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16. Abstract

The primary objective of this project was to develop laboratory protocols for using the Superpave gyratory compactor (SGC) in place of the Texas gyratory compactor (TGC) to design essentially all of the Texas Department of Transportation (TxDOT) dense-graded hot mix asphalt (HMA) paving mixtures. The specific goal was to recommend a design number of gyrations (N_{design}) using the SGC for each TxDOT mixture type that will most closely simulate a mixture formerly designed using the TGC (Tex-204-F).

TxDOT HMA mixtures included Type A, Type B, Type C, Type D, Type Course Matrix High Binder CMHB-C, and Type CMHB-F. Researchers conducted the experiment in four steps including 1) SGC compaction of plant mixed materials, 2) SGC compaction of laboratory mixed materials, 3) determination of optimum asphalt content using the SGC, and 4) indirect tension testing of mixtures. The number of SGC gyrations that most closely simulated the TGC design for each mixture type was recommended. Researchers discovered that the TGC and the number of SGC gyrations to match the TGC were producing mixtures with comparatively low asphalt contents that may yield poor performance.

Therefore, Phase II was developed and implemented to determine an acceptable SGC design procedure using fewer gyrations than those proposed following Phase I. In both phases, more than 60 HMA mixture designs with related materials that had been designed by TxDOT personnel using the TGC were studied using the SGC. Phase II determined that mixtures indicating good performance in the Hamburg test can be designed using a considerably lower number of SGC gyrations than the number that will match optimum asphalt contents from the TGC. The final recommended SGC design gyrations should accommodate adequate asphalt in the mixture to improve resistance to cracking, raveling, and aging as well as decrease permeability while providing acceptable rutting resistance.

17. Key Words
Hot Mix Asphalt, Mixture Design, Texas Gyratory Compactor, Superpave Gyratory Compactor, Optimum Asphalt Content

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DESIGN OF TXDOT ASPHALT MIXTURES USING THE SUPERPAVE GYRATORY COMPACTOR

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DISCLAIMER

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CHAPTER 1
BACKGROUND AND INTRODUCTION

BACKGROUND

The Strategic Highway Research Program (SHRP) expended great effort in developing the Superpave gyratory compactor (SGC) as a modern, technologically advanced tool for design of hot mix asphalt (HMA) paving mixtures and for preparation of realistic test specimens for laboratory evaluation. Researchers used the Texas gyratory compactor (TGC) and TxDOT design process (i.e., optimum asphalt content [OAC] depending on the compaction mechanism) as the paradigm for the SGC apparatus and the Superpave design process. Since the widely accepted SGC was designed to produce specimens similar to actual pavement layers and, since TxDOT's current series of HMA paving mixtures have demonstrated acceptable performance, TxDOT desires to replace the TGC with the SGC for design of its current repertoire of dense-graded mixtures.

OBJECTIVE AND SCOPE OF WORK

The original objective of this work was to develop and verify protocols for using the SGC to design TxDOT HMA paving mixtures including CMHB mixtures. The specific goal was to recommend a design number of gyrations (N_{design}) using the SGC for each TxDOT mixture type that most closely simulates a mixture designed using the TGC (Tex-204-F).

This was the first of several tasks to be performed as part of TxDOT Research Project 0-4203. From the beginning of this research project, TxDOT and the researchers gave this work high priority. This task, "Implementation of the Superpave Gyratory Compactor in TxDOT" was initially performed in several subtasks. This initial effort (as originally planned) will be termed as Phase I in this report. Because the recommended number of SGC gyrations to produce specimens similar to those from the TGC in Phase I were quite high, and thus produced mixtures with extremely low asphalt contents, a Phase II experiment was designed and implemented. Both Phase I and Phase II are briefly described in the following two subsections.

This report also contains "Guidelines for Selection of Hot Mix Asphalt Type for Specific Applications" (Appendix C). Information is provided and recommendations are made to aid the districts in developing custom HMA mixture selection guidelines for their decision-makers in the area offices.

Original Phase I Tasks

TxDOT mixtures included in Phase I were Type A, Type B, Type C, Type D, Type CMHB-C, and Type CMHB-F. The experiment was conducted in four separate steps:

1. Twenty-one plant mixed HMA mixtures were obtained from haul units, reheated in the laboratory, and compacted, using the SGC, to the air void level specified in the TGC mixture design. The number of SGC gyrations was recorded.
2. Thirty-six HMA mixture designs along with associated aggregates and asphalts were obtained from the TxDOT districts and HMA mixtures were prepared and compacted (using the SGC) to an air void level below that specified in the TGC mixture design. Technicians recorded the SGC compaction curves and interpolated the number of SGC gyrations to achieve the TGC design air voids.
3. Based on the findings in Step 2, the number of SGC gyrations that most closely yielded the TGC design air void content was selected for each mixture type. Using 28 sets of materials as specified in the TGC design, the SGC with the preselected number of gyrations was used to determine their optimum asphalt contents.
4. Indirect tension tests were conducted in accordance with Tex-226-F using 6-inch diameter specimens compacted to 7±0.5 percent air voids using the SGC.

A report of the Phase I effort and results was submitted to TxDOT in September 2002 and is summarized in Appendix B. Based on the findings from Phase I, the researchers recommended the number of SGC gyrations required to produce the optimum asphalt contents that most closely simulated that produced by the TGC (Table 1).

Table 1. Recommended Number of SGC Gyrations to Simulate TGC Mixture Design - Phase I.

Mixture Type	Recommended No. of SGC Gyrations
A	100
B	110
C	160
D	160
CMHB-C	140
CMHB-F	160

Phase II Task

The findings and recommendations from Phase I literature review and testing indicated that the TGC and the number of SGC gyrations to produce mixtures similar to the TGC produced HMA mixtures with very low binder contents. This was viewed as a potential problem particularly in concert with the recent nationwide move toward harder asphalts. Dry mixtures might promote poor compaction, fatigue cracking, raveling, permeability, and moisture susceptibility. Therefore, the research team and the TxDOT project directors designed a subsequent experiment to examine the use of a lower number of SGC gyrations than those recommended following Phase I. The goal was to provide HMA mixtures with good durability. Five common TxDOT mixtures were included: Type A, Type B, Type C, Type D, and Type CMHB-C. Each mixture type contained two different coarse aggregate types: limestone (LS), and river gravel (RG). The experiment was conducted in three steps.

1. Determine the optimum asphalt contents for several types of HMA mixtures composed of two different common types of aggregate with three different asphalt grades using three different SGC compaction levels.
2. Evaluate rutting resistance of all mixtures designed in the previous step using the Hamburg Wheel Tracking Device (HWTD).
3. Analyze results from Steps 1and 2, and recommend a number of SGC gyrations for design of each TxDOT mixture type.

The main body of this report will concentrate mainly on the Phase II effort, results, and recommendations.

CHAPTER 2
LITERATURE REVIEW

TEXAS GYRATORY COMPACTOR vs. SUPERPAVE GYRATORY COMPACTOR

Although the SGC was developed using the basic mechanical principles of the TGC, there are significant differences in the two devices. Advantages of the SGC over the TGC include the following:

- SGC produces larger specimens that can accommodate aggregate particles up to 2 inches (1.5-inch nominal maximum size).
- By measuring specimen height and estimating density during the compaction process, the SGC can estimate compactability of mixtures.
- Density versus number gyrations in the SGC can help identify weak aggregate structures that collapse very quickly to lower air void levels (i.e., potentially rut-susceptible and/or tender mixes).
- TGC involves more manual control and is thus more prone to human errors, which can adversely affect repeatability (within-laboratory variability) and reproducibility (between-laboratory variability) during determination of OAC.

Based on past experience of the researchers and reports from TxDOT's Bituminous Branch (Izzo, 1999), it does not appear likely that adjusting only the number of gyrations of the SGC (gyration angle = 1.25°) can produce specimens basically identical to those produced by the TGC (gyration angle = 5.8°). The lower angle of the SGC imparts significantly less mechanical energy into the specimen during each gyration. Different angles of gyration have different influences on the orientation of the aggregates, particularly the larger aggregates. The *differences* between specimens (air void structure, aggregate orientation, voids in the mineral aggregate [VMA], and density gradient) prepared using the TGC and SGC will not likely be consistent because these differences will depend on the shear resistance of the mixture (i.e., maximum particle size, particle size distribution, binder and mastic rheology, and, probably, other factors). Figures 1 and 2 show the Texas gyratory compactor and Superpave gyratory compactor, respectively.

Figure 1. Texas Gyratory Compactor.

In the Project 0-4203 proposal, the researchers expressed this concern and stated, "…it is not likely to determine a simple relationship to transition from the TGC to the SGC for all TxDOT HMA mixtures of a given type." Although the SGC can produce the same volume of air voids as the TGC in a given mixture type, the resulting optimum binder content and engineering properties of the compacted mixtures may be measurably different because of different aggregate orientations and different density gradients within the specimens. Findings in Button et al. (1994) and Von Quintus et al. (1991) support these postulations.

Figure 2. Superpave Gyratory Compactor.

PERTINENT FINDINGS BY OTHER AGENCIES

Texas Gyratory Compactor

Prior to their adoption of the Superpave HMA mixture design and analysis protocols, Colorado Department of Transportation (DOT) specified the Texas gyratory compactor for determination of optimum asphalt content of HMA mixtures during their design. Aschenbrener and Currier (1993) used the TGC to design 16 mixtures in an evaluation of the Hamburg and Georgia loaded-wheel testers. They found that, even though the mixtures were designed at relatively low air voids (3 to 4 percent), they were very resistant to rutting according to the French rutting tester and the Asphalt Pavement Analyzer (APA). Their data supported higher asphalt contents. They stated that increasing the asphalt contents could still produce rut-resistant mixtures and possibly increase resistance to fatigue cracking and durability. They achieved higher binder contents by reducing the end-point stress in the Texas gyratory compactor from 150 to 100 psi. Although they did not mention it, clearly, higher binder contents would also provide improved resistance to moisture damage. In subsequent personal communications with Mr. Aschenbrener, he stated that they even used 75- and 50-psi end-point stresses with the TGC for mixes designed for low-volume roads. His subjective evaluation of performance on these roadways after several years has shown them to be satisfactory.

Contrary to findings by Colorado DOT (Aschenbrener and Currier, 1993), Mr. Dale Rand and other TxDOT pavement engineers have stated that it is a common process to reduce (by about 0.3 percent) the optimum asphalt content of HMA mixtures determined using the TGC when the mixture is applied in the field because it is apparently too high. Mr. Greg Cleveland indicated that the contractor and his desire to economize the mixture is also involved in the decision to lower the OAC. The amount of this OAC reduction depends on the amount of aggregate degradation (production of fines) during plant mixing, aggregate gradation, climate, compaction equipment, etc. Lowering the OAC could, of course, have negative effects on moisture susceptibility, fatigue and low-temperature cracking resistance, compactability, and permeability of the resulting pavement layer. Because of the cooler average temperatures in Colorado, particularly in the mountainous regions where moisture and freeze-thaw cycles are common, the higher asphalt contents may be more suitable there than in Texas.

D’Angelo and Ferragut (1991) demonstrated that it is common for plant-produced HMA compacted in the laboratory to yield lower air voids than the design requirements. Nonetheless, the point here is that there appears to be a practical amount of latitude in the “optimum” asphalt content of an HMA mixture. It therefore appears that, if a typical TxDOT Type “X” mixture is designed using the SGC with a predetermined number of gyrations, some of these mixtures will have different asphalt contents than if they were designed using the TGC, but will likely perform satisfactorily. Further, as indicated above, the contractor can adjust the asphalt content in the field during construction to conform to the specific circumstances.

Superpave Gyratory Compactor

Utility and Benefits of the SGC

The SGC is not the perfect compactor for producing specimens that manifest all the properties of field-compacted HMA pavement layers. It may, however, be the best available compactor for conveniently producing laboratory-scale 6-inch diameter HMA specimens. It is convenient, versatile, and provides important information related to the engineering properties of HMA. Further, it is becoming, and may be, the most widely accepted and used HMA compaction device in the world.

During SHRP Project A-005, Button et al. (1994) found that TGC compaction most often produced specimens similar to pavement cores when compared to Exxon rolling wheel, Elf linear kneading, and rotating-base Marshall compactors. Based on this and other work (Von Quintus et al., 1991), the SHRP researchers developed the Superpave gyratory compactor (from a 6-inch TGC) as a tool for measuring compactability and, to a limited extent, predicting performance of HMA mixtures (Cominsky et al., 1994; McGennis et al., 1994). Anderson and Bahia (1997) and McGennis (1997) were among the first to point out that slope of the compaction curve is useful in estimating mixture shear resistance, which should be related to tenderness and/or rutting. Reports from National Cooperative Highway Research Program (NCHRP) Study 9-7 (Cominsky et al., 1998) and NCHRP Project 9-9 (Brown et al., 1999) discuss SGC compaction properties including compaction slope. Many engineers believe that $N_{initial}$ provides useful information regarding compactability of HMA. Excessive density at $N_{initial}$ indicates a potential tender mix, and, conversely, inadequate density indicates the contractor may have difficulty achieving the required density. Buchanan and Brown (2001) concluded that the precision of the SGC was better than the mechanical Marshall hammer.

Although the SGC can provide useful information about mixture quality, it is not an HMA testing device. Regarding HMA mixture quality control (QC), Cominsky et al. (1998) stated that measured volumetric properties from the SGC may fail to detect changes in gradation or asphalt content and will indicate the process is in control when it is not. This occurs most commonly when the asphalt content and gradation are simultaneously varying. They concluded, therefore, that field test devices should be used in concert with the SGC to measure performance-based engineering properties for QC. Anderson et al. (2000) showed that high-temperature shear stiffness of HMA mixtures can differ greatly at the same compaction level while the mixtures meet all the Superpave volumetric criteria.

The original Superpave N_{design} compaction matrix contained 28 levels (four temperatures × seven traffic levels). Brown et al. (1996) found that the recommended gyration levels may be excessive for lower levels of traffic. Brown and Buchanan (1999) recommended reducing the number of N_{design} compaction levels from 28 to four (i.e., 50, 70, 100, and 130 gyrations) to address all traffic levels. They advised that the requirement for 11 percent air voids at $N_{initial}$ for low-volume roads was too stringent. They further recommended designing mixtures to N_{design} gyrations and not $N_{maximum}$ and suggested that the slope of the compaction curve may not be a good indication of strength of the HMA aggregate structure. These recommendations indicate that the original Superpave approach was too conservative, which (in these authors' opinion) was probably the correct approach.

Some engineers believe the SGC produces "rich" mixtures. This is likely true for coarse mixture designs passing below the restricted zone (which Superpave initially recommended) where specific surface area is less than that for finer mixtures and yet the VMA requirements are the same. These conditions with the SGC can yield relatively thick asphalt films and thus coarse mixtures that are less rut resistant than finer mixtures composed of similar materials (Chowdhury et al., 2001). Incidentally, in a presentation to the Transportation Research Board (TRB) Expert Task Group on Superpave Mixtures/Aggregates, Galal and Gallivan (2001) reported that triaxial tests resulted in up to about 0.5 percent lower OAC than standard Superpave design procedures using the SGC.

In a study of a limited number of materials, Tashman et al. (2000) found that field cores had similar air void distribution patterns irrespective of compaction procedure. Most often, the highest voids were near the top and decreased with depth until about one-third of the core thickness, after which they remained relatively uniform. There was no difference in horizontal distribution within a core. In a related follow-up study with limited mixtures, Masad et al. (2001) reported that for a given test mix, the combination of specimen height between 50 and 75 mm and a SGC compaction angle of 1.5° produced an internal HMA structure that best simulated field cores (i.e., internal structure including void distribution and aggregate orientation).

Angle of Gyration

Researchers have shown that the SGC is highly sensitive to angle of gyration (Blankenship et al., 1994). Butcher (1998), of Transport South Australia, reported that the percentage of air voids achieved by compacting to a specified number of gyrations or the number of gyrations required to achieve a specified air void value decreases exponentially with increasing angle. He also showed that maximum shear stress increases logarithmically with increasing angle but increases linearly with increasing vertical stress. He further demonstrated that the SGC is highly sensitive to gyratory angles less than 2° but much less sensitive to angles between 2° and 3°; thus, tolerances must be tighter at lower angles. As a result, he recommended a gyratory angle of 2° at a pressure of 240 kPa for use in *Australia*. (Note that Superpave requires 1.25° at 600 kPa.)

During their NCHRP 4-30 project, Button et al. (1997) questioned the SGC angle of gyration (1.25°) for large stone mixes. They showed that the small angle was insufficient to compact coarse-graded large-stone mixtures even when the vertical pressure was increased to such an extent that many stones were crushed at the ends of the specimen during compaction. When the angle was increased to about 5.8° (as in the TGC), the same mixtures were adequately compacted at much lower pressure and without excessive crushing of aggregate. The larger angle apparently imparted the mechanical energy necessary to orient and interlace the large, angular stones without the high pressure. The subsequent NCHRP Project 9-9, "Refinement of the SGC Procedure," unfortunately, specifically disallowed investigation of the angle of gyration.

Potential of SGC to Reveal Performance-Related Mix Properties

As mentioned above, $N_{initial}$ and the slope of the initial portion of the SGC compaction curve have been hypothesized to reveal certain mixture properties. Bahia et al. (1998), at the University of Wisconsin, believe the current method of interpretation of the results from the SGC and the design criteria are biased toward the performance under traffic and do not give proper consideration for constructability of mixtures. They separated SGC densification curves into different regions to represent 1) the construction compaction requirements, and 2) the traffic densification to a selected air void level or to "terminal" densification. They introduced the concept of compaction energy index, which is the change in volume of a specimen as a function of the number of gyrations (response measured by the SGC), as an indicator of densification characteristics. The compaction energy index and the traffic densification index are used as new measures to relate to construction and in-service performance of HMA mixtures. They indicated that controlling these indices is expected to allow optimization of HMA construction and traffic requirements. Although some of their findings contradict conventional wisdom, the concept may have value in characterizing HMA.

The University of Wisconsin group (Guler et al., 2000) later developed a gyratory load-cell and plate assembly (GLPA) for measuring HMA shear resistance during compaction with any SGC. It is a simple, thin cylindrical device that is inserted on top of the mixture in the compaction mold that gives continuous measure of shear resistance under gyratory loading during compaction. They hypothesized that bulk shear resistance from the GLPA is a good indicator of the compactability of HMA mixtures and their potential resistance to rutting under traffic. They demonstrated that shear resistance is highly sensitive to gradation, asphalt content, and temperature (i.e., asphalt or, rather, mastic viscosity). Although they have not validated relationships with field performance, they stated that the device offers potential as a low-cost tool to complement volumetric properties from the SGC.

Mallick (1999) found that the gyratory ratio, the ratio of the number of gyrations required to achieve 2 percent voids and 5 percent voids, was suitable for characterizing HMA. He stated that a gyratory ratio of 4 can be used to differentiate between stable and unstable mixes and, further, that mixes with a gyratory ratio less than 4 may be unstable. He admitted that his theory has not been field validated (only five mixes tested) and that several questions must be resolved before a final method can be prepared. Intuitively, it would appear that critical void levels will decrease as maximum aggregate size increases.

During NCHRP 9-16, “Relationship between Superpave Gyratory Compaction Properties and Permanent Deformation of Pavements in Service,” Anderson (2002) evaluated several SGC compaction parameters and found that the best parameter related to asphalt mixture shear stiffness and rutting potential was N-SR$_{max}$. He defined N-SR$_{max}$ as the number of gyrations at which the stress ratio (shear stress divided by vertical stress) reaches a maximum value. He measured N-SR$_{max}$ using a Pine AFG1 SGC modified with a shear measurement system that produces a unitless stress ratio. He used several HMA mix variations of gravel and limestone to demonstrate the utility of N-SR$_{max}$ and to identify threshold values for separating mixtures with good and poor expected performance. He noted that *none* of the evaluated SGC parameters appeared to be capable of identifying differences in mixture performance based on asphalt binder stiffness and that N-SR_{max} is not intended to replace the need for actual mechanical property testing but to identify if and when further performance-related testing is needed.

These methods for characterizing HMA during SGC compaction appear to have merit and may provide useful tools after further development and validation.

The Trend Toward Reduction in N_{design} Using the SGC

Although Superpave was successful in improving rutting resistance of HMA, many have expressed concern about durability of these mixtures. Concerns include fatigue and other types of cracking, raveling, and permeability. Several state DOTs, which adopted the basic Superpave mixture design system have subsequently reduced their N_{design} values from those initially proposed by SHRP (Maupin, 2003; Aschenbrener and Harmelink, 2002; Alabama DOT, 2003). As a result of lowering N_{design} and thus increasing optimum asphalt content, some of these DOTs have reported notable improvements in HMA durability and performance.

Virginia DOT researchers (Maupin, 2003) simply added 0.0, 0.5, and 1.0 percent asphalt to certain existing mixture designs and conducted comparative tests on the mixtures. He first determined the SGC compactive effort that yielded the same air voids that had been achieved in the field for each mix. He measured permeability, rutting resistance (APA), and fatigue properties (flexural beam). He reported tremendous benefit in reducing permeability when only 0.5 percent asphalt was added. Of course, fatigue properties increased with asphalt content. With lower permeability, the long-term benefits of fatigue may be further augmented. Rutting did not appear to be problematic even with the addition of 1.0 percent asphalt.

Colorado DOT engineers (Aschenbrener and Harmelink, 2002) found that air voids in Superpave HMA surface mixtures after up to six years of traffic had not attained the design air void contents. They concluded that the mixtures were designed to be too stiff (OAC too low) for the existing traffic and environmental conditions and that less gyratory compaction is justified.

Brown and Mallick (1998) compacted HMA in the SGC at different gyration levels and compared the density of corresponding in-place cores obtained from pavement test sections at various levels of cumulative traffic. They obtained cores from Alabama, Idaho, South Carolina, New Mexico, and Wisconsin with different levels of traffic. The cores were taken immediately after construction and after one, two, and three years of service. Air void contents and densities of the cores were measured. They found that the number of SGC gyrations required to achieve the one and two-year in-place densities were below 100 for all mixtures and concluded that N_{design} may be too high for low traffic volume roadways. They indicated that an N_{design} of 46 gyrations was appropriate for a mix with an average maximum air temperature of less than 39°C and 1 million Equivalent Single Axle Loads (ESALs).

Phase I of this project indicated that finer mixtures demanded significantly higher N_{design} values. However, in their development of mix design criteria for 4.75-mm mixtures, James et al. (2003) recommended 75 SGC gyrations for N_{design}. Further, they recommended the following design criteria: air voids - 4 percent, VMA - 16 percent (plus maximum of 18 percent VMA to avoid excessive OACs), and Void Filled with Asphalt (VFA) - 78 percent. For roadways with little or no heavy traffic, they recommended 50 SGC gyrations.

CHAPTER 3
EXPERIMENTAL DESIGN

INTRODUCTION

The objective of this project was essentially to develop and verify laboratory protocols for using the Superpave gyratory compactor in place of the Texas gyratory compactor to design essentially all of TxDOT's repertoire of dense-graded hot mix asphalt paving mixtures. Phase I of this project was completed as planned, and a report of findings along with recommendations was submitted to TxDOT in September 2002. The recommended number of SGC gyrations for the different types of mixtures ranged from 100 to 160 (Table 1). Findings in Phase I indicated that more work was needed in this area primarily to determine if it is appropriate and advisable to use a lower number of SGC gyrations for HMA mix design and possibly use only two ranges of gyrations (e.g., <100 gyrations for Types A and B mixtures and <140 gyrations for Types C, D, and CMHB mixtures).

The TxDOT Project Monitoring Committee (PMC) and the researchers were concerned that the mixtures designed using the SGC with the number of gyrations recommended in Phase I may be too "dry" (i.e., contain insufficient asphalt) and thus subject to premature cracking, raveling, aging, and/or excessive permeability. In fact, this has been a concern for mixtures designed using the standard TGC procedures for several years, particularly for the harder binders being used since the introduction of Superpave. Therefore, following Phase I of this project, a subsequent comprehensive test plan was developed to determine if it is appropriate to use a lower number of gyrations than those recommended for design of TxDOT mixtures.

TxDOT and Texas Transportation Institute (TTI) engineers decided to pursue further research using the five primary types of mixture used by TxDOT to determine the optimum asphalt content for different types of mixtures at three levels of SGC gyrations. Two HMA compositions (termed crushed limestone and river gravel) for each type of TxDOT mixture were tested (Table 2). Two performance grade (PG) binders were used for three types of mixtures and three PG binders were used for the remaining two types of mixtures. In this report, HMA "mixture design" will mainly refer to determination of optimum asphalt content to meet the specified air void criteria at specified SGC compaction levels (Table 2).

As a matter of interest, the researchers compared the gradations of the standard TxDOT types of HMA mixtures with those of the Superpave specifications in order to evaluate the possibility of (or justify) using the recommended Superpave gyration levels for the dense-graded TxDOT mixtures. These comparative plots are provided in Appendix A. The TxDOT mixture gradation zones do not lie within the Superpave control points for any type of mixture except for Type F. Therefore, the researchers proceeded with Phase II as planned.

Table 2 shows the test matrix used in Phase II. As shown in the table, OACs for each aggregate blend were determined using either two or three grades of asphalt. The most popular surface course mixtures (Types C and D) were used with three grades of asphalt. All mixtures designed using the different SGC gyration levels were tested using the HWTD to ensure that each mixture would pass appropriate TxDOT criteria. The other three types of mixtures (Types A, B, and CMHB-C) were designed using two PG asphalts (PG 64-22 and PG 76-22). This enabled interpolation to estimate OACs for the PG 70-22.

Table 2. Experimental Plan for Phase II.

Mix Type	Aggregate Type	Binder Type	Determine OAC			Hamburg @ each OAC
			No. Gyrations 1	No. Gyrations 2	No. Gyrations 3	
A	Limestone	PG 64	60	90	120	X
		PG 76	"	"	"	X
	River Gravel	PG 64	"	"	"	X
		PG 76	"	"	"	X
B	Limestone	PG 64	"	"	"	X
		PG 76	"	"	"	X
	River Gravel	PG 64	"	"	"	X
		PG 76	"	"	"	X
C	Limestone	PG 64	80	120	140	X
		PG 70	"	"	"	X
		PG 76	"	"	"	X
	River Gravel	PG 64	"	"	"	X
		PG 70	"	"	"	X
		PG 76	"	"	"	X
D	Limestone	PG 64	"	"	"	X
		PG 70	"	"	"	X
		PG 76	"	"	"	X
	River Gravel	PG 64	"	"	"	X
		PG 70	"	"	"	X
		PG 76	"	"	"	X
CMHB-C	Limestone	PG 64	"	"	"	X
		PG 76	"	"	"	X
	River Gravel	PG 64	"	"	"	X
		PG 76	"	"	"	X

MIXTURE INFORMATION

The researchers obtained or developed 10 mixture designs (5 mixture types × 2 aggregate types) each with one asphalt binder. These designs were obtained either from the districts or a contractor.

Aggregate

Aggregates for the limestone designs were obtained from the Colorado Materials plant at Hunter, Texas. Although these mixtures were composed primarily of crushed limestone, of significance, most of them contained some natural field sand. The Types A and B limestone mixtures contained 10 percent siliceous field sand. The Types C and D limestone mixtures contained 15 percent siliceous field sand. The Type CMHB-C limestone mixture contained no field sand.

