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16. Abstract
To improve the performance of hot-mix asphalt concrete at high temperatures, crumb-rubber is typically used. Although hot-mix asphalt concrete consisting of crumb-rubber has been successfully placed and have performed well over the years, the laboratory design and preparation of specimens are sometimes problematic. The current mix design procedure (Tex-232-F) is cumbersome and requires preparing a large number of laboratory specimens to carry out an appropriate mix design. The purpose of this research project is to identify the problems with and provide solutions to the current procedure. In addition, the mix design procedure using Superpave Gyratory Compactor is also included in this report.

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Mix Design Procedure for Crumb Rubber Modified Hot Mix Asphalt

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ABSTRACT

To improve the performance of hot-mix asphalt concrete at high temperatures, crumb-rubber is typically used. Although hot-mix asphalt concrete consisting of crumb-rubber has been successfully placed and have performed well over the years, the laboratory design and preparation of specimens are sometimes problematic. The current TxDOT mix design procedure (Tex-232-F) is cumbersome and requires preparing a large number of laboratory specimens to carry out an appropriate mix design. The purpose of this research project is to identify the problems with and provide solutions to the current procedure. In addition, the mix design procedure using Superpave Gyratory Compactor is also included in this report.

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CHAPTER 1 INTRODUCTION

1.1 Problem Statement

To improve the performance of hot mix asphalt concrete (HMAC), crumb-rubber (CRM) is typically added. The modified mix is commonly known as CRM-HMAC. The CRM is typically added and mixed to the asphalt cement before mixing it with the aggregates through a process commonly known as the wet process. As shown in Figure 1, the main advantage of the CRM is that it improves the rutting resistance of the HMAC at higher temperatures without increasing the stiffness at the lower temperatures. This also allows for the safe disposal of a large number of waste tires with minimal environmental concerns.

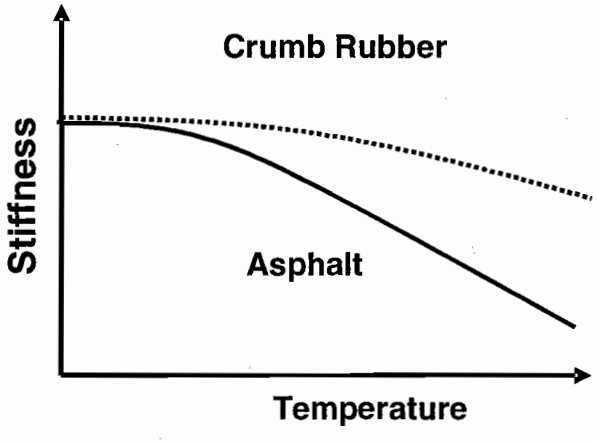

FIGURE 1 Influence of Temperature on Stiffness of Asphalt Consisting of CRM

Although the CRM-HMAC pavements have been successfully placed and have performed well over the years, the laboratory preparation of specimens in some cases has proven to be problematic. The sources of the problem include the stickiness of crumb-rubber asphalt cement, the temperature and method of mixing crumb rubber in asphalt cement, the expansion of specimens after removal from the mold, etc. Another issue specific to TxDOT is the current mix design procedure (Tex-232-F). This procedure is cumbersome and requires preparation of quite a large number of laboratory specimens before the appropriate mix design of CRM-HMAC can be determined. Occasionally, the mix design using laboratory-prepared mixes differs from the mix design using plant-produced mixes.

The CRM-HMAC mixes that perform well in the field often fail the Hamburg Wheel Tracking Device (HWTD) tests as specified in Tex-242-F. Another commonly specified test to evaluate the performance of the CRM-HMAC mixes is the static creep test (Tex-231-F). The static creep test has questionable repeatability. In addition, the specimens for the test method Tex-232-F are prepared with the Texas Gyratory Compactor (TGC). However, the new mixture performance tests including the HWTD are carried out on specimens prepared with the Superpave Gyratory Compactor (SGC).

In view of the above discussion, it can be concluded that the CRM-HMAC mix design procedure (Tex-232-F) needs to be modified to reduce the specimen preparation time, to streamline the specimen preparation and handling process, to ensure that mix design based on plant mixes or laboratory prepared specimens are similar, and to include the SGC device in the specimen preparation.

1.2 Research Objective and Scope

The main objective of this study is to evaluate and modify the existing Tex-232-F procedure. The main purpose of this evaluation and modification is: to streamline the existing procedures and to eliminate the discrepancy between the mix design of the laboratory-prepared and plant-produced CRM-HMAC mixes. The streamlining effort includes reducing the number of specimens required for determining the appropriate proportions of the aggregates and CRM. To minimize the discrepancy, the various components of the mix design procedure are evaluated and modified. The mix components that are focused on include the crumb rubber and asphalt cement blending procedure, the measurement of the specific gravity and gradation of fine material, the appropriate mixing and compaction temperatures of the CRM-HMAC, the handling of specimens after compaction, and the inclusion of the SGC in the process of proportioning the aggregates and CRM.

To achieve the objectives of this study, two different mixes were studied. A material consisted of Rankin screener was used to determine the best way to modify the test method Tex-232-F. In addition, another material consisted of Balmorhea screener was used to ensure that the modifications to the Tex-232-F procedure were applicable to other materials.

1.3 Organization of the Report

Problem statement, research objective and organization of the report are presented in this chapter. In Chapter Two, the background information and research approach is presented. The results of various parameters evaluated are included in Chapter Three. The summary and conclusion are included in Chapter Four.

CHAPTER 2 BACKGROUND

2.1 Introduction to Crumb Rubber System

To better understand the crumb rubber hot mix asphalt concrete, it is essential to know about the contents of the crumb rubber (CRM) and how it is manufactured. Thus, a brief introduction is reproduced herein from USDOT/FHWA Report No. FP25.

> *Tire rubber, the principal component of CRM, is primarily a composite of natural rubber, synthetic rubber, and carbon black. Historically, passenger tires contained approximately 20 percent natural and 26 percent synthetic rubber, whereas truck tires contained approximately 33 percent natural and 21 percent synthetic rubber. Industry sources today indicate that passenger car tires typically contain approximately 16 percent natural and 31 percent synthetic rubber, whereas truck tires contain approximately 31 percent natural and 16 percent synthetic rubber. (7 Other sources of raw material for CRM include peel from over-the-road vehicles and buffings (a by-product of the retreading process).*
>
> *Raw material may be delivered to the processing plant as whole, cut, or shredded tires or buffing waste; the form depends on the capabilities of the processing plant. Whole tires require the least amount of preprocessing but are bulky and limit shipping capacity. Tires that have been minimally processed (typically cut, split, or sectioned, improve handling and shipping. Shredded tire rubber approximately 150 mm (6 in.) square is the preferred form of raw material for producing CRM. Buffing waste, because of its small size and generally high quality, is typically diverted to other rubber manufacturing processes. The quality of the raw material is a critical factor in producing a "quality" CRM and is inevitably the responsibility of the CRM processor.*
>
> *Although there are several methods for processing scrap tires, the primary goal of each is to reduce the size (Figure 2) and separate the steel belting and fiber reinforcing from the rubber. Processing scrap tires into CRM may generally be divided into two general categories: ambient grinding/granulating and cryogenic grinding.*
>
> *As the name implies, ambient grinding/granulating involves tearing and shearing at room temperature. The ambient process consists of a series of crackermills or granulators, screeners, conveyors, and various types of magnets to remove steel as necessary. A schematic of a typical crackermill grinding system is shown in Figure 2. The crackermill process is currently the most common and productive method of producing CRM. The end product is usually an irregularly shaped particle with a large surface area, varying in size from 4.75 mm (0.187 in.) to 0.425 mm (0.017 in.) (i.e., the No. 4 to No. 10 sieves). These particles are*

typically referred to as ground CRM. The granulator produces a cubical, more uniformly shaped particle with lower surface area over a range of sizes, usually from 9.5 mm to 2 mm (i.e., 3/8 in. to No. 10 sieves), called granulated CRM. Micro-milling, also an ambient and sometimes slurry process, yields finely ground particles ranging in size from 425 microns to 75 microns (i.e., No. 40 to No. 200 sieves).

Cryogenic grinding (or separation) is accomplished at extremely low temperatures (-87°C to -198°C, -125°F to -325°F) by submersing the scrap tire rubber in liquid nitrogen. Below the glass transition temperature (-620°C, -800°F) the rubber is very brittle and easily fractured in a hammer mill to the desired size. Reportedly, the surface is glasslike, and thus has a much lower surface area than ambient ground CRM of similar gradation.

FIGURE 2 Crumb Rubber Produced Using Ambient Grinding

CRM improves the performance of hot-mix asphalt concrete (HMAC) as well as allows the recycling of a waste product. The main advantage of the CRM is that it improves the rutting resistance of the mix at higher temperatures without increasing the stiffness at lower temperatures. The process of mixing CRM in asphalt cement and mix design procedure followed by TxDOT are summarized in the following section.

2.2 Test Method Tex-232-F, Mixture Design Procedure for Crumb Rubber Modified Asphaltic Concrete

Test method Tex-232-F is a mixture design procedure for the HMAC containing CRM. The procedure provides information about the selection of optimal aggregate gradation, the blending of asphalt with CRM, and the selection of appropriate binder content based on volumetric analysis.

The test procedure (Tex-232-F) is included in Appendix A for reference purposes. The procedure can be divided into three sections. In the first section, the aggregate gradation is optimized to maximize the voids in mineral aggregates (VMA). The second section details the preferred method of mixing CRM with the asphalt cement. In the third section, the mixing and compaction of the blended CRM with aggregates are presented. In addition, it outlines the procedure for obtaining the optimal gradation and asphalt content that allows molding of specimens to 3% air void or voids in total mix (VTM). A brief discussion of each section is presented in the following paragraphs.

In the first section (optimization of gradation), the representative sample of proposed aggregates is obtained and sieve analysis is performed using test method Tex-200-F. The absorption and bulk specific gravity of the aggregates are also determined using test method Tex-201-F. After finding the gradation and specific gravities, an initial trial gradation is used by maintaining a ratio of 1.5 and 2.0 between the two coarsest sieves on which the aggregates are retained. For example, the initial gradation (shown in Column 2 of Table 1) yields a ratio of 1.67 (50/30) for the two coarsest sieves used. In addition, the procedure suggests maintaining an 80/20 ratio between the coarse and fine aggregate components. The procedure then suggests obtaining the grading factor for each sieve depending on the size of aggregates as per the following equations:

$$Grading\ Factor\ Coarse\ Aggregate = \frac{individual\ \%\ retained\ on\ each\ sieve}{total\ \%\ retained\ on\ 2.00mm\ (No.10)\ sieve} \tag{2.1}$$

$$Grading\ Factor\ Fine\ Aggregate = \frac{individual\ \%\ retained\ on\ each\ sieve}{total\ \%\ \text{passing}\ 2.00mm\ (No.10) - 60\%} \tag{2.2}$$

An example of grading factors obtained for each sieve is shown in Column 3 of Table 1. After obtaining the grading factors, the neat asphalt and aggregates are mixed (as per test method Tex-205-F) with 4% asphalt content for the following coarse-to-fine aggregates ratios (percent retained on No. 10 divided by percent passing No.10): 85/15, 80/20, 75/25, 70/30, 65/35, and 60/40. The specimens should be molded (as per test method Tex- 206-F) for each coarse-to-fine aggregate ratio to determine the specific gravity of the compacted specimens (G_{mb}). In addition, loose mixes are used to obtain the maximum theoretical specific gravity (G_{mm}) of the mix using test method Tex-227-F. The measured specific gravity of the compacted specimens (G_{mb}) is divided by the G_{mm} to determine the relative density of the molded specimens. The average volumetric proportion of the aggregates retained on the 2.00 mm (No. 10) sieve for each set of molded specimens is plotted against the corresponding relative density, as shown in Figure 3.

The proportion of the coarse aggregates that yields the maximum density plus 2.5% is used to determine the optimum asphalt content, as explained in the third section. For example, the appropriate proportion of the coarse aggregates is 62.5% (60% plus 2.5%) in Figure 3.

