.8	100
	12.5 mm - 9.5 mm	57.1	21.4	14.3	7.1	100
	9.5 mm - No. 4	64.3	28.6	5.4	1.8	100

The main goal of this research was to determine if smaller top-size gravel aggregates with ostensibly more crushed faces should be used in place of larger aggregates with fewer crushed faces to improve HMA performance. The following parameters were used to correlate with HMA mixture properties:

- percentage of aggregates with crushed faces,
- percentage of aggregates with high sphericity,
- percentage of rounded aggregates, and
- percentage of rounded and sub rounded aggregates.

The above parameters are given in terms of percentages for individual size fractions of the coarse aggregate. For example, aggregates retained on a ½-inch sieve may have 20 percent rounded aggregates. This percentage was converted to weight of mix by combining it with the weight percentage of the corresponding aggregate size in the given mix. That is, if the weight percentage of 0.5-inch retained aggregate in the mix is 25 percent, then the percentage of rounded particles contributed by this size fraction in the mix by weight would be 0.2 x 25 = 5 percent.

The total percentage of each parameter by weight of mix can then be estimated by adding the contribution of each size fraction. This calculation is based on the assumption that the weight of all particles in a given size fraction is constant; hence, the shape characteristic, which is essentially based on a number count, can be converted to weight percentage of mix by such a combination. Appendix B includes the details of the calculations, and Table 3.5 summarizes the results. Appendix C includes the shape parameter distribution for each size fraction from AIMS.

Table 3.5. Shape Parameters for Mix Designs.

Property	District	Type B	Type C	Type D
Percentage Crushed	Laredo	42.5	38.3	40.5
	Corpus Christi	39.3	37.0	33.5
	Pharr	47.4	26.5	30.1
High Sphericity	Laredo	8.7	7.8	6.9
	Corpus Christi	6.5	4.8	3.7
	Pharr	5.9	1.5	1.3
Rounded	Laredo	2.9	2.6	1.2
	Corpus Christi	0.9	0.5	0.5
	Pharr	2.5	1.1	1.0
Rounded + Subrounded	Laredo	13.1	11.9	10.0
	Corpus Christi	6.6	5.2	4.2
	Pharr	8.8	3.7	3.6

The parameters used to compare differences in aggregate properties are restricted to the coarse aggregate fraction only. This is because the fine aggregates for the three mixes within a given district were from the same source and possessed reasonably similar distributions. Moreover, the sphericity and angularity distribution of the fines for the different size fractions from each source were also quite similar. Based on this reasoning, any difference in mixture performance can be attributed to the difference in the shapes of the coarse aggregates and/or the maximum aggregate size.

The following observations were made from these comparisons:

- The percentage of crushed particles in the HMA mix decreased, in most cases, with a decrease in aggregate size (Table 3.5). This is despite the fact that the percentage of crushed faces in each size fraction generally increased with a decrease in the aggregate size (Table 3.2).
- The percentage of crushed-face particles in each mix (Tex-460-A) contradicts the data from the AIMS tests (Table 3.5). Since the image analysis is a more objective technique and quantifies the aggregate properties over the entire gradation, it is assumed to have greater reliability than the percentage of crushed faces.
- The percentage of high sphericity aggregates consistently decreased with a decrease in maximum aggregate size of the mix.
- The percentage of rounded and rounded + subrounded aggregates decreased with a decrease in maximum aggregate size, in most cases.
- The HMA mixtures from the Pharr District exhibited the most pronounced differences in the shape characteristics computed (Table 3.5).

RESULTS FOR HMA MIXTURE PROPERTIES

Each of the three mixtures from Corpus Christi and Laredo was designed using the TGC and included Types B, C and D. The three mixes from Pharr were designed using the SGC and were 19, 12.5 and 9.5 mm nominal maximum aggregate size. For brevity in the various discussions of this report, these latter three mixes may be referred to as Type B, Type C and Type D, respectively.

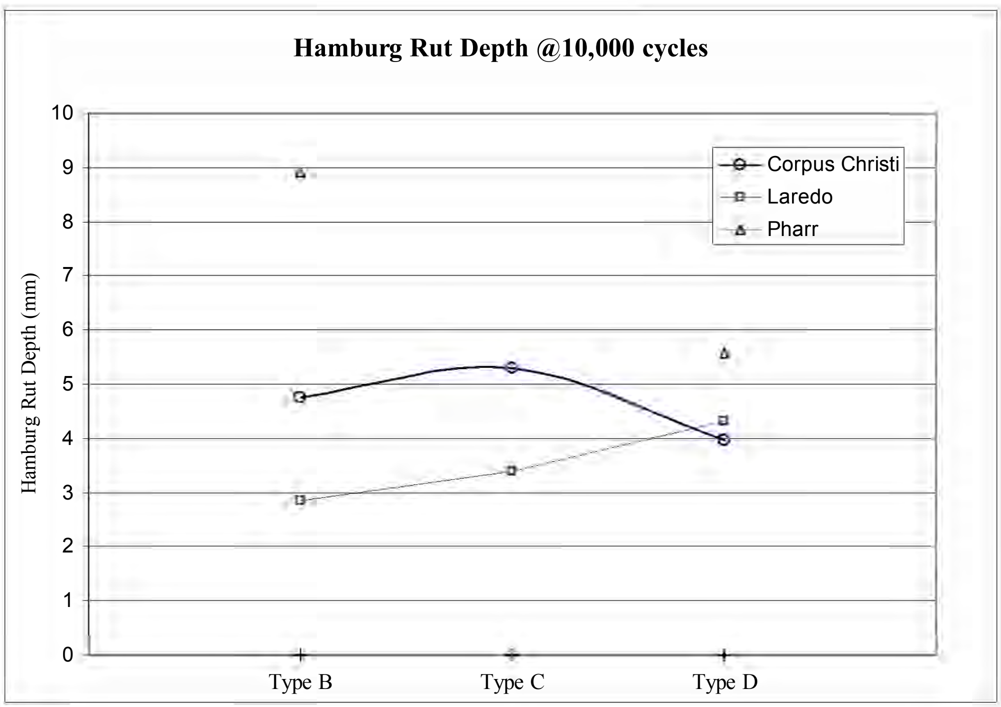
Hamburg Wheel Tracking Test. Results from the HWTD are summarized in Table 3.6 and Figure 3.1. All specimens were tested at 122°F. None of the specimens showed any visual evidence of stripping during the test. Although the TxDOT specifications require that a mix containing PG 64-22 must undergo 10,000 cycles with less than 0.5 inches of rutting, the mix designs in this research were tested to 20,000 cycles or failure (i.e., 0.5 inches of rutting), whichever came first. The mixes from Corpus Christi and Laredo survived 20,000 cycles without failing, and the results for these mixes were compared at both 10,000 and 20,000 cycles. All three mixes from the Pharr district failed at less than 15,000 cycles, therefore, comparisons of mixture performance were performed only at 10,000 cycles. The

12.5-mm mixture from Pharr failed at less than 10,000 cycles; this was likely due to the fine aggregate gradation and consequent lack of interlock of the coarse aggregate in the compacted mix.

Table 3.6. Hamburg Rut Depths (mm) at 10,000 Cycles.

Type	Corpus Christi			Laredo			Pharr		
	L	**R**	***Avg.***	**L**	**R**	***Avg.***	**L**	**R**	***Avg.***
B/19 mm	5.7	3.82	*4.76*	2.55	3.13	*2.84*	10.49	7.33	*8.91*
C/12.5 mm	5.07	5.52	*5.295*	3.18	3.64	*3.41*	--	--	*24.4*[1]
D/9.5 mm	3.06	4.89	*3.975*	4.36	4.26	*4.31*	7.35	3.81	*5.58*

[1]Value extrapolated based on average of left and right channels for last 2000 cycles.



Note: Extrapolated value of Pharr 12.5-mm mix not shown.

Figure 3.1. Hamburg Rut Depth at 10,000 Cycles.

Although Figure 3.1 indicates certain trends with respect to different maximum aggregate sizes, the results from the HWTD did not substantially differentiate between the properties of most of the different mixes. HWTD rut depths for the Corpus Christi and Laredo mixtures did not show any appreciable differences between the Type B, C, and D mixes.

The only mixture that performed poorly in the HWTD was the 12.5-mm Superpave mix from Pharr, which yielded notably more rutting than the corresponding two Pharr mixtures. By comparison to the other two Pharr mixtures, this 12.5-mm mix was much more fine graded (compare Figures A.7 through A.9). It is noteworthy that, while the HWTD identified the Pharr 12.5-mm mixture as failing TxDOT specifications, all three simple performance tests consistently indicated it had better rutting performance than the corresponding 9.5-mm and 19-mm Superpave mixtures.

Another noteworthy observation from the HWTD data is that there was no indication of susceptibility to water damage with the change in maximum size for any of these gravel aggregate mixes. All of the mixtures contained hydrated lime as an antistripping additive (Laredo mixes – 1.5 percent; Pharr mixes – 1 percent; Corpus Christi mixes – 1 percent, 1.25 percent, and 1.5 percent in Type B, C, and D, respectively). Although no mixtures were tested without lime, based on the authors' experience with siliceous gravel mixtures, the hydrated lime provided effectual resistance to moisture damage in the HWTD.

Dynamic Modulus Test. Dynamic modulus tests were performed at five temperatures and six frequencies. Test data were used to compare performance of the mixtures based on the following parameters:

- comparison of master curves,
- $E^*/\sin\phi$ at high temperatures to estimate rutting performance, and
- $E^* \sin\phi$ at low temperatures to compare cracking resistance.

Figures 3.2 through 3.4 were used to compare the shapes and extents of the master curves for the three mixtures from each district. Rutting performance of the mixtures was estimated by comparing the curves at higher reduced time values, which correspond to higher loading time or higher temperatures or both. Typically, a higher modulus value indicates a more rut resistant mix. For the mixes from Laredo and Pharr, the Type C mixes with intermediate NMAS exhibited the highest moduli. For the mixes from Corpus Christi, there is only a slight decrease in modulus from Type B to Type C, but the modulus drops significantly from Type C to Type D.

In order to make the comparison more specific, only the E*/sin ϕ values at 130°F and 1 Hz were compared. In general, a higher value indicates better rut resistance. Table 3.7 and Figure 3.5 illustrate this comparison. Once again, for the mixes from Laredo and Pharr, the Type C mixes demonstrate the best performance. For the mixes from Corpus Christi, rutting performance drops notably from the Type B to the Type C mix and is almost the same for the Type C and Type D mixes.

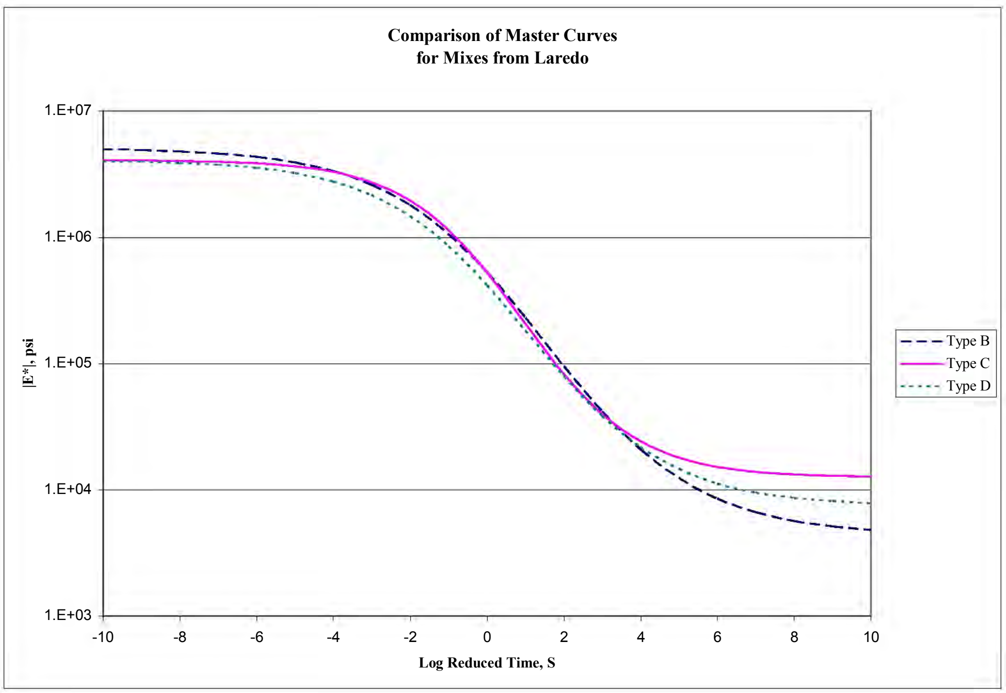


Figure 3.2. Master Curve for Mixes from Laredo District.