The siliceous river gravel mixture designs were obtained from the Yoakum and Atlanta Districts. Most of the gravel aggregates were acquired from Fordyce Gravel in Victoria, Texas. The basis for the river gravel mix designs for mixture Types A and CMHB-C originated at the Atlanta District. The Atlanta District supplied the Grade A gravel plus all aggregates for the CMHB-C gravel aggregate blend. Although these mixtures were composed primarily of partially crushed river gravel, each mixture type contained stone crusher screenings in the following quantities of materials:

- Type A – 5 percent Donnafill,
- Type B – 15 percent limestone screenings,
- Type C – 19 percent limestone screenings (plus 4 percent natural sand),
- Type D – 10 percent limestone screenings (plus 15 percent natural sand), and
- Type CMHB-C – 20 percent Donnafill.

Figures 3 through 7 depict the aggregate gradations used in these 10 mixtures.

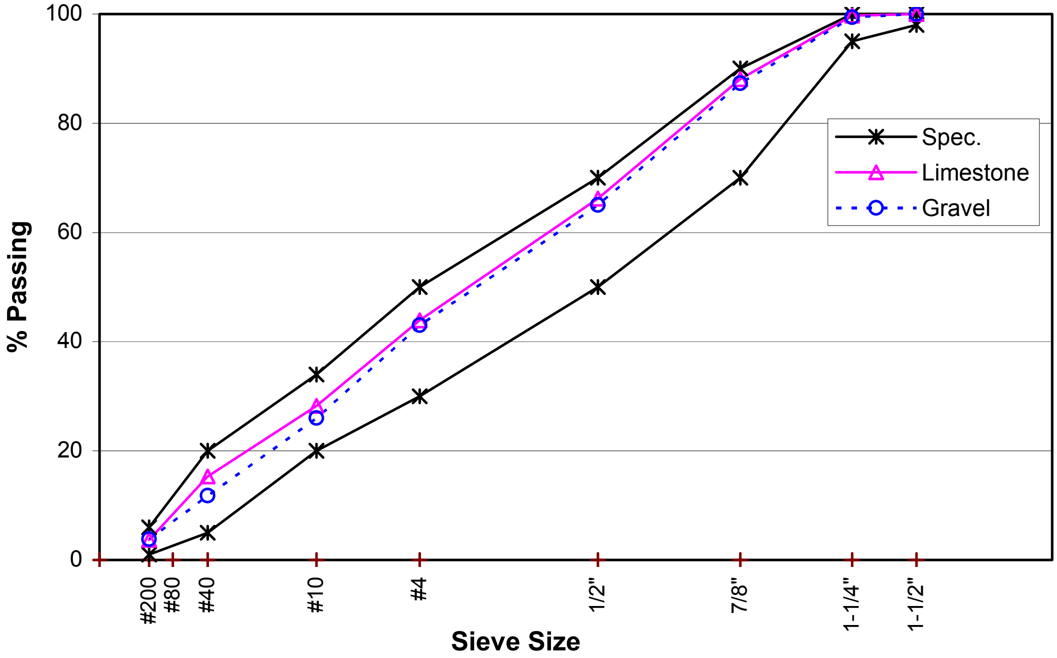

Figure 3. Type A Mixture Gradations and TxDOT Specifications.

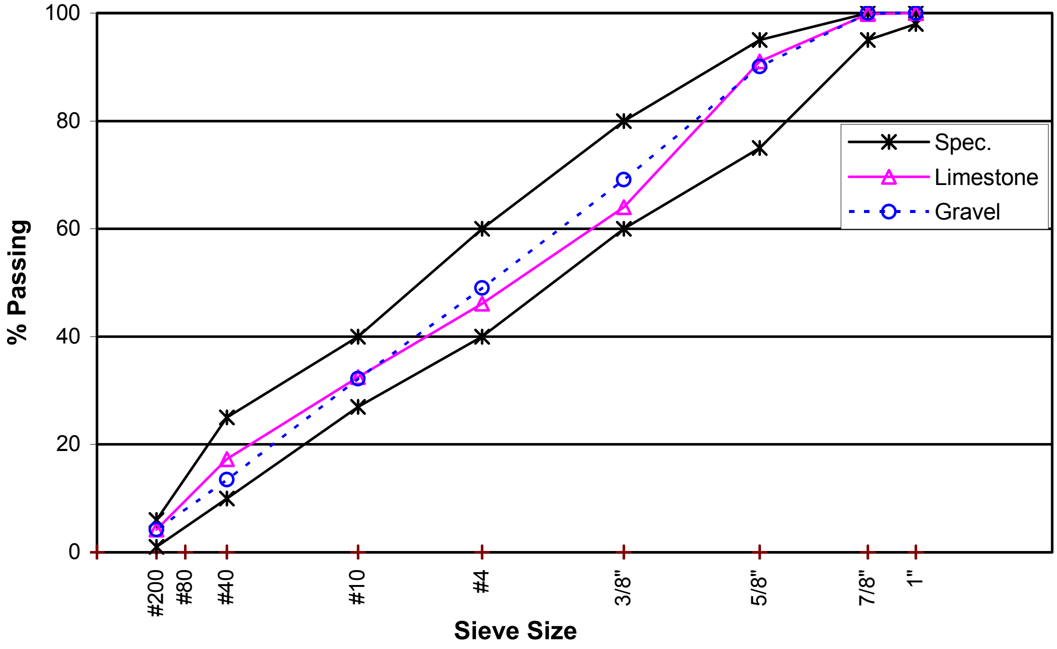

Figure 4. Type B Mixture Gradations and TxDOT Specifications.

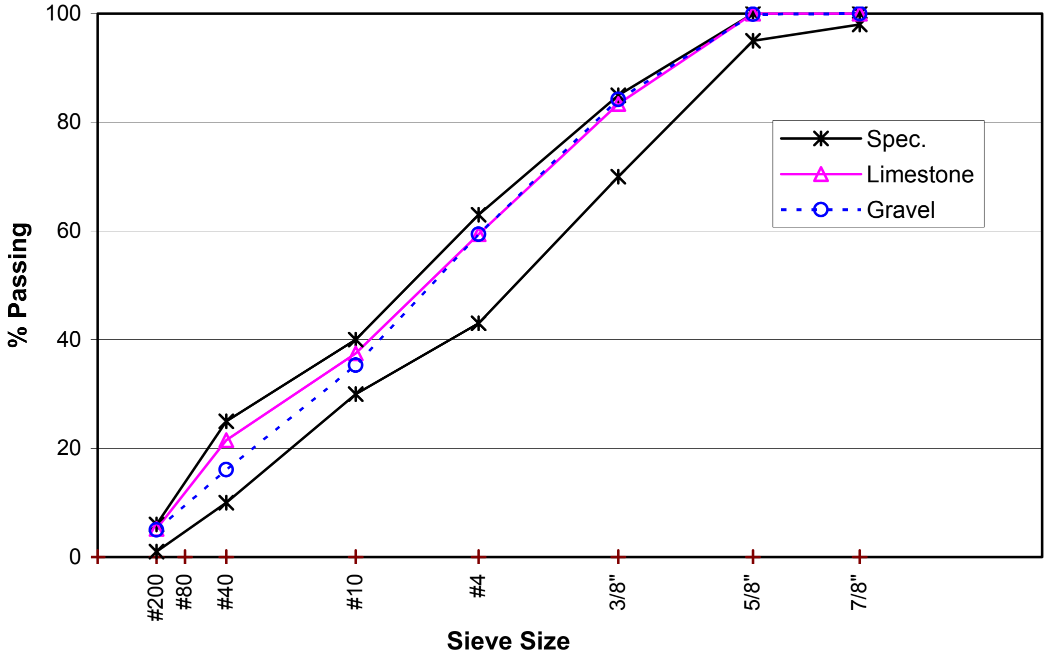

Figure 5. Type C Mixture Gradations and TxDOT Specifications.

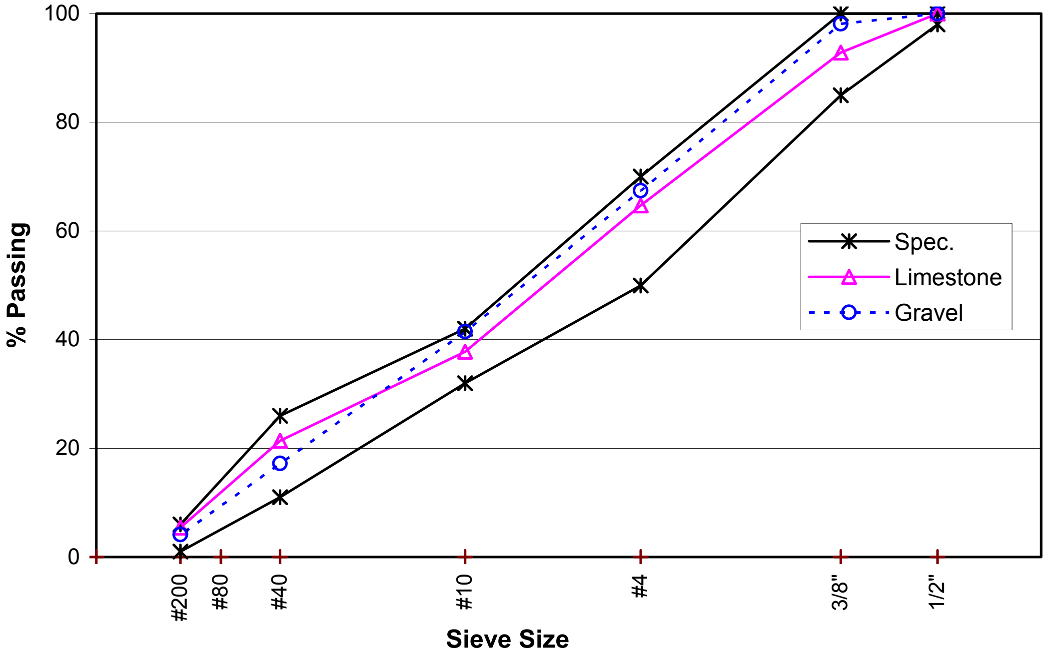

Figure 6. Type D Mixture Gradations and TxDOT Specifications.

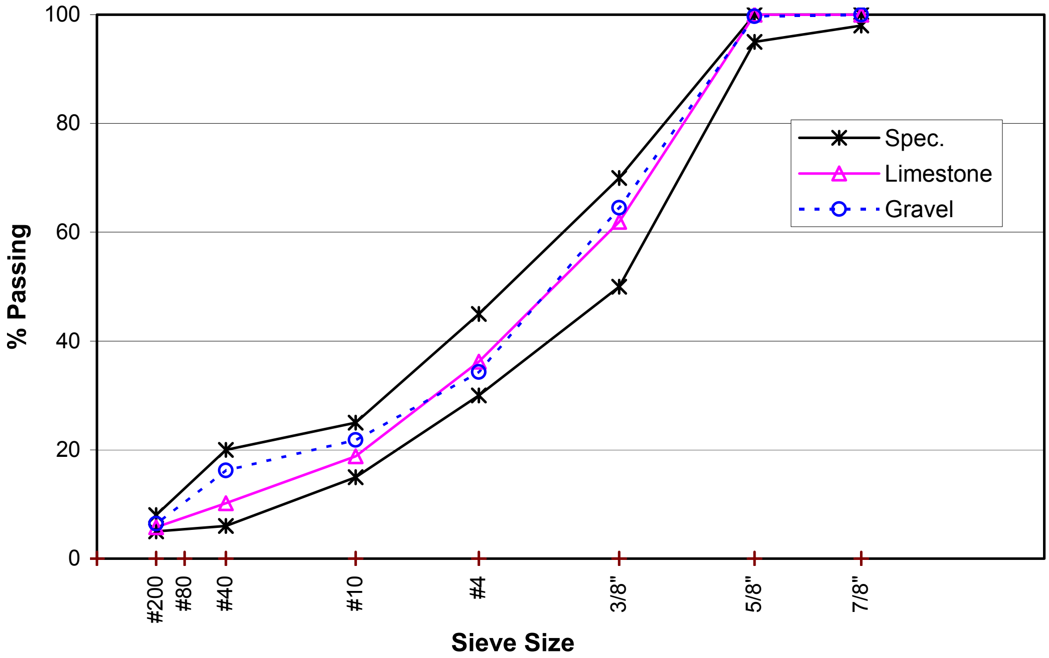

Figure 7. CMHB-C Mixture Gradations and TxDOT Specifications.

Asphalt

The authors obtained PG 64-22 and PG 76-22 asphalts from Marlin Asphalt in Corpus Christi, Texas (formerly known as Eagle Asphalt). They acquired PG 70-22 asphalt from Koch Materials Company at Fort Worth, Texas.

Additives

All of the limestone mixture designs required a liquid antistripping agent except the Type D mix, which required hydrated lime. All of the gravel mixture designs required 1 percent hydrated lime. These same antistripping agents were used in this experiment.

DESIGNING MIXTURES USING THE SGC

The goal of this work element was to determine the optimum asphalt content for selected mixtures using different SGC gyration levels and different grades of asphalt. The OACs were determined on the basis of design air voids of the original TxDOT mixture, which ranged from 3.0 to 4.0 percent. The SGC setup followed the Superpave recommendations (i.e., gyration angle of 1.25° and vertical pressure of 600 kPa). Industrial Process Control (IPC) in Australia, manufactured the ServoPac SGC used in this project.

The temperatures used for mixing, curing, and compaction were those recommended by TxDOT. Laboratory mixing followed Tex-205-F, "Laboratory Method of Mixing Bituminous Mixtures." Compaction of specimens followed Tex-241-F, "Superpave Gyratory Compacting of Test Specimens of Bituminous Mixtures," but at the specified gyration levels. Table 3 shows the temperatures used for the different asphalt grades.

Table 3. Mixing Compaction and Curing Temperature.

Asphalt Grade	Temperature °F (°C)		
	Mixing	Compaction	Curing
PG 64-22	290 (143)	250 (121)	250 (121)
PG 70-22	300 (149)	275 (135)	275 (135)
PG 76-22	325 (163)	300 (149)	300 (149)

CHAPTER 4
RESULTS AND DISCUSSION

DETERMINATION OF OPTIMUM ASPHALT CONTENT

Table 4 presents the OACs determined for each HMA mixture at the different conditions along with VMA and asphalt film thickness. Film thickness was calculated based on the method suggested by Hveem (Roberts et al., 1996). Surface area for each aggregate blend was calculated based on its gradation (Figure 8). The authors have reservations about the procedure for the surface area calculation based only on aggregate particle size distribution. Aggregate surface area computations depend primarily on the relative quantity of the finer aggregate sizes. Since the TxDOT master gradings call for only four sieves smaller than the No. 4 sieve, the accuracy of the surface area and subsequent film thickness calculations are a concern. Although film thickness may be used as a general guide, some highly respected members of the asphalt community believe that asphalt acts as mortar (filling voids between aggregates) in dense mixes and not as a film on aggregates, and thus that computations are of no value. However, these values are used herein only for the purpose of comparing relative asphalt film thicknesses. Using similar dense-graded materials, one would expect surface area to increase with a decrease in nominal maximum aggregate size. Typically, for a dense-graded mixture, more than one-half of the surface area comes from the minus No. 80 materials.

Plots of OAC versus number of gyrations for the mixture types studied are shown in Figures 9 through 13.

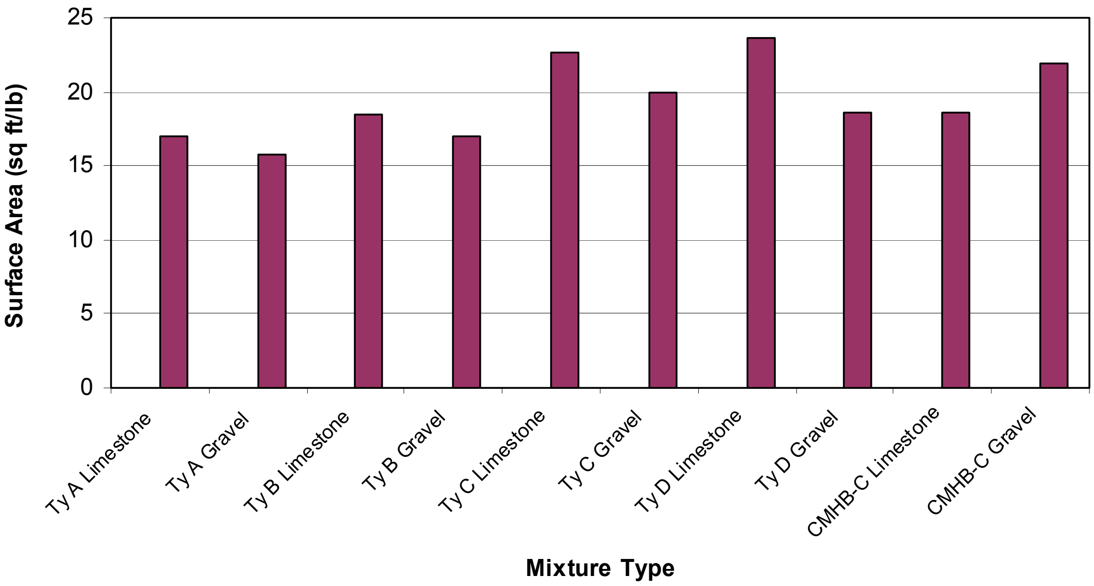

Figure 8. Calculated Surface Areas for Different Gradations Used.

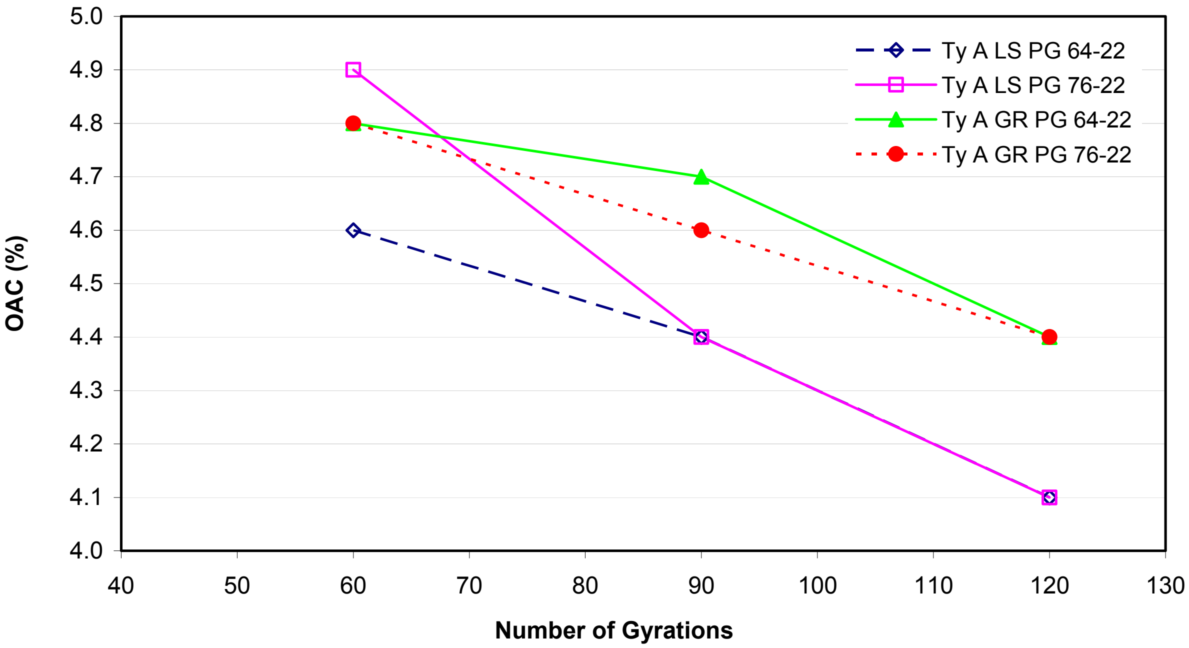

Figure 9. Optimum Asphalt Contents for Type A Mixtures.

Table 4. OACs Determined for All Mixtures.

Mixture Type	Coarse Aggregate Type	Asphalt Grade	SGC Gyrations Used	OAC (%)	Design Air Void Content (%)	VMA (%)	TxDOT VMA Criteria, Min (%)	Film Thickness (microns)
Type A	Limestone	PG 64-22	60	4.6	3.0	14.11	12.0	13.5
			90	4.4		13.69		12.9
			120	4.1		12.74		12.0
		PG 76-22	60	4.9		13.63		14.4
			90	4.4		12.87		12.9
			120	4.1		11.91		12.0
	River Gravel	PG 64-22	60	4.8	4.0	14.59		15.2
			90	4.7		14.43		14.9
			120	4.4		13.88		13.9
		PG 76-22	60	4.8		14.66		15.2
			90	4.6		14.31		14.5
			120	4.4		13.91		13.9
Type B	Limestone	PG 64-22	60	4.7	3.0	13.60	13.0	12.6
			90	4.4		13.00		11.8
			120	4.2		12.53		11.2
		PG 76-22	60	4.6		13.33		12.3
			90	4.3		12.66		11.5
			120	4.2		12.39		11.2
	River Gravel	PG 64-22	60	5.2	4.0	15.56		15.3
			90	4.8		14.89		14.1
			120	4.6		14.53		13.5
		PG 76-22	60	5.0		15.59		14.7
			90	4.7		15.04		13.8
			120	4.6		13.55		13.5
Type CMHB-C	Limestone	PG 64-22	80	6.6	3.5	18.86	14.0	18.0
			120	6.1		17.80		16.6
			140	5.8		17.18		15.7
		PG 76-22	80	6.2		18.02		16.9
			120	5.7		16.78		15.4
			140	5.4		15.88		14.6
	River Gravel	PG 64-22	80	5.3	3.5	15.29		12.1
			120	4.9		14.44		11.2
			140	4.7		13.94		10.7
		PG 76-22	80	5.4		15.45		12.4
			120	5.0		14.49		11.4
			140	5.0		14.49		11.4

Table 4. OACs Determined for All Mixtures (Continued).

Mixture Type	Coarse Aggregate Type	Asphalt Grade	SGC Gyrations Used	OAC (%)	Design Air Void Content (%)	VMA (%)	TxDOT VMA Criteria, Min (%)	Film Thickness (microns)
Type C	Limestone	PG 64-22	80	4.8	4.0	14.78	14.0	10.6
			120	4.5		14.12		9.9
			140	4.4		13.89		9.6
		PG 70-22	80	4.8		14.53		10.6
			120	4.4		13.75		9.6
			140	4.3		13.52		9.4
		PG 76-22	80	4.9		14.59		10.8
			120	4.6		14.11		10.1
			140	4.3		13.69		9.4
	River Gravel	PG 64-22	80	5.3	4.0	16.31		13.3
			120	5.3		16.31		13.3
			140	4.8		15.30		12.0
		PG 70-22	80	5.1		15.68		12.8
			120	4.8		15.09		12.0
			140	4.8		15.09		12.0
		PG 76-22	80	5.4		16.53		13.6
			120	5.2		15.97		13.1
			140	4.9		15.25		12.3
Type D	Limestone	PG 64-22	80	5.0	4.0	14.54	15.0	10.6
			120	4.8		14.23		10.1
			140	4.6		13.89		9.7
		PG 70-22	80	4.9		15.08		10.3
			120	4.5		13.98		9.5
			140	4.4		13.75		9.2
		PG 76-22	80	4.7		14.90		9.9
			120	4.6		14.64		9.7
			140	4.4		14.07		9.2
	River Gravel	PG 64-22	80	4.5	4.0	14.13		9.9
			120	4.5		14.13		9.7
			140	4.3		13.74		9.2
		PG 70-22	80	4.8		15.21		12.9
			120	4.6		14.68		12.3
			140	4.5		14.41		12.0
		PG 76-22	80	4.6		15.06		12.3
			120	4.5		14.80		12.0
			140	4.4		14.50		11.7

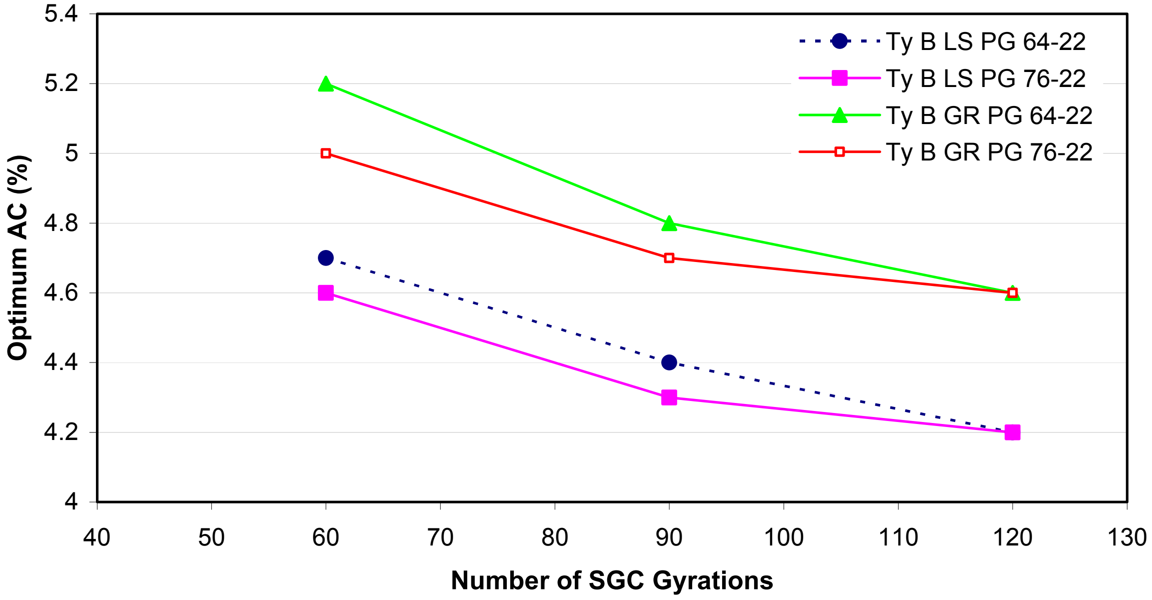

Figure 10. Optimum Asphalt Content for Type B Mixtures.

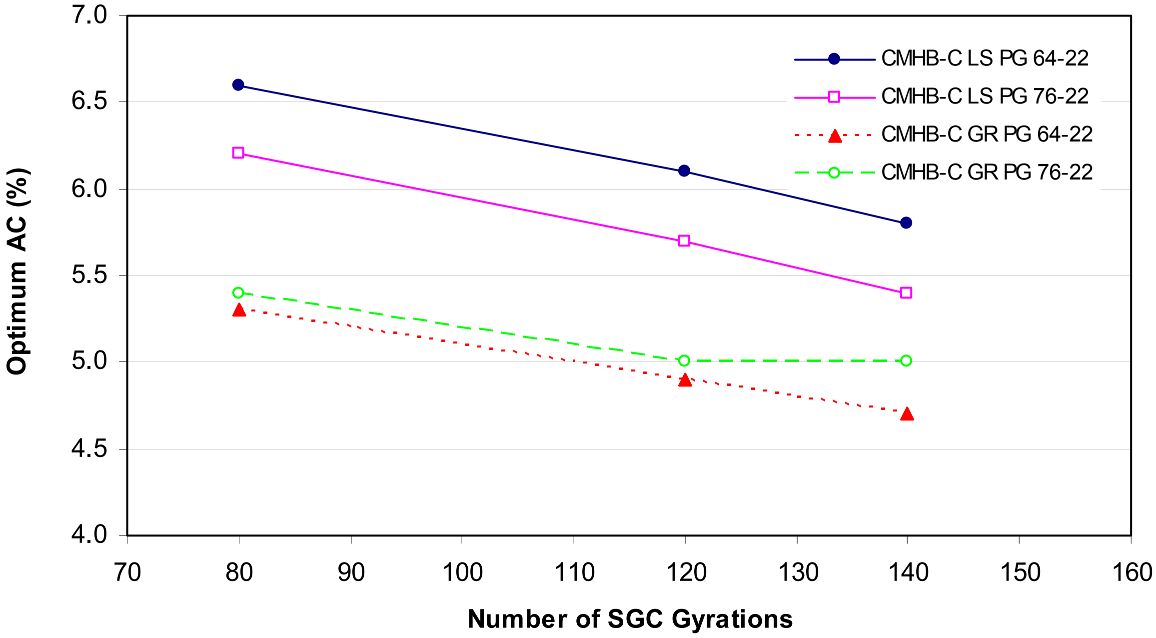

Figure 11. Optimum Asphalt Content for Type CMHB-C Mixtures.