TABLE 1. Evaluation of Various Coarse to Fine Aggregate Ratios to Identify Optimal Gradation

Sieve Size	Initial Gradation	Grading Factor	% Retained on 2.00 mm (No. 10)/% Passing 2.00 mm (No. 10)					
			60/40	65/35	70/30	75/25	80/20	85/15
12.5 mm - 9.5 mm (1/2 in. - 3/8 in.)	0							
9.5 mm - 4.75 mm (3/8- No.4)	50	50/80 = 0.625	37.5	40.6	43.8	46.9	50	53.1
4.75 mm- 2.00 mm (No. 4 - No. 10)	30	30/80 = 0.375	22.5	24.4	26.3	28.1	30	31.9
2.00 mm - 0.425 mm (No. 10 - No. 40)	10	10/(20-6) = 0. 714	24.2	20.8	17.1	13.6	10	6.4
0.425 mm - 0.180 mm (No. 40 - No. 80)	2	2/(20-6) = 0.143	4.9	4.1	3.4	2.7	2	1.3
0.180mm - 0.075 mm (No. 80-No. 200)	2	2/(20-6) = 0.143	4.9	4.1	3.4	2.7	2	1.3
Passing 0.075 mm (No. 200)	6	N/A	6	6	6	6	6	6
TOTAL	100		100	100	100	100	100	100

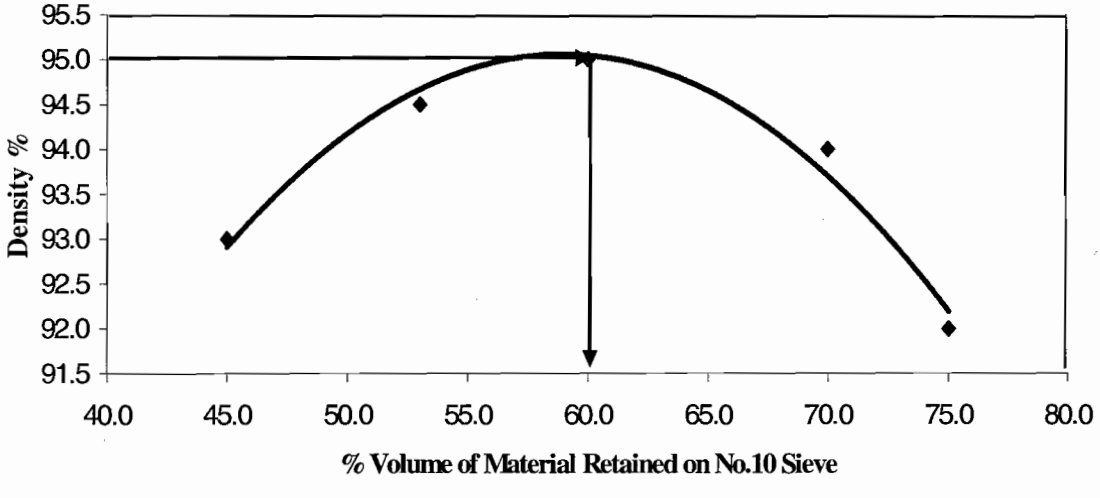

FIGURE 3 Relative Density versus % Volume of Material Retained on No. 10 Sieve

This process requires the preparation of 24 specimens (18 for the G_{mb} and 6 for the G_{mm} measurements) to just identify the appropriate gradations. This exercise is cumbersome and time consuming; therefore, needs to be modified.

Second section deals with the blending of the CRM with the asphalt. The test method Tex-232-F suggests manually blending the CRM and asphalt cement for about an hour at a temperature of 375 °F. At the end of the blending process, the physical properties (such as the penetration, viscosity, etc.) of the CRM blend are measured to ensure that the blend meets the Item 300 specifications. The temperature and the method of mixing (manual or mechanical) of the CRM into the asphalt cement play an important role in the physical properties of the blended CRM. It is quite possible that the blend produced at the asphalt plant is heated to a different temperature in comparison to the laboratory blend. This matter could contribute to the discrepancy between the performance of the laboratory-produced and plant-produced mixes. Therefore, the influence of the blending method and temperature need to be evaluated as well.

The third section explains the procedure for obtaining the optimal aggregate blend and asphalt content. For the initial estimate, the initial volume of aggregates should be 80% and the voids in mineral aggregates (VMA) 20% (Figure 4). Since the air voids of the molded specimens are supposed to be 3%, the volume of binder should be 17% (VMA minus air voids). Similarly, the volume of the fine aggregates is 80% minus the volume of coarse aggregates as shown in Figure 3. The weights of the aggregates and asphalt and their percentages are estimated using the specific gravities.

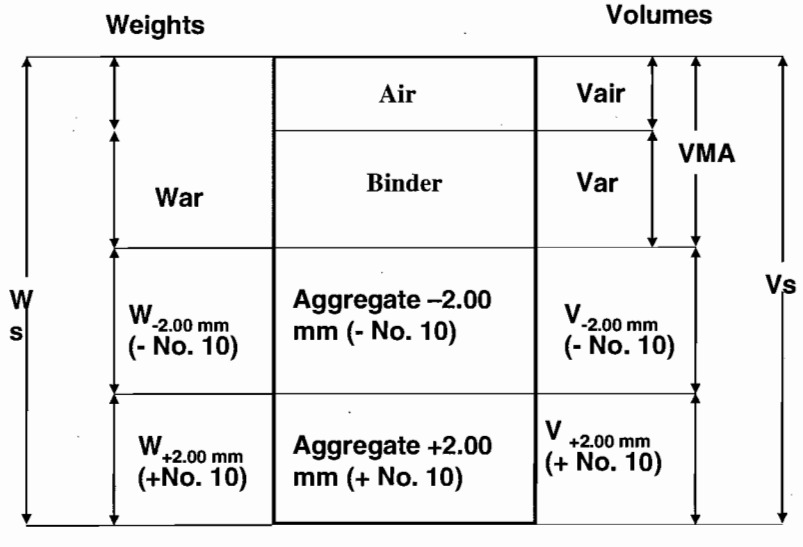

FIGURE 4 Volumetric Analysis of Molded Specimens

After the initial selection of the asphalt content and gradation, the procedure explains how to mix and compact the blended CRM with the aggregates. The aggregates are heated and maintained at 375 °F before mixing with the CRM blend. The mixing and compaction of the specimens are performed using test procedures Tex-205-F and Tex-206-F, respectively. A recent study (Turner Fairbanks Highway Research Center, http://www.tfhrc.gov/hnr20/recycle/waste/st2.htm) suggest that the temperatures of the CRM-HMAC blend at the time of mixing and compaction influence the compactability of the CRM-HMAC mixes; hence, the influence of mixing and compacting temperatures should be evaluated further.

To determine the optimal gradation and asphalt content that can provide a 97% relative density, the following steps have been proposed in the procedure:

1. The G_{mb} of the specimen molded using the initial estimate of the asphalt content and aggregate gradation is measured. If the relative density of the compacted specimen is 97 ± 0.2% for the selected asphalt content and gradation, performance-related tests, such as static creep test (Tex-231-F) or Hamburg Wheel Tracking test (Tex-242-F) are performed on it.

2. If the density of the compacted specimens is greater than 97.2 %, the percent volume of the coarse aggregates (retained on No.10 sieve) is increased by 5% and the percent volume of the fine aggregates (passing No.10 sieve) is decreased by 5%. A new set of specimens is molded and the density is measured. A plot between the measured density and the volume of the coarse aggregates is developed, as shown in Figure 5. The optimal volume of the coarse aggregates is determined by interpolating or extrapolating between the two data points. For example, the volume of the coarse aggregate required for a 97% relative density is 65% for the example shown in Figure 5. Therefore, the volume of the fine aggregates should be 15%. A new set of specimens can be prepared using this updated gradations and Step 1 can be followed.

3. If the density of the initial compacted specimens is less than 96.8%, the volume of the binder should be increased by 2% and the volume of the fine aggregates should be reduced by 2%. A plot between the measured density and the percent volume of the binder is developed as shown in Figure 6. The optimal binder content is obtained by interpolating or extrapolating between the two data points. For example, the volume of the binder required for a 97% relative density is 18% in Figure 6. A new set of specimens should be molded using the updated gradation and asphalt contents, and Step 1 should be repeated.

Some additional concerns should also be considered. For instance, the mixes with Rhyloite aggregates may not have similar affinity to water and asphalt. Since the mix design is based on the water absorption of the aggregates, it is quite possible that it can attribute to the discrepancy between the plant-prepared and the laboratory-prepared specimens. Also, the handling of the specimens after compaction is of concern. Typically, specimens containing the CRM expand after compaction which can lead to an erroneous estimate of the VTM.

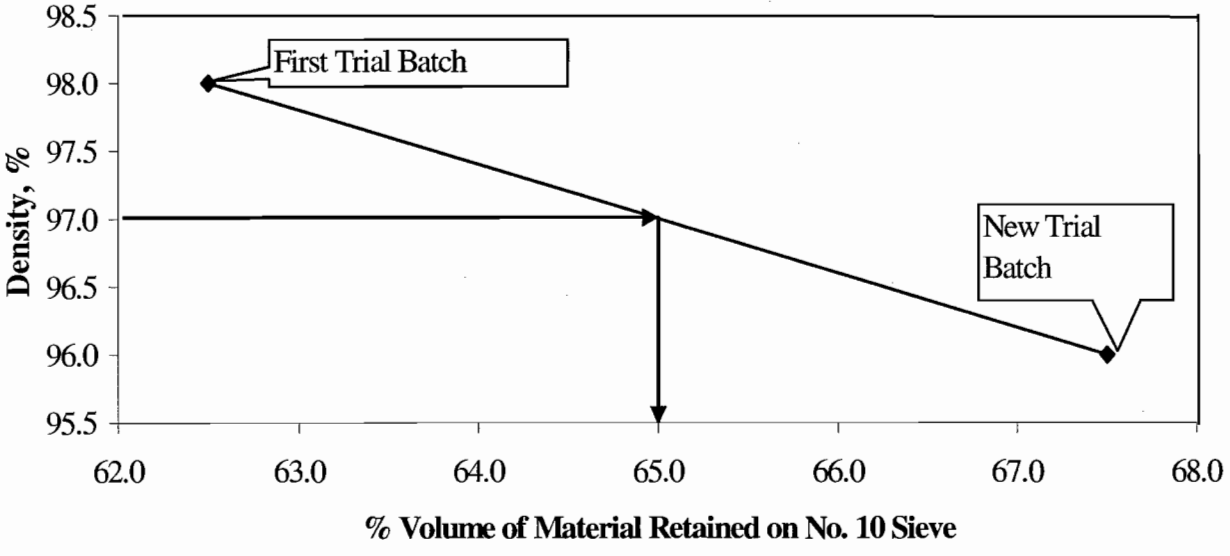

FIGURE 5 Relative Density versus Volume of Material Retained on No. 10 Sieve for New Mix Design

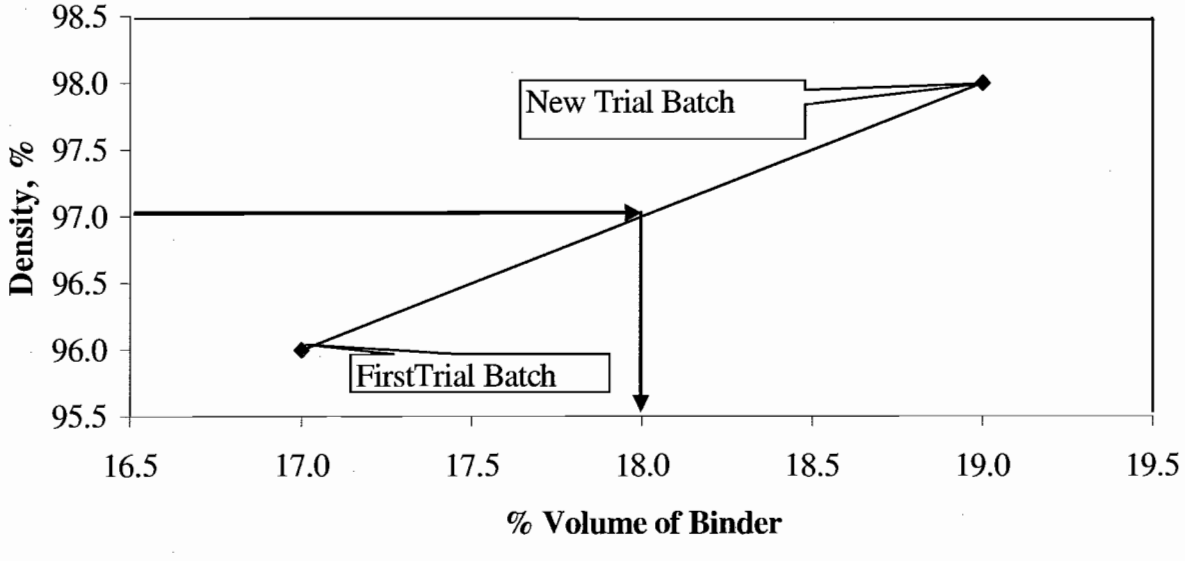

FIGURE 6 Relative Density versus % Volume of Binder

Typically, the CRM-HMAC specimens of 4 in. diameter and 2 in. height are prepared using the Texas Gyratory Compactor (TGC). However, the new performance tests including the Hamburg Wheel Tracking Device (HWTD) tests are performed on specimens prepared using the Superpave Gyratory Compactor (SGC). Since one of the objectives of this research is to include an appropriate performance test in the final mix design, it is essential that a procedure be developed to prepare the specimens using SGC with the appropriate number of gyrations.