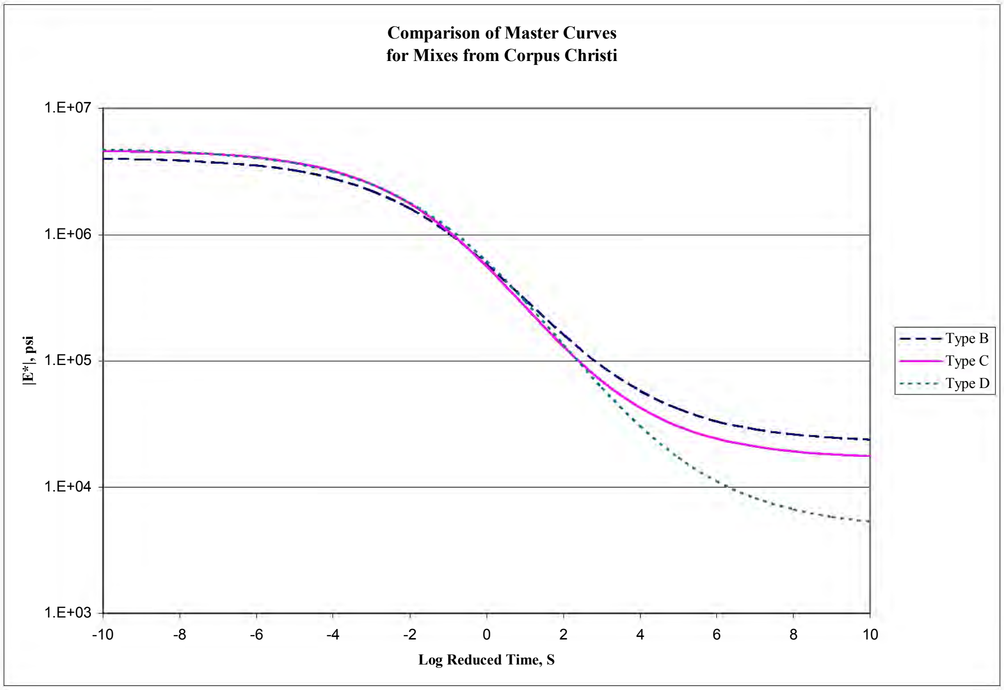


Figure 3.3. Master Curve for Mixes from Corpus Christi District.

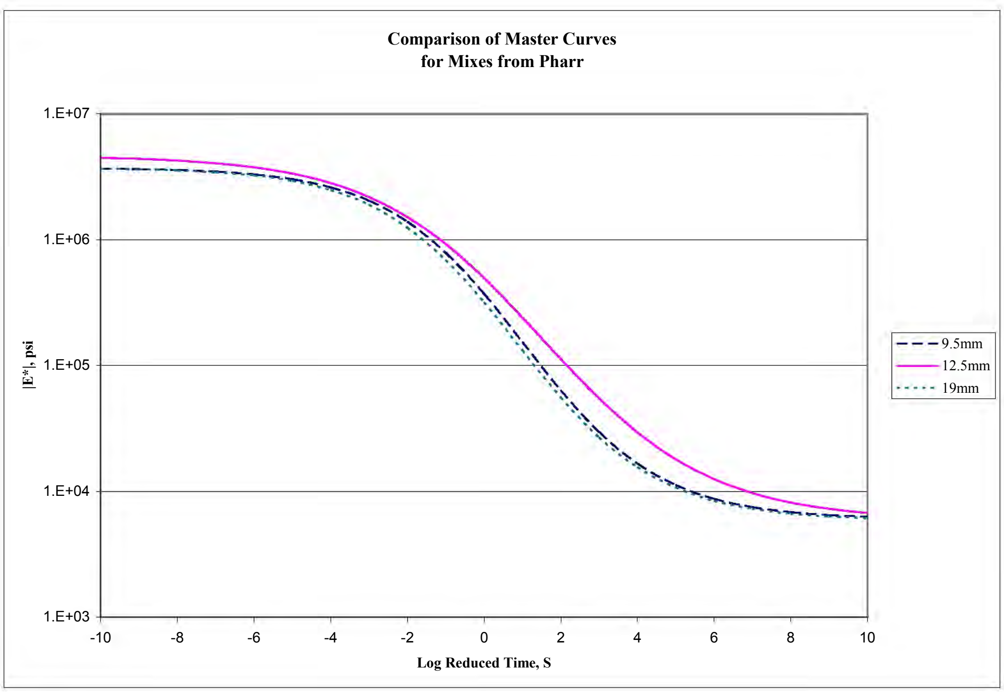


Figure 3.4. Master Curve for Mixes from Pharr District.

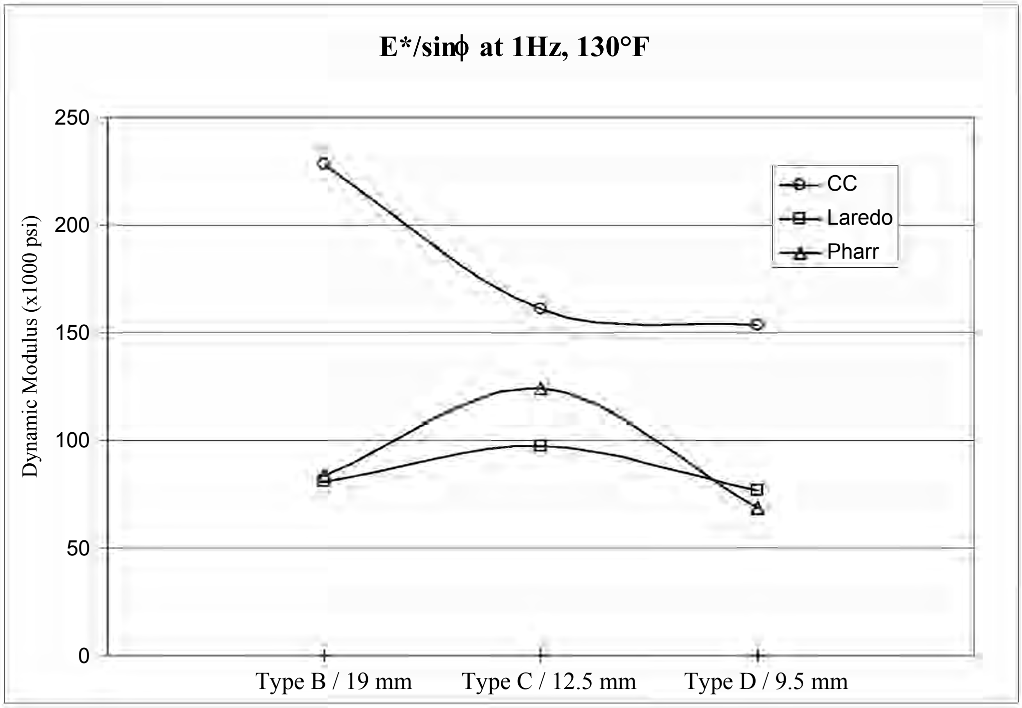


Figure 3.5. E*/sin ϕ at 1 Hz and 130°F.

Table 3.7. E*/sin ϕ (x1000 psi) at 1 Hz and 130°F to Compare Rutting Resistance.

Type	Corpus Christi			Laredo			Pharr		
	1	**2**	***Avg.***	**1**	**2**	***Avg.***	**1**	**2**	***Avg.***
B/19 mm	186	270	*228*	87	74	*81*	98	69	*84*
C/12.5 mm	152	170	*161*	108	86	*97*	101	146	*124*
D/9.5 mm	214	92	*153*	84	69	*77*	68	68	*68*

The dynamic modulus test data can be used to compare the fatigue and low temperature cracking properties of HMA mixes by examining E* sin ϕ at low temperatures and high frequencies. A qualitative comparison of the master curves for each district (Figures 3.2 to 3.4) in the low reduced time zone (which represents low temperature or high loading rates) indicates that, for practical purposes, there is no difference between the

Type B, C, and D mixes. In fact, there were no practical differences between any of the mixtures from the three districts.

Values of E* sin ϕ at 14°F and 10 Hz were computed and are compared in Table 3.8. Lower E* sin ϕ at these conditions indicates better fatigue resistance. Although, the average values indicate a general decrease in E* sin ϕ as the NMAS of the mixtures increase, this deduction cannot be conclusively stated due to the variability between the replicate tests and the smallness of the change, in some cases (Pharr). These data indicate that the mixtures with larger NMAS offer slightly more resistance to fatigue. An examination of asphalt contents, filler contents, filler-to-asphalt ratios, and quantity/character of manufactured sand/screenings did not help explain these data. Generally, those mixtures with the higher film thicknesses exhibited lower E* sin ϕ values or better fatigue resistance.

Table 3.8. E* sin ϕ (x1000 psi) at 10 Hz and 14°F to Compare Fatigue Resistance.

Type	Corpus Christi			Laredo			Pharr		
	1	**2**	***Avg.***	**1**	**2**	***Avg.***	**1**	**2**	***Avg.***
B/19 mm	222	332	*277*	267	371	*319*	316	366	*341*
C/12.5 mm	369	539	*454*	385	417	*401*	349	331	*340*
D/9.5 mm	299	309	*304*	474	381	*428*	320	369	*344*

Flow Time Test. The two parameters from the flow time test that can be used to compare rutting potential of HMA mixtures are the flow time value and the flow time slope. All tests were conducted 130°F and 20 psi static stress. Test results in terms of flow time value and flow time slope are shown in Tables 3.9 and 3.10 and Figures 3.6 and 3.7.

Table 3.9. Comparisons of Values (x1000 seconds) from the Flow Time Test.

Type	Corpus Christi			Laredo			Pharr		
	1	**2**	***Avg.***	**1**	**2**	***Avg.***	**1**	**2**	***Avg.***
B/19 mm	7.9	7.5	*7.7*	20.0	21.8	*20.9*	1.1	1.1	*1.1*
C/12.5 mm	8.6	12.0	*10.3*	39.0	50.0	*44.5*	39.8	39.8	*39.8*
D/9.5 mm	6.2	3.5	*4.9*	19.2	8.5	*13.9*	22.5	13.8	*18.2*

Table 3.10. Comparison of Flow Time Slopes.

Type	Corpus Christi			Laredo			Pharr		
	1	**2**	***Avg.***	**1**	**2**	***Avg.***	**1**	**2**	***Avg.***
B/19 mm	0.17	0.16	*0.17*	0.10	0.10	*0.10*	0.30	0.22	*0.18*
C/12.5 mm	0.19	0.20	*0.19*	0.09	0.09	*0.09*	0.15	0.16	*0.15*
D/9.5 mm	0.21	0.29	*0.25*	0.12	0.15	*0.13*	0.15	0.22	*0.26*

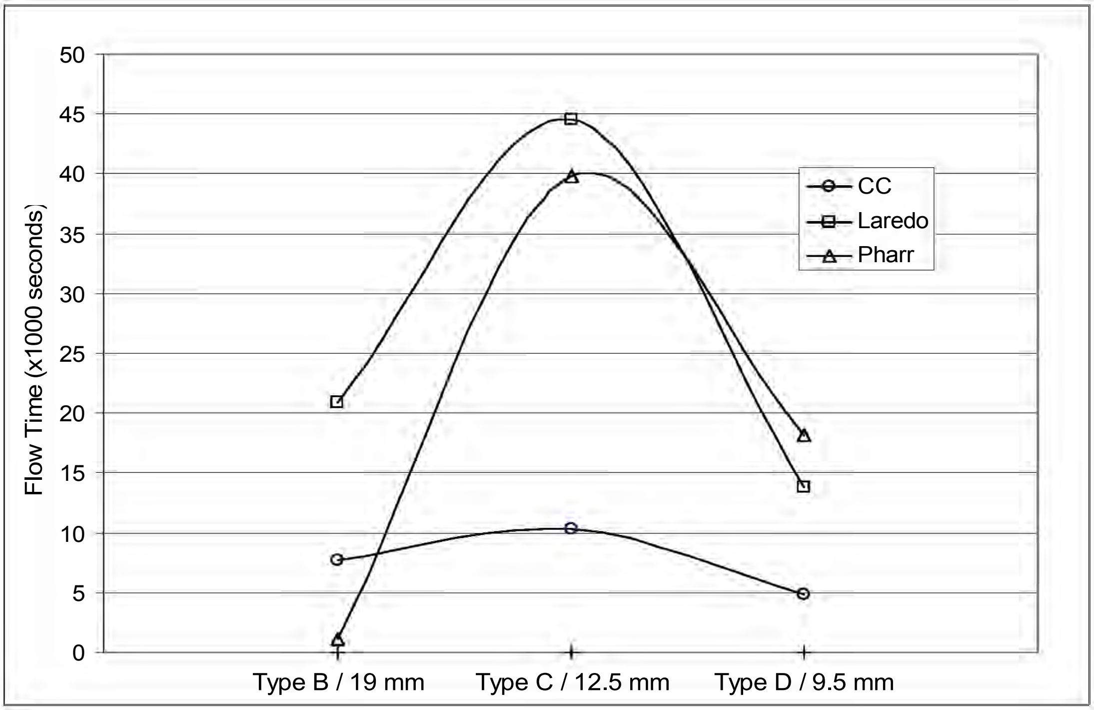


Figure 3.6. Comparison of Flow Time Values.