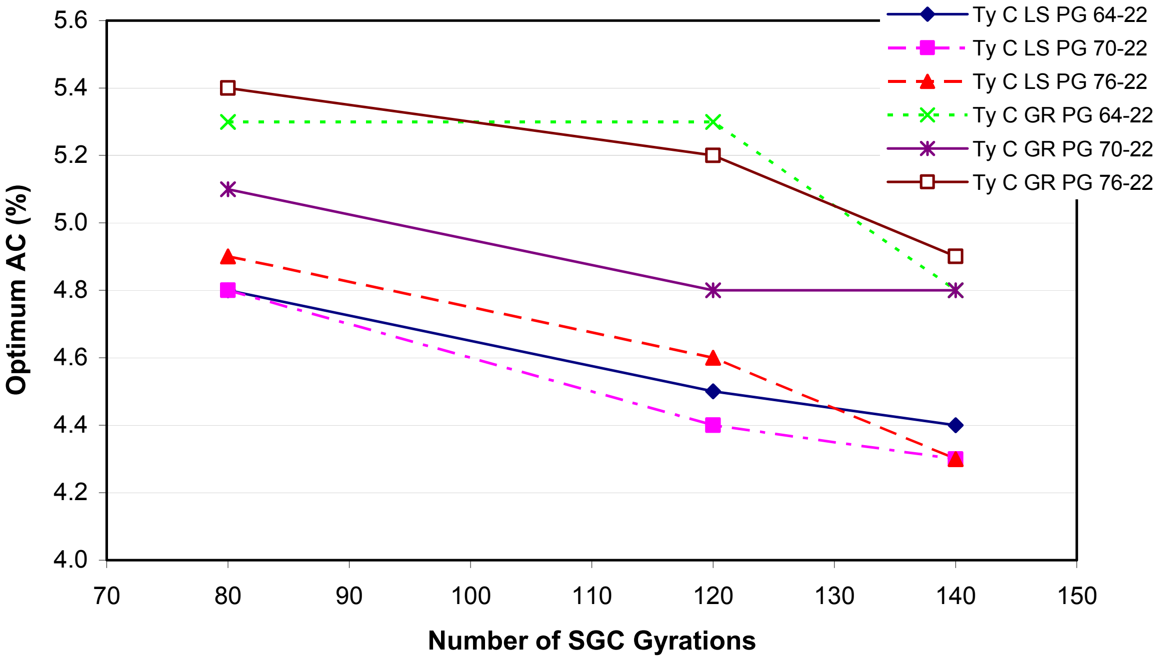

Figure 12. Optimum Asphalt Content for Type C Mixtures.

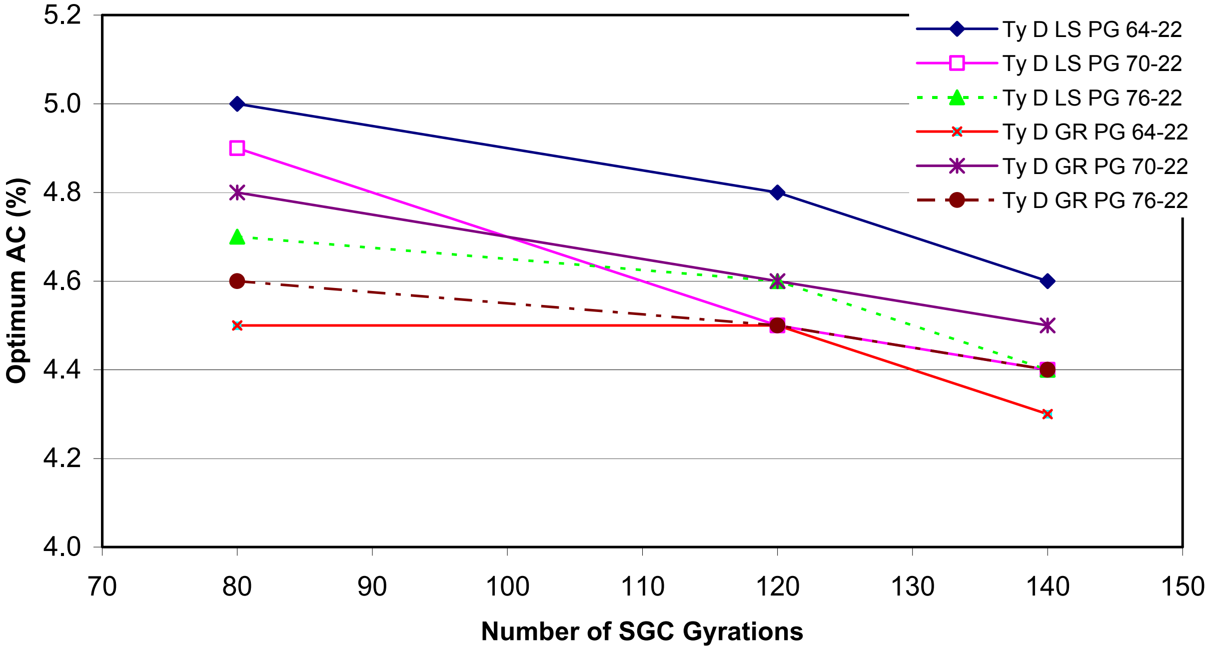

Figure 13. Optimum Asphalt Content for Type D Mixtures.

HAMBURG TEST RESULTS

All mixtures designed using the SGC compactor at the different gyration levels were tested using the HWTD to determine their rutting and moisture susceptibility. TxDOT method Tex-242-F was followed during this test. Four cylindrical specimens (two replicates) of each mixture were compacted at 7±1 percent air voids and tested. TxDOT criteria require a maximum HWTD rut depth of 0.5 inch (12.5 mm).

If the OACs for given mixtures were the same at two different compaction levels, only one set of specimens was tested on the HWTD. For example, the Type C river gravel mixtures designed with PG 70-22 yielded the same OAC (4.8 percent) at both 120 and 140 gyrations; therefore, only one set of specimens was tested. Hamburg testing was set up with a termination criterion of 0.5-inch (12.5-mm) rut depth or 20,000 cycles, whichever came first. Results of individual tests were analyzed using the TxDOT Hamburg Excel macro-spreadsheet. Table 5 shows the TxDOT requirements for Hamburg tests on mixtures using different PG binders. Table 6 shows the Hamburg test results. Detailed results are documented in Appendix A.

Results are normally reported in accordance with the TxDOT requirements; that is, the average rut depth for two replicate tests at the number of HWTD passes specified for each grade of asphalt binder (Table 6). In a few cases where a mixture failed prematurely, rut depths were projected to the specified number of load cycles for the grade of asphalt used in that mixture.

Table 5. HMA Requirement for HWTD Testing at 122°F (50°C).

High-Temperature Binder Grade	Minimum Number of Passes @ 0.5-inch Rut Depth
PG 64-XX	10,000
PG 70-XX	15,000
PG 76-XX or Higher	20,000

Table 6. Hamburg Test Results for All Mixtures.

Mixture Type	Aggregate	Asphalt Grade	Parameter	OACs (%) and Average Hamburg Rut Depth (mm)			TxDOT Requirement
				60 gyr	90 gyr	120 gyr	
Type A	Limestone	PG 64-22	OAC	4.6	4.4	4.1	Pass
			Rut Depth	11.18	6.97	9.33	
		PG 76-22	OAC	4.9	4.4	4.1	Pass
			Rut Depth	5.67	5.64	5.37	
	River Gravel	PG 64-22	OAC	4.8	4.7	4.4	Pass
			Rut Depth	5.82	6.58	6.02	
		PG 76-22	OAC	4.8	4.6	4.4	Pass
			Rut Depth	6.1	5.68	6.32	
Type B	Limestone	PG 64-22	OAC	4.7	4.4	4.2	Pass
			Rut Depth	7.1	9.15	5.46	
		PG 76-22	OAC	4.6	4.3	4.2	Pass
			Rut Depth	5.46	6.09	5.25	
	River Gravel	PG 64-22	OAC	5.2	4.8	4.6	Pass
			Rut Depth	9.08	8.07	6.41	
		PG 76-22	OAC)	5.0	4.7	4.6	Pass
			Rut Depth	5.46	6.09	5.25	
Mixture Type	**Aggregate**	**Asphalt Grade**	**Parameter**	**OACs (%) and Average Hamburg Rut Depth (mm)**			**TxDOT Requirement**
				80 gyr	**120 gyr**	**140 gyr**	
Type CMHB-C	Limestone	PG 64-22	OAC	6.6	6.1	5.8	Only 80 gyr fails,
			Rut Depth	17.50*	9.74	10.95	
		PG 76-22	OAC	6.2	5.7	5.4	Pass
			Rut Depth	7.44	5.96	8.47	
	River Gravel	PG 64-22	OAC	5.3	4.9	4.7	Pass
			Rut Depth	7.09	5.62	5.38	
		PG 76-22	OAC	5.4	5.0	5.0	Pass
			Rut Depth	4.81	4.81	4.81	

* Projected rut depth at 10K cycles.

Table 6. Hamburg Test Results for All Mixtures (Continued).

Mixture Type	Aggregate	Asphalt Grade	Parameter	OACs (%) and Average Hamburg Rut Depth (mm)			TxDOT Requirement
				80 gyr	120 gyr	140 gyr	
Type C	Limestone	PG 64-22	OAC	4.8	4.5	4.4	Only 140 gyr passes
			Rut Depth	12.47*	13.35#	8.21	
		PG 70-22	OAC	4.8	4.4	4.3	Pass
			Rut Depth	4.61	3.65	3.73	
		PG 76-22	OAC	4.9	4.6	4.3	Pass
			Rut Depth	7.8	10.52	10.55	
	Gravel	PG 64-22	OAC	5.3	5.3	4.8	Pass
			Rut Depth	8.83	8.83	4.02	
		PG 70-22	OAC	5.1	4.8	4.8	Pass
			Rut Depth	6.65	4.09	4.09	
		PG 76-22	OAC	5.4	5.2	4.9	Pass
			Rut Depth	3.8	2.66	4.09	
Type D	Limestone	PG 64-22	OAC	5.0	4.8	4.6	Pass
			Rut Depth	5.02	5.02	2.89	
		PG 70-22	OAC	4.9	4.5	4.4	Pass
			Rut Depth	6.28	8.16	3.39	
		PG 76-22	OAC	4.6	4.6	4.4	Pass
			Rut Depth	4.91	4.88	3.18	
	Gravel	PG 64-22	OAC	4.5	4.5	4.3	Pass
			Rut Depth	3.77	3.77	2.64	
		PG 70-22	OAC	4.8	4.6	4.5	Pass
			Rut Depth	2.91	3.07	2.3	
		PG 76-22	OAC	4.6	4.5	4.4	Pass
			Rut Depth	3.09	3.09	2.46	

* Rut depth at 4775 load cycles. # Projected value.

DISCUSSION OF RESULTS

Type A Mixtures

Optimum asphalt contents for the Type A mixtures were determined using PG 64-22 and PG 76-22 asphalts (Table 4 and Figure 9). The limestone mixture designed with PG 76-22 at 120 gyrations did not quite meet the VMA criteria. If necessary, the VMA criteria for this mixture could likely have been met by making small adjustments to the aggregate gradation or blend.

All of the Type A mixtures passed the Hamburg test (Table 6 and Figure 14) indicating that even those mixtures designed using 60 SGC gyrations should provide acceptable resistance to rutting.

On average, the curves for OAC versus number of SGC gyrations (Figure 9) for the Type A mixtures appear to form approximately straight lines between 60 and 120 gyrations. This indicates that the mixtures are being uniformly consolidated all the way to 120 gyrations, which may indicate that at least 120 gyrations is required to determine OACs for these mixtures. However, the Hamburg results indicate that all of the mixtures, even those designed at 60 SGC gyrations, met the TxDOT requirements. The Phase I findings indicated that 100 SGC gyrations for Type A mixtures most closely simulated the TGC. However, those findings also recognized that the TGC produced mixtures with extremely low asphalt contents. Therefore, based on all of the findings in Phases I and II, 90 SGC gyrations is recommended for design of Type A mixtures.

Type B Mixtures

Optimum asphalt contents for the Type B mixtures were determined using PG 64-22 and PG 76-22 asphalts (Table 4 and Figure 10). Following the original TGC design requirements, the limestone mixtures were designed at 3.0 percent air voids and the gravel mixtures were designed at 4.0 percent air voids using the SGC. The gravel mixtures consistently exhibited higher OACs than the limestone mixtures. Three of the limestone mixtures narrowly failed the VMA criteria (shaded cells in Table 4). Again, small adjustments in gradation could likely overcome these apparent deficiencies; however, meeting the VMA requirement was not a particular goal for this project. This finding does, however, beg the question, how did this

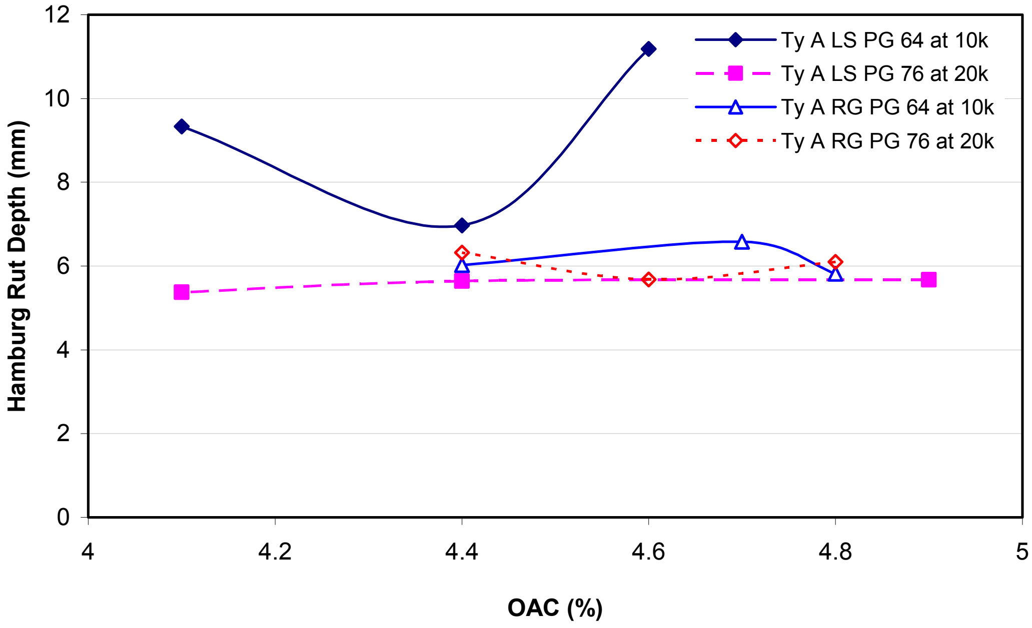

Figure 14. Hamburg Results of Type A Mixture at 10k and 20k Load Cycles.

limestone mixture pass the VMA criteria when originally designed using the TGC, which was shown in Phase I to simulate approximately 160 gyrations of the SGC.

All of the Type B mixtures passed the Hamburg test (Table 6 and Figure 15) indicating that even those mixtures designed using 60 SGC gyrations should provide acceptable resistance to rutting.

All of the curves for OAC versus number of SGC gyrations (Figure 10) for the Type B mixtures exhibit a decrease in slope between 90 and 120 gyrations. This indicates that the SGC compaction levels are nearing “terminal air voids” or “refusal density,” as referred to by Brown (1988), i.e., the maximum density of the mix without crushing significant numbers of aggregate particles. Based on these data, it appears that 90 SGC gyrations is certainly a viable choice for routine design of Type B mixtures.

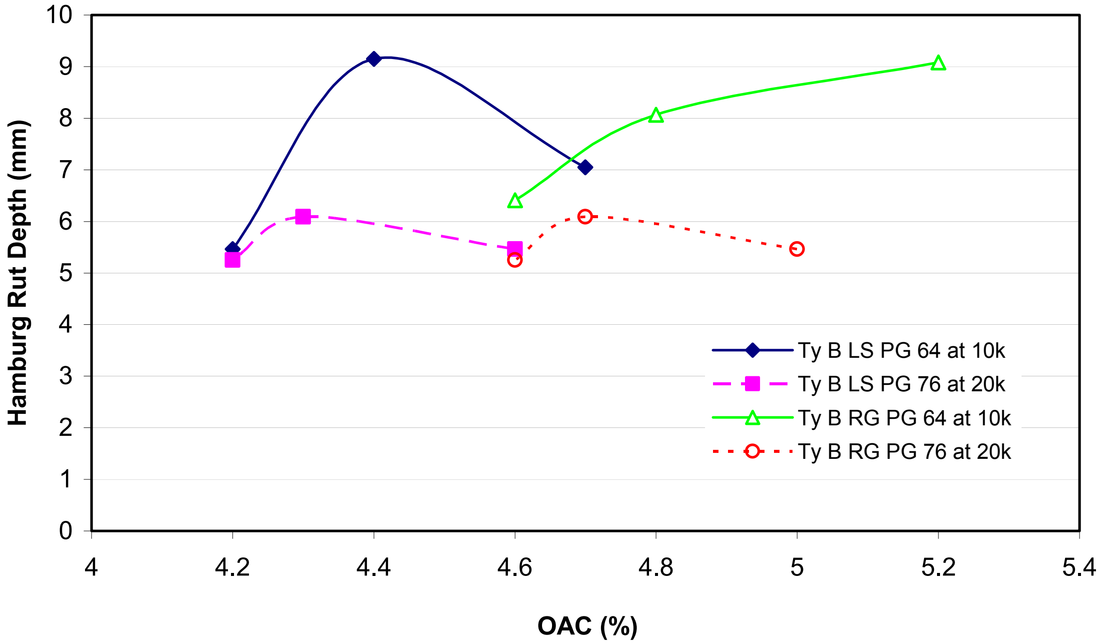

Figure 15. Hamburg Results of Type B Mixtures at 10k and 20k Load Cycles.

Type CMHB-C Mixtures

Optimum asphalt contents for Type CMHB-C mixtures were determined at 3.5 percent design air voids using PG 64-22 and PG 76-22 asphalt (Table 4 and Figure 11). As anticipated, the CMHB-C mixtures yielded higher OACs as compared to the other mixture types. All of the CMHB-C mixtures produced relatively high asphalt film thicknesses (Figure 8). The limestone CMHB-C mixture contained no field sand. Therefore, as might be expected when using the same design air void levels, the limestone mixtures yielded higher OACs than the gravel mixtures. Only one mixture designed at the highest gyration level (140 gyrations) barely failed the VMA criteria.

Only one mixture designed at the lowest gyration level (80 gyrations or highest asphalt content) and containing PG 64 asphalt failed the Hamburg criteria (Table 6 and Figure 16). It therefore appears that 120 SGC gyrations are suitable for design of Type CMHB-C mixtures.

Type C Mixtures

Realizing the widespread use of Type C mixtures in Texas, OACs were determined using three different asphalt grades: PG 64, PG 70, and PG 76 (Table 4 and Figure 12). OACs were ascertained on the basis of 4.0 percent design air voids. In most cases for the Type C mixtures, 120 gyrations and 140 gyrations yielded similar OACs; however, two of the mixtures showed significant drops in OAC from 120 to 140 gyrations. Four of the Type C limestone mixtures barely failed the VMA criteria. If required, a slight adjustment in the aggregate gradation could likely have accommodated the VMA requirement.

Three limestone mixtures failed the Hamburg criteria (Table 6 and Figure 17). Two were designed at 80 and 120 SGC gyrations and contained PG 64 asphalt. One was designed at 80 gyrations and contained PG 76 asphalt. This limestone mixture contained 15 percent natural sand. Inexplicably, the PG 70 asphalt yielded better performance than the PG 76 asphalt in this limestone mixture. All of the Type C gravel mixtures met the Hamburg criteria. Considering the fact that TxDOT uses the Hamburg as a screening test to avoid rut-susceptible mixtures, 120 SGC gyrations appear reasonable for design of Type C mixtures.

Type D Mixtures

Type D mixtures are also widely used in Texas and OACs were determined using all three asphalt grades (Table 4 and Figure 13). Most of the Type D mixtures did not meet the VMA requirement (shaded cells in Table 6). Four of the mixtures (three limestone and one gravel) were more than 1 percent below the required 15 percent VMA. The VMA requirement for these particular Type D mixtures may be too high or difficult to attain. The gradation of the limestone and gravel Type D mixtures is not much finer than their Type C counterparts. Further, Figure 8 reveals that the surface area of the Type D gravel mixture is comparable with other mixture types. Again, it is puzzling how these Type D mixtures met the VMA requirements during the original design process using the TGC, which Phase I indicated was reasonably simulated by 160 gyrations of the SGC. In fact, VMAs of the TGC designs were borderline at 15.0 and 15.1 percent for gravel and limestone mixtures, respectively, each containing PG 64 asphalt.

Several of the Types C and D mixtures yielded comparable OACs between 80 and 120 gyrations, but exhibited a sharper drop in OAC between 120 and 140 gyrations.

Recommendations from Phase I called for 160 SGC gyrations for design of Types C and D mixtures. These Phase II findings indicate that, on average, the Types C and D mixtures need more than 120 SGC gyrations to become fully consolidated or, that is, approach terminal compaction. Typically, engineers design surface mixtures at about 4 percent air voids, place them at about 6 to 8 percent air voids, and expect traffic to further compact them to some terminal air void level without reaching a hydrostatic state (i.e., near zero percent air voids). Using less than 160 SGC gyrations for design of Types C and D mixtures appear acceptable in view of the fact that all of the Type D mixtures and the vast majority of the Type C mixtures passed TxDOT's Hamburg requirements.

The fact that all of the Type D mixtures passed the Hamburg test (Table 6 and Figure 18) is remarkable considering that they all contained 15 percent natural sand. With some trepidation the researchers recommend 120 SGC gyrations for design of Type D mixtures.

General Discussions

Typically, for similarly graded mixtures containing 100 percent limestone or gravel, the limestone mixtures will require higher OACs than the corresponding gravel mixtures (due likely to the lower surface area and surface texture of the gravel particles and higher absorption of the limestone particles). This difference would be accentuated if the limestone mixtures were designed at 3.0 percent air voids while the gravel mixtures were designed at 4.0 percent air voids (as in this experiment). However, the limestone mixtures studied herein contained significant quantities of natural field sand, and the gravel mixtures contained various quantities of crushed stone screenings. Therefore, on average, the OACs for the gravel mixtures were higher than those for the corresponding limestone mixtures.

With all things equal, one might expect OAC to increase as the grade of asphalt increases. In this project, all things were not equal. In fact, the mixing and compaction temperatures varied with the grade of asphalt in accordance with the TxDOT requirements. This requirement (Tex-206-F) is designed to provide equivalent binder viscosities during compaction. Achieving equivalent binder, or more importantly, mastic viscosities during compaction (which, in general, may or may not be the case, depending on the type and quantity of filler and additives) blinds the compactor to the grade of the asphalt, thus any grade of binder with a given aggregate blend would theoretically result in the same OAC. In this project, the results show that

OAC for a given aggregate blend did not depend on the asphalt grade. When using the former TxDOT design procedure, which required the same temperature for all asphalt grades, OAC usually increased with the grade of asphalt.

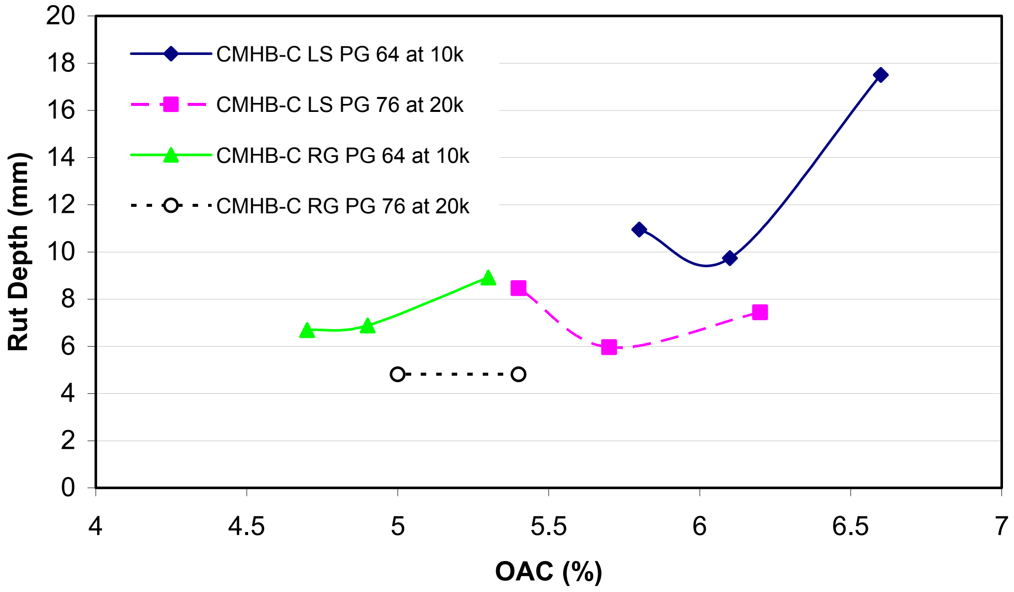

Figure 16. Hamburg Results of Type CMHB-C Mixtures at 10k and 20k Load Cycles.

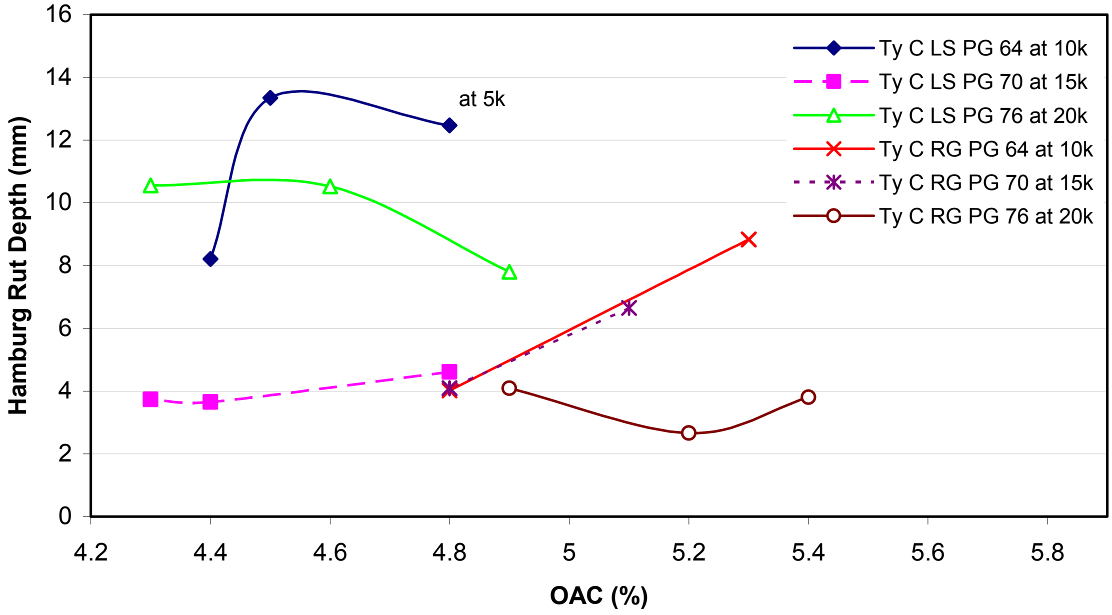

Figure 17. Hamburg Results of Type C Mixtures at 10k, 15k, and 20k Load Cycles.