Based on the above discussion, the following six items related to test method Tex-232-F should be further studied.

1. Streamline the cumbersome procedure for estimating the appropriate aggregate proportions.
2. Improve the measurement of the specific gravities and absorption.
3. Improve the blending method of the CRM and asphalt cement.
4. Evaluate the mixing and compaction temperatures of the CRM blend and aggregates,
5. Improve the handling of the specimens after compaction.
6. Incorporate the SGC in the preparation of the CRM-HMAC specimens.

Before conducting any experiments, a literature search was carried out to identify any suggested solutions to the items summarized above. The relevant information is summarized in the following sections.

2.3 Optimum Gradation Steps

To reduce the cumbersome steps required for optimizing the aggregate proportioning, the specifications from other state highway agencies were reviewed. The California Department of Transportation (CALTRANS, 2003) does not recommend the use of the CRM in the dense graded mixtures because of the insufficient void space. The Arizona DOT and South Carolina DOT made similar recommendations. However, none of them had process similar to the one specified in the test method Tex-232-F. Therefore, an experimental study is carried out here to document the benefits of the current procedure in obtaining the optimum gradation steps, and to come up with ways to optimize the steps.

2.4 Particle Size Analysis

Typically, the maximum amount of aggregates passing No. 200 sieve (fine content) is specified. However, the gradation of the fines is neither specified nor evaluated. It is quite possible that the gradation of the materials passing the No. 200 sieve can influence compactability of the mixes because the fines typically become part of the asphalt and may increase the stiffness of the binder. Therefore, it was decided to perform particle analysis test on the fines using Tex-238-F procedure to document any unusual observation determine.

2.5 Absorption and Specific Gravity of Aggregates

One of the reasons for the discrepancy between the field performance and lab results can be attributed to the mis-estimation of the absorption and specific gravity of the aggregates, as observed with the Rhyolite aggregates used by the Odessa District. The CRM-HMAC prepared with this aggregate performs well in the field even though the laboratory mix designs from such aggregates do not meet the specifications. This specific aggregate is vulcanized granite, very strong, and highly porous. Although it has large affinity to water, it may not have the same affinity to the asphalt cement. The mix design calculations based on the water absorption could be the reason for the discrepancy between the performance of the plant-prepared and laboratory-prepared specimens.

The two commonly used methods for measuring the absorption and specific gravity of the aggregates are the AASHTO T 84 and ASTM C 128. Both test procedures are similar to the TxDOT method with a few exceptions, as shown in Table 2. These methods use a cone and a tamp to determine the saturated surface dry (SSD) condition of aggregates. This process may not work well for angular or rough fine aggregates because they do not readily slump (Prowell and Baker, 2004). With the TxDOT method, the SSD condition is determined by observing the change in the color of the aggregates, which is subjective in nature. Recently, two automated devices (SSDetect and Corelok) have been evaluated by Prowell and Baker (2004). The SSDetect uses an infrared light source and detector to determine when the fine aggregates have reached the SSD condition. The Corelok device uses a combination of a calibrated pycnometer (Figure 7) and a vacuum sealing device to determine the specific gravities and absorption of the aggregates (see Table 2).

Prowell and Baker (2004) conducted tests on six different materials to see whether these two automated methods provide more precise results as compared to the AASHTO T 84 method. The statistical information for the specific gravity and absorption for six different materials are summarized in Tables 3 and 4, respectively. The results suggest that the SSDetect offers better precision as compared to the AASHTO T 84 procedure; however, the precision of the Corelok is not as high as the SSDetect (Prowell and Baker, 2004).

To address the issue of higher affinity to water as compared to oil for some aggregates, the California kerosene equivalent (CKE) method (California Test 303, 2000) was identified as a tool to be used because it uses oil (Kerosene) rather than water to find absorption.

Since UTEP owns the Corelok and CKE device, it was decided to perform bulk specific gravity tests using these devices in addition to the test method TxDOT (Tex-201-F) to document if any benefit is gained by changing the test procedure.

2.6 Asphalt Rubber Blend

The performance of the CRM-HMAC significantly depends on the quality of the asphalt rubber blend. The review of literature (Bahia and Davies, 1995) and discussions with the practitioner's (MACTEC, 2002) indicated that the quality of the blend depends on three components: the

physical properties of the CRM, the percentage of the CRM added to the neat asphalt cement, and the method and temperature of mixing the CRM with the neat asphalt cement. Although the quality of the asphalt cement can also influence the properties of the produced CRM blend, it deemed to be beyond the scope of this study. The CRM in added to the HMAC in two ways. In one method known as the wet process, the CRM is mixed with the neat asphalt. In the other method, known as dry process, the CRM is added to the aggregates. Again, TxDOT specifies only wet process; therefore, dry process is not discussed further.

TABLE 2. Comparison of Absorption and Specific Gravities Method

AASHTO T 84	TxDOT	Corelok (Figure 7)	CKE
• Method to find the water absorption values. • *Apparatus*: Pycnometer, Cone, Tamp, scale. • Need to soak sample in water for 15 to 19 hours. • Determining the SSD condition of the sand using the cone test.	• Method to find the water absorption values. • *Apparatus*: Pycnometer, scale. • Need to soak sample in water for 24±2 hours. • Determining the SSD condition by comparing the color of sample.	• Method to find the water absorption values. • *Apparatus*: Volumeter, plastic bags, Rubber sheets, Corelok vacuum machine, scale. • Oven dry sample for minimum of 24 hours at 220°F. • No need to find the SSD condition.	• Method to find the oil absorption values. • *Apparatus*: Centrifuge, Centrifuge cups, metal funnel, Kerosene, scale. • Oven dry sample for minimum of 24 hours at 220°F. • No need to find the SSD condition.

TABLE 3. Specific Gravity Test Results Using Different Methods (Prowell and Baker, 2004)

Material**	Corelok	SSDetect	T84	Corelok	SSDetect	T84
	Average	Average	Average	Standard Deviation	Standard Deviation	Standard Deviation
A	2.291	2.314	2.326	0.0323	0.0361	0.0363
B	2.923	2.909	2.881	0.0222	0.0110	0.0319
C	2.893	2.880	2.881	0.1114	0.0138	0.0531
D	2.723	2.811	2.831	0.0542	0.0245	0.0380
E	2.532	2.495	2.525	0.0473	0.0185	0.0223
F	2.539	2.531	2.547	0.0194	0.0161	0.0210

TABLE 4. Absorption Test Results Using Different Methods (Prowell and Baker, 2004)

Material**	Corelok	SSDetect	T84	Corelok	SSDetect	T84
	Average	Average	Average	Standard Deviation	Standard Deviation	Standard Deviation
A	6.7	5.6	4.8	0.43	0.65	0.79
B	0.6	0.7	1.4	0.28	0.11	0.35
C	0.8	1.1	1.4	0.57	0.13	0.61
D	2.8	1.4	1.0	0.34	0.27	0.32
E	2.0	2.3	1.8	0.42	0.29	0.27
F	2.0	1.8	1.7	0.50	0.28	0.28

*** A → Lime rock, B → Washed Diabase, C → Diabase, D → Slag, E → Rounded Natural (uncrushed) Sand, F → Angular Natural (uncrushed) Sand*

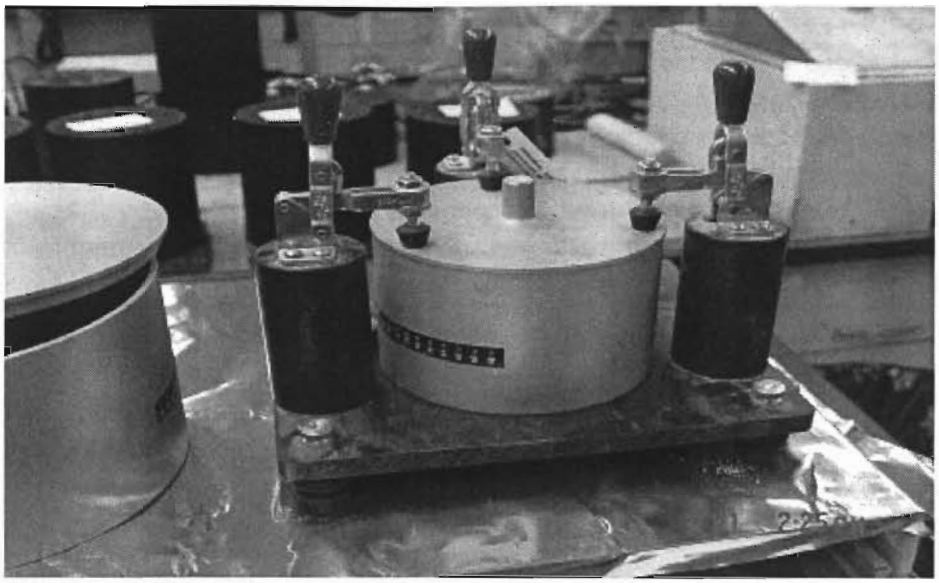

FIGURE 7 Corelok Device for Specific Gravity and Absorption Measurements

Test method Tex-232-F suggests mixing the crumb-rubber manually with the asphalt at 375 °F for one hour. The CRM is added in the neat asphalt (maintained at a temperature of 375 °F) and mixed manually using handheld laboratory stirrer. After mixing, it is placed in an oven maintained at 375 °F for half an hour. Again, the mix is manually stirred for five minutes and placed in the oven for an additional half an hour. As per MACTEC (2002), to meet the CALTRANS specifications a mixing temperature of 420 °F is used, and to meet the Arizona DOT specifications a temperature of 400 °F is necessary. Although TxDOT specifies a temperature of 375 °F, PaveTex Engineering and Testing, Inc. suggest heating the asphalt cement to 375 °F and adding the CRM to the heated asphalt. The mixture is stirred manually and placed in the oven maintained at 350 °F rather than 375 °F.

A study conducted by Bahia and Davies (1995) suggested mixing the rubber in asphalt using a low-shear mixer at a mixing speed that ranged between 2,000 rpm to 2,500 rpm, at a constant temperature 320 ± 5 °F (160 ± 5°C) for one hour.

CALTRANS (2002) specify the ranges for particular physical properties of the CRM blend as shown in Table 5. Table 6 describes the required properties for three CRM blend types as per Item 300. Type I or Type II, containing the CRM Grade C, is used for HMAC. Type II or Type III, containing the CRM Grade B, is used for surface treatment.

The time gap between the preparation of the CRM blend and the preparation of the CRM-HMAC specimens could influence its properties. The properties of asphalt rubber blend may meet the specifications provided in Tables 5 and 6 at the time of mixing the CRM with asphalt cement. However, it may not meet the specifications at the time of mixing with aggregates due to overheating. To keep the CRM blend within the specifications at the time of mixing with

aggregates, TxDOT Special Specifications 3092 suggests that the CRM blend shall not be held at temperatures greater than 350° F for a period of more than eight hours. Maricopa County (2000) specifications suggest that the asphalt rubber should not be held at temperatures above 250 °F (121 °C) for more than four days. The review of information indicates that the blended CRM is highly unstable if maintained at higher temperature for longer duration. The review also suggests that if the CRM blend is subjected to more than two reheat cycles, then the CRM blend should be discarded.