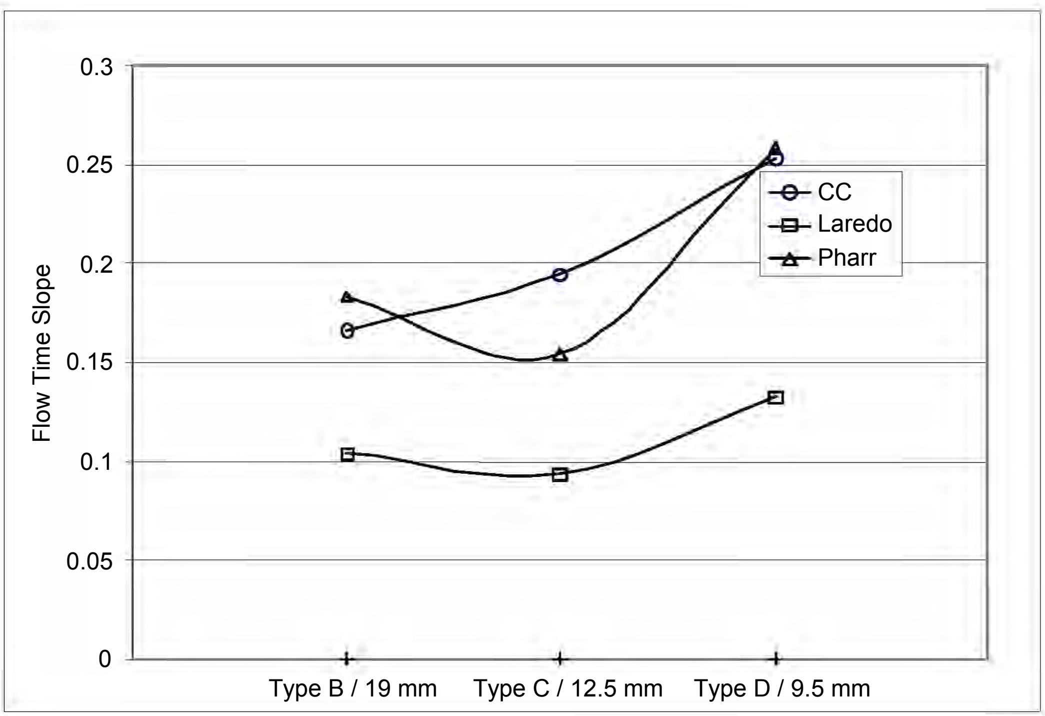


Figure 3.7. Comparison of Flow Time Slopes.

In general, a higher flow time value and a lower flow time slope indicates a mix that is more resistant to rutting. The flow time data indicate that the Type C mix performed the best as compared to the Type B or Type D mixes. The "optimum" effect of the intermediate NMAS is more evident in the mixes from Laredo and Pharr as compared to the mixes from Corpus Christi where the difference is nominal.

The flow time slope data indicate that the Type C mixes from Laredo and Pharr offer the best rutting performance. For the mixes from Corpus Christi, rutting performance consistently increases with an increase in NMAS, although this increase is more prominent from Type D to Type C mix than it is from Type C to Type B.

Flow Number Test. The flow number test was performed at 130°F using a peak load of 20 psi. The parameters that can be obtained from the flow number test for comparing rutting performance of the different mixtures are the flow number value and the flow number slope. In general, a higher flow number value and a lower flow number slope value indicate better rutting resistance of a mix. Unlike the flow time test, not all of the mixtures reached the tertiary flow stage within a reasonable test time and, therefore, the flow number parameter is not available for all mixes. Flow number slope can still be obtained and used for comparisons, even if the mixture does not reach the tertiary flow zone. Tables 3.11 and 3.12 present the flow number values and flow number slopes, respectively. Note that, in Table 3.11, the term "50+" indicates that the mixture did not undergo tertiary damage even after 50,000 cycles.

Average flow number slopes for the mixtures are shown graphically in Figure 3.8 and provide findings similar to those from the flow time tests. Figure 3.8 indicates that the mixtures with intermediate NMAS from Laredo and Pharr will likely offer better rutting performance than their counterparts and that the Type B mixture from Corpus Christi will yield more rutting resistance than its counterparts. This trend holds true for both the flow number value and the flow number slope parameters. Further, these findings are consistent with those from the flow time test.

Table 3.11. Comparison of Flow Number Values (x1000 cycles).

Type	Corpus Christi			Laredo			Pharr		
	1	**2**	***Avg.***	**1**	**2**	***Avg.***	**1**	**2**	***Avg.***
B/19 mm	50+	50+	*50+*	22	24	*23*	4	-[1]	*4.0*
C/12.5 mm	22	17	*19.5*	50+	50+	*50+*	50+	50+	*50+*
D/9.5 mm	12	9	*10.5*	50+	50+	*50+*	5	6	*5.5*

[1] Based on one replicate

Table 3.12. Comparison of Flow Number Slopes.

Type	Corpus Christi			Laredo			Pharr		
	1	**2**	***Avg.***	**1**	**2**	***Avg.***	**1**	**2**	***Avg.***
B/19 mm	0.43	0.43	*0.43*	0.52	0.52	*0.52*	0.54	0.49	*0.51*
C/12.5 mm	0.46	0.51	*0.49*	0.40	0.42	*0.41*	0.19	0.21	*0.20*
D/9.5 mm	--*	0.53	*0.53*	0.54	--*	*0.54*	0.55	0.48	*0.51*

* Anomalous data

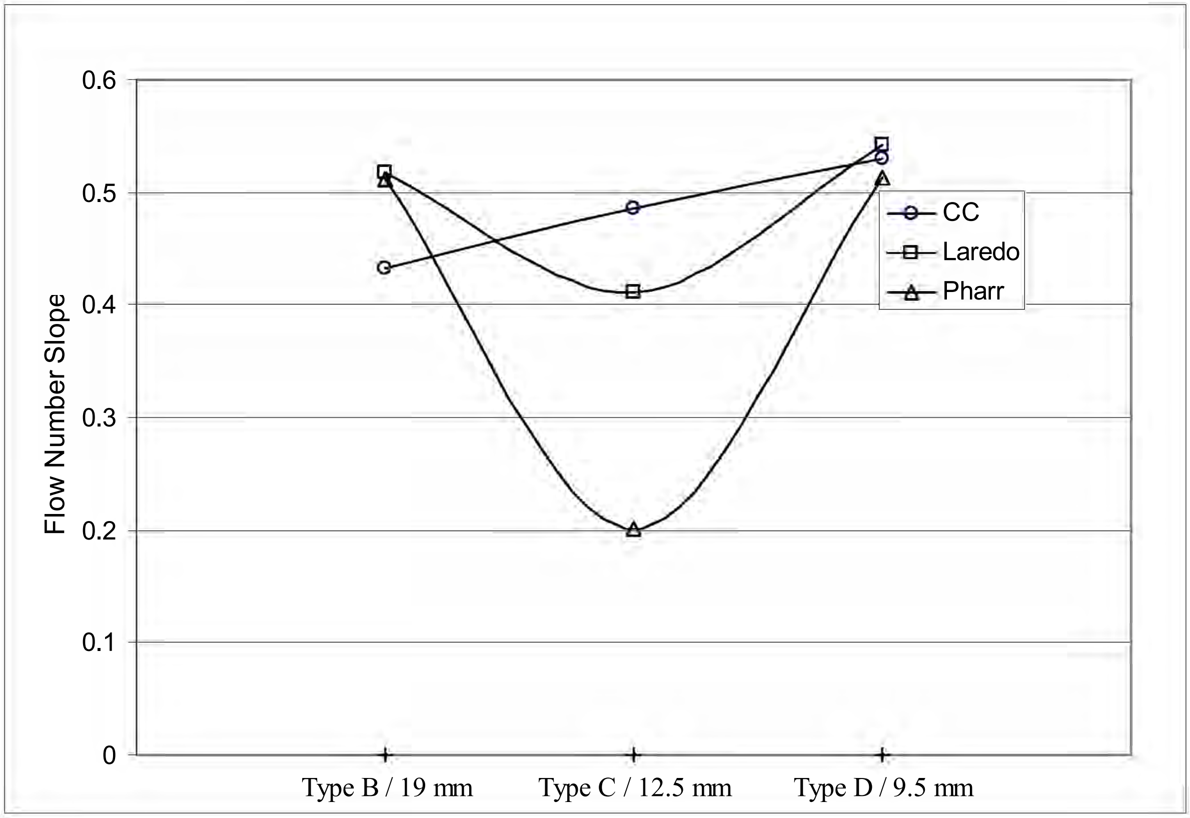


Figure 3.8. Comparison of Flow Number Slopes.

CHAPTER 4
CONCLUSIONS AND RECOMMENDATIONS

The primary objective of this research was to determine whether the use of smaller maximum aggregate size in designing HMA mixes with siliceous river gravels will increase the percentage of crushed and angular aggregates in the mix and thereby improve rutting performance of the mixture.

Summary and Discussion

Percentage of crushed faces (Tex-460-A) was included in the test program but was not included for correlating HMA material properties for two reasons. The main reason for this was that the test was not sensitive or quantitative enough to capture a wide range of aggregate shape parameters. This is substantiated by the fact that the percentage of aggregates with crushed faces measured in this project was shown to decrease with decrease in NMAS. Further, as discussed in Chapter 3, the variability associated with the two or more crushed face test is tremendous. One would expect that smaller crushed gravel aggregates from the same source should have more crushed faces, and this was verified by findings from image analysis.

Based on findings from previous TxDOT-sponsored research (Yeggoni et al., 1994), it appears that the 85 percent crushed face specification is suitable for optimizing HMA performance and cost of crushed river gravel aggregates. This study was not designed to address this issue. Generally, however, the findings indicate that the current specification is acceptable. That is, all of the mixtures except the fine-graded 12.5-mm Superpave mixture performed acceptably in the HWTD. These limited data suggest that, when HMA mixtures containing coarse South Texas crushed gravel, which meets the current specifications and provides reasonable stone-to-stone contact of the coarser aggregates, they will provide adequate performance.

The purpose of image analysis (AIMS) was to evaluate whether a reduction in the NMAS of the gravel aggregates generates a reduction of smooth and rounded particles in the mix. The three parameters that were extracted from the image analysis to assess the increase in angularity with a reduction in NMAS included three measures of rounded particles:

- percentage of high sphericity particles,
- percentage of rounded particles (related to angularity based on radius method), and
- percentage of rounded plus subrounded particles (related to angularity based on the radius method).

These image analysis parameters showed logical trends, with a decrease in all three parameters corresponding to a decrease in the NMAS of the mixtures. Between the Type B and Type C mixes, the most prominent decrease in shape characteristics was observed the in mixes from Pharr, and the least prominent decrease was in mixes from Corpus Christi. AIMS proved to be a valuable tool in quantitatively assessing the shape characteristics of aggregates over a wide range of values.