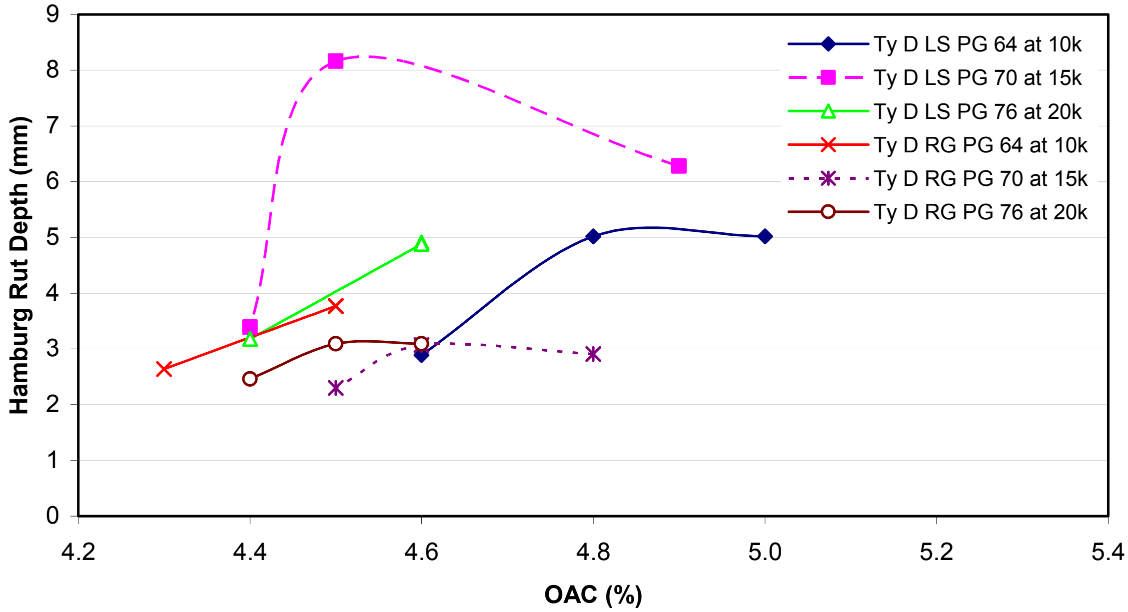

Figure 18. Hamburg Results of Type D Mixtures at 10k, 15k, and 20k Load Cycles.

CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

Following Phase I testing of both plant-mixed and lab-mixed HMA paving mixtures, researchers recommended the number of SGC gyrations for design of the common TxDOT types of mixtures to match OACs that would be produced by the TGC. Testing and observations indicated that these recommended numbers of gyrations would produce mixtures with insufficient asphalt contents to provide good durability and performance. Therefore, Phase II was designed and implemented. Conclusions and recommendations from the Phase II study are provided below.

CONCLUSIONS

- Phase II demonstrated that mixtures exhibiting good performance in the Hamburg test can be designed using a considerably lower number of SGC gyrations than the number that will match optimum asphalt contents from the TGC (as determined in the Phase I experiment). The recommended SGC design gyrations given below should accommodate adequate asphalt in the mixture to improve resistance to fatigue cracking and raveling and decrease permeability while providing acceptable rutting resistance.
- All Type A, B and D mixtures passed the TxDOT Hamburg criteria. Type C limestone, designed using PG 64 asphalt at 80 and 120 gyrations, failed the Hamburg criteria. Type CMHB-C limestone, designed using PG 64 asphalt at 80 gyrations, failed the Hamburg criteria.
- The gravel mixtures consistently outperformed the limestone mixtures in Hamburg testing. In fact, no gravel mixture failed the Hamburg criteria. The Types A and B limestone mixtures contained 10 percent natural sand, and the Types C and D limestone mixtures contained 15 percent natural sand. Conversely, the gravel mixtures contained various quantities of stone screenings. Further, most gravel mixtures contained 1 percent hydrated lime as an antistripping agent; whereas, most limestone mixtures contained a liquid antistripping agent (Table A3).
- Asphalt film thicknesses for the dense-graded Types C and D mixtures ranged from about 9 to 12 microns, while those for the Types A and B mixtures ranged from about 11 to 15

microns. This appears reasonable. As expected, those for the CMHB-C mixtures were somewhat higher. For typical dense-graded surface mixtures with a nominal maximum size of 3/8 inch to 0.75 inch, most researchers recommend an optimum asphalt film thickness of 9 – 10 microns (Sengoz and Agar, 2004; Kandhal and Chakraborty, 1996) or less (Camden et al., 1959; Goode and Lufsey, 1965). Kumar and Goetz (1977) stated that typical binder film thicknesses were between 5 and 15 microns. These same researchers generally agree that optimum film thickness increases as the surface area of the aggregate decreases, as was demonstrated in this project.

- The low VMA values, particularly for the Type D mixtures, that did not meet TxDOT requirements, are a concern. The original TGC designs for these mixtures exhibited borderline VMA values.
- Normally, one would expect that, as the viscosity of the asphalt binder increases the OAC would also increase. However, in this project, this trend was not indicated. The authors believe this outcome is likely due to the fact that all mixtures were produced at a prescribed compaction temperature and further complicated by the different types of filler and antistripping additives in the mixtures. This requirement (Tex-206-F) is designed to provide equivalent binder viscosities during compaction. Achieving equivalent viscosities during compaction (or rather mix design) blinds the compactor to the grade of the asphalt, thus any grade of binder with a given aggregate blend should result in the same OAC.
- As expected, a higher number of SGC gyrations generally yielded a lower optimum asphalt content. In some cases, however, the OACs for two different levels of gyration were identical to the nearest one-tenth of a percent.

RECOMMENDATIONS

Based on the findings from both Phases I and II of this project, the following recommendations are made.

- Use the following numbers of SCG gyrations for the respective types of HMA paving mixtures (see Table 7).

Table 7. Final Recommendation for Design SGC Compaction Level.

Mixture Type	No of SGC Gyrations
Type A	90
Type B	90
Type C	120
Type D	120
CMHB-C	120

- The terms "terminal air voids" and "refusal density" were used in discussions in the body of this report. Brown (1988) may have coined the terms while developing a design method to produce highly rut-resistant HMA mixtures in the United Kingdom. His basic concept was that, if the mixture is designed at its refusal density in the laboratory, then traffic will not compact a resulting pavement below that density and thus will not reach a hydrostatic state or rut. He estimated that, if the terminal air voids in the mix after trafficking can be maintained above 2 percent, then the mix will remain stable. TxDOT has followed this basic concept for many years. The authors recommend a follow-up study to further examine the rut-susceptibility of the mixtures evaluated herein. This simple follow-up study would use the SGC mixture design methods recommended above for all the TxDOT mixture types studied herein. A method would be developed (possibly using the SGC) or adopted (using another compaction method) for compacting HMA to refusal density. Each mix previously using the recommended methods (Table 7) would be compacted to its refusal density using the SGC, and the air void content would be measured to ensure that it is reasonable (e.g., above 2 percent).

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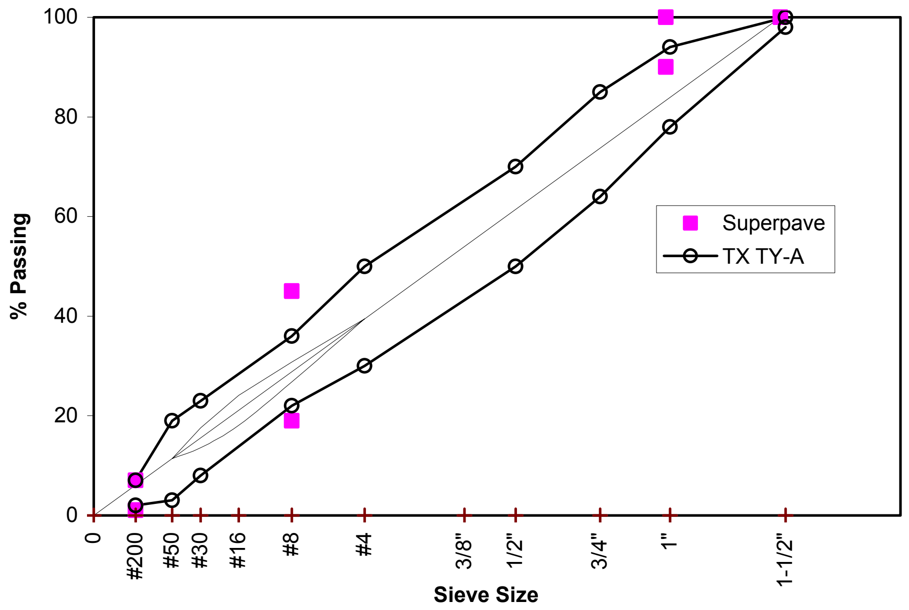
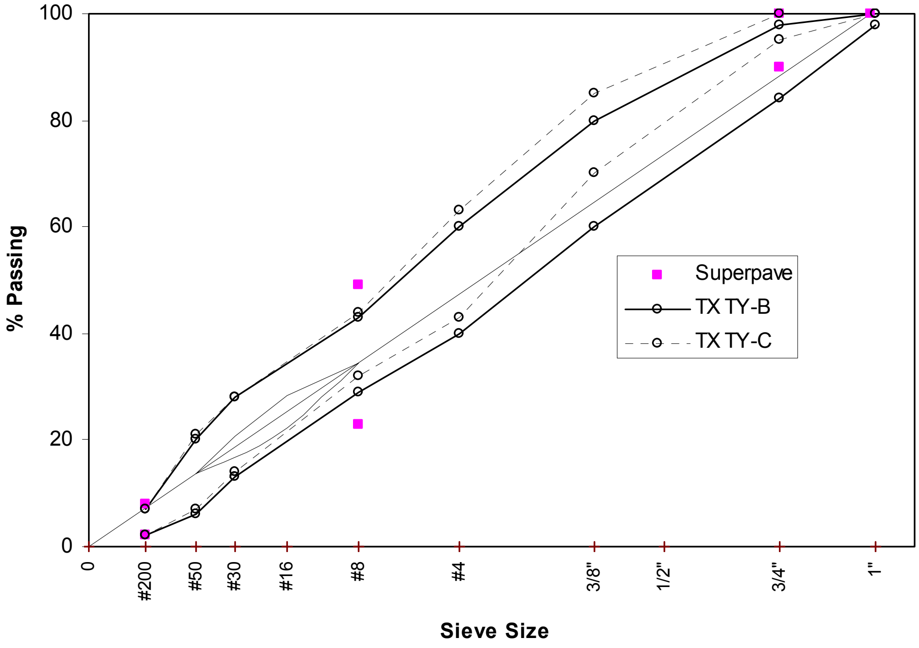
APPENDIX A:
COMPARISON OF TXDOT MIXTURE ON SUPERPAVE GRADATION



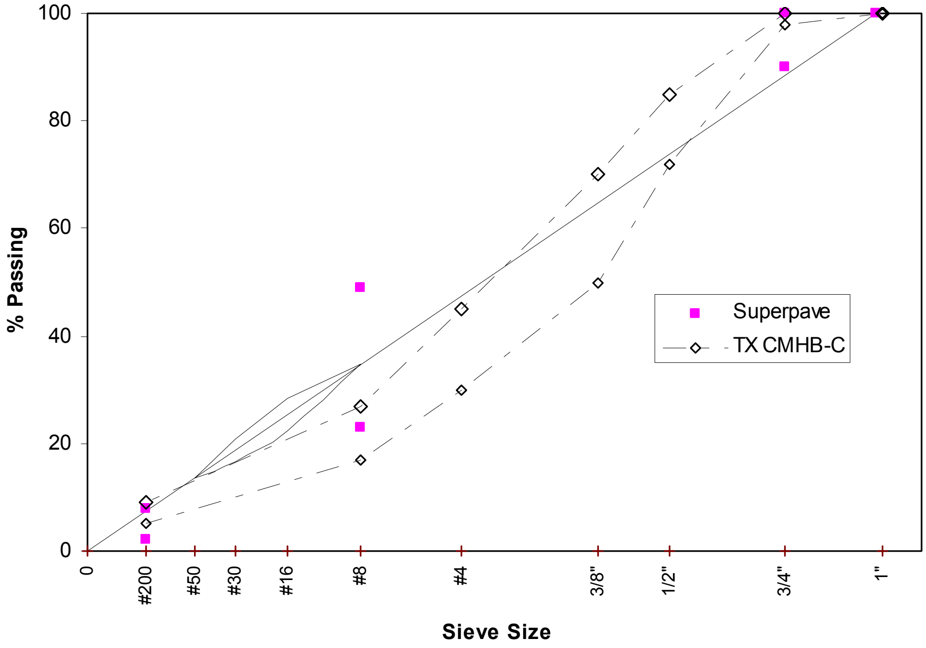
Minimum VMA: Superpave = 12% TX SP A: 13% TX Ty A: 12%

Figure A1. Gradation of 25 mm Maximum Nominal Aggregate Size (Similar to TX SP A) vs. Type A.



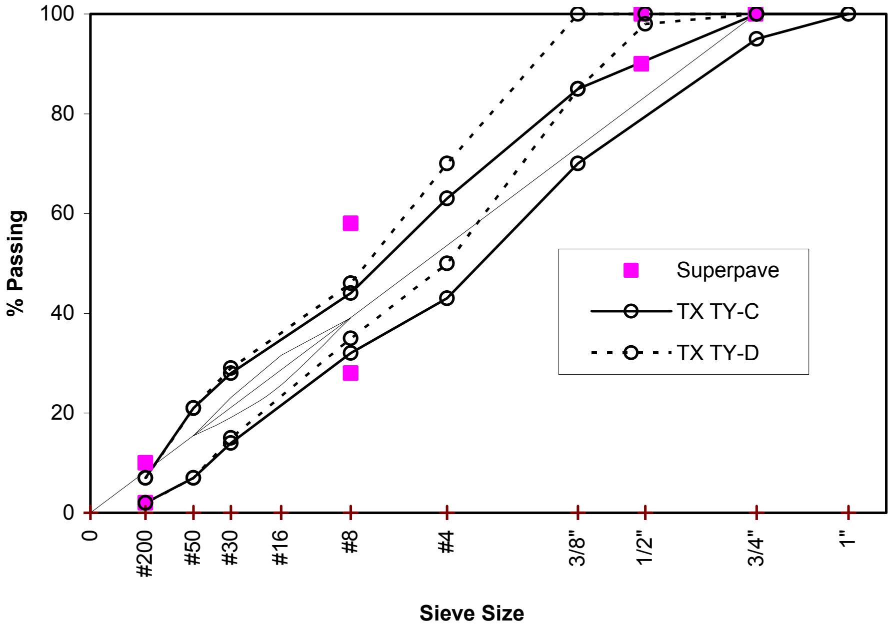
Minimum VMA: Superpave = 13% TX SP B = 14% TX TY-B = 13% TX TY-C = 14%

Figure A2. Gradation of 19 mm Maximum Nominal Aggregate Size (Similar to TX SP B) vs. Type B, Type C.



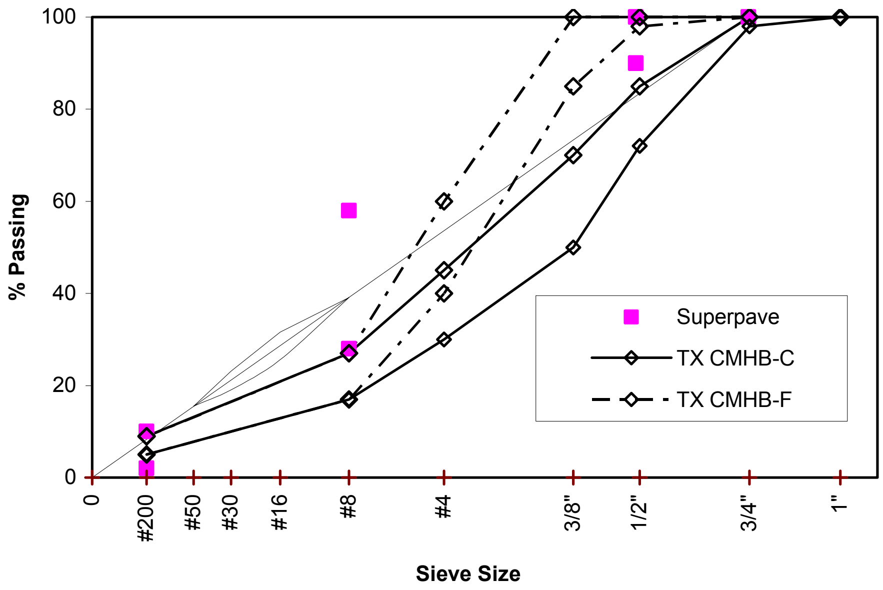
Minimum VMA: Superpave = 13% TX SP B = 14% TX CMHB-C = 14%

Figure A3. Gradation of 19 mm Maximum Nominal Aggregate Size (Similar to TX SP B) vs. CMHB-C.



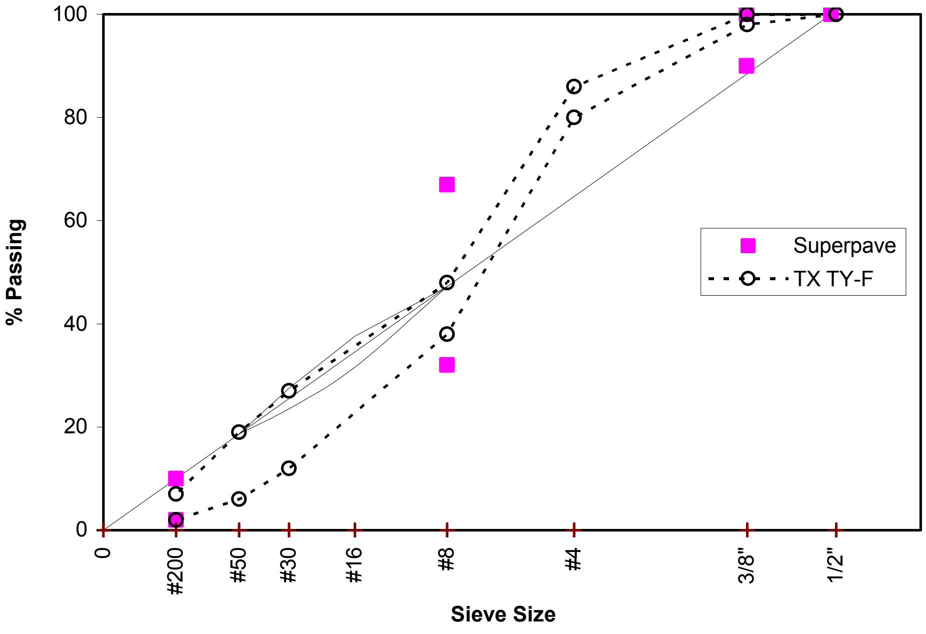
Minimum VMA: Superpave = 14% TX SP C = 15% TX Ty C = 14% TX Ty D = 15%

Figure A4. Gradation of 12.5 mm Maximum Nominal Aggregate Size (Similar to TX SP C) vs. Type C, Type D.



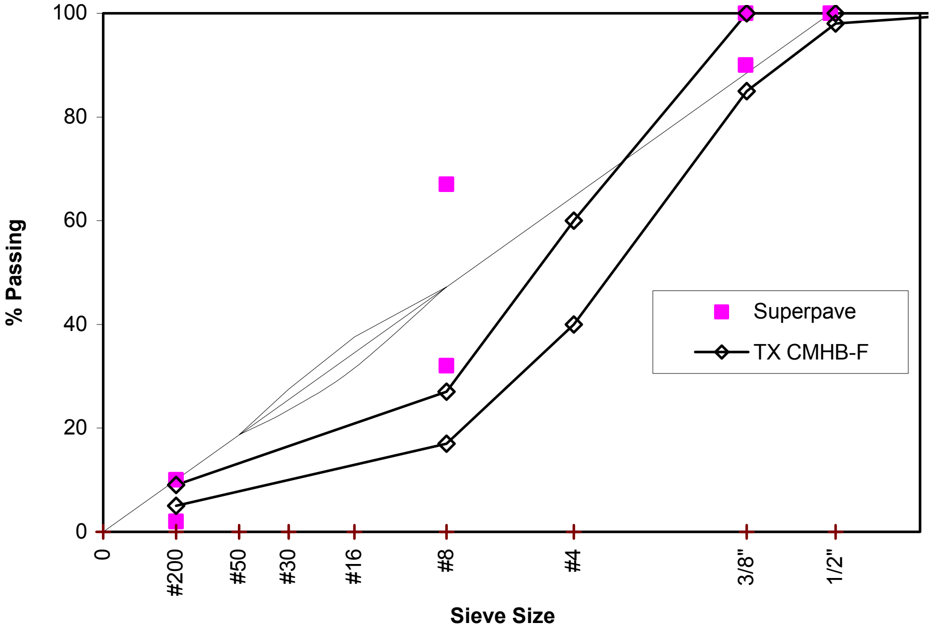
Minimum VMA: Superpave = 14% TX SP C = 15% TX CMHB-C = 14% TX CMHB-F = 15%

Figure A5. Gradation of 12.5 mm Maximum Nominal Aggregate Size (Similar to TX SP C) vs. CMHB-C, CMHB-F.



Minimum VMA: Superpave = 15% TX SP D = 16% TX TY-F = 16%

Figure A6. Gradation of 9.5 mm Maximum Nominal Aggregate Size (Similar to TX SP D) vs. Type F.



Minimum VMA: Superpave = 15% TX SP D = 16% TX CMHB-F = 15%

Figure A7. Gradation of 9.5 mm Maximum Nominal Aggregate Size (Similar to TX SP D) vs. CMHB-F.

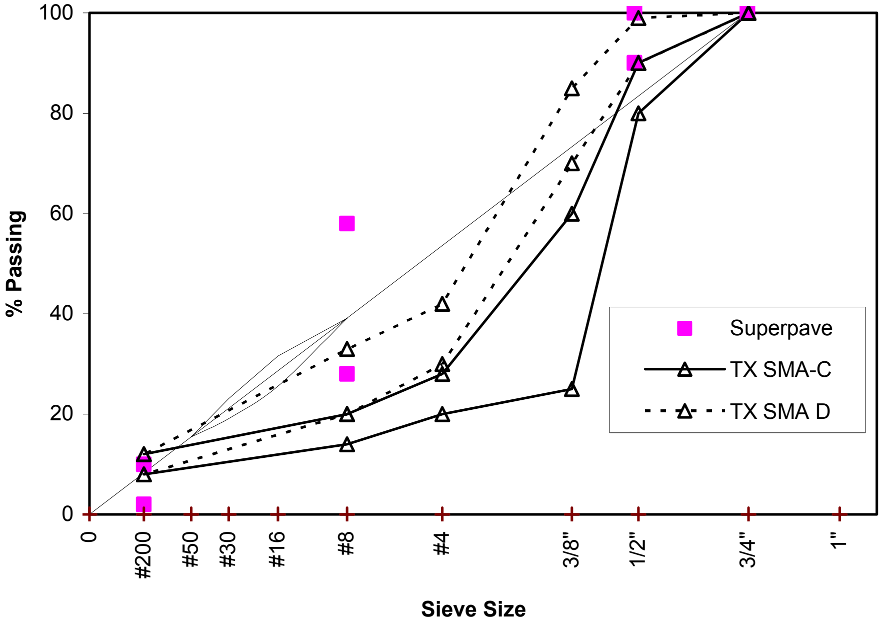


Figure A8. Comparisons of Superpave vs. TxDOT SMA Mixes.

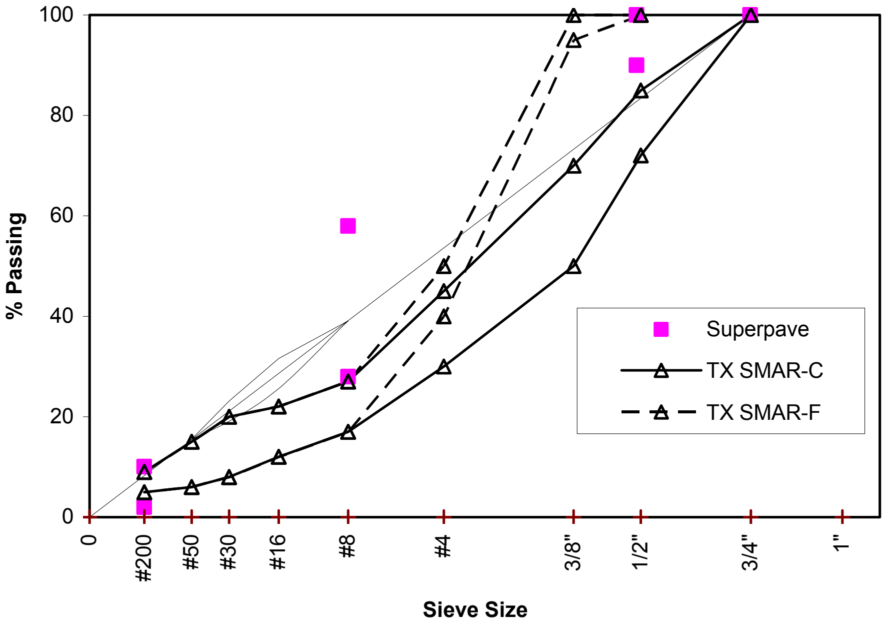


Figure A9. Comparisons of Superpave vs. TxDOT SMA Mixes.

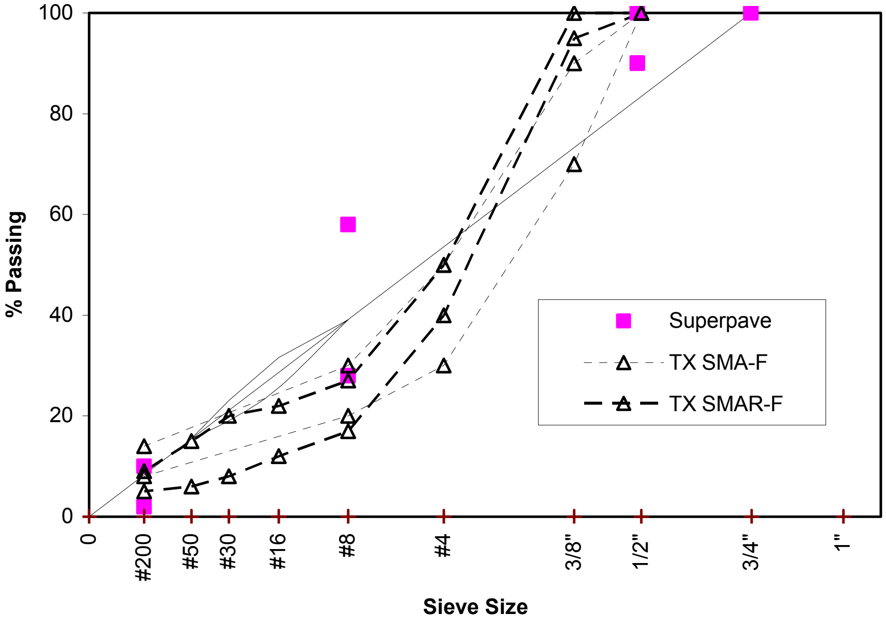


Figure A10. Comparisons of Superpave vs. TxDOT SMA Mixes.