In summary, the range of mixing temperature should be between 320 °F and 420 °F with duration of mixing of an hour. The blend must neither be kept at a higher temperature for longer duration nor be reheated more than two times. This discussion suggests that it would be better to mix the CRM with the asphalt on the same day on which the specimens are to be molded. In addition, the CRM blend is to be discarded if the CRM blend is not used within four hours of mixing.

TABLE 5. CALTRANS Specifications for CRM Blend

Test Performed	Minutes of Reaction					45 minutes Specification Limits
	45	90	240	360	1440	
Viscosity, Haake at 190°C, Pas, (10^{-3}), or cP	2400	2800	2800	2800	2100	1500-4000
Resilience at 25°C, % Rebound	27	--	33	--	23	18 minimum
Ring & Ball Softening Point, °C	59.0	59.5	59.5	60.0	58.5	52-74
Cone Pen. At 25°C, 150g, 5 sec, 1/10 mm	39	--	46	--	50	25-70

TABLE 6. Asphalt Rubber Binder Required Properties (ITEM 300)

Property	Binder Type					
	Type I		Type II		Type III	
	Min.	Max.	Min.	Max.	Min.	Max.
Apparent Viscosity @ 347 °F, cP	1,500	5,000	1,500	5,000	1,500	5,000
Penetration @ 25°C, 5 sec	25	75	25	75	50	100
Softening Point, °F	135	--	130	--	125	--

2.7 Preparation and Handling of CRM-HMAC Specimens

According to FHWA (http://www.tfhrc.gov/hnr20/recycle/waste/st2.htm), the temperature of the aggregates and CRM blend is crucial to the compactability of the mixes. The temperature drop during mixing is more significant and rapid for the CRM-HMAC mixes in comparison to the conventional mixes. Therefore, it would be appropriate to evaluate the influence of temperature on the mix compactability, and to suggest modifications to the compaction temperatures, if needed.

As per Kaloush (2004), the CRM-HMAC specimens expand after compaction inside the SGC mold horizontally as well as vertically. This expansion is minimal in the specimens prepared using the TGC because of the quantity of the CRM-HMAC material (approx. 2 lbs for the TGC versus 12 lbs for the SGC). The expansion of the specimen influences the level of air voids present inside the specimen. To prepare the specimens with 3% air voids or voids in total mix (VTM), a considerable number of gyrations are required using the SGC. Since the CRM-HMAC mix temperature drops rapidly, it requires more number of gyrations to compact the specimens to a specified VTM. The horizontal expansion can be contained if the specimen is removed from the mold 45 minutes after the specimen is compacted, and placed in a PVC mold as shown in Figure 8. To reduce the vertical expansion, Natu and Tayebali (1999) have suggested maintaining a stress of 600 kPa on the specimen after compaction. To achieve this stress, the emergency stop button of the SGC is pressed after the desired number of gyrations has been achieved. This step maintains the specified load on the specimen and minimizes the vertical expansion.

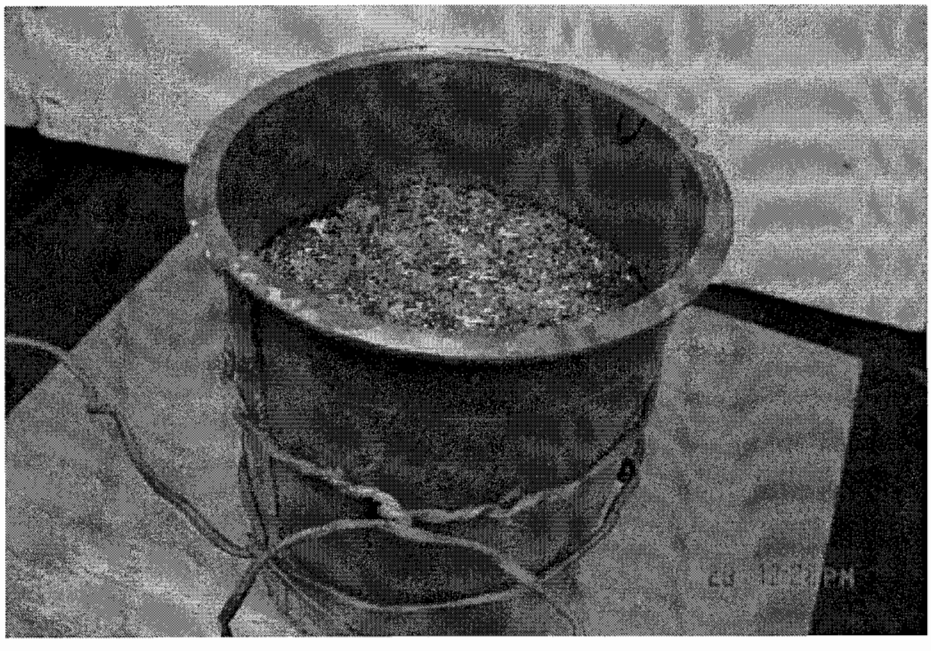

FIGURE 8 PVC Mold

CHAPTER 3 EVALUATION OF TEST METHOD TEX-232-F

To evaluate test method Tex-232-F, materials from two different mixes were supplied by the Odessa District. Both mixes consisted of the AC-10 neat asphalt, CRM and the coarse aggregate types from the same source. The main difference was the screener type. One mix was developed from the Rankin screener and the other set from the Balmorhea screener. Odessa District did not have any problems with the mix design with the Balmorhea screener but had significant problems with the mix design with the Rankin screener. The gradation of each aggregate type is shown in Figure 9 on a power 0.45 graph. In the remainder of this report, the two mixes are distinguished by the sources of the screener; namely Rankin (problem mix) and Balmorhea (reasonable mix).

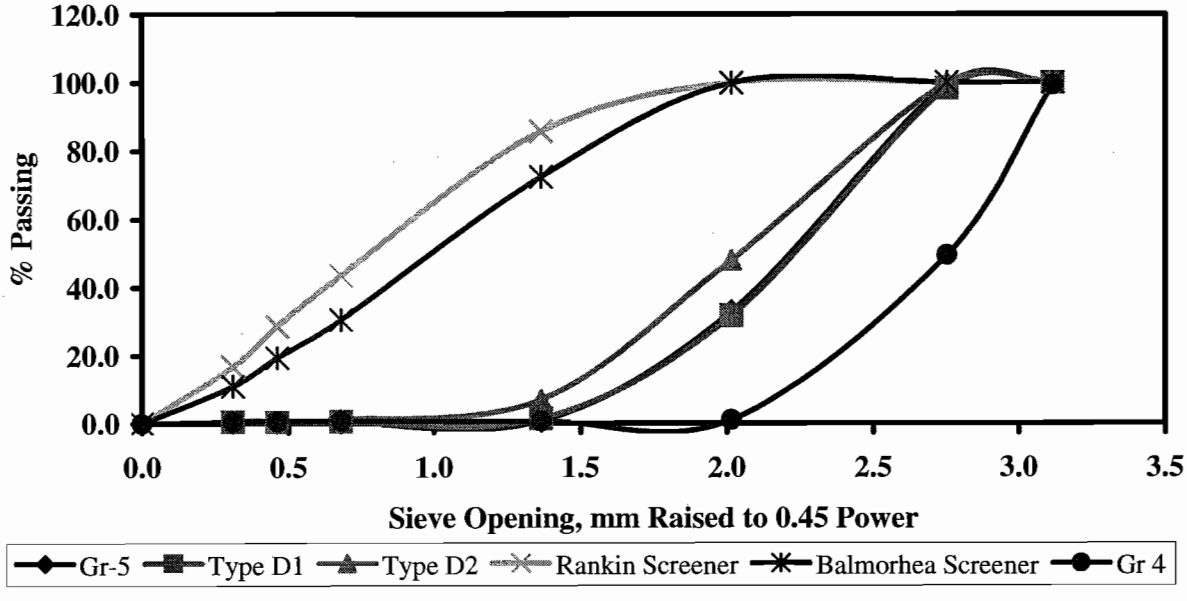

FIGURE 9 Sieve Analysis of Proposed Aggregates

3.1 Gradation Optimization Steps

As discussed previously, the aggregate optimization process is cumbersome. To simplify this process, it was decided to start with the example provided in the procedure to evaluate the benefits of the process.

In test method Tex-232-F, the first step is to blend the stockpiles such that the ratio between the two coarsest sieves on which the aggregates are retained is between 1.5 and 2.0. As explained in Chapter Two, this initial gradation is only used to determine the aggregate grading factors as shown in Table 1. To better understand these optimization steps, the gradations for various coarse-to-fine aggregate ratios are plotted in Figure 10. By changing the gradation from the 60/40 blend to the 85/15 blend, the gradation is becoming coarser between the # 4 and #40 sieve

sizes; thus, creating a gap graded blend. One of the advantages of a gap-graded mix is that it yields higher voids in mineral aggregates (VMA).

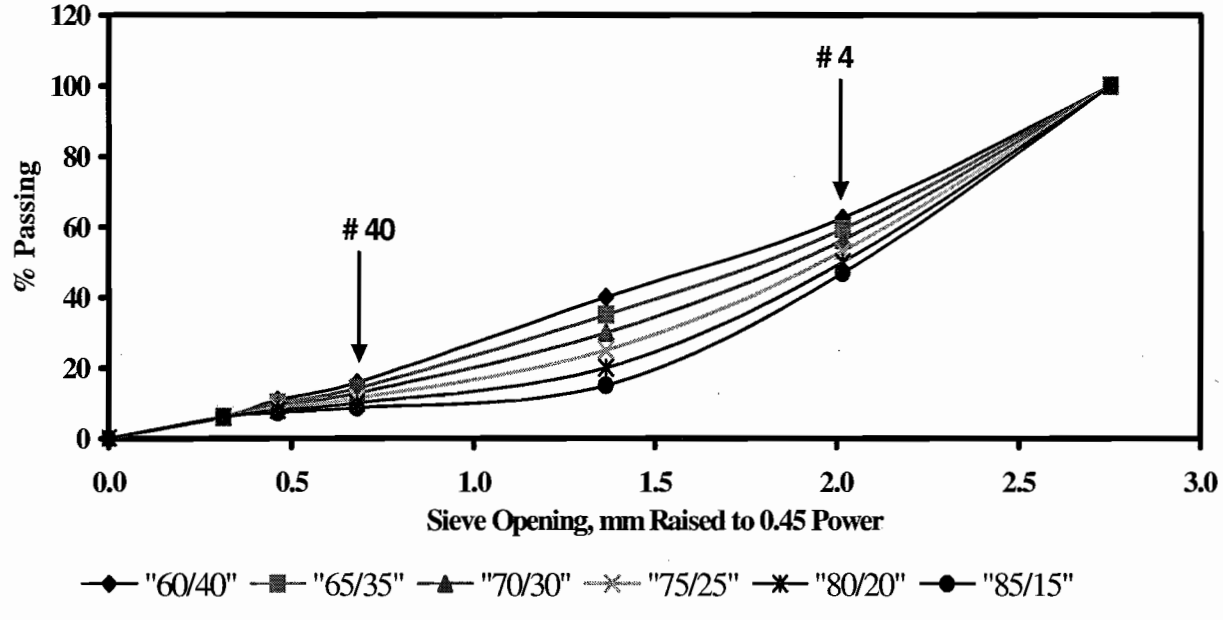

FIGURE 10 Shifting of Graph going from 60/40 to 85/15

In addition to the process proposed in Tex-232-F, the gradation should meet the limits recommended in SP 3092 and Item 346. These gradation limits, which are included in Table 7, are fairly similar with some differences in the sieve sizes specified. For example, SP 3092 specifies the limits for the No. 8 sieve while Item 346 specifies limits for the No.10 sieve. The maximum and minimum percent passing specifications from SP 3092, Item 346 and 85/15 gradations are plotted in Figure 11. The optimal gradation determined using grading factors should be within the gradation limits. For example, the blend gradation with coarse-to-fine aggregate ratios of 85/15 is within the specification envelopes; therefore, it is an acceptable optimal gradation.

To create a gap graded blend and to meet the gradation requirements of the SP3092 and/or Item 346, an optimization routine is implemented in an Excel sheet. The maximum and minimum gradation limits specified in SP 3092 and Item 346 are specified as constraints. The gradations of different lots are also entered as an input. Through an iterative process, the optimization tool determines the percentage of the materials from each lot so that the mix gradation is within the specification limits.