This study used only a portion of the potential data from AIMS, and this was aimed primarily at quantifying the rounded particles remaining in the crushed coarse gravels of the HMA mixtures studied. The data from this study alone cannot support conclusions related to the ability of image analysis to predict HMA mixture performance. However, earlier TxDOT-sponsored research (Yeggoni et al., 1994) clearly depicted the ability of a far less sophisticated image analysis method to predict HMA performance.

In the last 10 years, significant progress has been made regarding image analysis. According to Al-Rousan et al. (2004), AIMS can measure coarse aggregate form (in three dimensions), angularity, and surface texture. AIMS was used to develop a methodology for the classification of aggregates based on shape. This methodology was based on measuring the distribution of the shape characteristics of aggregates from a wide range of sources and varying sizes. The limits for the classification groups are determined using a cluster analysis. The new methodology offers several advantages over current image analysis techniques. It is based on the distribution of shape characteristics in an aggregate sample rather than average indices of these characteristics. Coarse aggregate form is determined based on three-dimensional analysis of particles, which allows distinguishing between flat, elongated or flat and elongated particles. Fundamental gradient and wavelet methods are used to quantify angularity and surface texture, respectively. The classification methodology can be used for the evaluation of the effects of different processes such as crushing techniques and blending based on aggregate shape distribution.

AIMS also lends itself to development of aggregate specifications based on the distribution of shape characteristics. Recent studies at TTI (Masad et al., 2001; Masad, 2003; Fletcher et al., 2003) have shown excellent correlations between laboratory performance of HMA and AIMS measurements of aggregate shape. However, the measurements to date were not comprehensive enough to develop aggregate acceptance criteria. Data generated in Project 0-4203 along with data from Federal Highway Administration projects conducted at TTI are currently being used to develop acceptance criteria for HMA and should be available to TxDOT in the spring of 2005.

The tests that were used to compare the different HMA mixtures included:

- Hamburg test for rutting resistance and moisture susceptibility,
- dynamic modulus test to resist to rutting and cracking,
- flow time test to resist to rutting, and
- flow number test to resist to rutting.

Technicians conducted these tests on three groups with three mixture designs in each group and two replicates for each mix design in accordance with industry standards. Since only three mixture designs were possible in each group, meaningful statistical comparisons were not feasible. Analyses of data from the performance tests were therefore limited to qualitative comparisons of the results for practical applications.

HWTD rut depths for the Corpus Christi and Laredo mixtures did not show any appreciable differences between the Type B, C, and D mixes. However, the comparatively fine-graded 12.5-mm mix from Pharr yielded notably more rutting than the corresponding two Pharr mixtures. While the HWTD identified the Pharr 12.5-mm mixture as failing TxDOT specifications, all three simple performance tests consistently indicated it had better rutting performance than its corresponding 9.5-mm and 19-mm mixtures. None of these HMA mixtures exhibited any evidence of moisture damage when tested in the HWTD. All of these siliceous gravel mixtures were treated with hydrated lime, which apparently was effective in protecting them from moisture damage.

Overall, based on results from dynamic modulus, flow number, and flow time tests, the Type C mixtures most often exhibited the best rutting performance. However, rutting performance of the Corpus Christi mixtures consistently increased with an increase in maximum aggregate size.

Generally, these findings do not support a change in operations toward the use of finer gravel mixtures with ostensibly more crushed faces in the coarser aggregate sizes to address rutting. Decreasing NMAS may adversely affect the performance of an HMA mixture unless counteracted by better shape characteristics (reduced spherical and rounded or low angularity particles). Comparing performance of the mixtures from Pharr and Corpus Christi further substantiates this hypothesis. For Pharr, a significant improvement in shape characteristics from the Type B to the Type C mix was reflected in an improvement in performance, while for Corpus Christi, the shape characteristics for the Type C mixture are only marginally better than the Type B mix, and performance of the Type C mix was poorer, in most tests.

Data from the dynamic modulus test indicated that all nine mixtures performed relatively similarly with regard to cracking resistance. The master curves for all nine mixtures converged at essentially the same point for the short loading times. Comparisons of $E^* \sin \phi$ revealed that, most often, the mixtures with the largest NMAS exhibited the best cracking resistance. However, these differences will probably have no measurable effect in a field environment.

CONCLUSIONS

Based on the test results, the following conclusions are offered for the particular types of mixtures evaluated:

- These findings do not support the use of finer South Texas gravel mixtures (Type D or 9.5 mm) with presumably more crushed faces in the coarse aggregate to improve rutting resistance. In fact, the finer crushed gravel mixes most often demonstrated the least rutting resistance in the simple performance tests. Aggregate shape, angularity, and texture and maximum aggregate size, along with other factors (e.g., gradation, quantity and quality of manufactured sand/screenings, filler type and quantity, filler-to-asphalt ratio), work together to influence rutting characteristics of HMA paving mixtures. Each mix must be evaluated and stand or fall on its own merit.

- A decrease in NMAS may adversely affect HMA rutting performance unless it is offset by improved shape characteristics (a reduction in spherical and rounded or low angularity particles).
- Based on simple performance tests, the intermediate NMAS materials (Type C and 12.5 mm) demonstrated the optimum performance regarding permanent deformation, in most cases.
- In this very limited data, the HWTD test showed that the two Type C mixtures exhibited slightly more rutting than their counterparts; whereas, the simple performance tests showed that these Type C mixtures most often exhibited the least rutting.
- Cracking resistance of the mixes was not appreciably affected by the change in NMAS as shown by the master curves and the $E^* \sin \phi$ parameter from dynamic modulus tests. The master curves indicated that there were no practical differences in cracking resistance between any of the nine mixtures from the three districts.
- Some absorptive aggregates selectively absorb the lighter oils from asphalt and thereby leave a somewhat hardened binder film between the aggregates. These gravels normally exhibit low absorption and thus do not substantially "preharden" the asphalt. Therefore, when using blends containing a high percentage of river gravel, one should consider using at least one grade harder asphalts (i.e., bump one grade).

RECOMMENDATIONS

The gradations of all but one of the HMA mixtures studied herein could be generally classified as coarse-graded mixtures (i.e., the gradation curve passed through or below the reference or restricted zone). The solitary fine-graded mixture (12.5-mm mix from Pharr) was the only mixture that failed the HWTD, and it failed unquestionably. A study is needed to develop HMA mixture designs using crushed South Texas gravel aggregates that provide a strong stone skeleton composed primarily of the coarse aggregates (e.g., coarse matrix high binder (CMHB), stone mastic asphalt (SMA), stone-filled gradations). The authors believe that it is possible to develop HMA mixture designs using these materials that can serve satisfactorily on high-volume, heavy-traffic roadways. To optimize economical designs, one may need to depart from the current mix design philosophy (i.e., design air voids, minimum voids in mineral aggregate, and hard asphalts). Simple methods are available to quantify the degree of coarse aggregate stone-to-stone contact (Button et al., 1997). A minimum acceptable value for stone-to-stone contact, particularly for these gravel aggregates, appears vital to ensure adequate performance on high-traffic roadways.

This recommended study should include a task to develop fine (e.g., Type F, 9.5 mm, and 4.75 mm) CMHB, SMA, and stone-filled mixture designs. In addition to high stability or rut resistance, other important benefits of these types mixtures include:

- ability to place in thinner lifts,
- smooth, quiet riding surface,
- good workability (easier placing and hand working than coarser mixtures,
- no segregation,
- little or no asphalt draindown,
- lower permeability than coarser mixtures, and thus
- improved durability over coarser mixtures.

In addition, the thicker asphalt films in these fine mixtures should provide good flexibility and, hence, crack resistance and healing of microcracks under traffic during hot seasons. Cooley and Brown (2001) have demonstrated that it is possible to develop high-quality fine mixes with strong stone skeletons. Although these fine mixtures may have higher asphalt contents than coarser mixtures and thus higher comparative cost, they can be placed in thinner lifts and may provide the districts with an important cost-effective addition to their repertoire of surface paving mixtures.

REFERENCES

Al-Rousan, T, E. Masad, L. Myers, and C. Speigelman. "A New Methodology for Shape Classification of Aggregates Used in Asphalt Mixes." Paper submitted for presentation at the 84th Annual Meeting (January 2005) and subsequent publication by the Transportation Research Board, Washington, D.C., August 2004.

Bhasin, A., J.W. Button, and A. Chowdhury. "Evaluation of Simple Performance Tests of HMA Mixtures from the South Central USA." Research Report FHWA/TX-03/9-558-1, Texas Transportation Institute, The Texas A&M University System, College Station, Texas, May 2003.

Button, J.W. and D. Perdomo. "Investigation of Rutting in Asphalt Concrete Pavements." Report No. FHWA/TX-89-1121-1, Texas Transportation Institute, The Texas A&M University System, College Station, Texas, 1989.

Button, J.W., W.W. Crockford, E.G. Fernando, H.L. Von Quintus, J.A. Scherocman, J.T. Harvey, and B. Coree. "Design and Evaluation of Large-Stone Asphalt Mixtures." NCHRP Report 386, National Cooperative Highway Research Program, National Research Council, Washington, D.C., 1997.

Chandan, C., K. Sivakumar, T. Fletcher, and E. Masad. "Geometry Analysis Of Aggregate Particles Using Imaging Techniques."*Journal of Computing in Civil Engineering*, American Society of Civil Engineers, Vol. 18, No. 1, 2004, pp. 75-82.

Chowdhury, A., J.W. Button, and J.P. Wikander. "Variability of Hamburg Wheel Tracking Devices." Report No. FHWA/TX-04/5-4977-01-1, Texas Transportation Institute, The Texas A&M University System, College Station, Texas, 2004.

Cooley, L.A., Jr. and E.R. Brown. "Potential of Using Stone Matrix Asphalt (SMA) for Thin Overlays." Proceedings, Annual Meeting of the Transportation Research Board (CD-ROM), National Research Council, Washington, D.C., 2001.

Estakhri, C.K., J.W. Button, E. Masad, and T. Fletcher. "Evaluation of Superpave Flat and Elongated Aggregate Specifications." International Center for Aggregates Research Project Report 202, Texas Transportation Institute, Texas A&M University System, College Station, 2004.

Fletcher, T., C. Chandan, E. Masad, and K. Sivakumar. "Aggregate Imaging System (AIMS) for Characterizing the Shape of Fine and Coarse Aggregates." *Journal of the Transportation Research Board No. 1832.* Transportation Research Board, National Research Council, Washington, D.C., 2003, pp. 67-77.

Kaloush, K.E. and M.W. Witczak. "Tertiary Flow Characteristics of Asphalt Mixtures." *Journal of Association of Asphalt Paving Technologists*, Volume 71, 2002, pp. 248-280.

Kandhal, P.S. and F. Parker. “Aggregate Tests Related to Asphalt Concrete Performance in Pavements.” National Cooperative Highway Research Program Report 405, 1998.

Kandhal, P.S. and L.A. Cooley, Jr. “Accelerated Laboratory Rutting Tests: Evaluation of the Asphalt Pavement Analyzer.” NCHRP Report 508, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C., 2003.

Kandhal, P.S. and R.B. Mallick. “Aggregate Tests for Hot Mix Asphalt: State of the Practice in North America.” Proceedings, Canadian Technical Asphalt Association, Vol. XLII, November, 1997.

Masad, E. “The Development of A Computer Controlled Image Analysis System for Measuring Aggregate Shape Properties.” NCHRP-IDEA Project 77 Final Report, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C., 2003

Masad, E., D. Olcott, T. White, and L. Tashman. “Correlation of Fine Aggregate Imaging Shape Indices with Asphalt Mixture Performance.” *Journal of the Transportation Research Board No. 1757*, Transportation Research Board, National Research Council, Washington, D.C., 2001, pp. 148 – 156.

Masad, E., T. Al-Rousan, J. Button, D. Little. Quarterly Report on NCHRP Project 4-30A, Test Methods for Characterizing Aggregate Shape, Texture, and Angularity.” National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C., June, 2004.

Pellinen, T.K. “Asphalt Mix Master Curve Construction Using Sigmoidal Fitting Function with Nonlinear Least Squares Optimization Technique.” 15th ASCE Engineering Mechanics Conference, Colombia University, New York, 2002.

Perdomo, D. and J.W. Button. “Identifying and Correcting Rut-Susceptible Asphalt Mixtures.” Report No. FHWA/TX-91/1121-2F, Texas Transportation Institute, Texas A&M University, College Station, Texas, 1991.