Table A1. Aggregate Blends Used in Different Mixtures.

Aggregate Blend	**Type A**		**Type B**		**Type C**		**Type D**		**Type CMHB-C**	
	LS	**RG**	**LS**	**RG**	**LS**	**RG**	**LS**	**RG**	**LS**	**RG**
Ty A Rock (Col. Mat.)	15%									
Ty B Rock (Col. Mat.)	20%		18%							
Ty C Rock (Col. Mat.)			15%		10%				34%	
Ty D Rock (Col. Mat.)	18%		18%		25%		25%		25%	
Ty F Rock (Col. Mat.)	17%		16%		25%		35%		25%	
Manf. Sand (Col. Mat.)	20%		23%		25%		25%			
Field Sand (Col. Mat.)	10%		10%		15%		15%			
LS Scrn. (Col. Mat.)				14%		18%		10%	16%	
Ty B Rock (Fordyce)				20%						
Ty C Rock (Fordyce)				10%		14%				
Ty D Rock (Fordyce)										
D/F Blend (Fordyce)				40%		53%		64%		
Manf. Sand (Fordyce)				15%		10%		10%		
Field Sand (Fordyce)						4%		15%		
Hydrated Lime (TXI)		1%		1%		1%		1%		1%
Ty A Rock (Atlanta)		38%								
Ty C Rock (Hanson)										34%
Ty D Rock (Hanson)		35%								45%
Ark. Granite L Rock (Donnafill)		5%								20%
Gravel Scrn. (Hanson)		21%								
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Table A2. Hamburg Results for All Mixtures.

Mixture Type	Aggregate	Asphalt	SGC Gyrations	OAC (%)	Hamburg Rut Depth (mm/load cycle)			TxDOT Criteria Pass/Fail
					LW	RW	Average	
Type A	Limestone	PG 64-22	60	4.6	12.36/9001	10.81/16900	11.59/12951	Avg pass
			90	4.4	9.63/20000	12.04/18450	10.84/19225	Pass
			120	4.1	12.05/11301	12.14/12150	12.1/11725	Pass
		PG 76-22	60	4.9	5.09/20000	6.25/20000	5.67/20000	Pass
			90	4.4	5.12/20000	6.15/20000	5.64/20000	Pass
			120	4.1	5.09/20000	5.65/20000	5.37/20000	Pass
	River Gravel	PG 64-22	60	4.8	7.43/20000	7.36/20000	7.4/20000	Pass
			90	4.7	7.29/20000	8.71/20000	8.0/20000	Pass
			120	4.4	9.34/20000	5.17/20000	7.26/20000	Pass
		PG 76-22	60	4.8	7.4/20000	4.8/20000	6.1/20000	Pass
			90	4.6	6.15/20000	5.2/20000	5.68/20000	Pass
			120	4.4	5.97/20000	6.67/20000	6.32/20000	Pass
Type B	Limestone	PG 64-22	60	4.7	12.0/13950	12.42/18201	12.21/16075	Pass
			90	4.4	11.4/9901	12.01/16050	11.70/12975	Pass
			120	4.2	11.04/13201	5.98/20000	8.51/16600	Pass
		PG 76-22	60	4.6	5.45/20000	5.46/20000	5.46/20000	Pass
			90	4.3	5.89/20000	6.28/20000	6.09/20000	Pass
			120	4.2	6.21/20000	4.3/20000	5.25/20000	Pass
	River Gravel	PG 64-22	60	5.2	10.25/20000	7.9/20000	9.08/20000	Pass
			90	4.8	6.45/20000	9.68/20000	8.07/20000	Pass
			120	4.6	6.04/20000	6.78/20000	6.41/20000	Pass
		PG 76-22	60	5.0	2.5/20000	4.17/20000	3.34/20000	Pass
			90	4.7	1.75/20000	2.07/20000	1.91/20000	Pass
			120	4.6	2.44/20000	3.04/20000	2.74/20000	Pass
CMHB-C	Limestone	PG 64-22	80	6.6	12.11/3860	10.88/6451	11.5/5140	Fail
			120	6.1	12.21/15351	10.69/7701	11.45/11526	Pass
			140	5.8	11.65/8101	11.51/16350	11.58/12225	Pass
		PG 76-22	80	6.2	8.47/20000	6.40/20000	7.44/20000	Pass
			120	5.7	4.38/20000	7.53/20000	5.96/20000	Pass
			140	5.4	8.46/20000	8.47/20000	8.47/20000	Pass
	River Gravel	PG 64-22	80	5.3	7.43/20000	10.40/20000	8.92/20000	Pass
			120	4.9	6.42/20000	7.33/20000	6.88/20000	Pass
			140	4.7	6.78/20000	6.59/20000	6.69/20000	Pass
		PG 76-22	80	5.4	4.38/20000	5.23/20000	4.81/20000	Pass
			120	5.0	4.82/20000	4.80/20000	4.81/20000	Pass
			140	5.0	4.82/20000	4.80/20000	4.81/20000	Pass

Table A2. Hamburg Results for All Mixtures (Continued).

Mixture Type	Aggregate	Asphalt	SGC Gyrations	OAC (%)	Hamburg Rut Depth (mm/at load cycle)			TxDOT Criteria Pass/Fail)
					LW	RW	Average	
Type C	Limestone	PG 64-22	80	4.8	12.71/5101	12.22/4441	12.47/4771	Pass
			120	4.5	12.32/9601	11.35/8301	11.84/8951	Pass
			140	4.4	12.01/12350	11.62/11001	11.81/11676	Pass
		PG 70-22	80	4.8	7.09/20000	7.64/20000	7.36/20000	Pass
			120	4.4	4.17/2000	5.87/20000	5.02/20000	Pass
			140	4.3	3.84/20000	3.92/20000	3.88/20000	Pass
		PG 76-22	80	4.9	7.37/20000	8.23/20000	7.8/20000	Pass
			120	4.6	13.68/20000	7.37/20000	10.52/20000	Pass
			140	4.3	10.5/20000	10.6/20000	10.55/20000	Pass
	River Gravel	PG 64-22	80	5.3	11.83/12051	12.04/10801	11.94/11426	Pass
			120	5.3	11.83/12051	12.04/10801	11.94/11426	Pass
			140	4.8	11.01/13051	11.78/15551	11.40/14301	Pass
		PG 70-22	80	5.1	5.4/20000	7.9/20000	6.65/20000	Pass
			120	4.8	3.98/20000	4.19/20000	4.09/20000	Pass
			140	4.8	3.98/20000	4.19/20000	4.09/20000	Pass
		PG 76-22	80	5.4	3.92/20000	3.68/20000	3.8/20000	Pass
			120	5.2	2.83/20000	2.48/20000	2.66/20000	Pass
			140	4.9	4.32/20000	3.86/20000	4.09/20000	Pass
Type D	Limestone	PG 64-22	80	5.0	11.54/15301	11.72/13501	11.63/14401	Pass
			120	4.8	11.54/15301	11.72/13501	11.63/14401	Pass
			140	4.6	12.24/16001	10.16/19551	11.2/17776	Pass
		PG 70-22	80	4.9	5.32/20000	7.23/20000	6.28/20000	Pass
			120	4.5	6.81/20000	9.51/20000	8.16/20000	Pass
			140	4.4	2.83/20000	3.94/20000	3.39/20000	Pass
		PG 76-22	80	4.7	3.06/20000	3.82/20000	3.44/20000	Pass
			120	4.6	3.06/20000	3.82/20000	3.44/20000	Pass
			140	4.4	2.63/20000	2.77/20000	2.7/20000	Pass
	River Gravel	PG 64-22	80	4.5	4.77/20000	7.63/20000	6.2/20000	Pass
			120	4.5	4.77/20000	7.63/20000	6.2/20000	Pass
			140	4.3	3.37/20000	3.81/20000	3.59/20000	Pass
		PG 70-22	80	4.8	3.05/20000	3.19/20000	3.12/20000	Pass
			120	4.6	3.37/20000	2.99/20000	3.18/20000	Pass
			140	4.5	4.97/20000	2.89/20000	3.93/20000	Pass
		PG 76-22	80	4.6	2.52/20000	3.65/20000	3.09/20000	Pass
			120	4.5	2.52/20000	3.65/20000	3.09/20000	Pass
			140	4.4	1.94/20000	2.97/20000	2.46/20000	Pass

Table A3. Hamburg Stripping Data for All Mixtures.

Mixture Type	Aggregate	Asphalt	Asphalt Content (%)	No. of SGC Gyrations	AntiStripping Agent	Stripping Rating
Type A	Limestone	PG 64-22	4.6	60	* 0.5% Kling Beta	Slight
		PG 64-22	4.4	90	0.5% Kling Beta	Slight
		PG 64-22	4.1	120	0.5% Kling Beta	Moderate
	Limestone	PG 76-22	4.9	60	0.5% Kling Beta	Slight
		PG 76-22	4.4	90	0.5% Kling Beta	Slight
		PG 76-22	4.1	120	0.5% Kling Beta	Slight
	River Gravel	PG 64-22	4.8	60	1% hydrated lime	None
		PG 64-22	4.7	90	1% hydrated lime	None
		PG 64-22	4.4	120	1% hydrated lime	Slight
	River Gravel	PG 76-22	4.8	60	1% hydrated lime	None
		PG 76-22	4.6	90	1% hydrated lime	None
		PG 76-22	4.4	120	1% hydrated lime	None
Type B	Limestone	PG 64-22	4.7	60	0.5% Kling Beta	Slight
		PG 64-22	4.4	90	0.5% Kling Beta	Slight
		PG 64-22	4.2	120	0.5% Kling Beta	Moderate
	Limestone	PG 76-22	4.6	60	0.5% Kling Beta	Slight
		PG 76-22	4.3	90	0.5% Kling Beta	None
		PG 76-22	4.2	120	0.5% Kling Beta	Slight
	River Gravel	PG 64-22	5.2	60	1% hydrated lime	Slight
		PG 64-22	4.8	90	1% hydrated lime	Moderate
		PG 64-22	4.6	120	1% hydrated lime	Slight
	River Gravel	PG 76-22	5.0	60	1% hydrated lime	None
		PG 76-22	4.7	90	1% hydrated lime	None
		PG 76-22	4.6	120	1% hydrated lime	None
CMHB-C	Limestone	PG 64-22	6.6	80	0.5% Kling Beta	Slight
		PG 64-22	6.1	120	0.5% Kling Beta	None
		PG 64-22	5.8	140	0.5% Kling Beta	None
	Limestone	PG 76-22	6.2	80	0.5% Kling Beta	-
		PG 76-22	5.7	120	0.5% Kling Beta	-
		PG 76-22	5.4	140	0.5% Kling Beta	-
	River Gravel	PG 64-22	5.3	80	1% hydrated lime	None
		PG 64-22	4.9	120	1% hydrated lime	None
		PG 64-22	4.7	140	1% hydrated lime	None
	River Gravel	PG 76-22	5.4	80	1% hydrated lime	None
		PG 76-22	5.0	120	1% hydrated lime	None
		PG 76-22	5.0	140	1% hydrated lime	None

- data was not recorded * Kling Beta Liquid Anti-stripping Agent was used as a percentage of binder.

Table A3. Hamburg Stripping Data for All Mixtures (Continued).

Mixture Type	Aggregate	Asphalt	Asphalt Content (%)	No of SGC Gyrations	AntiStripping Agent	Stripping Rating
Type C	Limestone	PG 64-22	4.8	80	0.5% Kling Beta	Heavy
		PG 64-22	4.5	120	0.5% Kling Beta	Heavy
		PG 64-22	4.4	140	0.5% Kling Beta	Heavy
	Limestone	PG 70-22	4.8	80	0.5% Kling Beta	Moderate
		PG 70-22	4.4	120	0.5% Kling Beta	Slight
		PG 70-22	4.3	140	0.5% Kling Beta	Slight
	Limestone	PG 76-22	4.9	80	0.5% Kling Beta	Slight
		PG 76-22	4.6	120	0.5% Kling Beta	Heavy
		PG 76-22	4.3	140	0.5% Kling Beta	Heavy
	River Gravel	PG 64-22	5.3	80	1% hydrated lime	Moderate
		PG 64-22	5.3	120	1% hydrated lime	Moderate
		PG 64-22	4.8	140	1% hydrated lime	Slight
	River Gravel	PG 70-22	5.1	80	1% hydrated lime	None
		PG 70-22	4.8	120	1% hydrated lime	None
		PG 70-22	4.8	140	1% hydrated lime	None
	River Gravel	PG 76-22	5.4	80	1% hydrated lime	None
		PG 76-22	5.2	120	1% hydrated lime	None
		PG 76-22	4.9	140	1% hydrated lime	None
Type D	Limestone	PG 64-22	5.0	80	1% hydrated lime	Heavy
		PG 64-22	4.8	120	1% hydrated lime	Heavy
		PG 64-22	4.7	140	1% hydrated lime	Moderate
	Limestone	PG 70-22	4.9	80	1% hydrated lime	Slight
		PG 70-22	4.5	120	1% hydrated lime	Moderate
		PG 70-22	4.4	140	1% hydrated lime	Moderate
	Limestone	PG 76-22	4.6	80	1% hydrated lime	Slight
		PG 76-22	4.6	120	1% hydrated lime	Slight
		PG 76-22	4.4	140	1% hydrated lime	Slight
	River Gravel	PG 64-22	4.5	80	1% hydrated lime	Moderate
		PG 64-22	4.5	120	1% hydrated lime	Moderate
		PG 64-22	4.3	140	1% hydrated lime	None
	River Gravel	PG 70-22	4.8	80	1% hydrated lime	None
		PG 70-22	4.6	120	1% hydrated lime	None
		PG 70-22	4.5	140	1% hydrated lime	None
	River Gravel	PG 76-22	4.6	80	1% hydrated lime	None
		PG 76-22	4.5	120	1% hydrated lime	None
		PG 76-22	4.4	140	1% hydrated lime	None

* Kling Beta Liquid Anti-stripping Agent was used as a percentage of binder.

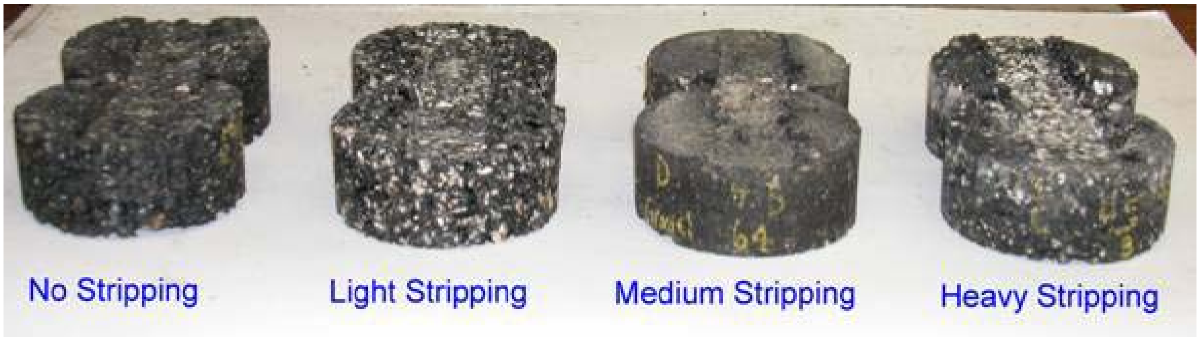


Figure A11. Hamburg-Induced Stripping Comparisons.

APPENDIX B:
PHASE I TEST RESULTS

INTRODUCTION

Background

The Strategic Highway Research Program expended great effort in developing the Superpave gyratory compactor (SGC) as a modern, technologically advanced tool for design of hot mix asphalt (HMA) paving mixtures and for preparation of realistic test specimens for laboratory evaluation. Researchers used the Texas gyratory compactor (TGC) and Texas Department of Transportation (TxDOT) design process (i.e., optimum asphalt content depending on the compaction mechanism) as the paradigm for the SGC apparatus and the Superpave design process. Since the widely accepted SGC was designed to produce specimens similar to actual pavement layers and since TxDOT's current series of HMA paving mixtures has demonstrated acceptable performance, TxDOT desires to replace the TGC with the SGC for design of its current repertoire of dense-graded mixtures.

Objectives and Scope of the Study

The objective of this work was to develop and verify protocols for using the SGC to design TxDOT HMA paving mixtures including coarse matrix high binder (CMHB) mixtures. The specific goal was to recommend a design number of gyrations (N_{design}) using the SGC for each TxDOT mixture type that most closely simulates a mixture designed using the TGC (Tex-204-F). This was the first of several tasks to be performed as part of TxDOT Research Project 0-4203. TxDOT and the researchers gave this work high priority, as it needed to be accomplished before several of the other tasks can be properly completed because all cylindrical specimens prepared for testing in subsequent tasks should be designed and/or prepared using the SGC procedures developed in this task.

TxDOT mixtures included in this task were Type A, Type B, Type C, Type D, Type CMHB-C, and Type CMHB-F. Unfortunately, no Type F mixtures were available from any district during this project. Only one Type CMHB-F mixture was accessible during the project.

Researchers conducted the experiment in four separate phases:

1. Twenty-one plant mixed HMA mixtures were obtained from haul units, reheated in the laboratory, and compacted using the SGC to the air void level specified in the TGC mixture design. Researchers recorded the number of SGC gyrations.

2. Thirty-six sets of aggregate and asphalt along with their associated HMA mixture designs were obtained from the TxDOT districts, and HMA mixtures were prepared and compacted (using the SGC) to an air void level below that specified in the TGC mixture design. SGC compaction curves and the number of gyrations to achieve the TGC design air voids were recorded.
3. Based on the findings in Item 2, above, the number of SGC gyrations was selected for each mixture type that most closely yielded the TGC design air void content. Using 28 sets of aggregates of the same gradation (aggregate blend) as specified in the TGC design, the SGC with the preselected number of gyrations was used to determine their optimum asphalt contents (OAC).
4. Researchers conducted indirect tension tests in accordance with Tex-226-F using 6-inch diameter specimens compacted to 7 ± 0.5 percent using the SGC.

The researchers and the TxDOT Project Monitoring Committee believed that the number of SGC gyrations to simulate the TGC designs could be determined from Steps 1 and 2 as indicated in the original experiment plan. Subsequent testing proved this was not possible; therefore, Step 3 was added to the test program.

For each TxDOT mixture type, the number of SGC gyrations that most accurately produces the optimum asphalt content that would be determined using the TGC is recommended in the section titled Conclusions and Recommendations.

EXPERIMENTAL PROGRAM

The main objective of Task 2 was to develop and verify protocols for using the SGC to design essentially all TxDOT HMA paving mixtures. The specific goal was to recommend a design number of gyrations (N_{design}) using the SGC for each TxDOT mixture type that most closely simulates a mixture designed using the TGC (Tex-204-F). The following types of HMA mixtures were obtained from the districts and studied: Type A, Type B, Type C, Type D, Type CMHB-C and Type CMHB-F. No Type F mixtures were available from any TxDOT district during this project.

The experiment was conducted in four phases:

1. Plant mixed HMA mixtures were obtained from haul units, reheated in the laboratory, and compacted using the SGC to the air void level specified in the TGC mixture design. The number of SGC gyrations was recorded.
2. Aggregate and asphalt, along with their associated HMA mixture designs, were obtained from TxDOT districts, and HMA mixtures were prepared and compacted using the SGC to the air void level specified in the TGC mixture design. Researchers recorded the number of SGC gyrations.
3. Based on the findings in Item 2 above, the number of SGC gyrations was selected for each mixture type that most closely yielded the TGC design air void content. Using aggregates of the same gradation (blend) as specified in the TGC design, the SGC and preselected number of gyrations were used to determine the optimum asphalt content.
4. Indirect tension tests were conducted in accordance with Tex-226-F using 6-inch diameter specimens compacted to 7 ± 0.5 percent using the SGC.

The findings are presented below by phase. This report provides conclusions from the laboratory study and recommendations for designing TxDOT dense-graded HMA mixtures using the SGC.

FINDINGS FROM STEP 1 – SGC COMPACTION OF PLANT MIXES

Researchers conducted a preliminary study to rapidly determine the number of SGC gyrations required to achieve the TGC air voids by sampling plant mixed materials from haul trucks. Technicians reheated the HMA samples, compacted them using the SGC, and recorded the number of gyrations required to achieve the TGC design air voids. Twenty mixtures of five different types were sampled. Three specimens of each type mixture were compacted using the SGC to determine the average number of gyrations. Plant mixtures were used in this phase to quickly estimate the magnitude of the task. Table B1 shows results from SGC compaction of plant mixed materials.

The number of SGC gyrations required to achieve the TGC design air void content ranged from 56 (a Type B mix) to 242 (a Type CMHB-C mix) gyrations. The average number of SGC gyrations for plant mixes of all types, inclusive, was 138. For the three similar specimens compacted using the SGC to obtain the average values reported, repeatability of the number of gyrations was excellent, with the number of gyrations to obtain the desired air void content normally varying less than ±10 gyrations.

These results exhibited significant variation in SGC gyrations to obtain TGC design air voids for the different types of HMA mixtures and the different mixtures of a given type (Table B1). However, for a given mixture, variation in SGC gyrations to obtain the TGC design air void level was generally quite small. On average, the design number of SGC gyrations significantly exceeded 100, indicating that (based on Superpave criteria) most of the mixtures should withstand relatively high levels of traffic or that they could handle higher asphalt contents. Further, it is well known that reheating of plant mixtures can harden the asphalt and, thus, yield a higher number of SGC gyrations than might be expected if using neat materials. From this preliminary work, researchers determined that it would be necessary to enter Step 1 and use the neat materials to prepare mixtures in the laboratory to better define the relationships between the TGC and the SGC.

Table B1. Number of SGC Gyrations to Obtain TGC Design Air Voids - *Plant Mixed*.

Mixture Type	Source of Mixture	No. of SGC Gyrations to TGC Design Air Voids (average of 3 tests)	Average No. Gyrations for Mix Type
A	Lufkin, #H00-24	109	132
	Wichita Falls, #C01-0107	154	
B	El Paso, South Quarry B	120	92
	Lufkin, #H0021	81	
	Lufkin, #H9935	66	
	Paris, #25204	135	
	Pharr, #WB-B01(HP-Plus)	56	
C	Atlanta, #33604	238	159
	Lufkin, #30040	147	
	Lufkin, #30043	131	
	Paris, #35203	119	
D	El Paso, #0002-05-039	108	134
	El Paso, #D-Mix (South Quarry)	152	
	Paris, #45201	195	
	Pharr, #2001-2-D	82	
F	None Available	--	--
CMHB-C	Atlanta, #H01-17	182	174
	Atlanta, #H01-16	242	
	Bryan, #H0026	83	
	Bryan, #CDS001	190	
CMHB-F	Odessa, #701601	--	--

FINDINGS FROM STEP 2 – SGC COMPACTION OF LABORATORY MIXES

Measuring SGC Gyrations to Obtain TGC Air Voids

In this phase of the work, 36 HMA mixtures of six different types were tested to determine the number of SGC gyrations to achieve the TGC design air voids. A wide variety of aggregates (e.g., gravel, limestone, sandstone, and quartzite) and asphalt materials with and without lime and other antistripping agents comprised these mixtures. Selected TxDOT districts provided mixture designs for the selected materials that were obtained using the TGC in accordance with Tex-204-F and Tex-206-F. Three specimens of each mixture type were prepared in the laboratory using the SGC with the same aggregate, aggregate gradation, asphalt, and asphalt content as used in the TxDOT mix design. The number of SGC gyrations required to achieve the TGC design air voids was recorded. Table B2 describes the mixtures and summarizes the results. Appendix A shows detailed results.

To ensure matching the aggregate gradations used in the laboratory to those used during the TGC design as closely as possible, technicians sieved the individual aggregates received and adjusted the gradations as necessary to match the gradations listed on the mixture designs. They then blended these aggregates in accordance with the job mix formula provided by TxDOT in the mixture design. Aggregate materials for five of the mixture designs (those listed in Table B2 from Corpus Christi, El Paso, and Pharr) were collected by TxDOT personnel from the cold feed belt at the plant and were thus already blended when they arrived. These five materials were not sieved in the laboratory to adjust their gradations. Rather, an appropriate sized sample was obtained from these materials using an aggregate sample splitter, and the materials were used with their as-arrived gradations.

Mixing and compaction using the SGC were performed in accordance with Tex-241-F using the temperatures specified for the particular grade of asphalt. The uncompacted asphalt-aggregate mixtures were short-term aged for two hours at the specified compaction temperature in accordance with Tex-241-F. Researchers used these same aggregate gradation adjustment, mixing, aging, and compaction procedures described here in Phase 3, which is discussed below.

Table B2 reveals an order of magnitude variation in the number of SGC gyrations required to produce the TGC design air void level for the mixtures studied. The SGC gyrations varied from 44 (a Type D mix) to 470 (a Type C mix). The number of SGC gyrations and variation in the SGC gyrations was consistently lower for the coarser Types A and B mixes, indicating that they are more easily compacted. Coefficients of variation (C_v) are shown in Table B2. Direct comparisons of the coefficients of variation for the different mix types may not be statistically valid since the number of each mixture type are not equivalent. Additionally, for the Type A and B mixtures, the average number of SGC gyrations to obtain TGC air voids was nearer to 100 than any other mixture type. There was no trend indicating that the number SGC gyrations to obtain TGC voids varied consistently with mix type (i.e., maximum aggregate size).

One of the Type C mixtures (Atlanta #33604) that required a large number of gyrations (387) to reach the TGC design air void content was designed at 3.5 percent air voids. However, the other Type C mixture (Atlanta #H01-19) requiring a large number of gyrations (470) to reach the TGC design air voids was designed at 4 percent air voids. All of the Type CMHB-C mixtures were designed using the TGC at 3.5 percent air voids and yielded, generally, about the same average number of SGC gyrations to reach design air voids as the Type C and Type D mixtures. There appeared to be no correlation between the number of SGC gyrations to attain the TGC design air voids and the design air void value.

Researchers found no correlation between the number of SGC gyrations to reach design air voids and the aggregate type (quarried stone or crushed gravel) or gradation (amount of filler or sand or coarseness/fineness of gradation). Repeatability of determining the number of gyrations to design air voids using the SGC and similar laboratory mixed specimens was again excellent, except for three mixtures (Laredo Type C-#2229, Paris Type D #45201, and Atlanta Type CMHB-C #H01-16).

Effect of Changing Gyratory Angle of SGC

For the Type CMHB-F mixture (Odessa #701601), the SGC required 380 gyrations to attain the TGC design air voids (3 percent). However, when the angle on the IPC ServoPac gyratory compactor was increased from 1.25° to 2.5°, the design air void level was attained at 95 gyrations. The researchers are not suggesting that the compaction angle of the SGC be altered for use by TxDOT. This merely demonstrates that the SGC at a 2.5° angle imparts significantly more mechanical energy than it does at a 1.25° angle, which infers that the TGC (with a 5.8° angle) imparts significantly more mechanical energy per gyration than the standard SGC. Researchers further surmised that the air void distributions within a 6-inch diameter SGC specimen and a 4-inch diameter TGC specimen are different.