TABLE 7. Gradation Limits Specified in ITEM 346 and SP3092

Sieve	Percent Passing			
	Item 346		SP 3092	
	Minimum	Maximum	Minimum	Maximum
3/4	100	100	N/A	N/A
1/2	100	100	N/A	N/A
3/8	95	100	98	100
#4	40	50	40	50
#8	17	27	N/A	N/A
#10	N/A	N/A	15	25
#16	12	22	N/A	N/A
#30	8	20	N/A	N/A
#40	N/A	N/A	6	20
#50	6	15	N/A	N/A
#80	N/A	N/A	6	18
#200	5	9	4	8

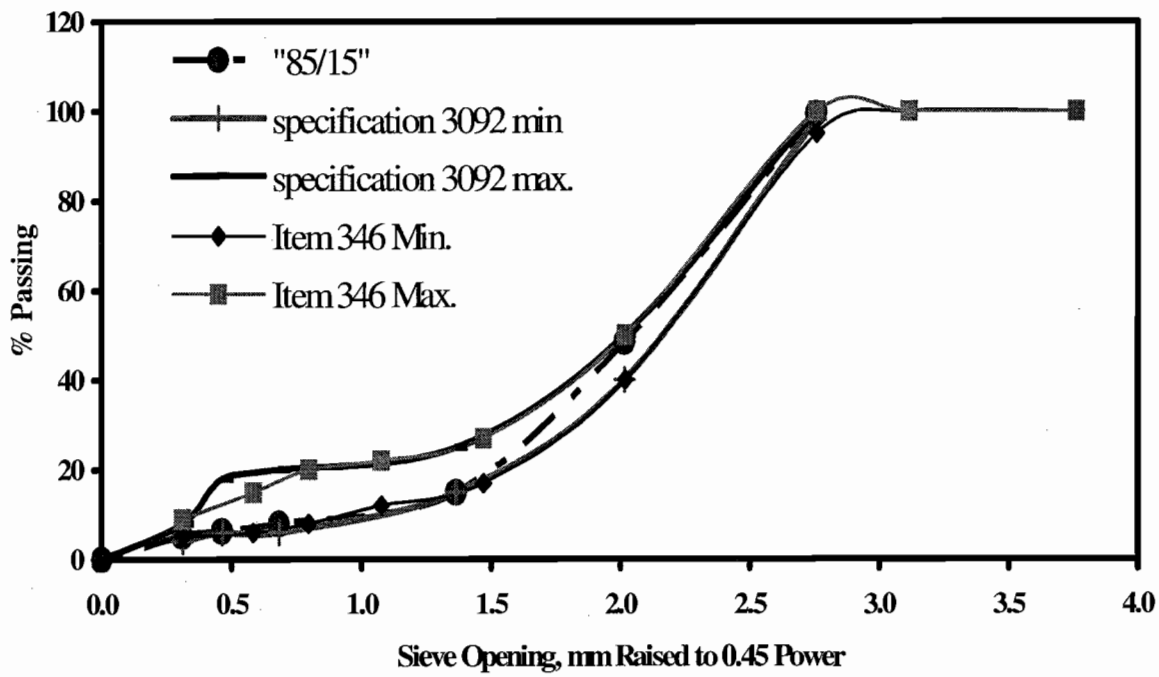

FIGURE 11 Specification Limits with Identified Optimal Gradation

As an initial verification, the gradations from the example provided in the Tex-232-F procedure were entered in the Excel sheet to identify the optimal blend gradation. The results from the three iterations needed are shown in Figures 12, 13 and 14 for the first, second and final iteration, respectively.

To demonstrate the benefits of using this analytical tool, the blend gradations of the Rankin and Balmorhea mixes obtained as per Tex-232-F are compared with the results from the excel sheet in Table 8. The gradations are almost identical from the two methods. The advantage of the analytical method is that the process of preparing 18 specimens is replaced with less than 2 minutes (after data entry) of the computation to identify the optimal gap graded blend. At that point, only two specimens (and loose mix for G_{mm} measurement) are needed to estimate the volumetric parameters presented in Figure 4.

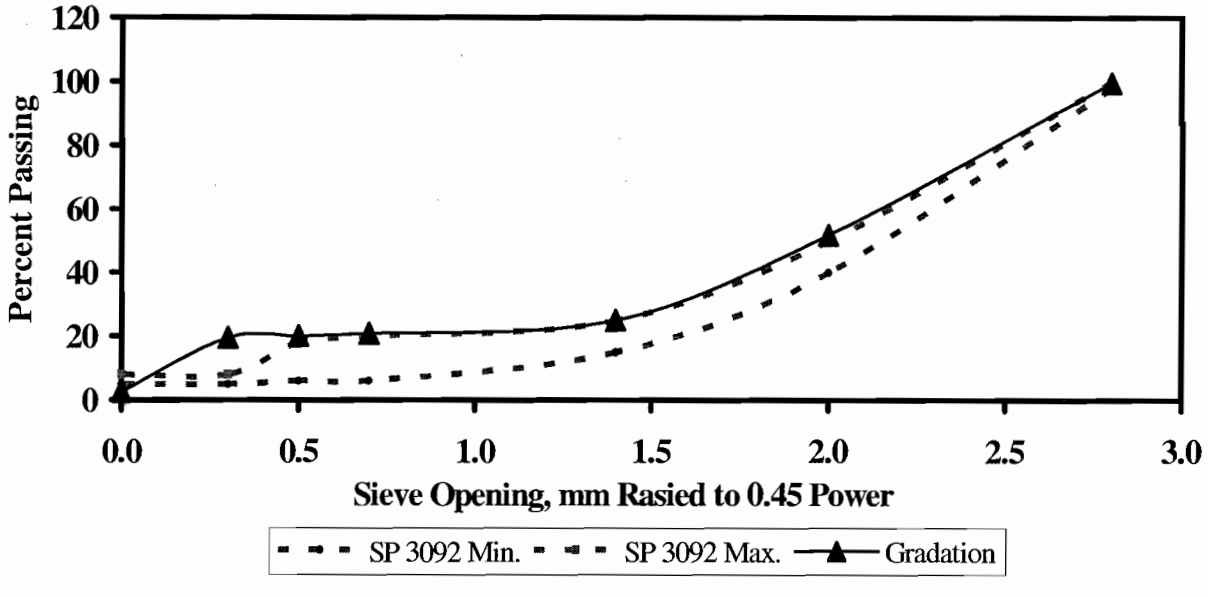

FIGURE 12 Blend Gradation After First Iteration

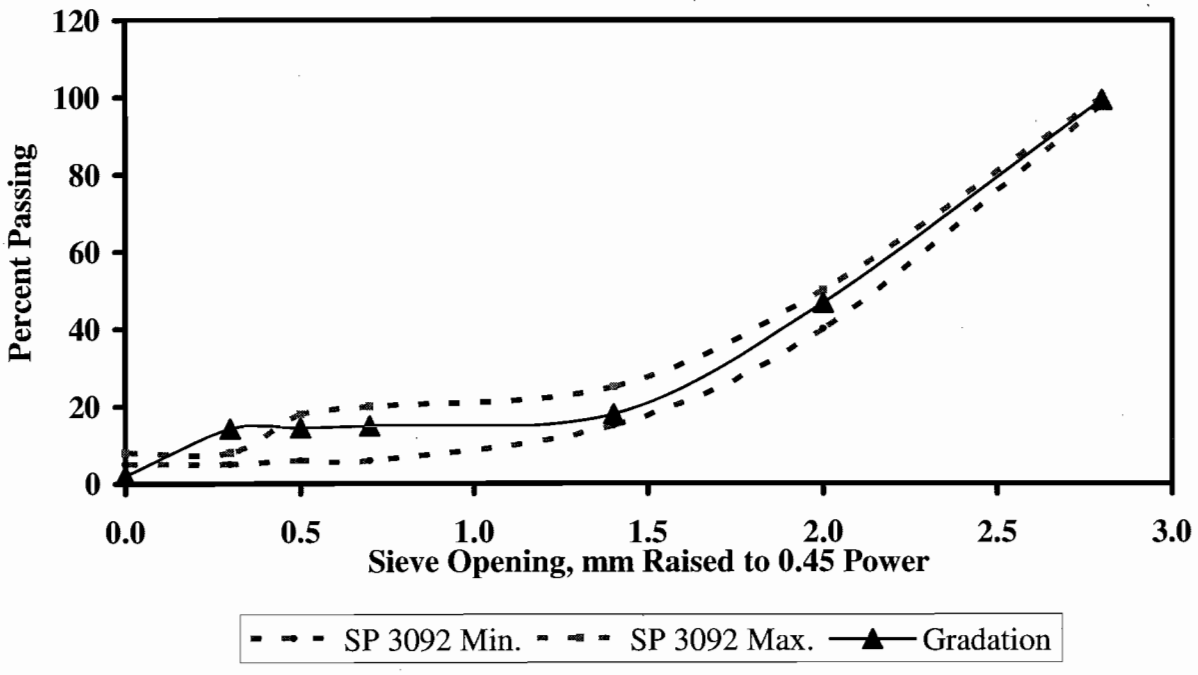

FIGURE 13 Blend Gradation After Second Iteration

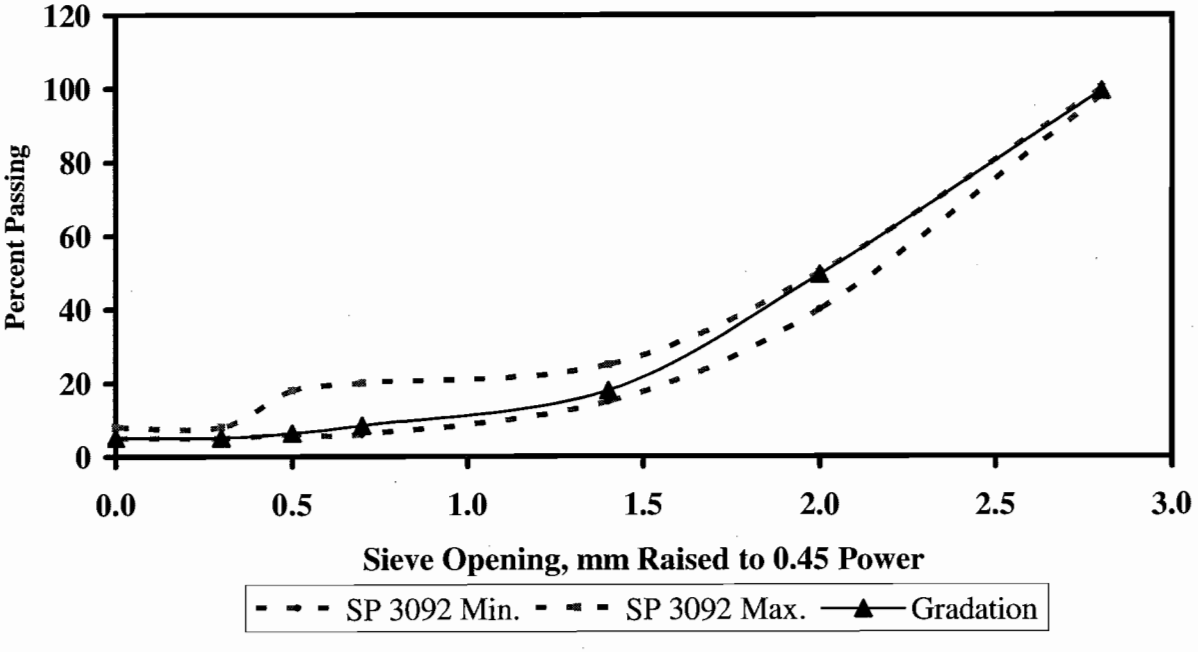

FIGURE 14 Blend Gradation After Final Iteration

TABLE 8. Gradation Obtained using Solver and Tex-232-F for Rankin Screener and Balmorhea Screener Mixes

Sieve Size	Percent Passing							
	SP 3092		ITEM 346		Material with Balmorhea Screener		Material with Rankin Screener	
	Minimum	Maximum	Minimum	Maximum	Analytical	TxDOT	Analytical	TxDO
3/4	100	100	N/A	N/A	100	100	100	100
1/2	100	100	N/A	N/A	100	100	100	100
3/8	95	100	98	100	99.4	99.3	99.4	96.9
#4	40	50	40	50	49.5	47.1	49.5	47.9
#8	17	27	N/A	N/A	-	-	-	-
#10	N/A	N/A	15	25	18	20.2	20.7	22.0
#16	12	22	N/A	N/A	-	-	-	-
#30	8	20	N/A	N/A	-	-	-	-
#40	N/A	N/A	6	20	8.4	9.0	10.7	10.8
#50	6	15	N/A	N/A	-	-	-	-
#80	N/A	N/A	6	18	6.3	6.1	7.5	7.5
#200	5	9	4	8	5.1	4.3	5	5.8

To further verify the benefits of using the Excel sheet, a Type D mix commonly used by the El Paso District was optimized. The variation in the relative density with the percent volume retained on No. 10 sieve using the test method Tex-232-F is shown in Figure 15. A maximum relative density of 84.8% can be observed at a relative volume of coarse aggregate of 57.5%. The gradation corresponding to this relative coarse aggregate volume is presented in Figure 16. The gradation curve is within the specification limits for the finer sieve sizes; however, it is out of bound for the coarser higher sieve sizes (especially for sieve sizes coarser than No. 4. The analytical optimized gradation from the excel sheet (Figure 16) is within the specifications throughout. This indicates that the analytical tool is more appropriate for optimizing the gradation while satisfying the gradation limits as compared to the method proposed in test method Tex-232-F. In terms of volumetric parameters, the optimized gradation obtained using analytical tool provides sufficient levels of VMA. This procedure should be incorporated in the modified specifications.