Witczak, M.W., K. Kaloush, T. Peillinen, M.E. Basyouny, and H.V. Quintus. “Simple Performance Test for Superpave Mix Design.” National Cooperative Highway Research Program Report No. 465, Transportation Research Board, Washington, D.C., 2002.

Yeggoni, M., J.W. Button, and D.G. Zollinger. “Influence of Coarse Aggregate Shape and Surface Texture on Rutting of Hot Mix Asphalt Concrete.” Report No. FHWA/TX-94/1244-6, Texas Transportation Institute, Texas A&M University, College Station, Texas, 1994.

Yildirim, Y. and T. Donmez. “Effects of Using Crushed Gravel on Rutting of HMA Mixtures.” Interagency Report 0045-1, Center for Transportation Research, The University of Texas, Austin, Texas, 2002.

APPENDIX A
GRADATIONS FOR MIX DESIGNS

Table A.1. Gradation for Mixes from Corpus Christi.

Sieve Size "	CC Type B	CC Type C	CC Type D
1"	100.0		
7/8"	98.2	100.0	
5/8"	89.9	98.0	
1/2"		99.1	100.0
3/8"	70.0	78.7	92.1
#4	52.9	58.4	61.7
# 10	32.7	33.0	34.5
# 40	13.3	13.4	14.9
# 80	5.0	5.1	6.6
#200	2.7	2.6	3.8
Pan	0.0	0.0	0.0

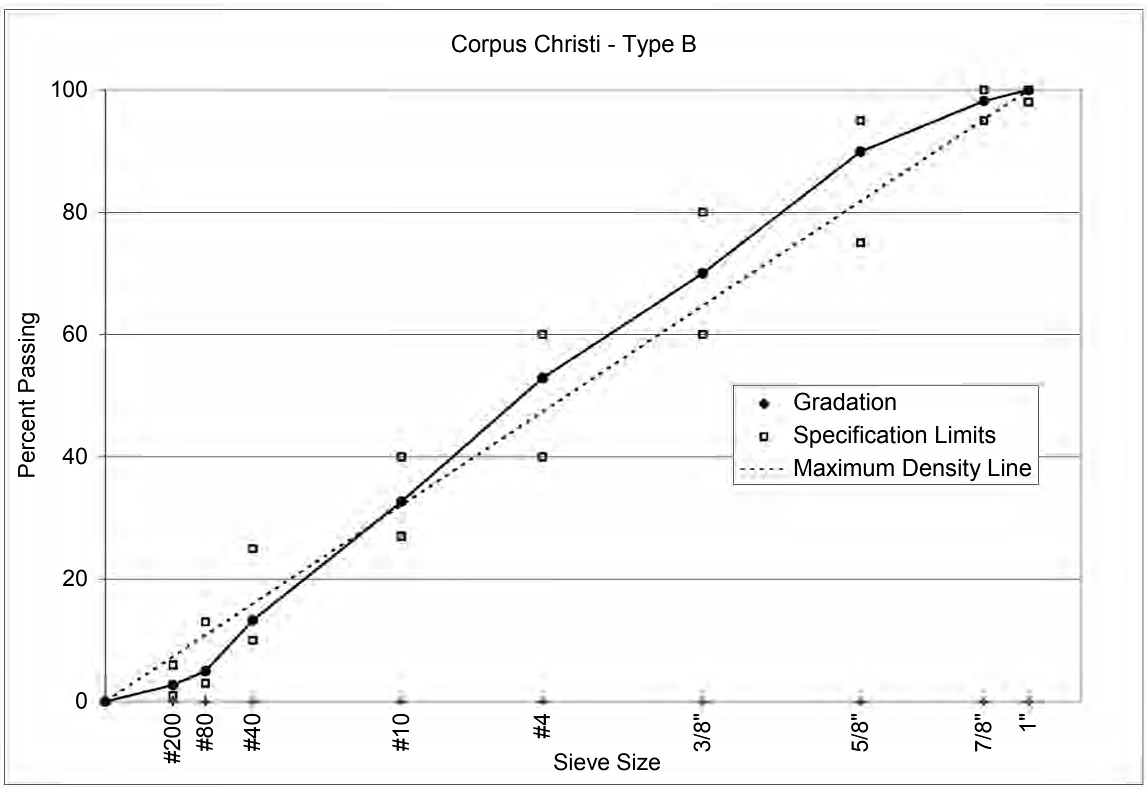


Figure A.1. Gradation of Type B Mix from Corpus Christi.

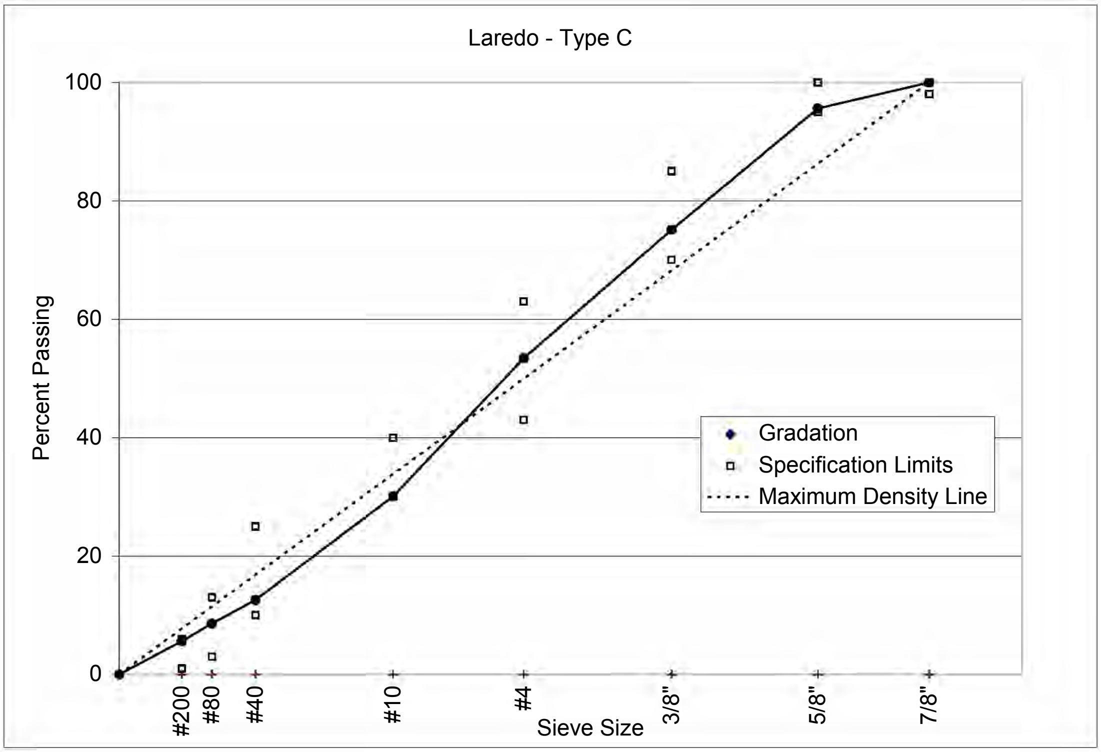


Figure A.2. Gradation of Type C Mix from Corpus Christi.

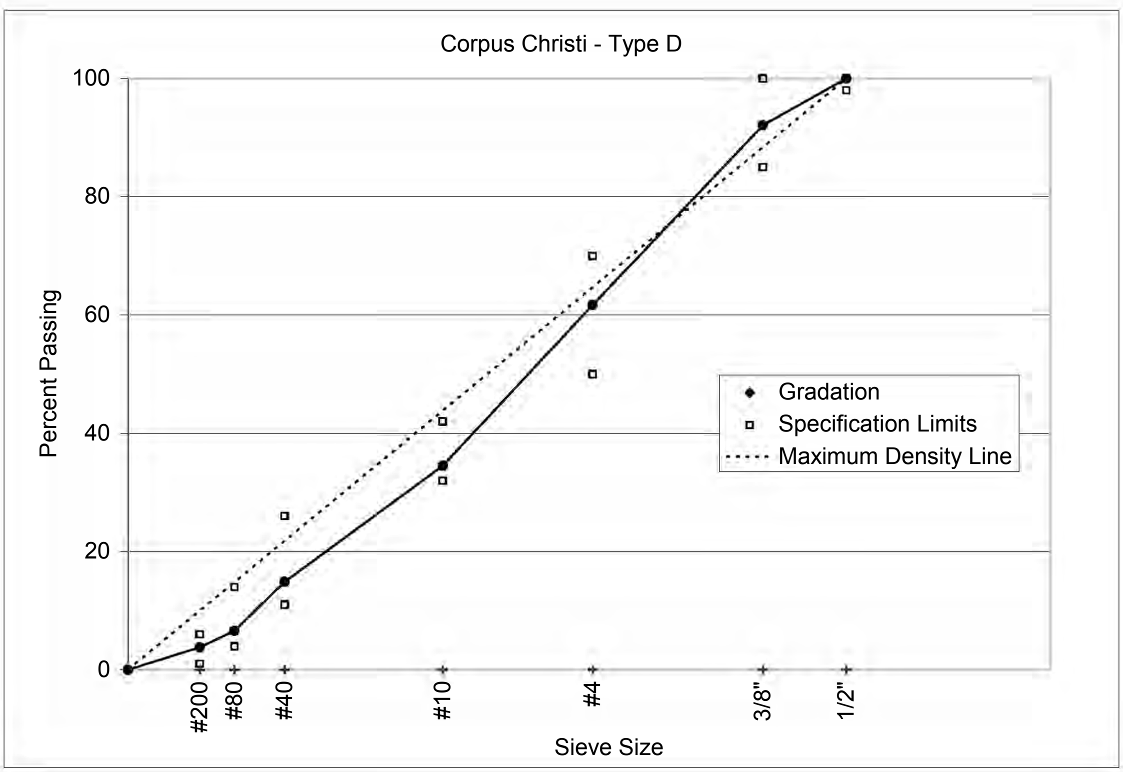


Figure A.3. Gradation of Type D Mix from Corpus Christi.

Table A.2. Gradation for Mixes from Laredo.

Sieve Size	Laredo Type B	Laredo Type C	Laredo Type D
1"	100.0		
7/8"		100.0	
5/8"	93.8	95.6	
1/2"		99.1	100.0
3/8"	72.6	75.1	86.8
#4	48.2	53.4	52.6
# 10	27.2	30.1	33.0
# 40	11.3	12.6	12.8
# 80	7.3	8.6	8.5
#200	4.6	5.6	5.8
Pan	0.0	0.0	0.0

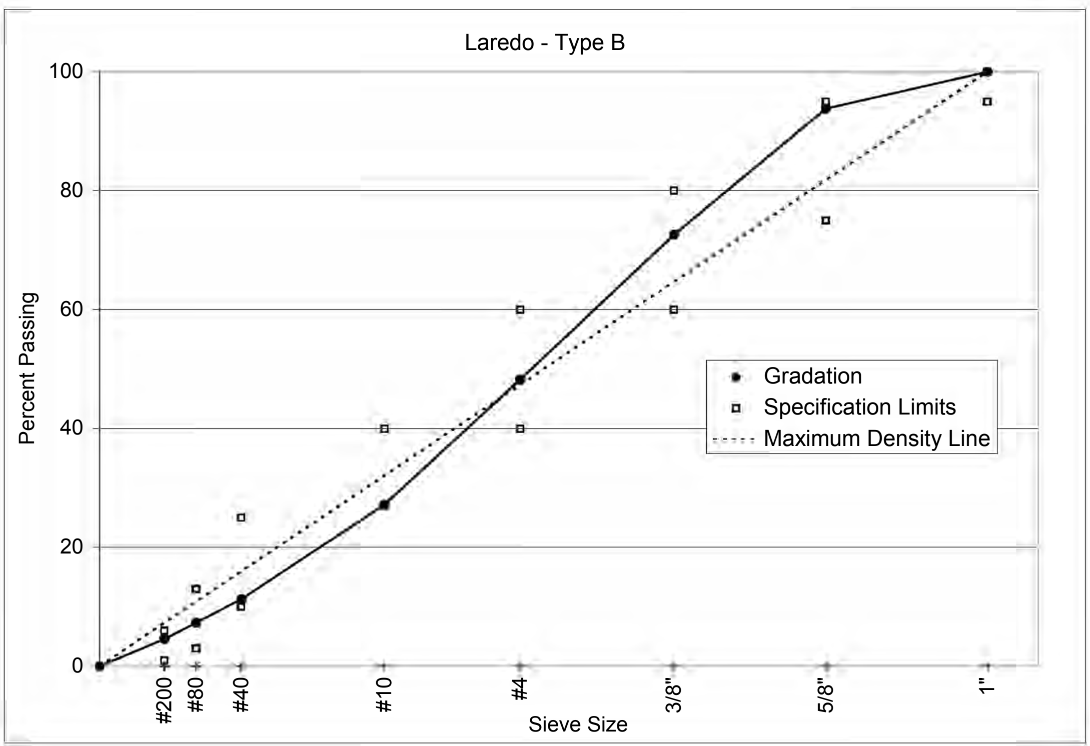


Figure A.4. Gradation of Type B Mix from Laredo.