Results of Step 2

Results of this phase of the work indicate that, as expected, there is no simple transition from the TGC to a selected number of gyrations using the SGC for each TxDOT mixture type. At this point of the project, the researchers and the TxDOT Project Monitoring Committee were not comfortable in recommending a specific number of SGC gyrations to simulate the TGC. In order to address this issue, researchers developed and performed a third approach (Step 3).

Table B2. Number of Gyrations Using SGC to Obtain Design Air Voids from TGC – *Lab Mixed Specimens*.

Mix Type	Source of Mixture	Mix Characteristics	No. of SGC Gyrations to TGC Design Air Voids (average of 3 tests)	Average No. Gyrations
A	Laredo, #2	Gravel + scrngs + 10% sand + 1.5% lime + 3.4% PG 76-22	88	96 CV = 26%
	Lufkin, #H00-24	Limestone + scrngs + 10% sand + 1% lime + 3.4% PG 64-22	112	
	Wichita Falls, #C01-0107	Limestone + scrngs +12% sand + 1% lime + 3.3% PG 64-22	66	
	Austin, #RTI-A1	Limestone + screenings + 13% sand + 4.6% PG 64-22	130	
	San Antonio, #VH-A-2001	Limestone (Helotes) + 15% silica sand, 3.9% PG 64-22	85	
B	Atlanta, #H01-21	67% Gravel + screenings + 10% sand + 3.8% PG 76-22	43	97 CV = 41%
	Bryan, #CDS 003a	Limestone + sand/gravel + scrngs + 1% lime + 4.6% PG 64-22	93	
	El Paso, South Quarry B	Limestone + sand, 4.8% AC 20 HVB	103	
	Ft Worth, #0-3662	Limestone + screenings + 10% sand + PermaTac + 4.3% PG 64-22	88	
	Lufkin, #H0021	Limestone + scrngs + 6% sand + lime + 4.0% PG 64-22	44	
	Lufkin, #H9935	Limestone + scrngs + 13% sand + 3.8% PG 64-22	132	
	Paris, #25204	Sandstone + scrngs + bottom ash + 1% lime + 5.4% PG 64-22	156	
	Pharr, #WB-B01(HP-Plus)	Gravel + scrngs + 15% sand + HPplus antistrip + 5.0% PG 64-22	119	

Table B2. Number of Gyrations Using SGC to Obtain Design Air Voids from TGC – Lab Mixed Specimens (Continued).

Mix Type	Source of Mixture	Mix Characteristics	No. of SGC Gyrations to TGC Design Air Voids (average of 3 tests)	Average No. Gyrations
C	Atlanta, #33604	Sandstone + screenings + 1% lime + 5.6% PG 76-22	387	181 CV = 82%
	Atlanta, #H01-18	Gravel + Donnafill + 1% lime + 4.4% PG 76-22	60	
	Atlanta, #H01-19	Quartzite + scrngs + Donnafill + 1% lime + 4.6% PG 76-22	470	
	Atlanta, #H01-20	Sandstone + scrngs + Donnafill + 1% lime + 4.5% PG 76-22	228	
	Corpus Christi, #C-6	Gravel + limestone scrngs+ 15% sand + 1% lime + 5.3% PG 70-22	82	
	Ft Worth, #10-TXIC-01	Limestone + 15% sand + antistrip + 4.7% PG 76-22	72	
	Laredo, #1	Gravel + scrngs + 13% sand + 1.5% lime + 4.3% PG 76-22	136	
	Laredo, #2229	30% RAP + granite + scrngs + 1.5% lime + 4.0% PG 64-22	71	
	Lufkin, #30040	Limestone + scrngs + 5% sand + 1% lime + 4.3% PG 70-22S	115	
	Lufkin, #30043	Gravel/limestone blend + scrngs 5% sand + 1% lime, 4.4% PG 70-22S	50	
	Paris, #35203	Sandstone + scrngs + 12% bottom ash + 1% lime + 5.8% PG 64-22	324	

Table B2. Number of Gyrations Using SGC to Obtain Design Air Voids from TGC – Lab Mixed Specimens (Continued).

Mix Type	Source of Mixture	Mix Characteristics	No. of SGC Gyrations to TGC Design Air Voids (average of 3 tests)	Average No. Gyrations
D	Ft. Worth, #42-TXID-00	Limestone + 15% sand + HP plus antistrip + 5.0% PG 64-22	44	145 CV = 51%
	Ft. Worth, #0-3661	Limestone + scrngs + 10% sand + PermaTac + 4.8% PG 64-22	173	
	El Paso, #0002-05-039	Gravel + sand + 5.2% PG 76-16	60	
	El Paso, #D-Mix (South Quarry)	Limestone + sand + UP5000 + 5.0% PG 76-16	190	
	Paris, #45201	Sandstone + scrngs +10% bottom ash +1% lime + 6.1% PG 64-22	182	
	Pharr, #2001-2-D	Gravel + scrngs + 14% sand + 1% lime + 5.3% PG 76-22	220	
F	None located	--	--	--
CMHB-C	Atlanta, #H01-15	Gravel + Donnafill +1% lime + 4.7% PG 76-22	82	153 CV = 46%
	Atlanta, #H01-17	Sandstone + scrngs + Donnafill + 1% lime + 4.8% PG 76-22	171	
	Atlanta, #H01-16	Quartzite + screenings + Donnafill + 1% lime + 4.8% PG 76-22	246	
	Bryan, #H0026	Limestone + screenings + 1% lime + 4.5% PG 76-22	85	
	Bryan, #CDS001	Limestone + sand/gravel + 1% lime + 4.4% PG 64-22	181	
CMHB-F	Odessa, #701601	Rhyolite + screenings + 7.3% PG 70-22	380	380

FINDINGS FROM STEP 3 – SGC COMPACTION TO DETERMINE OPTIMUM ASPHALT CONTENT

Based on the findings in Step 2, the researchers recommended using the same aggregate types and gradations and same binder with the SGC and a preselected number of design gyrations (N_{design}) to determine the OAC and compare with the original OAC determined using the TGC (Tex-204-F). Based on the results from Step 2, the following number of SGC gyrations were selected for each type of mix: Type A—100 gyrations, Type B—110 gyrations, and Types C, D, and CMHB-C mixes—160 gyrations. Researchers evaluated a total of 28 mixtures in Step 3. Five mixtures each of Types A, B, D, and CMHB-C and eight Type C mixtures were tested. More Type C mixtures were tested since more of this mix type is routinely used by TxDOT for pavement surfaces.

Researchers used the following procedure for each type of mixture: two samples each (6-inch diameter by 6-inch height) at four or five different asphalt contents were compacted using the SGC. The asphalt contents utilized were in steps of 0.5 percent above and below the estimated value of the original OAC from the TGC mix design. Maximum specific gravity (Rice value) and the bulk specific gravity for all mixtures at the different asphalt contents was determined using the procedures described in Tex-227-F, Determination of Maximum Specific Gravity using Calibrating Metal Vacuum Pycnometer; and Tex-207-F, Determination of Bulk Specific Gravity of Samples, respectively. These values were then used to determine the air void contents and VMA of each specimen. Researchers plotted a graph of air voids versus asphalt content for each mixture and determined the OAC by interpolating the asphalt content at the TGC design air void content, which was typically 4.0 percent except for the Type CMHB-C mixtures, which were designed at 3.5 percent air voids.

The OAC values obtained using the SGC, were compared with the OAC values determined using the TGC. VMA values of the mixture designed using the SGC were also determined and compared with corresponding values obtained using the TGC. Table B3 shows these results. Researchers observed that the difference between the OAC determined using the SGC and the TGC is less than 10 percent, on average. Similar results were found when comparing the VMA of the SGC and TGC mixtures of the same type.

Table B3. Comparison of OAC and VMA from TGC vs. Those Obtained Using the SGC.

MIX TYPE - A

N = 100 for SGC

Source of Mixture	Design % Air Voids	OAC (%)		VMA (%)			% Diff. for OAC	% Diff. for VMA
		TGC	SGC	TGC	SGC			
Austin, #RTI-A1	4.0	4.6	4.8	14.2	14.6		3.3	2.8
San Antonio, #VH-A-2001	4.0	3.9	3.6	12.9	12.2		-6.7	-5.4
Laredo, #2	4.0	3.4	3.8	--	12.8		11.2	--
Lufkin, #H00-24	4.0	3.4	3.5	12.2	12.3		2.9	0.4
Wichita Falls, C01-0107	4.0	3.3	4.2	11.9	14.1		25.8	18.1

MIX TYPE - B

N = 110 for SGC

Source of Mixture	Design % Air Voids	OAC (%)		VMA (%)			% Diff. for OAC	% Diff. for VMA
		TGC	SGC	TGC	SGC			
Atlanta, #H01-21	4.0	3.6	3.6	13.0	12.5		0.8	-3.8
Bryan, #CDS 003a	4.0	4.6	4.9	14.6	15.2		5.4	4.1
Lufkin, #H0021	4.0	4.0	3.3	13.5	11.7		-18.8	-13.3
Paris, #25204	4.0	5.4	5.9	15.4	17.1		9.8	11.0
Pharr, #WB-B01	4.0	5.0	5.4	15.4	16.3		8.2	5.8

MIX TYPE - C

N = 160 for SGC

Source of Mixture	Design % Air Voids	OAC (%)		VMA (%)			% Diff. for OAC	% Diff. for VMA
		TGC	SGC	TGC	SGC			
Atlanta, #33604	3.5	5.6	5.6	16.1	16.1	^	0.5	-0.3
Atlanta, #H01-18	4.0	4.4	4.2	14.0	13.8		-3.6	-1.8
Atlanta, #H01-19	4.0	4.6	5.2	14.6	15.9		12.0	8.9
Ft. Worth, #10 TXIC 01	4.0	4.7	4.3	14.8	14.0		-8.7	-5.7
Laredo, #1	4.0	4.3	3.8	?	12.7	*	-12.3	
Laredo, #2229	4.0	4.0	4.5	16.1	16.1		12.5	-0.3
Paris, #35203	4.0	5.8	6.7	16.8	18.7		15.5	11.3
Lufkin, #30040	4.0	4.4	3.9	14.1	13.2		-11.4	-6.4

Table B3. Comparison of OAC and VMA from TGC vs. Those Obtained Using the SGC (Continued).

MIX TYPE - D

N = 160 for SGC

Source of Mixture	Design % Air Voids	OAC (%)			VMA (%)			% Diff. for OAC	% Diff. for VMA
		TGC	SGC		TGC	SGC			
Ft. Worth, #0-3661	4.0	4.8	4.3		15.2	14.0	*	-10.6	-7.9
El Paso, #0002-05-039	4.0	5.2	3.9		16.2	13.1		-25.4	-19.1
El Paso, #D-Mix South Quarry	4.0	5.0	5.0		16.0	15.4		0.8	-4.1
Paris, #45201	4.0	6.1	6.3		17.4	17.7	*	2.5	1.4
Pharr, #2001-2-D	4.0	5.3	5.7		15.8	16.9		8.3	6.6

MIX TYPE – CMHB-C

N = 160 for SGC

Source of Mixture	Design % Air Voids	OAC (%)			VMA (%)			% Diff. for OAC	% Diff. for VMA
		TGC	SGC		TGC	SGC			
Atlanta, #H01-15	3.5	4.7	4.2		14.1	13.1	^	-10.6	-7.1
Atlanta, #H01-17	3.5	4.8	4.2		14.1	12.9	^	-13.3	-8.9
Atlanta, #H01-16	3.5	5.0	5.0		14.6	15.1	^	0.8	3.1
Bryan, #H0026	3.5	4.6	4.2		14.0	13.3	^	-7.8	-4.9
Bryan, #HCDS001	3.5	4.4	4.4		13.8	13.8	^	0.9	-0.4

NOTES:

TxDOT formula was used for computing VMA.

* Indicates value of specific gravity of asphalt assumed as 1.03 in absence of data.

^ Air voids are 3.5 percent (all others are 4 percent air voids).

In order to determine if the preselected number of SGC gyrations for each type of mix resulted in an OAC that is closest to the TGC design value, the OAC for each mix was determined at different numbers of SGC gyrations. Table B4 presents the results of this comparison. Table B4 shows averages of the differences between the OACs from the TGC and those subsequently obtained from the SGC, along with standard deviations of these average differences. To most closely match the OAC from the TGC with that from the SGC, one would select the number of SGC gyrations that gives lowest combination of average difference and lowest standard deviation.

A computer malfunction caused the loss of the SGC compaction data for five of the Type C mixes. These data were required in order to compute the OAC at a number of SGC gyrations different from 160; that is, at 100, 120, and 140 gyrations. A comparison of the air void contents versus the number of SGC gyrations for the last 60 gyrations (100 to 160) was accomplished by interpolating the data available from the remaining three Type C mixes. Researchers plotted the available data and observed that, within the desired range (i.e., 100 to 160 gyrations), the relationship between the air voids and number of gyrations was linear with varying degrees of slopes. Researchers then used this plot to interpolate the missing data.

Table B4. Comparisons of Optimum Asphalt Content at Different SGC Gyration Levels.

MIX TYPE - A

Source of Mixture	OAC, %								
	TGC	SGC @ N 100	% Diff. for N 100	SGC @ N 90	% Diff. for N 90	SGC @ N 80	% Diff. for N80	SGC @ N 70	% Diff. for N 70
Austin, #RTI-A1	**4.6**	4.8	3.3	4.9	6.7	5.1	11.1	5.5	18.9
San Antonio, #VH-A-2001	**3.9**	3.6	-6.7	3.7	-5.9	3.7	-4.9	3.8	-3.6
Laredo, #2	**3.4**	3.8	11.2	3.9	15.6	4.0	18.8	4.2	22.9
Lufkin, #H00-24	**3.4**	3.5	2.9	3.6	6.5	3.8	11.8	4.0	17.6
Wichita Falls, #C01-0107	**3.3**	4.2	25.8	4.3	29.7	4.4	32.4	4.5	35.2
	Average % Difference		7.3		10.5		13.8		18.2
	Standard Deviation		12.1		13.2		13.5		14.0

MIX TYPE - B

Source of Mixture	OAC, %								
	TGC	SGC @ N 110	% Diff. for N 110	SGC @ N 100	% Diff. for N 100	SGC @ N 90	% Diff. for N 90	SGC @ N 80	% Diff. for N 80
Atlanta, #H01-21	**3.6**	3.6	0.8	3.7	1.9	3.7	3.6	3.8	5.0
Bryan, #CDS 003a	**4.6**	4.9	5.4	4.9	7.0	5.0	9.3	5.1	11.5
Lufkin, #H0021	**4.0**	3.3	-18.8	3.4	-15.8	3.5	-13.3	3.6	-9.8
Paris, #25204	**5.4**	5.9	9.8	6.1	12.0	6.2	13.9	6.3	15.7
Pharr, #WB-B01	**5.0**	5.4	8.2	5.5	9.8	5.5	10.6	5.6	11.4
	Average % Difference		1.1		3.0		4.8		6.8
	Standard Deviation		11.6		11.1		10.8		10.0

Table B4. Comparisons of Optimum Asphalt Content at Different SGC Gyration Levels (Continued).

MIX TYPE - C

Source of Mixture	OAC, %								
	TGC	**SGC @ N 160**	**% Diff. for N 160**	**SGC @ N 140**	**% Diff. for N 140**	**SGC @ N 120**	**% Diff. for N 120**	**SGC @ N 100**	**% Diff. for N 100**
Atlanta, #33604	**5.6**	5.6	0.5	5.7	2.0	5.8	3.0	5.8	4.1
Atlanta, #H01-18	**4.4**	4.2	-3.6	4.3	-1.4	4.4	0.2	4.5	1.8
Atlanta, #H01-19	**4.6**	5.2	12.0	5.3	15.7	5.4	17.4	5.5	19.3
Ft. Worth, #10-TXIC-01	**4.7**	4.3	-8.7	4.5	-5.3	4.6	-2.6	4.7	-0.6
Laredo, #1	**4.3**	3.8	-12.3	3.9	-8.6	4.1	-5.3	4.2	-2.3
Laredo, #2229	**4.0**	4.5	12.5	4.5	12.8	4.5	13.3	4.6	14.0
Paris, #35203	**5.8**	6.7	15.5	6.8	17.8	6.9	19.7	7.0	21.4
Lufkin, #30040	**4.4**	3.9	-11.4	4.0	-8.2	4.2	-4.5	4.5	1.1
	Average % Difference		0.6		3.1		5.1		7.4
	Standard Deviation		11.4		10.8		10.1		9.4

MIX TYPE - D

Source of Mixture	OAC, %								
	TGC	**SGC @ N 160**	**% Diff. for N 160**	**SGC @ N 140**	**% Diff. for N 140**	**SGC @ N 120**	**% Diff. for N 120**	**SGC @ N 100**	**% Diff. for N 100**
Ft. Worth, #0-3661	**4.8**	4.3	-10.6	4.4	-8.8	4.3	-10.0	4.6	-3.5
El Paso, #0002-05-039	**5.2**	3.9	--	4.1	--	4.2	--	4.4	--
El Paso, #D-Mix So Qry	**5.0**	5.0	0.8	5.1	2.0	5.4	7.0	5.6	12.0
Paris, #45201	**6.1**	6.3	2.5	6.3	3.4	6.4	4.9	6.5	6.6
Pharr, #2001-2-D	**5.3**	5.7	8.3	5.8	10.0	5.9	11.7	6.0	13.2
	Average % Difference		0.23		1.67		3.4		7.06
	Standard Deviation		7.9		7.8		9.4		7.6

Table B4. Comparisons of Optimum Asphalt Content at Different SGC Gyration Levels (Continued).

MIX TYPE - CMHBC

Source of Mixture	OAC, %								
	TGC	**SGC @ N 160**	**% Diff. for N 160**	**SGC @ N 140**	**% Diff. for N 140**	**SGC @ N 120**	**% Diff. for N 120**	**SGC @ N 100**	**% Diff. for N 100**
Atlanta, #H01-15	**4.7**	4.2	-10.6	4.3	-8.3	4.5	-4.9	4.7	-0.9
Atlanta, #H01-17	**4.8**	4.2	-13.3	4.8	0.4	5.0	4.0	5.2	8.3
Atlanta, #H01-16	**5.0**	5.0	0.8	5.1	2.4	5.2	4.6	5.4	7.4
Bryan, #H0026	**4.6**	4.2	-7.8	4.4	-4.1	4.6	-0.9	4.8	4.3
Bryan, #HCDS001	**4.4**	4.4	0.9	4.9	12.0	5.3	20.5	5.8	31.8
	Average % Difference		-6.0		0.0		4.6		10.2
	Standard Deviation		6.6		7.7		9.6		12.6

DISCUSSION OF RESULTS FROM STEPS 1 THROUGH 3

After a certain number of SGC gyrations, the curves for air voids versus the number of gyrations become much less sensitive to the number of gyrations, i.e., the curve tends to become flat. In other words, after a certain number of gyrations, several additional SGC gyrations yield only a very small decrease in the air void level. This phenomenon explains, to some extent, the extremely large number of SGC gyrations that were required for certain mixes to obtain the TGC design air voids in Steps 1 and 2.

For the Type A mixes, the average difference between the OAC obtained using the SGC at 100 gyrations and the OAC obtained using the TGC was only +7.3 percent. In terms of the percentage of asphalt content, this difference would mean an average increase of about 0.27 percentage points in the OAC when the SGC is used at 100 gyrations. Note that four out of the five Type A mixtures produced at 100 SGC gyrations had higher OACs than the TGC design value. Both the average difference in the OAC and the variance of the differences increase as the number of gyrations decreases (Table B4). This is also evident from the fact that the slope of the curve for air voids versus the number of SGC gyrations increase significantly as the number of gyrations is reduced from 100 to 90 or less. The difference between the OACs for the TGC and SGC ranged from –0.3 to +0.9 percentage points at 100 SGC gyrations. For the Type A mixes, it may be concluded that the SGC will most closely simulate the TGC mix design at just above 100 gyrations. The researchers recommend 110 SGC gyrations for designing Type A mixtures.

For the Type B mixes, the average difference between the OAC obtained using the SGC at 110 gyrations and the OAC obtained using the TGC was only 1.1 percent higher. In terms of the percentage of asphalt content, this difference would mean an average increase of less than 0.05 percentage points in the OAC when the SGC is used at 110 gyrations instead of the TGC. Further, when the OAC is calculated at 100 and 90 gyrations of the SGC, the average increase in the OAC is about 0.14 and 0.22 percentage points, respectively. Therefore, the researchers recommend 110 SGC gyrations for designing Type B mixtures.

When designing the Type C mixtures at 160 SGC gyrations, the average difference between the OACs using the SGC and the TGC was only 0.6 percent. This translates into an average increase of 0.03 percentage points in the OAC when using the SGC. However, when compared to the general range of SGC gyrations recommended by the Superpave manual, this figure seemed to be quite high. Therefore, researchers also estimated OACs for 140, 120, and 100 SGC gyrations. The results indicated there was an average increase in asphalt content of about 0.15, 0.24, and 0.35 percentage points respectively, for each of these levels of gyrations. The range of the difference between the OACs for the TGC and SGC ranged from –0.5 to +0.9 percentage points for 160 SGC gyrations and from –0.1 to +1.2 percentage points for 100 SGC gyrations. The fact that 160 SGC gyrations was required to match the OAC for the TGC indicates that the TGC provides relatively low asphalt contents, that is, produces mixtures suitable for high-volume roadways. The recommended number of SGC gyrations for design of Type C mixtures is 160.

The Type C mix from Paris, with an OAC of 5.8 percent from the TGC, yielded an OAC of 6.7 percent from the SGC. This mix contained sandstone, manufactured sand, and bottom ash with PG 64-22 binder plus 1 percent lime (VMA = 16.8). Compaction work during Step 2 showed this was a very tough mix, that is, very resistant to densification using the SGC with 5.8 percent binder. Although the SGC design (at 160 gyrations) required 6.7 percent binder, this mix should still be resistant to permanent deformation and, possibly, even more durable and resistant to cracking. Hamburg testing should be performed to verify the quality of this mix.

For the Type D mixes, the average difference between the OAC obtained using the SGC at 160 gyrations was only 0.23 percent higher than the OAC obtained using the TGC. In terms of the percentage of asphalt content, this difference would mean an average increase of less than 0.02 percentage points in the OAC when the SGC is used at 160 gyrations. Again, researchers calculated the OACs at different numbers of SGC gyrations, e.g., 140, 120, and 100 gyrations. The results indicated that there was an average increase in asphalt content by about 0.09, 0.18, and 0.40 percentage points, respectively, for each of these levels of gyrations. The range of the differences between the OACs for the Type D mixtures was +0.4 to –0.5 percentage points at 160 SGC gyrations and +0.7 to –0.2 percentage points at 100 SGC gyrations. The recommended number of SGC gyrations for design of Type D mixtures is 160.

Five Type D mixtures were designed, but only four were included in the comparative analysis (see Table B4). The aggregate for the El Paso #0002-05-039 mixture was obtained from the cold feed belt. Subsequent sieve analysis revealed that the gradation used with the

SGC was significantly finer than the TGC design gradation. Since the aggregates were already blended when received, it was not possible to correct the gradation, as technicians did with the individual aggregates. Therefore, this mix was not included in the comparison. Technicians checked the gradations of the other aggregates obtained from the cold feed belt, and they were relatively close to the design gradations.

For the Type CMHB-C mixes, the difference between the OAC obtained using the SGC at 160 gyrations and the OAC obtained using the TGC averaged 6.0 percent lower. In terms of the actual asphalt content, this difference would mean an average decrease in the OAC by 0.3 percentage points when the SGC is used at 160 gyrations. Researchers computed the OACs at different numbers of SGC gyrations, e.g., 140, 120, and 100 gyrations. The results indicated that there would be an average increase in OAC of about 0.02, 0.22, and 0.48 percentage points, respectively, for each of these levels of gyrations. The smallest difference and variation was observed at 140 gyrations. The ranges of the difference between the OACs were –0.6 to 0 percentage points for 160 SGC gyrations and –0.4 to +0.5 percentage points for 140 SGC gyrations. Although not shown in Table B4, these values were also determined for 150 gyrations, and the difference averaged –2.8 percent. Therefore, the recommended number of SGC gyrations for design of Type CMHB-C mixtures is 140. Because of the lower energy level imparted by the SGC, the relatively coarser gradation (lower specific surface area) and higher binder content of the Type CMHB-C mixture yielded significantly thicker asphalt films (more lubricant) on the aggregate and thus fewer SGC gyrations to match the TGC design than the similar maximum aggregate size Type C mixtures.

For the vast majority of these mixtures, Texas Transportation Institute personnel determined OACs using the SGC that were within ±0.5 percentage points of those determined by TxDOT personnel using the TGC. One should note that the materials used in this project were sampled at a time later than the materials originally used in the TGC design, which likely contributed to this difference. Data from TxDOT's Statewide Bituminous Proficiency Report (1999 – 2002) indicate there is a consistent variation (year to year) in density of similar specimens compacted using a TGC by different TxDOT laboratories. Average standard deviation of density for two mixes for each of four years was 0.63 percent. By plotting this standard deviation on each side of several typical TGC mixture design curves and interpolating the range of the OACs, one can state, as an extrapolation, that the OAC of a given mixture designed by several TxDOT laboratories using the TGC will routinely vary by ±0.3 percentage points. Further, TxDOT's standard operating procedure permits adjustment of the OAC during initial pavement construction.

Incidentally, a recent study by Huber et al. (2002) utilized similar materials and four different design methods (Marshall, Superpave, French Laboratoire Central des Ponts et Chausses [LCPC], and hybrid method using Superpave equipment with LCPC principles) to select aggregate gradations *and* determine OACs. Their four OACs for this material varied by only ±0.4 percentage points even when the different design methods called for somewhat different aggregate gradations.

For the current Superpave volumetric design method, the design number of gyrations (N_{design}) ranges from 50 to 125 and is a function of the traffic level. Table B5 shows the range of values for N_{design}, $N_{maximum}$, and $N_{initial}$ for each traffic level.

Table B5. Superpave Design Gyratory Compactive Effort (after FHWA, 2000).

Design ESALs (millions)	Compaction Parameters		
	$N_{initial}$	N_{design}	$N_{maximum}$
< 0.3	6	50	75
0.3 to < 3	7	75	115
3 to < 10	8	100	160
$\geq$ 30	9	125	205

The maximum N_{design} value for the highest level of traffic is 125 gyrations. Since N_{design} values significantly higher than this have been recommended for designing TxDOT mixture Types C, D, CMHB-C, and CMHB-D, this may be an indicator that the asphalt contents required to match the TGC for these mixture types may be relatively low or that the TGC design method yields mix designs with these gradations that should be resistant to rutting at high traffic levels.

Slopes of the SGC compaction curves were recorded (Table B8) and compared to the number of SGC gyrations to attain TGC design air voids. Researchers found no correlation. There was, however, an apparent correlation with the aggregate properties. Seven mixtures exhibited compaction slopes greater than 0.16. Of these seven, five contained gravel as the coarse aggregate; the other two contained limestone coarse aggregate that contained 10 percent and 15 percent sand. Of the 36 mixtures studied, 10 contained crushed gravel. Crushed rounded gravels and many field sands may have smooth, rounded faces and thus can contribute to low HMA mixture shear strength. Although no objective measurements of aggregate particle shape and texture were performed, the authors surmise that the gravels and sands in the mixtures promoted the higher compaction slopes. Further, it is noteworthy that the SGC detected these potentially lower-strength materials. None of the Type A or CMHB mixtures exhibited compaction slopes greater than 0.16.