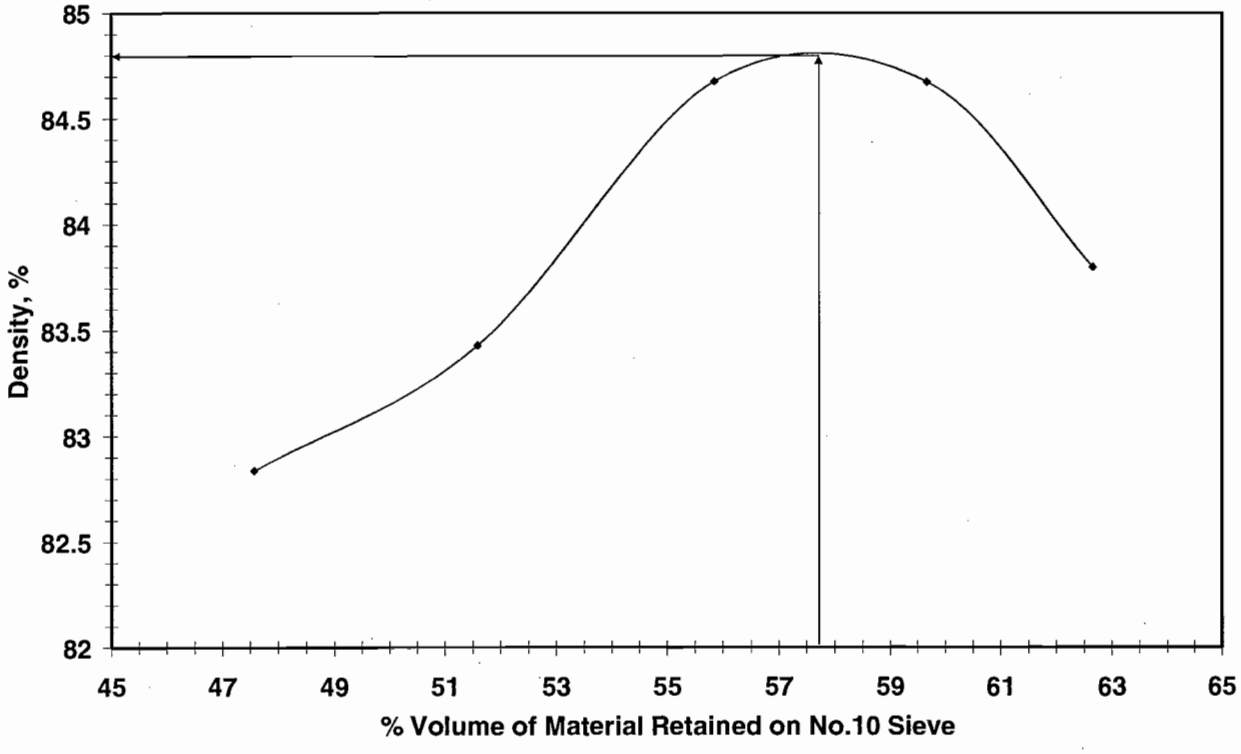

FIGURE 15 Relative Density vs. % Volume of Coarse Aggregate for Type D mix

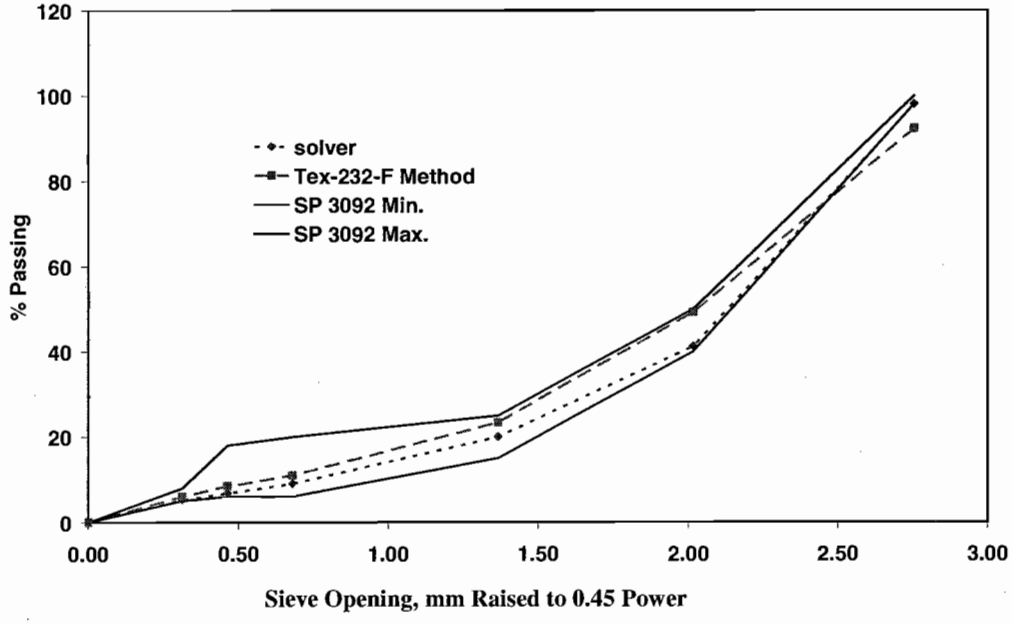

FIGURE 16 Gradation Obtained Using Solver and Tex-232-F Methods

3.2 Absorption and Specific Gravity of Aggregates

As mentioned in Section 2.2, test methods Tex-201-F, AASHTO T84, Corelok and CKE were selected to estimate the absorption and specific gravities of aggregates. The absorption and specific gravities estimated using these methods for the two mix types are summarized in Tables 10 and 11, respectively. Each test was repeated five times to determine the average values, the standard deviations, and the coefficients of variation.

From Table 9, the Corelok method generally provided the lowest absorption values followed by the AASHTO T84 test method. The CKE and Tex-201-F methods provided reasonably similar results for all aggregate types. This results are in concurrence with the results obtained by Prowell and Baker (2004) that the absorption values obtained using the Corelok are typically lower than those from the AASHTO T84 (see Table 4). The standard deviations varied from 0% for the CKE to 0.6% for the test method Tex-201-F. The CKE is the most repeatable test. For the other three test methods, the repeatability varied between different aggregate types. A clear trend could not be observed to identify which test is more appropriate.

TABLE 9. Aggregate Absorption Estimates Obtained Using Different Methods

Method	Statistical Parameters	Gr 4	Gr-5	Type D	Rankin Screener	Balmorhea Screener
Tex-201-F	Avg., %	2.4	1.9	2.4	7.7	7.0
	S.D.*, %	0.16	0.03	0.01	0.60	0.1
	COV+, %	6.8	1.7	0.3	11.0	3.6
AASHTO T84	Avg., %	1.9	1.9	2.1	4.6	3.6
	S.D., %	0.03	0.07	0.33	0.12	0.09
	COV, %	1.3	3.8	16.1	6.6	3.5
Corelok	Avg., %	1.1	1.3	1.4	3.8	2.6
	S.D., %	0.07	0.01	0.01	0.02	0.13
	COV, %	6.9	0.9	0.4	0.5	6.1
CKE	Avg., %	2.5	1.5	2.2	5.6	6.7
	S.D., %	0	0	0	0	0
	COV, %	0	0	0	0	0

* S.D. standard deviation
+ COV coefficient of variation

In terms of the bulk specific gravity (Table 10) the Corelok test method provided the highest specific gravities as compared to the Texas and AASHTO methods. For example, the Corelok method estimated the specific gravity to be 2.545 for the Gr 5 aggregate while test method Tex-

201-F estimated it to be 2.479. This trend is similar to that reported by Prowell and Baker (2004). In terms of repeatability, test method Tex-201-F is generally the least repeatable in comparison to the other two methods. In addition, the precision level is aggregate dependent. For example, a COV of 2.1% is observed for the Rankin screener while only a COV of 0.1% is observed for the Balmorhea screener for test method Tex-201-F. According to Prowell and Baker, the Corelok and AASHTO T84 exhibited similar levels of repeatability. The test results presented in Table 11 show similar trends. For example, the COV for Gr5 is 0.01% and 0.004% for AASHTO T84 and Corelok methods, respectively.

TABLE 10. Bulk Specific Gravity Estimates Using Different Methods

Method	Statistical Parameters	Gr 4	Gr-5	Type D	Rankin Screener	Balmorhea Screener
Tex-201-F	Avg., %	2.457	2.479	2.411	2.280	2.394
	S.D., %	0.003	0.01	0.04	0.05	0.00
	COV, %	0.1	0.05	1.8	2.1	0.10
AASHTO T84	Avg., %	2.471	2.400	2.465	2.288	2.432
	S.D., %	0.001	0.001	0.01	0.002	0.001
	COV, %	0.05	0.01	0.34	0.07	0.03
Corelok	Avg., %	2.541	2.545	2.547	2.470	2.537
	S.D., %	0.003	0.0001	0.001	0.008	0.008
	COV, %	0.11	0.004	0.06	0.34	0.32

Although the estimated absorption and specific gravities are method dependent, it is not clear which method is better in comparison to the other methods. Even though the Corelok method is less user dependent, the test results indicate that the Tex-201-F method can reasonably be used to estimate the specific gravities and absorptions. It can be concluded that test method Tex-201-F should be maintained in the procedure.

3.3 Particle Size Analysis

The two mixes selected for initial evaluation are from similar source except for the screenings. The so-called problem mix contained the Rankin screening, and the reasonable mix contained the Balmorhea screening. This indicated that the problem could be with the type of screenings used. The gradation curves presented in Figure 9 suggest that the Balmorhea screening is finer than the Rankin screening. Similarly, the Rankin screening exhibits a lower specific gravity and a higher absorption in comparison to the Balmorhea screening.

The presence of very fine particles in the screening can influence the levels of relative density of the compacted specimens. It is possible that similar diameter very fine particles may stick together (or form a chain) which may reduce the levels of relative density of the specimens. Laser Diffraction tests (test method Tex-238-F) were performed on materials passing the No. 200 sieve to further determine the gradation of the fines of the screenings. The results are presented in Figures 17 and 18 for the Balmorhea and Rankin screenings, respectively. The Rankin screening has a concentration of more than 10% of particle sizes within the range of 9 to 10 μm, whereas the Balmorhea screening's concentration in that range is typically less than 7%. It seems that the only factor that could influence the relative density of the compacted specimens is the presence of more than 10% particles in the 9 to 10 μm range. However, it is difficult to draw a definite conclusion on the basis of only two screenings. Therefore, test method Tex-238-F can be included as a method for evaluating the problem mixes in the future. In other words, if the estimated binder content is lower than 7%, test method Tex-238-F test should be performed to identify the particle distribution of screening passing the No. 200 sieve. If a significant percentage (say more than 10%) of very fine particles is present, the screener should be replaced with a different one.