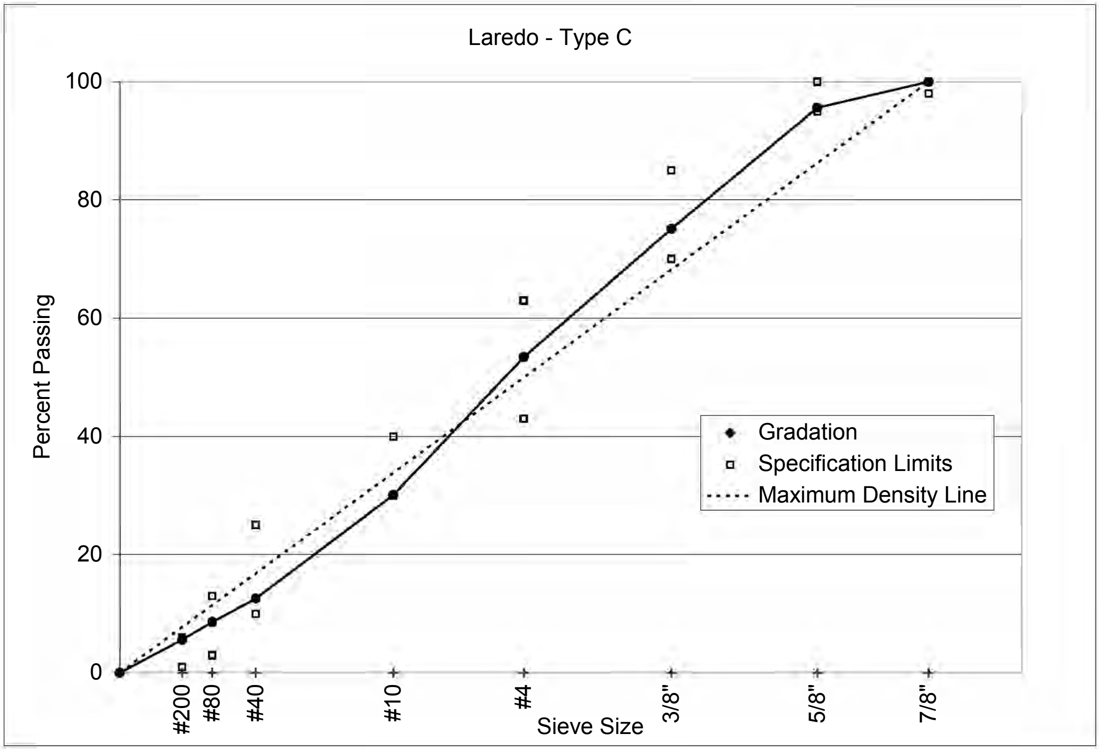


Figure A.5. Gradation of Type C Mix from Laredo.

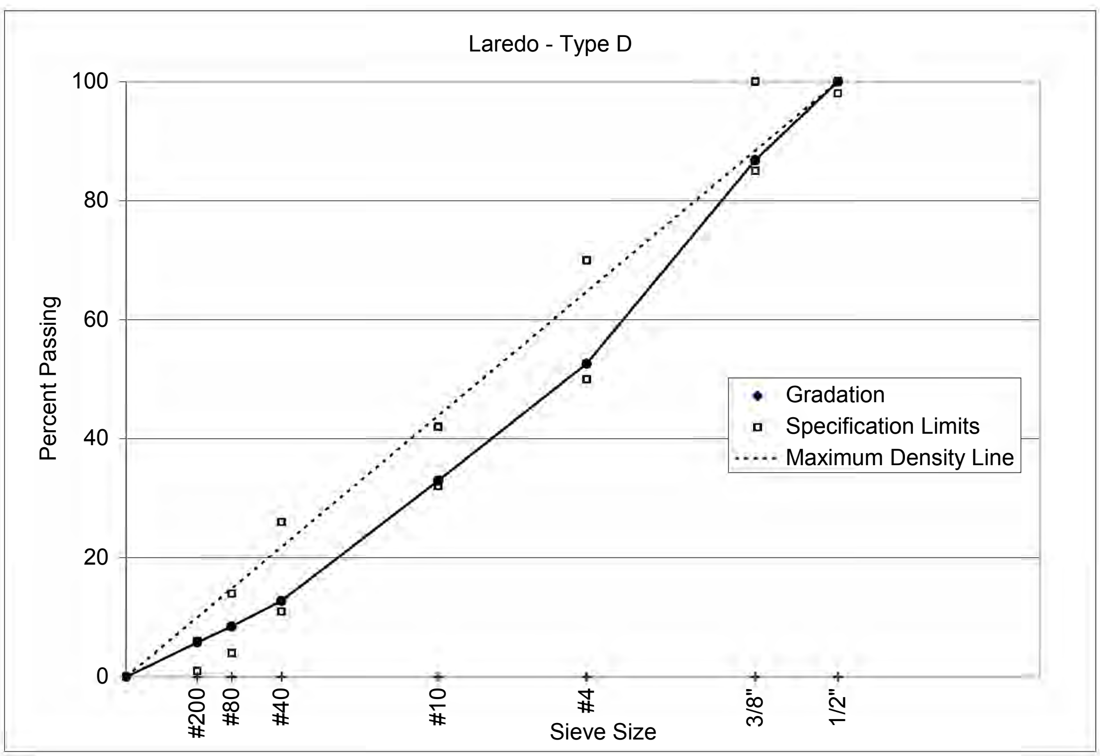


Figure A.6. Gradation of Type D Mix from Laredo.

Table A.3. Gradation for Mixes from Pharr.

Sieve Size, mm	Pharr 19 mm	Pharr 12.5 mm	Pharr 9.5 mm
25	100.0		
19	100.0	100.0	
12.5	89.5	99.1	99.6
9.5	64.4	90.0	93.0
4.75	37.5	66.5	63.1
2.36	27.8	48.3	38.3
1.18	19.9	32.9	25.5
0.600	14.8	23.2	19.3
0.300	10.7	16.9	14.0
0.15	4.5	9.6	7.2
0.075	3.2	5.5	5.0

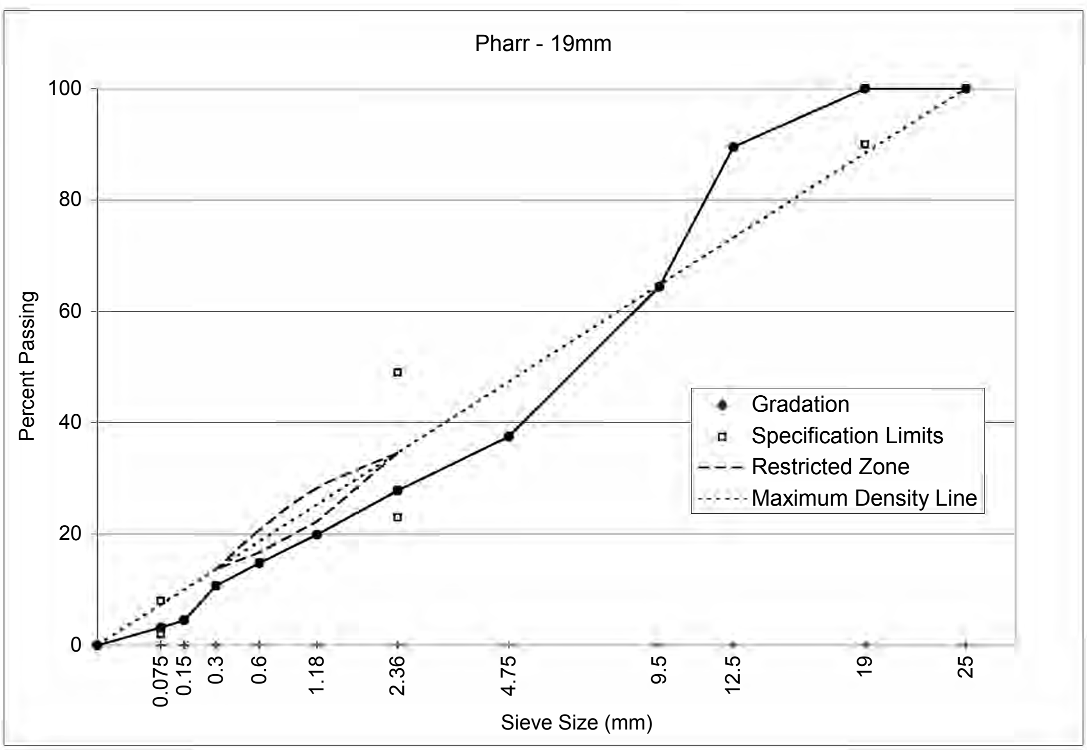


Figure A.7. Gradation of 19-mm Mix from Pharr.

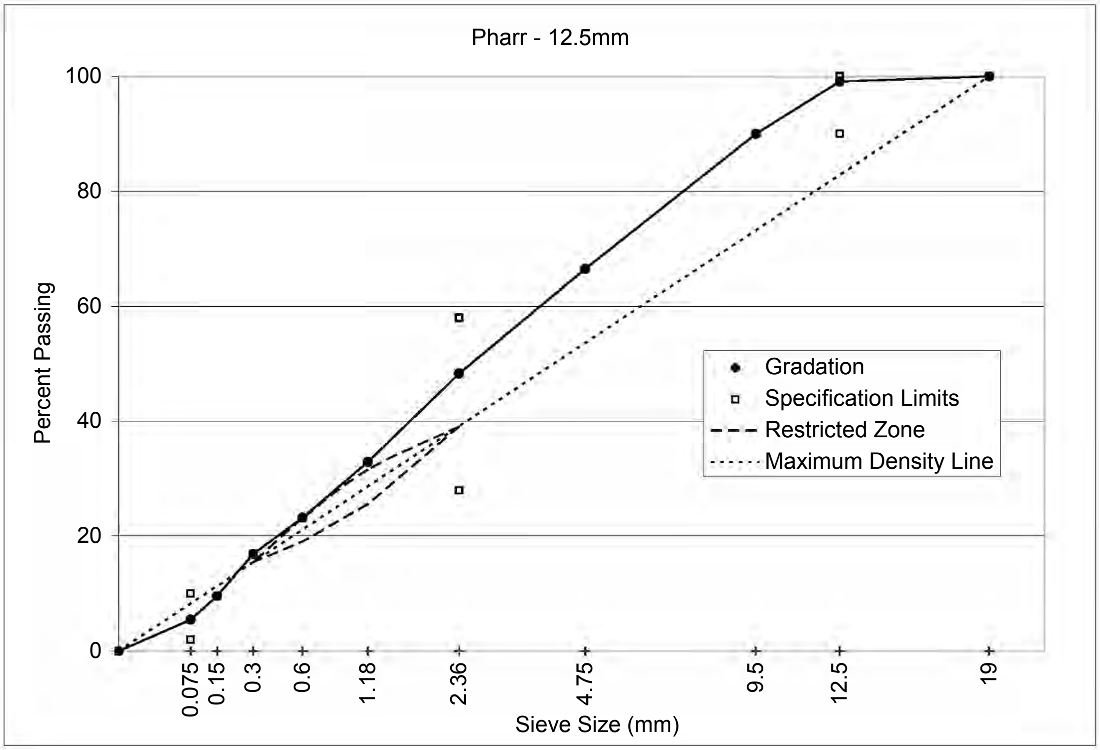


Figure A.8. Gradation of 12.5-mm Mix from Pharr.