Seven mixtures exhibited compaction slopes less than 0.06 (Table A1, Appendix A). Of these seven, three contained sandstone, two contained quartzite, one contained limestone, and one contained gravel. Only the limestone and gravel mixtures contained sand (15 percent and 14 percent, respectively). The other five contained crusher screenings and/or Donnafill (a very angular crushed fine granite material). Therefore, lower SGC compaction slope generally appears to denote mixtures with high internal friction or shear strength.

STEP 4 – INDIRECT TENSION TESTING

Researchers conducted indirect tension tests (IDTs) on the selected mixtures to estimate the cracking potential of different mixes. IDTs were conducted in triplicate on 6-inch diameter specimens in accordance with Tex-226-F, Procedure for Indirect Tensile Test. The total vertical load at failure and the strain at failure were recorded in order to establish relative resistance to cracking of the mixtures. Table B6 shows results from the IDTs for the different types of mixtures along with the corresponding average air void contents at which the mixtures were prepared. Appendix A contains detailed test data.

All mixtures were prepared using the OACs determined using the SGC. All specimens were compacted using the SGC to 7 ± 1 percent air voids (93 ± 1 percent density) in accordance with Tex-531-C. TxDOT Specification Item 340 for dense-graded HMA and Item 344 for performance design mixtures require a tensile strength of 85 to 200 psi (may exceed 200 psi when approved). All of the mixtures met this specification.

One Type A mixture, RTI-A1 from the Austin District, barely met the minimum specified tensile strength value. However, it exhibited the highest strain at failure for any

Type A mix and was exceeded by only one other mix (Type CMHB-C, #H01-17 from Atlanta). The relatively higher strain at failure may offset the lower tensile strength value, thus providing an acceptable mixture.

Table B6. Indirect Tensile Test Values for the Different Mixture Types.

Mix Type	Design Number	Average Air Voids, %	Average Failure Strain, in/in	Average Tensile Strength, psi	CV Tensile Strength, %
A	Austin, #RTI-A1	7.0	0.14	85	20
	San Antonio, #VH-A-2001	7.0	0.10	128	26
	Laredo, #2	6.7	0.10	124	16
	Lufkin, #H00-24	6.4	0.09	165	5
	Wichita Falls, #C01-0107	7.4	0.11	125	17
B	Atlanta, #H01-21	7.0	0.08	166	17
	Bryan, #CDS003a	7.2	0.09	123	23
	El Paso, South Quarry B	7.53	0.12	124	4
	Ft Worth, #0-3662	7.5	0.11	122	16
	Lufkin, #H0021	7.1	0.10	143	23
	Lufkin, #H9935	7.5	0.11	101	9
	Paris, #25204	7.0	0.11	162	13
	Pharr, #WB-B01 (HP plus)	7.4	0.12	103	25
C	Atlanta, #33604	7.5	0.12	189	6
	Atlanta, #H01-18	6.6	0.11	155	20
	Atlanta, #H01-19	7.2	0.13	149	6
	Atlanta, #H01-20	7.5	0.09	179	5
	Corpus Christi, #C-6	6.9	0.13	162	10
	Ft. Worth, #10-TXIC-01	7.1	0.12	144	10
	Laredo, #1	7.3	0.14	118	1
	Laredo, #2229	7.3	0.05	104	4
	Lufkin, #30040	7.3	0.10	194	11
	Paris, #35203	7.5	0.11	157	6
	Lufkin, #30043	7.3	0.10	186	5

Table B6. Indirect Tensile Test Values for the Different Mixture Types (Continued).

Mix Type	Design Number	Average Air Voids, %	Average Failure Strain, in/in	Average Tensile Strength, psi	CV Tensile Strength, %
D	Ft Worth, #0-3661	7.1	0.14	100	3.8
	El Paso, #000-05-039	7.3	0.11	138	15
	El Paso, #D-Mix (South Quarry)	7.4	0.09	169	17
	Paris, #45201	7.5	0.10	158	9
	Pharr, #2001-2-D	7.1	0.12	101	23
	Ft. Worth, #42TX-ID-00	7.5	0.12	108	4
CMHB-C	Atlanta, #H01-15	7.1	0.10	91	17
	Atlanta, #H01-17	7.4	0.15	145	34
	Atlanta, #H01-16	6.5	0.12	148	20
	Bryan, #H0026	6.8	0.09	141	14
	Bryan, #CDS001	7.0	0.09	177	28
CMHB-F	Odessa, #701601	7.2	0.14	115	2

CONCLUSIONS AND RECOMMENDATIONS

Researchers developed protocols for using the SGC to design TxDOT's basic repertoire of HMA paving mixtures. Specifically, researchers determined a design number of gyrations (N_{design}) using the SGC for each TxDOT mixture type that most closely simulates optimum asphalt contents determined using the TGC (Tex-204-F). The project included the following types of HMA mixtures: Type A, Type B, Type C, Type D, Type CMHB-C and Type CMHB-F. Based on the findings from this work, the following conclusions and recommendations are proffered.

- During compaction using the SGC, the slope of the air voids versus number of gyrations curve tends to become relatively flat after a certain number of gyrations. Thus, beyond this point, a change in air voids (density) is not very sensitive to an increasing number of gyrations. For this reason, some mixtures that were compacted during Steps 1 and 2 exhibited an inordinate number of gyrations to obtain the design density established by the TGC.

- Although there are significant differences in the compaction mechanisms between the SGC and the TGC, the SGC can be successfully used to design mixtures (rather, determine OAC) that simulate those designed using the TGC.

- For the vast majority of the mixtures studied herein, the OACs determined by TTI personnel using the SGC were within ±0.5 percentage points of those previously determined by TxDOT personnel using the TGC.

- For the mixtures studied, the number of SGC gyrations required to determine the optimum asphalt content that most closely simulated the OAC determined using the TGC are listed in Table B7.

Table B7. Recommended Number of SGC Gyrations to Simulate TGC Mixture Designs.

Mixture Type	Recommended Number of SGC Gyrations
A	100
B	110
C	160
D	160
CMHB- C	140
CMHB-F	160*

* This is an extrapolation since only one Type CMHB-F mix was available from TxDOT during this project.

- The researchers recommend using the SGC to determine OAC of TxDOT's repertoire of HMA paving mixtures. Table B7 shows the recommended N_{design} value for each mixture type. The current practice of making minor adjustments in the final OAC based on field experience during construction should be continued.
- Advantages of the SGC over the TGC include the following:
  - SGC produces larger specimens, which can accommodate aggregate particles up to 2 inches (1.5-inch nominal maximum size).
  - By measuring specimen height and estimating density during the compaction process, the SGC can estimate compactability of mixtures.
  - Density versus number of gyrations in the SGC can help identify weak aggregate structures that collapse very quickly to low air void levels (i.e., potentially rut-susceptible and/or tender mixtures).
  - TGC requires more manual control and is thus more prone to human errors that can adversely affect repeatability (within-laboratory variability) and reproducibility (between-laboratory variability) during determination of OAC.

Table B8. SGC Gyrations Required for Reaching TGC Air Voids – *Laboratory Mixed Specimens.*

Mix Type	Design Number	Mix Character	No. of SGC Gyrations to TGC Design Air Voids	Avg. No. Gyrations (Design)	Avg Slope of SGC Comp. Curve	Avg. No. of Gyrations (Initial)	Air Voids at $N_{initial}$	Standard Deviation (Design Gyrations)	Coefficient of Variation (Design Gyrations)	Average CV	CV on the Basis of All Individual Des. No. of Gyr.
A	Laredo, #2	Gravel + sand + 1.5% lime, 3.4% AC	86 87 92	88	-0.124	8	14	3.21	3.64	5.50	24.55
	Lufkin, #H00-24	Limestone + sand + 1% lime, 3.4% AC	117 117 105	113	-0.086	8	13	6.93	6.13		
	Wichita Falls, #C01-0107	Limestone + 12% sand + 1% lime 3.3% AC	63 65 71	66	-0.117	7	11	4.16	6.28		
	Austin, #RTI-A1	Limestone + 13% sand + 4.6% AC	124 139 127	130	-0.074	9	13	7.94	6.11		
	San Antonio, #VH-A-2001	Limestone (Helotes) + 15% silica sand, 3.9% AC	85 89 80	85	-0.090	7	11	4.51	5.33		
B	Atlanta, #H01-21	80% Gravel + 10% sand, 3.8% AC	40 43 46	43	-0.213	5	12	3.00	6.98	6.69	39.27
	Bryan, #CDS003a	Limestone + gravel + 1% lime, 4.6% AC	89 89 101	93	-0.105	8	13	6.93	7.45		
	El Paso, South Quarry B	Limestone + sand, 4.8% AC	98 98 113	103	-0.116	8	15	8.66	8.41		
	Ft Worth, #0-3662	Limestone + sand + PermaTac, 4.3% AC	87 87 92	89	-0.099	8	12	2.89	3.26		
	Lufkin, #H0021	Limestone + 6% sand + 1% lime, 4.0% AC	41 41 52	45	-0.220	6	13	6.35	14.22		
	Lufkin, #H9935	Limestone + 13% sand, 3.8% AC	121 131 146	133	-0.068	9	12	12.58	9.48		
	Paris, #25204	Sandstone + bottom ash + 1% lime, 5.4% AC	156 156 156	156	-0.064	10	13	0.00	0.00		
	Pharr, #WB-B01 (HP-Plus)	Gravel+ sand+ antistrip, 5.0% AC	115 116 123	118	-0.053	9	10	4.36	3.69		

Table B8. SGC Gyrations Required for Reaching TGC Air Voids – *Laboratory Mixed Specimens* (Continued).

Mix Type	Design Numbers	Mix Character	No. of SGC Gyrations to TGC Design Air Voids	Avg. No. Gyrations (Design)	Avg. Slope of SGC Comp. Curve	Avg. No. of Gyrations (Initial)	Air Voids at $N_{initial}$	Standard Deviation (Design Gyrations)	Coefficient of Variation (Design Gyrations)	Average CV	CV on the Basis of All Individual Des. No. of Gyr.
C	Atlanta, #33604	Sandstone + screenings + 1% lime, 5.6% AC	330 445 365	380	-0.031	14	15	58.95	15.51	9.15	80.22
	Atlanta, #H01-18	Gravel + Donnafill + 1% lime, 4.4% AC	60 60 60	60	-0.160	6	13	0.00	0.00		
	Atlanta, #H01-19	Quartzite + screenings + Donnafill +1% lime, 4.6% AC	410 510 500	473	-0.024	16	15	55.08	11.64		
	Atlanta, #H01-20	Sandstone + screenings + Donnafill + 1% lime, 4.5% AC	240 205 240	228	-0.049	12	15	20.21	8.85		
	Corpus Christi, #C-6	Gravel + LS screenings + 15% sand + 1% lime, 5.3% AC	74 74 95	81	-0.118	7	13	12.12	14.97		
	Ft. Worth, #10-TXIC-01	Limestone + sand + antistrip, 4.7% AC	68 70 76	71	-0.130	7	12	4.16	5.84		
	Laredo, #1	Gravel + 13% sand + 1.5% lime, 4.3% AC	122 141 147	137	-0.072	9	13	13.05	9.55		
	Laredo, #2229	30%RAP (gravel) +Granite+ 1.5% lime, 4.0% AC	50 69 94	71	-0.170	7	15	22.07	31.08		
	Lufkin, #30040	Limestone + 5% sand + 1% lime, 4.3% AC	115 116 117	116	-0.083	8	13	1.00	0.86		
	Lufkin, #30043	Gravel/Limestone Blend + 5% sand + 1% lime, 4.4% AC	49 51 50	50	-0.181	6	12	1.00	2.00		
	Paris, #35203	Sandstone+ 12% bottom ash+ 1% lime, 5.8% AC	324 325 323	324	no data	13	no data	1.00	0.31		

Table B8. SGC Gyrations Required for Reaching TGC Air Voids – *Laboratory Mixed Specimens* (Continued).

Mix Type	Design Number	Mix Character	No. of SGC Gyrations to TGC Design Air Voids	Avg. No. Gyrations (Design)	Avg. Slope of SGC Comp. Curve	Avg. No. of Gyrations (Initial)	Air Voids at $N_{initial}$	Standard Deviation (Design Gyrations)	Coefficient of Variation (Design Gyrations)	Average CV	CV on the Basis of All Individual Des. No. of Gyr.
D	Ft. Worth, #42-TXID-00	Limestone + 15% sand + HP antistrip, 5.0% AC	38 48 47	44	-0.206	6	12	5.51	12.42	7.56	48.97
	Ft. Worth, #0-3661	Limestone + sand + PermaTac, 4.8% AC	173 173 173	173	-0.064	10	14	0.00	0.00		
	El Paso, #0002-05-039	Gravel+ sand, 5.2% AC	60 60 60	60	-0.166	6	13	0.00	0.00		
	El Paso, #D-Mix (South Quarry)	Limestone + sand + UP5000 antistrip, 5.0% AC	184 190 200	191	-0.055	11	14	8.08	4.22		
	Paris, #45201	Sandstone + 10% bottom ash + 1% lime, 6.1% AC	154 185 214	184	-0.057	10	14	30.01	16.28		
	Pharr, #2001-2-D	Gravel + sand + 1% lime, 5.3% AC	195 220 250	222	-0.040	11	13	27.54	12.42		
F	None Available			--		--		--	--	--	--
CMHB-C	Atlanta, #H01-15	Gravel + Donnafill + 1% lime, 4.7% AC	81 82 83	82	-0.132	7	13	1.00	1.22	10.40	44.75
	Atlanta, #H01-17	Sandstone + screenings + Donnafill + 1% lime, 4.8% AC	150 150 196	165	-0.074	10	15	26.56	16.06		
	Atlanta, #H01-16	Quartzite + screenings + Donnafill + 1% lime, 4.8% AC	218 218 302	246	-0.054	12	16	48.50	19.71		
	Bryan, #H0026	Limestone + screenings + 1% lime, 4.5% AC	83 83 89	85	-0.151	7	15	3.46	4.08		
	Bryan, #CDS001	Limestone + gravel + 1% lime, 4.4% AC	167 171 203	180	-0.058	10	13	19.73	10.94		
CMHB-F	Odessa, #701601	Rhyolite + 7.3% AC	364 367 410	380	-0.031	14	14	25.74	6.77		

Table B9. Indirect Tension Test Data for Different Types of Mixes.

Mix Type	Design Number	Height, cm	Air Voids, %	Load, lb	Tensile Strain, in/in	Tensile Strength, psi	Average Tensile Strength, psi	CV Tensile Strength, %
A	Austin, #RTI A1	52.43	7.5	1272.70	0.12	66.50	84.56	19.8
		51.93	6.9	1662.07	0.18	87.68		
		52.21	6.5	1896.09	0.13	99.49		
	San Antonio, #VH-A-2001	52.49	7.1	2140.49	0.10	111.73	128.37	25.8
		52.61	6.7	3198.43	0.08	166.56		
		52.66	7.3	2053.57	0.12	106.83		
	Laredo, #2	52.24	6.7	1936.40	0.10	101.55	123.65	15.8
		52.57	6.9	2509.63	0.10	130.78		
		52.05	6.4	2633.33	0.10	138.61		
	Lufkin, #H00-24	52.43	6.3	2994.71	0.10	156.48	164.98	5.0
		52.93	6.5	3339.69	0.10	172.85		
		52.46	6.5	3171.29	0.07	165.61		
	Wichita Falls, #C01-0107	52.50	7.4	2856.47	0.10	149.07	124.98	16.8
		52.65	7.5	2135.33	0.10	111.11		
		52.63	7.3	2204.66	0.13	114.77		

Table B9. Indirect Tension Test Data for Different Types of Mixes (Continued).

Mix Type	Design Number	Height, cm	Air Voids, %	Load, lb	Tensile Strain, in/in	Tensile Strength, psi	Average Tensile Strength, psi	CV Tensile Strength, %
B	Atlanta, #H01-21	53.03	7.3	2616.30	0.10	135.16	166.46	16.5
		52.78	7.0	3433.32	0.07	178.21		
		53.10	6.8	3605.64	0.07	186.02		
	Bryan, #CDS003a	52.72	7.5	1749.05	0.10	90.89	123.43	22.9
		52.50	6.7	2707.34	0.08	141.27		
		52.77	7.4	2660.50	0.10	138.12		
	El Paso, South Quarry B	52.71	7.7	2506.01	0.12	130.25	123.99	4.4
		52.49	7.5	2373.50	0.12	123.88		
		53.05	7.6	2309.37	0.12	119.26		
		52.97	7.5	2256.40	0.12	116.70		
		52.90	7.4	2502.26	0.12	129.58		
		52.80	7.5	2394.73	0.10	124.25		
	Ft. Worth, #0-3662	52.71	7.6	1964.87	0.12	102.13	122.18	15.8
		52.71	7.1	2706.98	0.12	140.70		
		52.64	7.8	2377.09	0.10	123.72		
	Lufkin, #H0021	52.80	7.4	2040.38	0.13	105.87	142.99	23.2
		52.58	7.0	3252.82	0.08	169.48		
		52.64	6.9	2951.91	0.08	153.63		
	Lufkin, #H9935	52.80	7.5	1760.14	0.13	91.33	101.25	9.2
		52.93	7.4	2121.04	0.10	109.78		
		52.72	7.6	1975.05	0.10	102.63		

Table B9. Indirect Tension Test Data for Different Types of Mixes (Continued).

Type	Design Number	Height, cm	Air Voids, %	Load, lb	Tensile Strain, in/in	Tensile Strength, psi	Average Tensile Strength, psi	CV Tensile Strength, %
B	Paris, #25204	53.04	6.8	2715.04	0.10	140.23	161.78	12.6
		52.71	7.5	3165.42	0.12	164.52		
		53.09	6.8	3499.53	0.10	180.58		
	Pharr, #WB-B01 (HP plus)	52.43	7.2	1433.50	0.13	74.90	102.81	24.8
		52.51	7.5	2083.75	0.12	108.71		
		52.48	7.5	2391.07	0.12	124.82		
C	Atlanta, #33604	52.58	7.6	3524.53	0.10	183.63	188.79	6.4
		52.75	7.5	3468.73	0.12	180.16		
		52.75	7.5	3900.89	0.13	202.58		
	Atlanta, #H01-18	52.54	6.5	2762.38	0.13	144.03	155.34	20.2
		52.63	6.5	2518.81	0.10	131.12		
		52.56	6.9	3661.83	0.10	190.87		
	Atlanta, #H01-19	53.33	6.9	2703.26	0.15	138.87	149.22	6.0
		53.32	7.4	2998.93	0.12	154.08		
		53.72	7.2	3033.51	0.12	154.71		
	Atlanta, #H01-20	52.70	7.3	3403.63	0.12	176.95	178.51	5.4
		52.75	7.3	3268.87	0.08	169.78		
		52.58	7.8	3624.04	0.08	188.81		

Table B9. Indirect Tension Test Data for Different Types of Mixes (Continued).

Mix Type	Design Number	Height, cm	Air Voids, %	Load, lbs	Tensile Strain, in/in	Tensile Strength, psi	Average Tensile Strength, psi	CV Tensile Strength, %
C	Corpus Christi, #C-6	52.65	6.5	3486.84	0.13	181.43	162.22	10.4
		52.62	6.9	2984.64	0.12	155.39		
		52.72	7.2	2883.04	0.15	149.83		
	Ft. Worth, #10-TXIC-01	52.18	7.1	2852.08	0.12	149.74	143.98	10.3
		52.28	7.0	2958.56	0.12	155.03		
		52.30	7.2	2427.56	0.13	127.16		
	Laredo, #1	52.34	7.2	2274.62	0.17	119.06	118.20	1.1
		52.24	7.6	2226.33	0.13	116.75		
		52.31	7.1	2268.17	0.13	118.79		
	Laredo, #2229	54.24	7.1	1999.58	0.08	101.00	103.77	3.7
		49.80	7.5	1965.04	0.00	108.11		
		52.79	7.3	1969.25	0.07	102.19		
	Lufkin, #30040	52.42	7.2	4045.15	0.10	211.40	193.95	10.6
		52.21	7.4	3795.35	0.10	199.15		
		52.30	7.2	3270.45	0.10	171.31		
	Paris, #35203	53.09	7.2	2873.29	0.10	148.27	156.77	5.8
		52.86	7.6	3003.88	0.12	155.68		
		52.77	7.7	3204.52	0.10	166.36		
	Lufkin, #30043	52.28	7.8	3371.70	0.10	176.68	186.02	4.5
		52.31	7.2	3682.65	0.10	192.86		
		52.22	7.0	3593.17	0.10	188.50		

Table B9. Indirect Tension Test Data for Different Types of Mixes (Continued).

Mix Type	Design Number	Height, cm	Air Voids, %	Load, lb	Tensile Strain, in/in	Tensile Strength, psi	Average Tensile Strength, psi	CV Tensile Strength, %
D	Ft. Worth, #0-3661	52.60	7.1	1862.36	0.13	97.00	100.11	3.8
		52.61	7.0	1900.07	0.15	98.94		
		52.46	7.3	1999.25	0.13	104.40		
	El Paso, #000-05-039	53.14	7.2	2244.68	0.12	115.72	138.41	14.5
		52.35	7.4	2934.25	0.12	153.55		
		52.94	7.4	2820.65	0.08	145.96		
	El Paso, #D-Mix (South Quarry)	52.97	7.3	2636.95	0.10	136.38	168.82	16.7
		52.61	7.5	3575.38	0.08	186.18		
		52.95	7.4	3554.49	0.08	183.90		
	Paris, #45201	53.31	7.5	2749.04	0.10	141.27	157.86	9.1
		52.99	7.2	3190.25	0.12	164.93		
		52.90	7.7	3232.13	0.08	167.38		
	Pharr, #2001-2-D	52.86	6.8	1481.08	0.13	76.76	101.00	22.6
		53.21	7.3	2024.27	0.12	104.22		
		52.83	7.3	2353.33	0.12	122.03		
	Ft. Worth, 42TX-ID-00	52.79	7.5	2170.10	0.13	112.62	108.25	3.8
		52.91	7.5	2017.94	0.10	104.48		
		52.63	7.4	2068.14	0.13	107.65		

Table B9. Indirect Tension Test Data for Different Types of Mixes (Continued).

Mix Type	Design Number	Height, cm	Air Voids, %	Load, lbs	Tensile Strain, in/in	Tensile Strength, psi	Average Tensile Strength, psi	CV Tensile Strength, %
CMHB-C	Atlanta, #H01-15	57.86	6.9	1554.80	0.10	73.62	91.06	16.6
		52.16	7.5	1895.89	0.10	99.58		
		50.79	7.0	1854.10	0.10	100.00		
	Atlanta, #H01-17	53.01	6.9	2528.22	0.09	130.66	147.97	34.1
		51.57	7.7	2042.17	0.25	108.49		
		50.67	7.5	3786.79	0.10	204.76		
	Atlanta, #H01-16	55.05	6.3	2386.77	0.10	118.79	147.95	20.5
		51.27	6.6	2728.09	0.13	145.77		
		51.05	6.7	3341.00	0.13	179.29		
	Bryan, #H0026	52.96	6.9	2674.25	0.08	138.33	140.79	13.7
		51.46	6.9	2308.41	0.08	122.89		
		50.75	6.6	2985.26	0.10	161.15		
	Bryan, #CDS001	52.72	7.1	4274.65	0.10	222.13	176.55	28.2
		51.11	6.7	3432.02	0.08	183.98		
		50.79	7.3	2290.15	0.08	123.54		
CMHB-F	Odessa, #701601	52.98	7.6	2240.21	0.12	115.84	114.84	1.9
		52.87	7.0	2245.36	0.17	116.34		
		52.85	7.1	2166.97	0.12	112.34		

APPENDIX C:
MIXTURE SELECTION GUIDE

Guidelines for Selection of Hot Mix Asphalt Type for Specific Applications

Background

The 1993 *Guide for Design of Pavement Structures* (AASHTO, 1993) outlines the considerations for pavement type selection in its Appendix B. The primary factors to be considered include traffic (which they point out are notoriously inaccurate), soil characteristics, weather, construction considerations, recycling, as well as cost comparisons of initial construction, periodic rehabilitation, anticipated life, and maintenance and salvage values. Secondary factors include performance of similar pavements in the area, adjacent existing pavements, conservation of materials and energy, availability of local materials, and traffic safety.

The Asphalt Pavement Alliance (APA, 2004) states that pavement type selection should be a road-user oriented process and suggests further considerations including safety, user delay, speed of construction, tire-pavement noise generation, ride quality, and ease of rehabilitation. HMA paving mixtures are expected to perform over long periods of time under a variety of traffic, climatic, and substrate conditions. Specialized HMA mixtures have been developed to meet particular needs. A range of asphalt grades is available to optimize service under a variety of circumstances. Additionally, TxDOT has developed an aggregate classification system intended to guide the designer in specifying the minimal acceptable quality material for the project and conserve the top-quality materials for high-type pavements.

When hot mix asphalt is the preferred pavement type, the *HMA Pavement Mix Type Selection Guide* (NAPA, 2001) provides designers with valuable general guidelines for selecting appropriate mixture types while considering factors such as traffic, environment, subsurface pavement structure, existing pavement condition and preparation, and economics. In this concise 20-page document, the specific mixture types targeted are fine- and coarse-graded dense mixes, permeable friction courses (PFC), and stone matrix asphalt (SMA). NAPA's guidelines are designed to maximize the effectiveness and success of these mixture types. No guide can cover every situation that will be encountered, but they can be valuable reference tools to both pavement designers and field personnel.

The Australian *Selection and Design of Asphalt Mixes* (AAPA, 1997) points out that HMA may be used for construction of new pavements or maintenance/rehabilitation of existing pavements, which may involve one or more of these: strengthening the pavement structure, correction of surface irregularities, and/or provision of a new wearing surface. Selection of the appropriate mixture will depend on all of the items mentioned above plus structural performance requirements and surface characteristics required. Consideration of all of the factors in the preceding paragraphs plus layer thickness will lead to selection of:

- type of asphalt mix,
- nominal size of aggregate,
- grade of asphalt binder, and
- classification of aggregate.

HMA mixture type selection and layer thickness design may depend on the availability and use of other materials such as polymer-modified asphalts or geosynthetics. TxDOT Project 0-4824, "Guidelines for Selecting Asphalt Mixtures and Evaluation of Polymer-Modified Mixes," which is due for completion in August 2005, should produce detailed guidelines for selecting optimum asphalt mixture types for specific TxDOT circumstances of traffic, environment, and substrate conditions. These guidelines will address the use of polymer-modified binders. "Guidelines for Using Geosynthetics with HMA Overlays to Reduce Reflective Cracking" (Button and Lytton, 2003) provide useful information when designing an overlay for a pavement exhibiting significant cracking.

The taxpaying public expects highway engineers to make effectual decisions regarding mixture type selections. NAPA (2001) points out that contractors have expressed concerns regarding state and local agencies incorporating high quality aggregates in their HMA mixtures for both high-volume and low-volume traffic use, resulting in the unnecessary increase of construction costs, in some cases. Further, with required staff reductions and retirements of experienced pavement specialists from many government agencies, there is a need to provide guidance to those responsible for designing and specifying the applications of HMA mix types.

If HMA pavement is selected, then further guidelines are needed to recommend alternative types of HMA mixtures for the specific situation as well as design and analysis procedures for those alternative mixtures. New design procedures using the Superpave gyratory compactor in place of the Texas gyratory compactor are provided in Report 4203-1 (Button et al., 2004). Evaluation procedures related to rutting and moisture susceptibility are recommended in the body of this report.