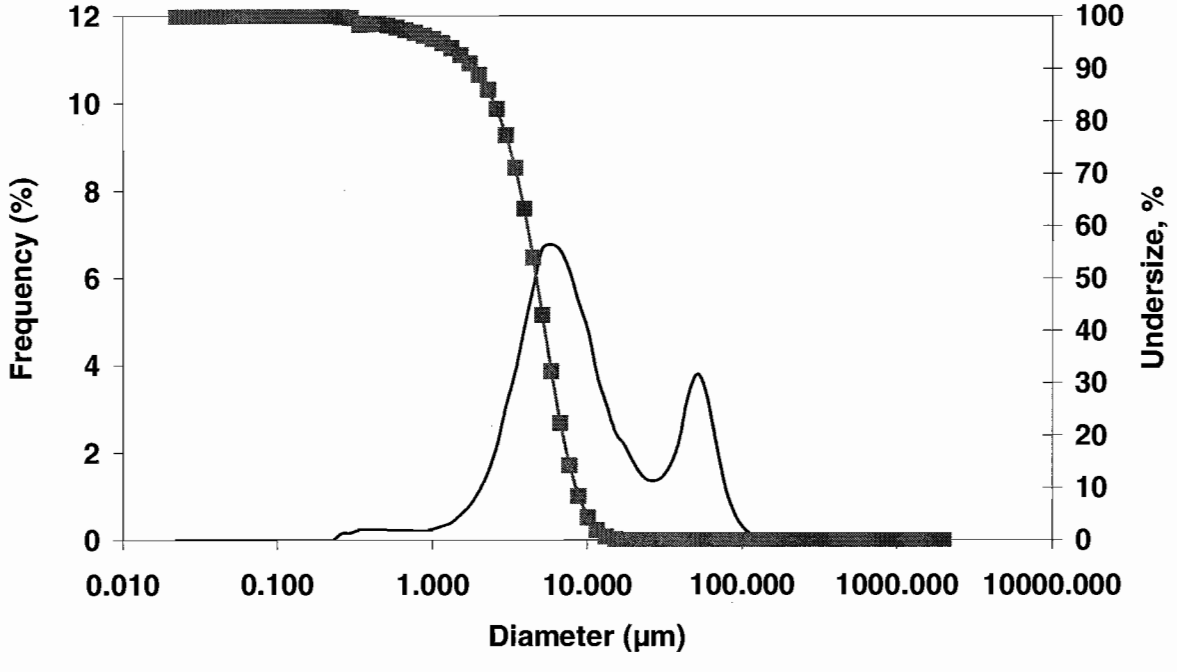

FIGURE 17 Particle Analysis of Balmorhea Screener

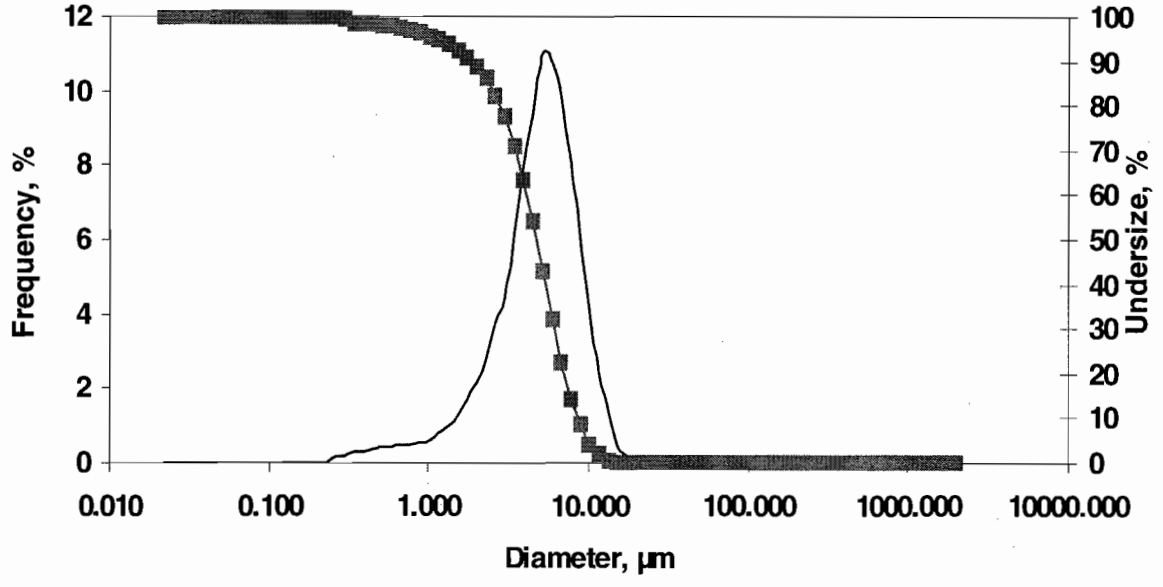

FIGURE 18 Particle Analysis of Rankin Screener

3.4 Asphalt Rubber Blend

The physical properties (like viscosity, penetration, etc.) of the blended CRM depend on the gradation of the ground rubber, temperature and method of mixing of the CRM and asphalt. Sieve analysis of crumb rubber was performed to identify CRM blend type as specified in Item 300. The results are presented in Table 11 and plotted in Figure 19 along with the acceptable bounds specified in Item 300. The CRM meets TxDOT gradation specifications for Grade C. As per Item 300, the Grade C CRM is used for Type I or Type II asphalt which is suitable for surface layer.

TABLE 11. Crumb Rubber Gradations

Sieve Size	Percentage (%) Passing
#8	100
#10	99.9
#30	98.69
#50	33.3
#100	8.65
Pan	0

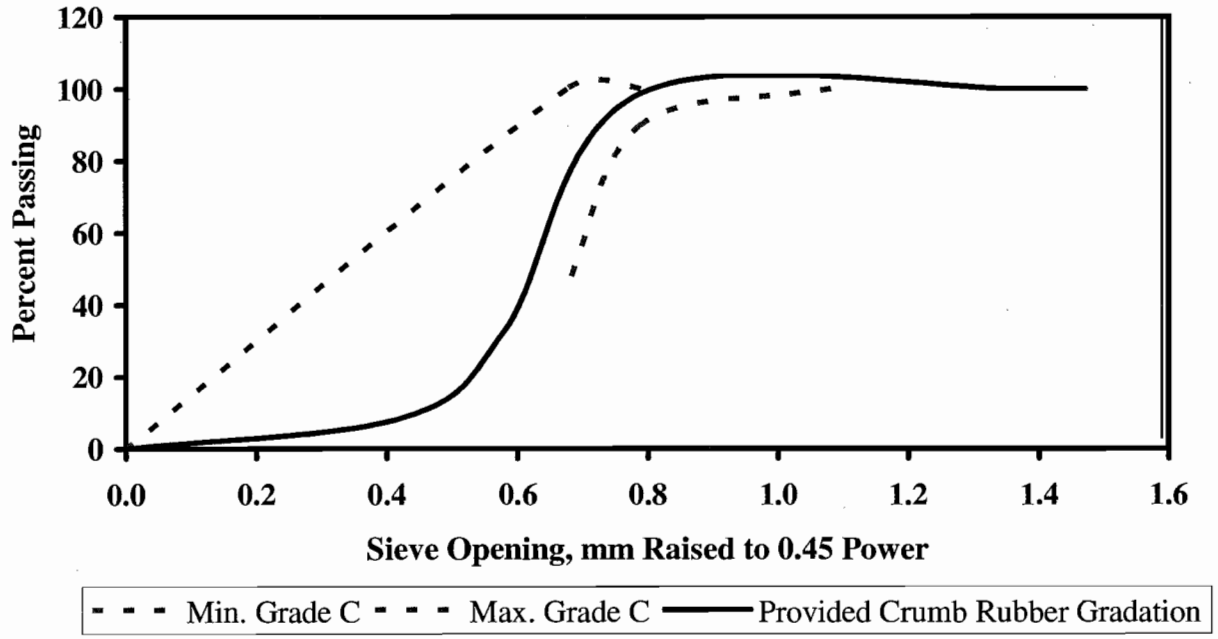

FIGURE 19 Crumb Rubber Gradation

After establishing the grade of the crumb rubber, it was blended with the neat asphalt. The mix design provided by Odessa District indicated that 18% of CRM was used. In addition, the minimum amount of CRM specified by CALTRANS and other DOT's is 18% by total binder mass. Therefore, all of the blends were prepared using 18% CRM by weight of the asphalt (AC-10).

The CRM blends were prepared either manually or by using a low shear mixer at different temperatures. In the manual method, the CRM blend was prepared by heating a known quantity of asphalt cement to a specified temperature and adding 18% CRM to the heated asphalt. The mixture was slowly stirred until all rubber particles were wetted with asphalt. The sample was then placed in oven at the specified temperature of mixing. The mixture was stirred after 30 minutes and again placed in the oven for another 30 minutes. With the mechanical mixer, the asphalt and CRM were mixed continuously for 1 hour at a specified temperature.

Although Item 300 specifies various physical properties requirements, only two tests were performed to evaluate the influence of mixing method and temperature on physical properties of CRM blend. The penetration tests were performed to identify changes at the intermediate service temperatures and while the DSR tests were performed to identify influence at the higher temperatures. Replicate penetration tests were performed on the CRM blends produced at three temperatures (350 °F, 400 °F, and 420°F) and for two mixing methods (manual and with a mixer).

The replicate DSR tests were performed at three temperatures (52, 64, and 76 °C; 126, 147, and 169 °F). For preparing blend at 350 °F, the asphalt cement was maintained at 375 °F before blending in CRM, as proposed by PaveTex Engineering Inc (Section 2.6). For remaining blends, the asphalt was maintained at the specified temperature before and after mixing CRM.

The penetration values, obtained at 77 °F and 59 °F (25°C and 15 °C), are summarized in Table 13. All blends prepared at different temperatures with different methods of mixing met the specifications. The penetration test results at different temperatures are also plotted in Figure 20. The penetration values for the blend manually prepared at 420 °F are significantly higher than those blends mixed at 350 °F, indicating that the higher mixing temperature will produce a less stiff mix. The penetration values seem to be impacted by the interaction between the mixing temperature and mixing method. For example, the penetration values at a temperature of 15 °C increased from 34 to 37 when the CRM was added manually at 350 °F but it decreased to 22 when the CRM was added with the mixer at the same temperature. On the other hand at higher mixing temperatures the penetration values decreased when the CRM was added manually as compared to using the mixer. The test results indicate that the increase in temperature or use of mixer may be initiating some sort of chemical reaction and/or shearing the CRM; therefore, further evaluation is required before proposing changes to the method of mixing and/or temperature of mixing.