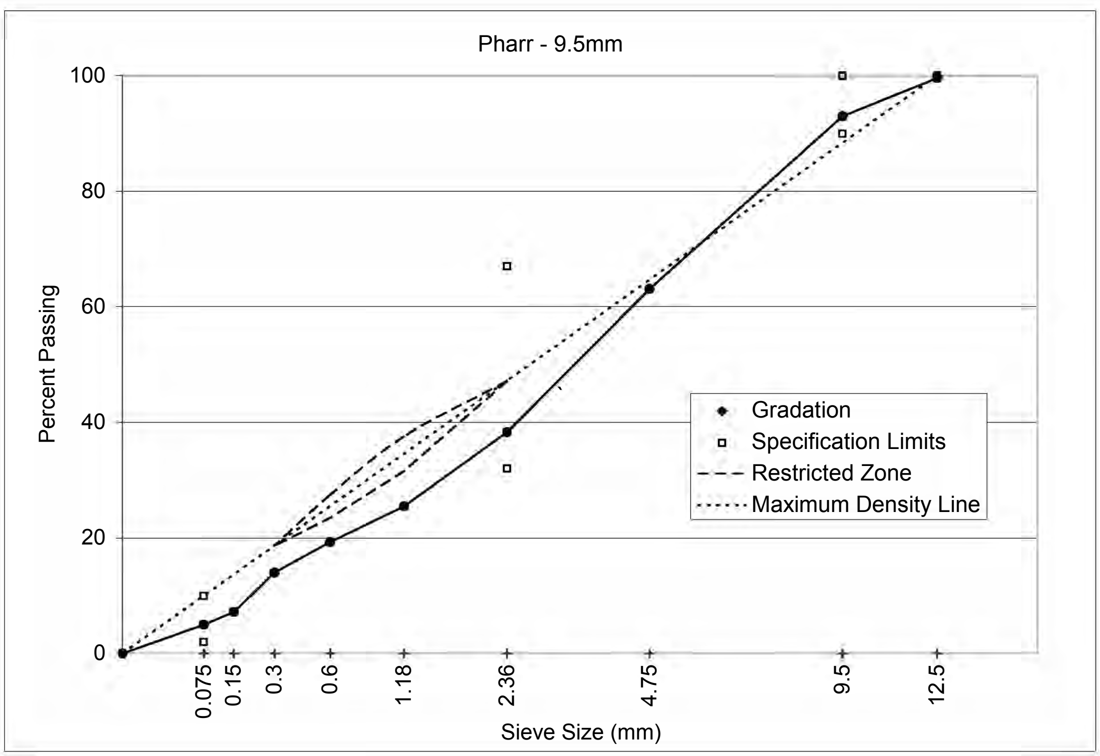


Figure A.9. Gradation of 9.5-mm Mix from Pharr.

APPENDIX B
AGGREGATE PROPERTIES FOR ALL MIXES

Table B.1. Sphericity Using AIMS for Laredo Mixes.

Size Retained	% High Sphericity each size fraction	% Size fraction by wt. of mix	% High Sphericity by wt. of mix	% Size fraction by wt. of mix	% High Sphericity by wt. of mix	% Size fraction by wt. of mix	% High Sphericity by wt. of mix
5/8"	23.2	6.2	1.4384	4.4	1.0208	0	0
3/8"	19.7	21.2	4.1764	20.5	4.0385	13.2	2.6004
#4	12.5	24.4	3.05	21.7	2.7125	34.2	4.275
TOTAL			8.7		7.8		6.9

Table B.2. Sphericity Using AIMS for Corpus Christi Mixes.

Size Retained	% High Sphericity each size fraction	% Size fraction by wt. of mix	% High Sphericity by wt. of mix	% Size fraction by wt. of mix	% High Sphericity by wt. of mix	% Size fraction by wt. of mix	% High Sphericity by wt. of mix
7/8"	37.5	1.8	0.675	0	0	0	0
5/8"	21.4	8.3	1.7762	2	0.428	0	0
3/8"	12.5	19.9	2.4875	19.3	2.4125	7.9	0.9875
#4	8.9	17.1	1.5219	22.3	1.9847	30.4	2.7056
TOTAL			6.5		4.8		3.7

Table B.3. Sphericity Using AIMS for Pharr Mixes.

Size Retained	% High Sphericity each size fraction	% Size fraction by wt. of mix	% High Sphericity by wt. of mix	% Size fraction by wt. of mix	% High Sphericity by wt. of mix	% Size fraction by wt. of mix	% High Sphericity by wt. of mix
12.5mm	30.3	10.5	3.1815	0.9	0.2727	0.4	0.1212
9.5mm	9	25.1	2.259	9.1	0.819	6.6	0.594
#4	1.8	26.9	0.4842	23.2	0.4176	29.9	0.5382
TOTAL			5.9		1.5		1.3

Table B.4. Percentage Rounded Particles Using AIMS for Laredo Mixes.

Size Retained	% Rounded in each size fraction	% size fraction by wt. of mix	% Rounded by wt. of mix	% size fraction by wt. of mix	% Rounded by wt. of mix	% size fraction by wt. of mix	% Rounded by wt. of mix
5/8"	16.1	6.2	0.9982	4.4	0.7084	0	0
3/8"	9	21.2	1.908	20.5	1.845	13.2	1.188
#4	0	24.4	0	21.7	0	34.2	0
TOTAL			2.9		2.6		1.2

Table B.5. Percentage Rounded Particles Using AIMS for Corpus Christi Mixes.

Size Retained	% Rounded in each size fraction	% size fraction by wt. of mix	% Rounded by wt. of mix	% size fraction by wt. of mix	% Rounded by wt. of mix	% size fraction by wt. of mix	% Rounded by wt. of mix
7/8"	5.4	1.8	0.0972	0	0	0	0
5/8"	5.4	8.3	0.4482	2	0.108	0	0
3/8"	0	19.9	0	19.3	0	7.9	0
#4	1.8	17.1	0.3078	22.3	0.4014	30.4	0.5472
TOTAL			0.9		0.5		0.5

Table B.6. Percentage Rounded Particles Using AIMS for Pharr Mixes.

Size Retained	% Rounded in each size fraction	% size fraction by wt. of mix	% Rounded by wt. of mix	% size fraction by wt. of mix	% Rounded by wt. of mix	% size fraction by wt. of mix	% Rounded by wt. of mix
12.5mm	1.8	10.5	0.189	0.9	0.0162	0.4	0.0072
9.5mm	7.1	25.1	1.7821	9.1	0.6461	6.6	0.4686
#4	1.8	26.9	0.4842	23.2	0.4176	29.9	0.5382
TOTAL			2.5		1.1		1.0

Table B.7. Percentage Rounded + Subrounded Particles Using AIMS - Laredo.

Size Retained	% Rounded + Sub-rounded in each size fraction	% size fraction by wt. of mix	% Rounded + Sub-rounded by wt. of mix	% size fraction by wt. of mix	% Rounded + Sub-rounded by wt. of mix	% size fraction by wt. of mix	% Rounded + Sub-rounded by wt. of mix
5/8"	32.13	6.2	1.99206	4.4	1.41372	0	0
3/8"	33.9	21.2	7.1868	20.5	6.9495	13.2	4.4748
#4	16.1	24.4	3.9284	21.7	3.4937	34.2	5.5062
TOTAL			13.1		11.9		10.0

Table B.8. Percentage Rounded + Subrounded Particles Using AIMS - Corpus Christi.

Size Retained	% Rounded + Sub-rounded in each size fraction	% size fraction by wt. of mix	% Rounded + Sub-rounded by wt. of mix	% size fraction by wt. of mix	% Rounded + Sub-rounded by wt. of mix	% size fraction by wt. of mix	% Rounded + Sub-rounded by wt. of mix
7/8"	26.8	1.8	0.4824	0	0	0	0
5/8"	21.5	8.3	1.7845	2	0.43	0	0
3/8"	12.5	19.9	2.4875	19.3	2.4125	7.9	0.9875
#4	10.7	17.1	1.8297	22.3	2.3861	30.4	3.2528
TOTAL			6.6		5.2		4.2

Table B.9. Percentage Rounded + Subrounded Particles Using AIMS - Pharr.

Size Retained	% Rounded + Sub-rounded in each size fraction	% size fraction by wt. of mix	% Rounded + Sub-rounded by wt. of mix	% size fraction by wt. of mix	% Rounded + Sub-rounded by wt. of mix	% size fraction by wt. of mix	% Rounded + Sub-rounded by wt. of mix
12.5mm	14.3	10.5	1.5015	0.9	0.1287	0.4	0.0572
9.5mm	21.4	25.1	5.3714	9.1	1.9474	6.6	1.4124
#4	7.2	26.9	1.9368	23.2	1.6704	29.9	2.1528
TOTAL			8.8		3.7		3.6

APPENDIX C
SPHERICITY AND ANGULARITY DISTRIBUTION USING AIMS

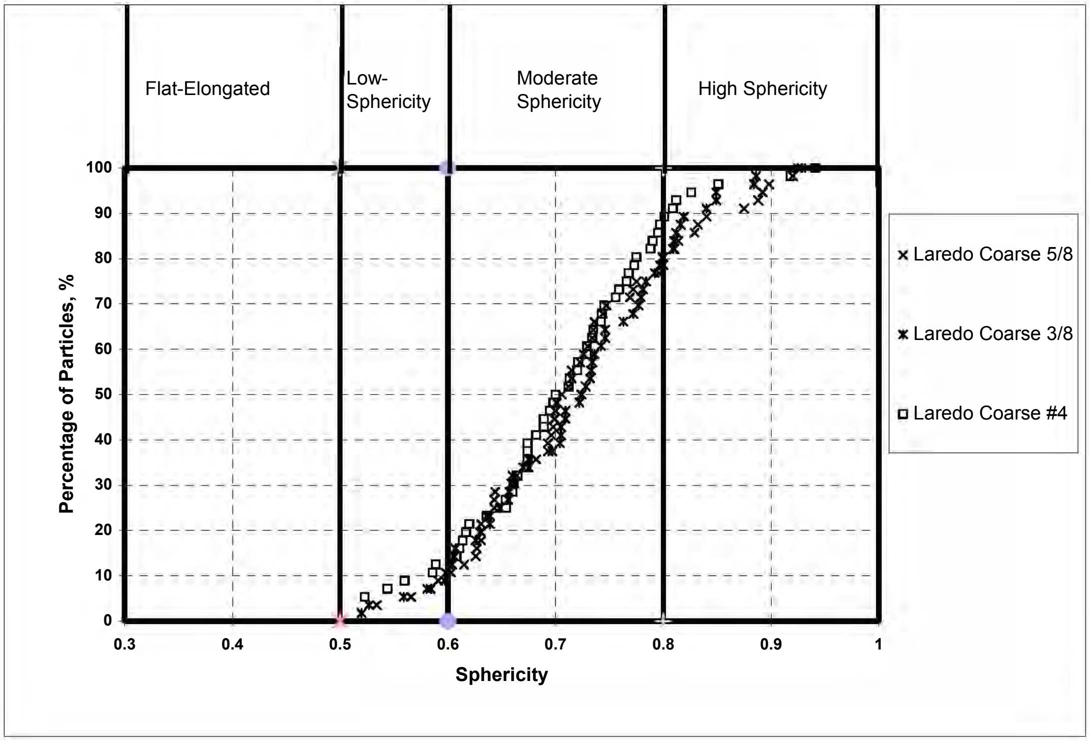


Figure C.1. Distribution of Spherical Particles in Laredo Mixes.