During the course of this research project, TxDOT Flexible Pavements Branch developed "Mixture Selection Guide for Flexible Pavements," (TxDOT, 2004) that presents advantages and disadvantages of the four standard TxDOT types of HMA paving mixtures. During this same period, the Waco District developed simplified tables to guide the flexible pavement designer in selecting the optimum type of HMA mix for common functional pavement classifications (TxDOT, 2004a). This new information is shown below with a few minor modifications.

TxDOT Mixture Type Selection Guide for Flexible Pavements

Introduction

This mixture selection guide for flexible pavements provides designers with recommendations for selecting HMA types based on factors such as traffic volume, loading characteristics, design speed and desired performance characteristics. Recommendations regarding mixture type selection are provided in the three tables contained within this guide. Table C1 contains a listing of relative hot mix rankings. Table C2 contains a summary of mixture types, sizes, and uses. Table C3 contains a listing of recommended choices for surface mixtures. This guide covers the four major HMA types listed in the Department's 2004 Standard Specification book. The four mixture types are:

- Items 340 and 341 – Dense-graded Mixtures,
- Item 342 - Permeable Friction Course,
- Item 344 - Performance Design Mixtures, and
- Item 346 - Stone Matrix Asphalt (SMA).

Table C1. Relative Hot Mix Rankings (Subjective - 0 to 5 Scale with 5 Being the "Best").

Mixture Characteristic	Dense-Graded (Items 340/341)	PFC (Item 342)	Performance Design Mixes (Item 344)	SMA (Item 346)	Determining Factors
Resistance to Rutting	2-5	4-5	3-5	4-5	Stone-on-stone contact & binder stiffness
Resistance to Cracking	1-4	3-5	2-4	4-5	Total volume of asphalt in mix, binder film thickness
Resistance to Segregation	1-4	5	3-4	4-5	Gradation, uniformity and aggregate size
Resistance to Raveling	2-4	2-4	3-4	4-5	Toughness of mastic and resistance to segregation
Ability to Resist High Shear Forces (hard turning motions)	2-4	2-4	3-4	4-5	Toughness of mastic and resistance to raveling
Resistance to Moisture Damage	2-4	3-5	3-4	4-5	Binder film thickness and potential adverse permeability
Resistance to Freeze/Thaw Damage	3-4	2-4	3-4	4-5	Binder film thickness and potential permeability
Potential Permeability	3-4	N/A	2-4	4-5	Ability to compact to a relatively high in place density
Long Term Durability	2-3	3-4	3-4	4-5	Binder film thickness and toughness
Wet Weather Traction	2-4	4-5	3-4	3-4	Texture, permeability, and resistance to hydroplaning
Wet Weather Visibility	2-3	4-5	2-4	2-4	Texture and ability to quickly drain surface water
Noise Reduction (comfort)	3-4	4-5	3-4	3-4	Ability to buffer noise and surface texture
Aesthetically Pleasing	3-4	4-5	3-4	3-5	Texture, uniformity and resistance to segregation
Ease of Compaction	2-4	4-5	2-3	3-4	Volume of mastic, VMA, and toughness
Ability to "hand work"	3-5	2-3	2-4	2-3	Aggregate gradation and binder stiffness
Affordability (Initial Cost)	4-5	2-4	3-4	2-3	Aggregates, additives and production rates

Table C2. Summary of Mixture Types, Sizes and Uses.

Mixture Type/ Size	Nominal Aggregate Size (inches)	Minimum Lift Thickness (inches)	Maximum Lift Thickness (inches)	Typical Location of Pavement Layer
Items 340/341				
Type A Mix	1 ½	3.0	6.0	Base
Type B Mix	1	2.5	5.0	Base/Intermediate
Type C Mix	¾	2.0	4.0	Intermediate/Surface
Type D Mix	½	1.5	3.0	Surface layer
Type F Mix	3/8	1.25	2.5	Surface layer
Item 342				
PFC (PG 76 mixture)	½	3/4	1.5	Surface
PFC (AR mixture)	½	3/4	1.5	Surface
Item 344				
SP A	1	3.0	5.0	Base
SP B	¾	2.25	4.0	Base/Intermediate
SP C	½	1.5	3.0	Intermediate/Surface
SP D	3/8	1.25	2.0	Surface
CMHB-C	¾	2.0	4.0	Intermediate/Surface
CMHB-F	3/8	1.5	3.0	Surface
Item 346				
SMA-C	¾	2.25	4.0	Intermediate/Surface
SMA-D	½	1.5	3.0	Intermediate/Surface
SMA-F	3/8	1.25	2.5	Surface
SMAR-C	¾	2.0	4.0	Intermediate/Surface
SMAR-F	3/8	1.5	3.0	Surface

Table C3. Recommended Choices for Surface Mixtures.

Posted Speed (mph)	Traffic Volume / Load Demand		
	Low	Medium	High
< 45	1. Dense-graded mix 2. Performance design mix	1. Performance design mix 2. Dense-graded mix	1. SMA 2. Performance design mix 3. Dense-graded mix
≥ 45	1. Dense-graded mix 2. Performance design mix 3. PFC	1. PFC 2. Performance design mix 3. Dense-graded mix	1. PFC 2. SMA 3. Performance design mix 4. Dense-graded mix

Note: A high load demand can be defined as having a high amount of cumulative axle loads, a high shear environment caused by decelerating/turning movements, slow moving or standing traffic with heavy axle loads.

This guide is intended to provide general recommendations based on the experiences of the engineering staff in the Flexible Pavements Branch of the TxDOT Construction Division (TxDOT, 2004). This guide is not intended to be used as Department policy. Districts are encouraged to make mixture selection choices based on engineering judgment along with the recommendations provided in this guidance document. A number of factors should be considered when selecting which HMA mixture is most appropriate for the intended application. Some of the factors that should be considered are listed below:

- previous experience with similar mixture types;
- volume of truck traffic, traffic flow characteristics;
- pavement geometric considerations;
- lift thickness of paving layers;
- condition of underlying pavement;
- availability of local materials;
- climatic and environmental conditions;
- cost (initial as well as life cycle); and
- selected performance grade (PG) binder.

It is important that the designer select the proper mixture for the intended application. It is also very important that the designer select the appropriate PG binder and aggregate properties for the intended application. These topics will not be covered in this guide since most TxDOT districts have guidelines or policies currently in place that address binder and aggregate property selection. Those needing additional assistance should contact their district pavement engineer, district construction engineer, laboratory personnel, or the Construction Division.

General Description of Hot Mix Asphalt (HMA) Mixtures

Item 340 is a method specification for conventional dense-graded mixtures.

Typical Use: Item 340 is typically used for projects with small quantities of HMA. Item 340 is generally not recommended for projects with more than 5000 tons of HMA. Conventional dense-graded mixtures can be used for a wide variety of applications; however, under Item 340, it is recommended that the use of dense-graded mixtures be limited to miscellaneous applications such as routine maintenance work, backfilling utility cuts, driveways, and other similar applications.

Advantages: The primary advantage of dense-graded mixtures compared to other mixtures is lower initial cost. Another advantage is that most contractors and HMA producers are generally familiar with the production and placement of dense-graded mixtures. Dense-graded mixtures have been used in Texas for over 50 years and have performed well in most applications.

The mixtures listed in Item 340 are identical to those listed in Item 341. In contrast to Item 341, which is a quality control/quality assurance (QC/QA) specification, Item 340 does not prescribe QC/QA measures. This may be an advantage in miscellaneous applications where QC/QA measures are not warranted.

Disadvantages: Dense-graded mixtures cannot accommodate high asphalt contents without becoming unstable and susceptible to rutting. Relatively low amounts of asphalt are typically used in dense-graded mixtures, which in turn, makes them more susceptible to cracking and more permeable. Generally speaking, dense-graded mixtures can be designed to be either highly rut resistant or highly crack resistant but not both. Dense-graded mixtures are not typically designed to have stone-on-stone contact. Their strength/stability characteristics are derived primarily from the quality of the intermediate and fine aggregate. Attempting to “coarsen” the mix to make the mix more rut resistant often has adverse effects. Coarsening the mix often leads to a drier mix and one that is more difficult to compact, more permeable and more susceptible to segregation.

The texture of dense-graded surface mixtures (Types C, D, and F) is relatively low; therefore, wet weather traction will typically be lower than the coarser graded mixtures, depending on the aggregate type, size, and mineralogy.

Dense-graded mixtures are currently designed using a Texas gyratory compactor (TGC). The TGC has a relatively high compactive effort and unlike the Superpave gyratory compactor (SGC), the TGC compactive effort cannot be varied to match the intended application. Therefore, the TGC tends to produce a dry, lean mix regardless of the application. Ideally, one would want to design a richer mix for a low-volume/low-demand roadway and a leaner mix for a high-volume/high-demand roadway. More asphalt in the mix reduces the risk of cracking and less asphalt reduces the risk of rutting. It is possible to increase or decrease the amount of asphalt in the mixture by adjusting the target laboratory-molded density down or up from the standard value of 96.0 percent. Seldom is the target lab density adjusted down from the standard of 96.0 percent; however, it is common practice to adjust the target laboratory-molded density up to 97.0 percent or higher in order to get more asphalt into the mixture. This practice is acceptable and actually encouraged where warranted; however, it should be noted that some mixtures may become susceptible to rutting if they contain too much asphalt, especially if the asphalt is relatively soft (e.g., PG 64-22).

Under Item 340, most of the responsibilities are on the Department rather than the contractor. On projects that warrant QC/QA, it could be risky to use Item 340 unless the department representatives are familiar with the roles and responsibilities required under method specifications.

Item 341 is a QC/QA specification for conventional dense-graded mixtures.

Typical Use: Dense-graded mixtures in Item 341 can be used for a wide variety of applications ranging from new construction to overlays. Dense-graded mixtures may be appropriate for applications ranging from high-volume (or high-demand) roadways to low-volume (or low-demand) roadways depending on the specified binder grade, aggregate properties, etc. Dense-graded mixtures can be used as base, intermediate, or surface layers.

Advantages: The primary advantage of dense-graded mixtures compared to other mixtures is lower initial cost. Another advantage is that most contractors and HMA producers are generally familiar with the production and placement of dense-graded mixtures. Dense-graded mixtures have been used in Texas for over 50 years and have performed well in most applications.

The mixtures listed in Item 341 are identical to those listed in Item 340. In contrast to Item 340, which is a method specification, Item 341 prescribes numerous QC/QA measures to be taken by both the contractor and the Department. The vast majority of the QC/QA measures are the responsibility of the contractor.

Disadvantages: Dense-graded mixtures cannot accommodate high asphalt contents without becoming unstable and susceptible to rutting. Relatively low amounts of asphalt are typically used in dense-graded mixtures, which in turn, makes them more susceptible to cracking and more permeable. Generally, dense-graded mixtures can be designed to be either highly rut resistant or highly crack resistant but not both.

Dense-graded mixtures are not designed to have stone-on-stone contact. Their strength/stability characteristics are derived primarily from the quality of the intermediate and fine aggregate. Attempting to "coarsen" the mix to make the mix more rut resistant often has an adverse effect. Coarsening the mix often leads to a drier mix and one that is more difficult to compact, more permeable and more susceptible to segregation.

Dense-graded mixtures are currently designed using a TGC. The TGC has a relatively high compactive effort and unlike the SGC, the TGC compactive effort cannot be varied to match the intended application. Therefore, the TGC tends to produce a dry, lean mix regardless of the application. Ideally, one would want to design a richer mix for a low-volume/low-demand roadway and a leaner mix for a high-volume/high-demand roadway. More asphalt in the mix reduces the risk of cracking and less asphalt reduces the risk of rutting. It is possible to increase or decrease the amount of asphalt in the mixture by adjusting the target laboratory-molded density down or up from the standard value of 96.0 percent. Seldom is the target lab density adjusted downward from the standard of 96.0 percent; however, it is common practice to adjust the target laboratory-molded density up to 97.0 percent or higher in order to get more asphalt into the mixture. This practice is acceptable and actually encouraged where warranted; however, it should be noted that some mixtures may become susceptible to rutting if they contain too much asphalt especially if the asphalt is relatively soft, e.g., PG 64 -22.

The texture of dense-graded surface mixtures (Types C, D, and F) is relatively low; therefore, wet weather traction will typically be lower than the coarser graded mixtures, depending on the aggregate type, size, and mineralogy.

Under Item 341, both the contractor and the Department have numerous responsibilities in terms of QC/QA measures. This degree of control may not be warranted on extremely small projects or miscellaneous type projects.

Item 342 is a method specification for Permeable Friction Courses (PFC).

Typical Use: PFC mixtures are used as the surface course on high-speed roadways to optimize the safety and comfort characteristics of the roadway. For this guide, a high-speed roadway is defined as one having a posted speed limit of 45 mph or higher. The standard PFC mixture contains PG 76-22 and fibers and is recommended for the vast majority of applications where PFC is warranted. Asphalt-Rubber (A-R) PFC can be used as an alternate to the standard PFC. A-R PFC is generally more expensive than the standard PFC; however, its unique properties warrant its use in certain applications. As a general rule, A-R PFC is recommended over the standard PFC when placed as an overlay on an existing concrete pavement, when a high degree of noise reduction is desired, and when placed as an overlay on a pavement that has a high amount of cracking. Although both types are excellent at draining water and reducing noise, standard PFC tends to drain water better than the A-R PFC but is generally not considered to be as quiet as the A-R PFC.

Advantages: As opposed to all other types of hot mix, PFC is designed to let water drain through the mixture down to the underlying layer. PFC mixtures significantly reduce water spray, improve wet weather visibility and visibility of pavement markings, significantly reduce tire noise, restore ride quality, and reduce glare. PFC mixtures have stone-on-stone contact and relatively high amounts of asphalt binder. As a result, they offer good resistance to rutting and cracking. PFC mixtures are relatively easy to design and place. PFC mixtures require only a minimal amount of compaction with a static roller. This helps facilitate a smooth riding surface. PFC mixtures provide a roadway that has a uniform yet coarse surface texture. The coarse texture and permeable mix characteristics improve wet weather traction.

PFC mixtures contain approximately 20 percent air voids and they are typically placed only 1.5 inches thick; therefore, the yield per ton of mix is relatively high. PFC weighs approximately 90 to 95 lbs/square yard per inch of depth as opposed to the standard weight for most hot mix, which is approximately 110 lbs/square yard per inch.

Disadvantages: PFC mixtures typically have a higher initial cost compared to conventional dense-graded mixtures. PFC mixtures contain more asphalt (6 percent minimum, 8 percent minimum for A-R PFC) compared to conventional mixtures. The asphalt used in PFC mixtures contains a high amount of polymers (or asphalt-rubber as an option). In addition to polymers, PFC mixtures require the use of fibers (not required with asphalt-rubber) and may require the use of hydrated lime. All of these additives not only add to the initial cost, but they sometimes require that producers make modifications to their HMA production processes.

PFC mixtures must be placed on top of a pavement that is structurally sound and relatively impermeable. A surface treatment (under seal) or level-up layer may be needed prior to placing the PFC. When used on low-speed roadways, PFC mixtures can clog up more quickly thus negating the beneficial drainage characteristics. PFC mixtures tend to freeze faster and thaw slower (similar to a bridge) compared to conventional mixtures. PFC mixtures are not as resistant to high shearing forces; therefore, they should be avoided on pavements where there are hard turning maneuvers combined with braking (e.g., short radius exit ramps, turnouts). PFC is not recommended for mill and inlay operations.

Generally, it is not good to place any type of hot mix in cool or cold weather. PFC mixtures can be particularly difficult to place in cool weather because they are placed in thin lifts, they cool rapidly and they contain a high amount of polymer-modified binder. They do not lend themselves well to applications that require a significant amount of handwork.

Item 344 is a QC/QA specification for performance design mixtures which include traditional Superpave mixtures as well as coarse matrix-high binder (CMHB) mixtures.

Typical Use: Although they are typically used on medium- to high-volume roadways, performance design mixtures may be appropriate for applications ranging from high-volume (or high-demand) roadways to low-volume (or low-demand) roadways depending on the specified design number of gyrations (N_{design}), binder grade, aggregate properties, etc. Performance design mixtures can be used as base, intermediate, or surface layers. Performance design mixtures can be used for a wide variety of applications ranging from new construction to overlays.

Advantages: As compared to Item 341, one of the primary advantages of performance design mixtures is that the mixture design procedures allows one to adjust the binder content (by adjusting the N_{design} level) depending on the intended application. For example: a mix for a low-volume roadway can be designed using a low N_{design} level, which will yield a mixture with a higher optimum asphalt content. The higher asphalt content will help mitigate cracking and provide greater durability. Conversely, a mix for a high-volume roadway can be designed using a high N_{design} level, which will yield a mixture with a lower optimum asphalt content, thus minimizing rutting.

Another advantage is that performance design mixtures can be designed coarse enough to have stone-on-stone contact. Achieving stone-on-stone contact can yield a mix that is highly resistant to rutting and have a coarse surface texture. The coarse surface texture can be beneficial in terms of wet weather traction.

Disadvantages: Compared to regular dense-graded mixtures, performance design mixtures can be more difficult to compact. Failing to achieve proper in-place density can cause potential permeability problems and shorten the performance life of the pavement. In some cases, performance design mixtures can be "too dry" in terms of asphalt content. This can result in a mixture that is susceptible to cracking.

Compared to SMA mixtures, performance design mixtures have a gradation that is not as "gap graded" as an SMA mixture. As a result, performance design mixtures typically contain less asphalt than SMA mixtures and may therefore be more susceptible to cracking and water infiltration. CMHB mixtures are not recommended for mill and inlay projects.

During compaction, a significant number of Superpave mixtures have experienced a phenomenon known as intermediate temperature tenderness. These mixtures may experience tenderness (or pushing) during compaction. This tenderness does not typically appear until several roller passes have been made, and the mat begins to cool (usually in the 240°F range). Contractors can overcome this phenomenon by ceasing compaction once the tenderness is observed and then resuming compaction once the mat cools to approximately 180°F.

Item 346 is a QC/QA specification for stone matrix asphalt mixtures.

Typical Use: SMA mixtures are typically used as a surface mix or intermediate layer in the pavement structure on high-volume (or high-demand) roadways. SMA mixtures are often used as the intermediate layer when PFC mix is used as the surface layer. A standard SMA mixture contains PG 76-22 and fibers and is recommended for the vast majority of applications where SMA is specified. Asphalt Rubber SMA can be used as an alternate to the standard SMA. A-R SMA is generally more expensive than the standard SMA; however, its unique properties warrant its use in certain applications. As a general rule, A-R SMA is recommend over standard SMA when placed as an overlay on an existing concrete pavement, when a high degree of noise reduction is desired, and when placed as an overlay on a pavement that has a high amount of cracking.

Advantages: SMA mixtures provide both excellent rut resistance and crack resistance. SMA mixtures have a high concentration of coarse aggregate, which facilitates stone-on-stone contact. The voids in the coarse aggregate skeleton are filled with fibers, mineral filler, and a relatively high amount (6 percent minimum) of polymer-modified asphalt. This combination of materials allows for a "rich" mixture that is resistant to cracking while, at the same time, being highly resistant to rutting. SMA mixtures are considered to be relatively impermeable particularly when compared to performance design mixtures. SMA mixtures result in a pavement layer that has a high degree of surface texture that is beneficial in terms of wet weather traction.

Disadvantages: SMA mixtures typically have a higher initial cost compared to other mixtures. SMA mixtures contain more asphalt (6 percent minimum) compared to conventional mixtures. The asphalt used in SMA mixtures contains a high amount of polymers (or asphalt-rubber as an option). In addition to the polymers, SMA mixtures require the use of fibers (not required with asphalt-rubber) and mineral filler and may require the use of lime. These additives not only add to the initial cost, but they often require that the producer make modifications to their HMA production processes. SMA mixtures may require higher quality aggregates than conventional mixtures. SMA mixtures usually require a significant compactive effort; however, they produce a pavement layer with a higher density compared to conventional mixtures.

Generally, it is not good to place any type of hot mix in cool or cold weather. SMA mixtures can be particularly difficult to place in cool weather because they are placed in thin lifts and they contain a high amount of polymer-modified binder. They do not lend themselves well to applications that require a significant amount of handwork.

Waco District HMA Mixture Type Selection Guide

The Waco District pavement engineer and construction engineer and their staffs are developing a very straightforward guide to assist their area engineers and their staffs in selecting the best type of HMA mixture for particular circumstances of functional roadway classification as well as traffic quantity and loads (TxDOT, 2004a). A working draft of their guidelines is shown in Tables C4 through C7. This guide shows preferences of the Waco District staff. The Waco District does not currently use Type CMHB mixtures; therefore, these types of surface mixtures are not recommended in Table C4.

Abbreviations shown in Tables C4 through C7 are:

- Permeable Friction Course – PFC;
- Stone Matrix Asphalts – SMA-C and SMA-D;
- Performance Designed Mixtures – SP-A, SP-B, SP-C and SP-D;
- Dense-Graded Hot Mix Asphalt – Type A, Type B, Type C, Type D; and
- Two-Course Surface Treatments – TCST.

Table C4. Guide for Selecting HMA Type for Pavement Surface for Typical Circumstances.

Functional Classification	Present ADT[7]	Design Year 18 Kip ESAL (in millions)	Recommended Mixtures[1]
All	All	greater than 30	PFC or (SMA-D or SMA-F)[2]
Interstate Highway[5] Main Lanes	All	All	PFC or (SMA-D or SMA-F)[2]
US Highways	between 20,000 and 12,000	between 30 and 20	PFC or (SMA-D or SMA-F)[6]
	between 12,000 and 8000	between 20 and 10	(SMA-D or SMA-F)[6]
	less than 8000	between 10 and 5	(Ty C or Ty D) or (SP-C or SP-D)[6]
		less than 5	Ty C or Ty D
State Highways (Trunk System)	between 20,000 and 12,000	between 30 and 20	PFC or (SMA-D or SMA-F)[6]
	between 12,000 and 8000	between 20 and 10	(SMA-D or SMA-F)[6]
	less than 8000	between 10 and 5	(Ty C or TY D) or (SP-C or SP-D)[6]
		less than 5	Ty C or Ty D
State Highways (Non-Trunk System)	between 20,000 and 12,000	between 30 and 20	PFC or (SMA-D or SMA-F)[6]
	between 12,000 and 8000	between 20 and 10	(SMA-D or SMA-F)[6] (Ty C or Ty D) or (SP-C or SP-D)[6]
	less than 8000	between 10 and 5	(Ty C or Ty D) or (SP-C or SP-D)[6]
		less than 5	Ty C or Ty D
Farm-to-Market (FM) Roads[3]	High Volume greater than 8000	greater than 2	(Ty C or Ty D) or (SP-C or SP-D)[6]
	Moderate Volume[4] between 8000 and 1000	between 2 and 0.25	(Ty C or Ty D) or Two-course surface treatment
	Low Volume[4] less than 1000	less than 0.25	TCST

[1] Recommended mixtures are in order of Waco District preference for the functional roadway classification, traffic volume, and loading.

[2] Use coarse aggregate quality requirements (Heavy Duty Mixture) as stated in the 2004 Standard Specifications (Table 1: Items 342, 344 & 346).

[3] Hot mix surfaces, as a rule, are not placed on low-volume FM roads.

[4] FM roads include spurs, undesignated loops, business routes, and local roads that are in an urban setting.

[5] Frontage roads on IH 35 should follow US Highway criteria.

[6] Coarse aggregate quality requirements for normal duty HMA surface course (Items 344 & 346) are shown in Table C5.

[7] Average Daily Traffic

Table C5. Coarse Aggregate Quality Requirements for HMA Surface Courses.

Properties	Test Method	SMA-D or F SP-C or D
Coarse Aggregate		
Surface Aggregate Classification	AQMP[4]	As shown on plans
Deleterious Material, %, Max	Tex-217-F, Part I	1.0
Decantation, %, Max	Tex-217-F, Part II	1.0
Micro-Deval Loss, %, Max	Tex-461-A	Note[1]
Los Angeles Abrasion, %, Max	Tex-410-A	35
Magnesium Sulfate Soundness Loss, 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, @ 3:1, %, Max	Tex-280-F	10
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 other additives, combined as used in the job-mix formula (JMF).

[4] Aggregate Quality Monitoring Program

Table C6. Guide for Selecting HMA Type for Pavement Base for Typical Circumstances.

Functional Classification	Present ADT	Design Year 18 KIP ESAL (in millions)	Recommended Mixtures[1]
All	All	greater than 30	(SP-A or SP-B)[2] or SMA-C[2]
Interstate Highway[4] Main Lanes	All	All	(SP-A or SP-B)[2] or SMA-C[2]
US Highways	between 20,000 and 2000	between 30 and 20	(SP-A or SP-B)[5], (Ty A or Ty B) or SMA-C[5]
	between 12,000 and 8000	between 20 and 10	(Ty A or Ty B), (SP-A or SP-B)[5] or SMA-C[5]
	less than 8000	between 10 and 5	(Ty A or Ty B) or (SP-A or SP-B)[5]
		less than 5	Ty A or Ty B
State Highways (Trunk System)	between 20,000 and 2000	between 30 and 20	(SP-A or SP-B)[5], (Ty A or Ty B) or SMA-C[5]
	between 12,000 and 8000	between 20 and 10	(Ty A or Ty B), (SP-A or SP-B)[5] or SMA-C[5]
	less than 8000	between 10 and 5	(Ty A or Ty B) or (SP-A or SP-B)[5]
		less than 5	Ty A or Ty B
State Highways (Non-Trunk System)	between 20,000 and 2000	between 30 and 20	(SP-A or SP-B)[5,] (Ty A or Ty B) or SMA-C[5]
	between 12,000 and 8000	between 20 and 10	(Ty A or Ty B), (SP-A or SP-B)[5] or SMA-C[5]
	less than 8000	between 10 and 5	(Ty A or Ty B) or (SP-A or SP-B)[5]
		less than 5	Ty A or Ty B
Farm-to-Market Roads[3]	High Volume greater than 8000	greater than 2	Ty A or Ty B or (SP-C or SP-D)[5]
	Moderate Volume[4] between 8000 and 1000	between 2 and 0.25	Ty A or Ty B
	Low Volume[4] less than 1000	less than 0.25	Ty A or Ty B

[1] Recommended mixtures are in order of Waco District preference for the functional roadway classification, traffic volume and loading.

[2] Use coarse aggregate quality requirements as stated in the 2004 Standard Specifications (Table 1 – Item 344 & 346).

[3] FM Roads include spurs, undesignated loops, business routes, and local roads that are in an urban setting.

[4] Frontage roads on IH 35 should follow US Highway criteria.

[5] Coarse aggregate quality requirements for normal duty HMA base courses (Items 344 & 346) are shown in Table C7.

Table C7. Coarse Aggregate Quality Requirements for HMA Base Courses.

Properties	Test Method	SP-A or B SMA-C
Coarse Aggregate		
Surface Aggregate Classification	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 Loss, %, Max	Tex-461-A, Part I	Note[1]
Los Angeles Abrasion, %, Max	Tex-410-A	40
Magnesium Sulfate Soundness Loss, 5 cycles, %, Max	Tex-411-A	30[2]
Coarse Aggregate Angularity, Two Crushed Faces, %, Min	Tex-460-A, Part I	85[3]
Flat and Elongated Particles, @ 5:1, %, Max	Tex-280-F	10
Fine Aggregate		
Linear shrinkage, %, Max	Tex-107-E	3
Combined Aggregate[4]		
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] Unless otherwise shown on plans.
[3] Unless otherwise shown on plans. Only applies to crushed gravel.
[4] Aggregates, without mineral filler, RAP, or other additives, combined as used in the job-mix formula.

References for Appendix C

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