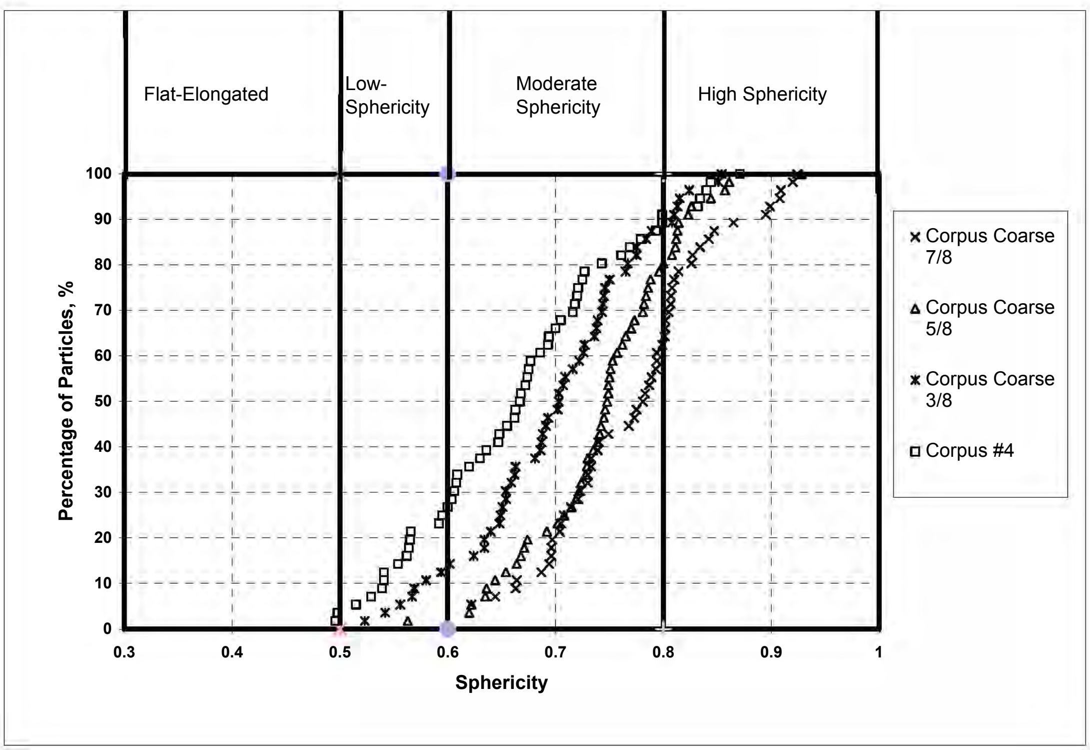


Figure C.2. Distribution of Spherical Particles in Corpus Christi Mixes.

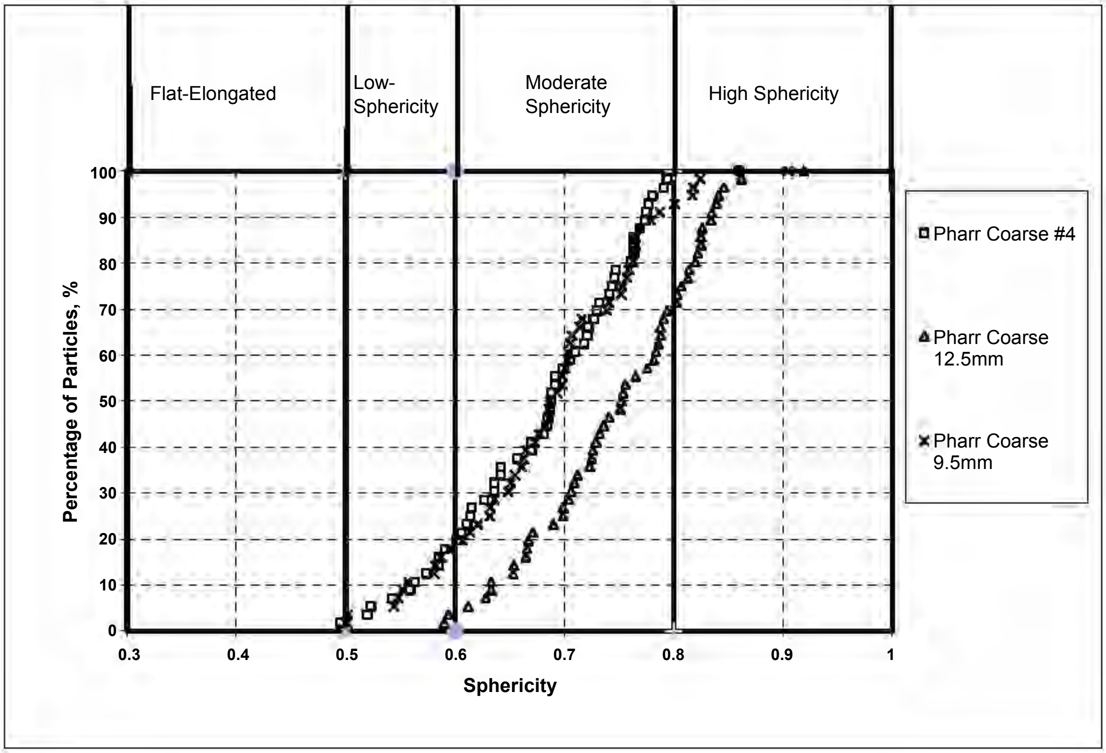


Figure C.3. Distribution of Spherical Particles in Pharr Mixes.

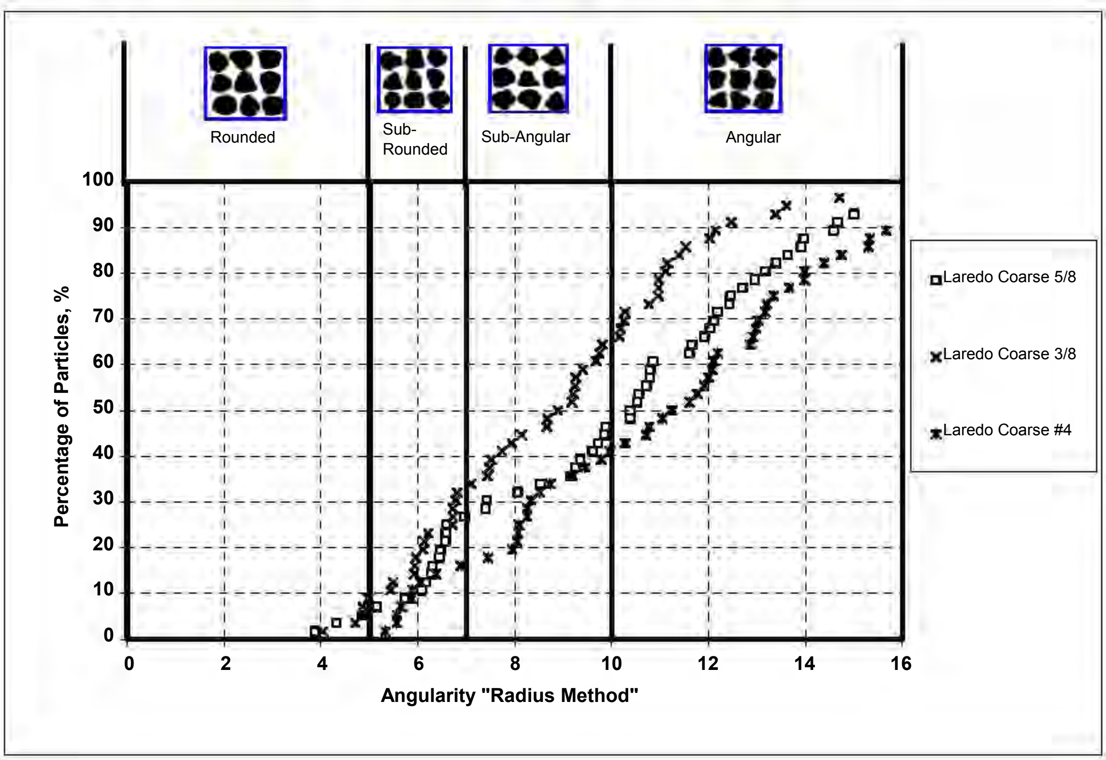


Figure C.4. Angularity Distribution of Particles in Laredo Mixes.

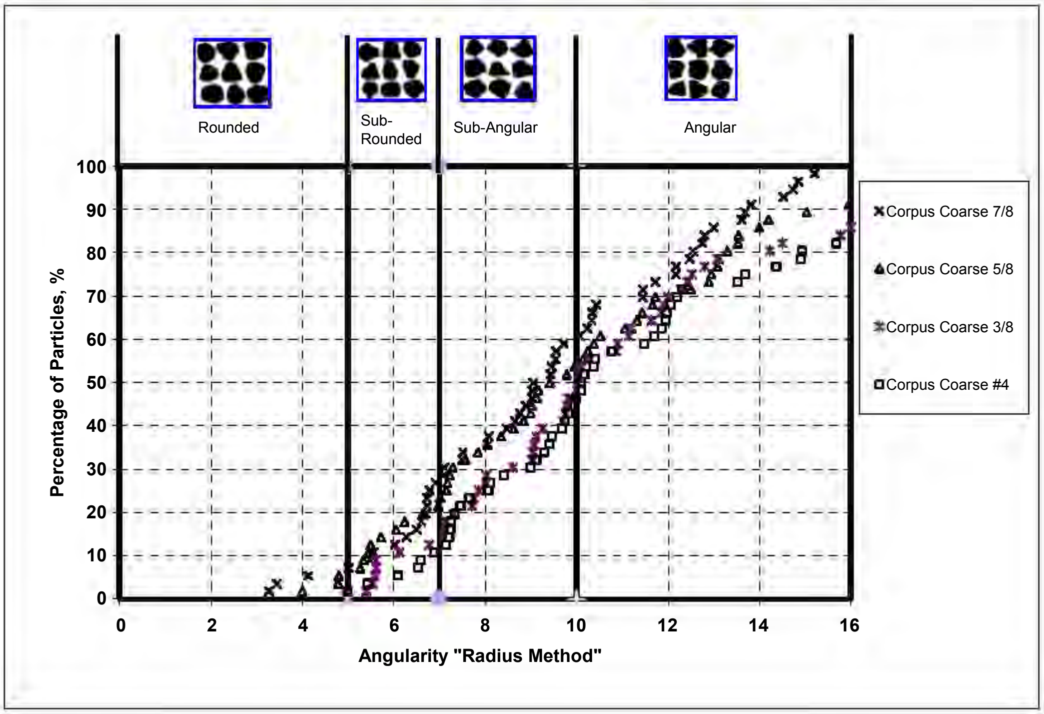


Figure C.5. Angularity Distribution of Particles in Corpus Christi Mixes

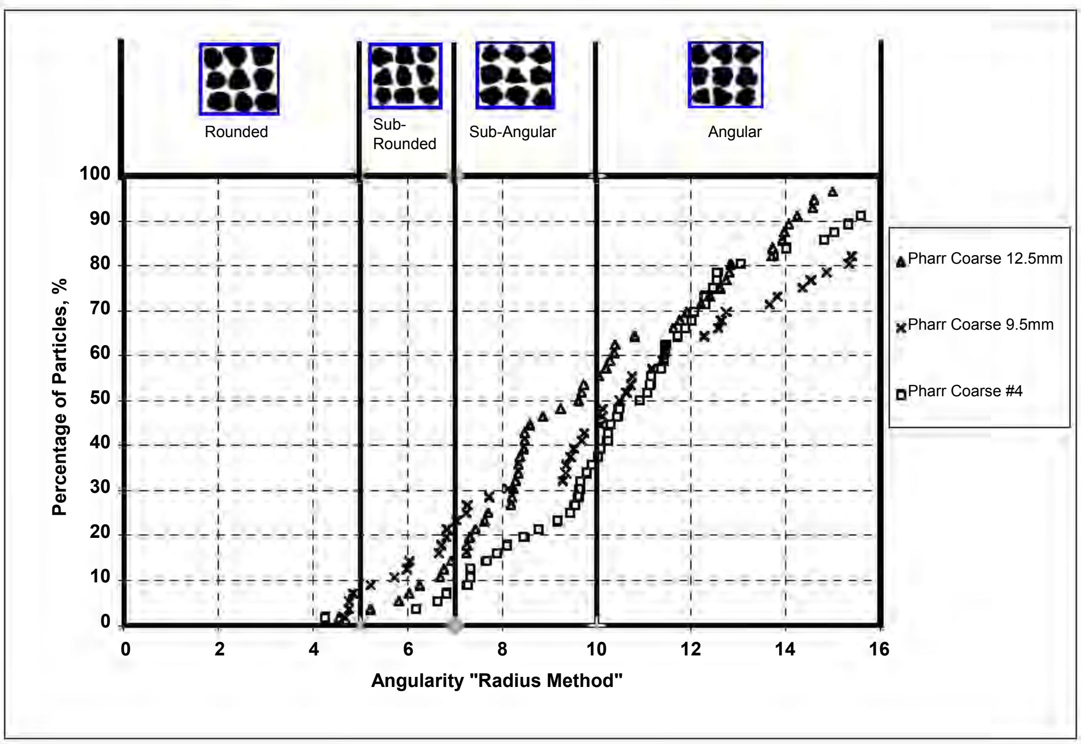


Figure C.6. Angularity Distribution of Particles in Pharr Mixes.