TABLE 12. Penetration Values of Different Asphalt Rubber Binder Mixtures

Temp., °F (°C)	AC-10	AC10 mixed with CRM						CALTRANS Spec.	TxDOT Spec.
		Manual @ 350°F	Mixer @ 350°F	Manual @ 400°F	Mixer @ 400°F	Manual @ 420°F	Mixer @ 420°F		
59 (15)	34	37	22	52	22	56	43		
77 (25)	67	38	65	56	43	106	72	25 – 75	20

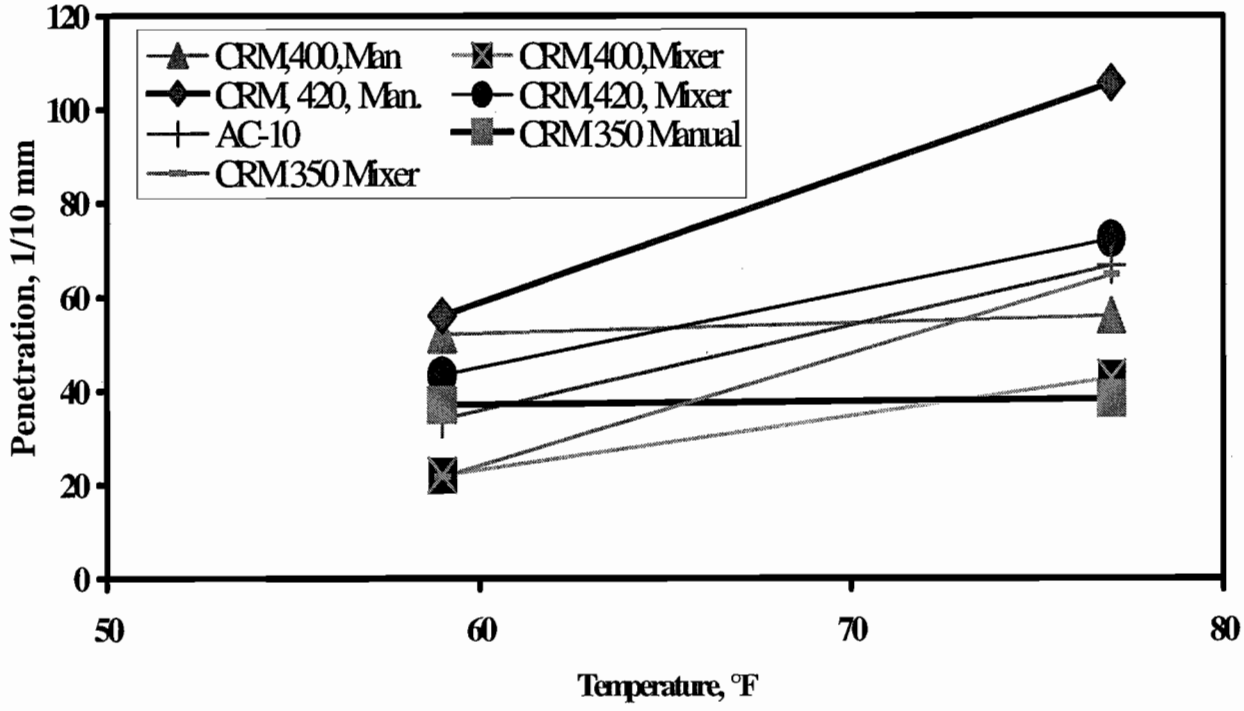

FIGURE 20 Penetration Values of All Binders

The complex modulus tests on the blends were also performed using the DSR. The DSR tests were performed in frequency sweep mode rather than single frequency, as specified in Superpave PG specifications. Tests were performed at seventeen frequencies from 0.01 Hz to 21 Hz at each test temperature. Typical test results for a manually prepared blend at 350 °F are shown in Figure 21. As expected, the complex modulus increases with a decrease in temperature. For comparison purposes, it is essential that the data is shifted horizontally to produce master curve at one temperature using the time-temperature superposition principle. The shifted master curve at 64 °C (147 °F) is shown in Figure 22. As expected, the complex modulus data for the higher temperature (76 °C or 169 °F) had to be shifted to the left while the data for the lower temperature (52 °C or 126 °F) had to be shifted to the right to generate the master curve. The master curve can be developed in terms of $G^*/\sin\delta$, elastic modulus, viscous modulus, or complex modulus. Since asphalt exhibits viscoelastic behavior, the stiffness depends on the temperature as well as rate of loading. The complex modulus of asphalt is the algebraic sum of viscous and elastic modulus. The rutting potential (or permanent deformation) of the asphalt cement increases with increase in viscous modulus, decrease in complex modulus, decrease in phase angle, and decrease in $G^*/\sin\delta$ (ratio of complex modulus to sine of phase angle). Therefore, the master curves were developed to identify influence of blending method and temperature on minimizing rutting potential.

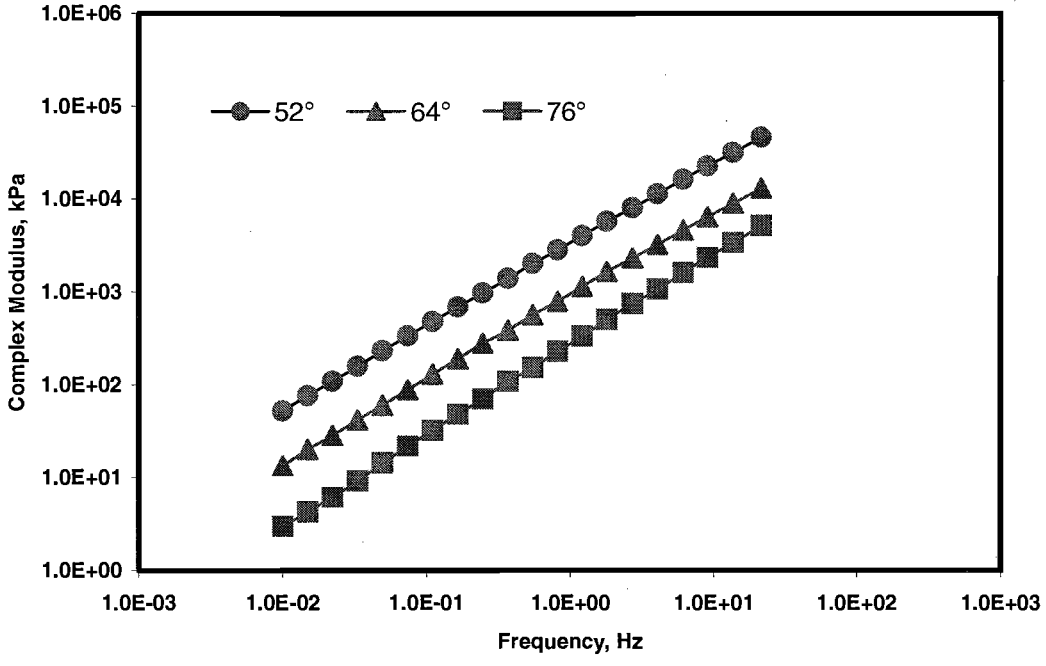

FIGURE 21 Test Results for Blend Prepared Manually at 350 °F

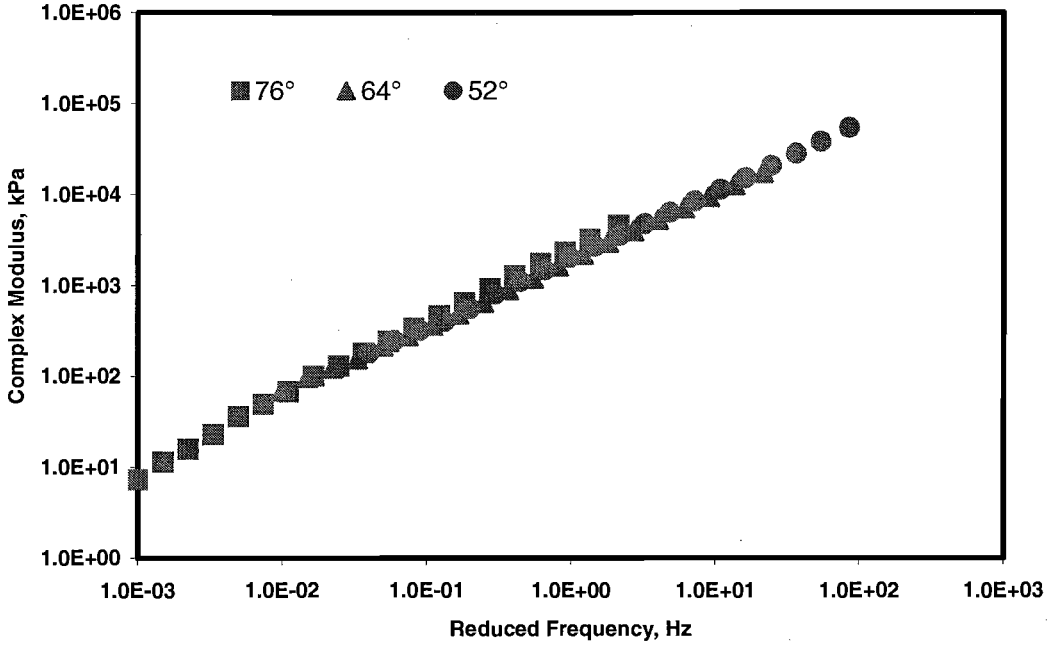

FIGURE 22 Master Curve for Blend Prepared Manually at 350 °F

This process was repeated for all blends, and the results are shown in Figures 23 through 26, respectively. The data presented in Figure 23 suggests that the G*/sinδ values are similar at higher frequencies (or lower temperatures) in comparison to the lower frequencies (or higher temperatures). The manual and mixer methods produced different results. For instance, the blend mixed with the mixer at 350 °F exhibited lower G*/sinδ values in comparison to the blend mixed manually at the same temperature. On the other hand, at mixing temperatures of 375 °F and higher, this trend is reversed. The blend prepared with the mixer at 375 °F and the blend mixed manually at 350 °F exhibited higher G*/sinδ values in comparison to other temperatures; hence, will be less prone to permanent deformation or rutting potential.

The elastic moduli for the blends are presented in Figure 24. The results exhibit similar trends as observed for the G*/sinδ results. The only difference seems to be that the blend prepared using the mixer at 375 °F exhibited higher elastic modulus in comparison to the blend prepared manually at 350 °F. The other difference observed is that the measured elastic moduli for all temperatures and methods exhibit higher variability in comparison to the G*/sinδ.it.

The viscous modulus versus the reduced frequency data, as shown in Figure 25, exhibit similar trends to those observed in Figures 22 and 23. The test results presented in Figures 24 and 25 indicate that the mixing of the CRM with asphalt is increasing both the elastic as well as the viscous component of the blend. Since performance of HMAC at lower service temperature depends on elastic modulus, an increase in elastic modulus may make HMAC prone to low temperature cracking. The results for the complex modulus presented in Figure 26 validate the observations presented in Figures 24 and 25.

Based on the DSR and penetration test results, it can be concluded that the temperature of mixing and the method of mixing play an important role in the physical properties of the blend. The increase in the blending temperature might be initiating some sort of chemical reactions, and the mixer might be shearing the CRM. Therefore, it would not be beneficial to change the temperature of mixing or using a shear mixer. In addition, the blend produced manually at 350 °F exhibited higher complex modulus values in comparison with other methods. Therefore, after initial mixing of the CRM blend, it should be maintained at 350 °F rather than 375 °F.

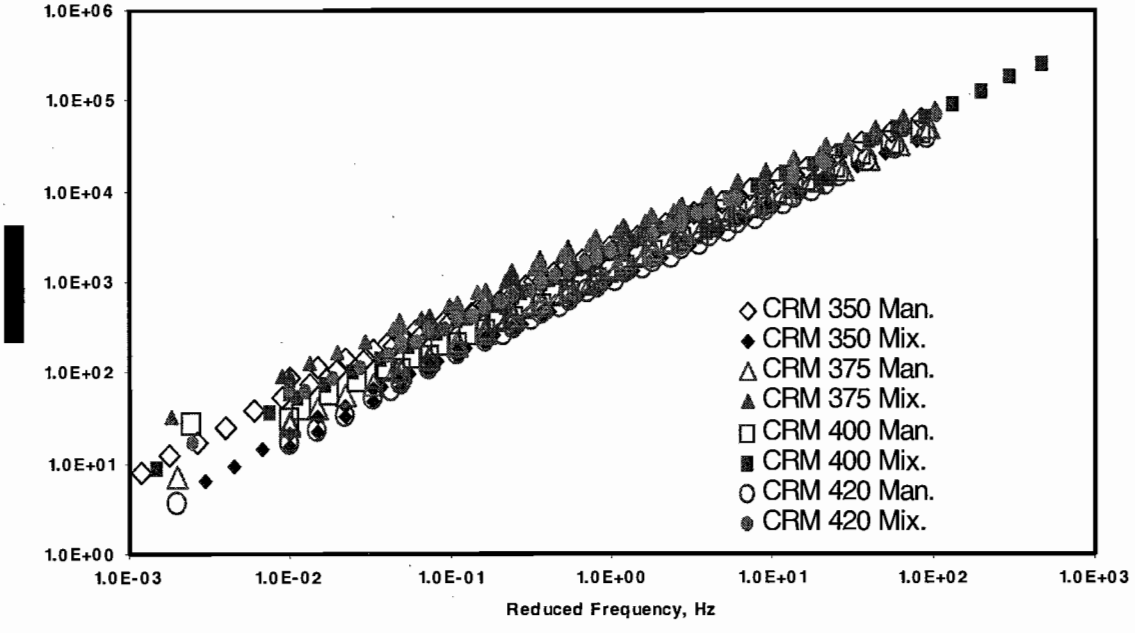

FIGURE 23 G*/sinδ Master Curve for Different Mixing Methods and Temperatures

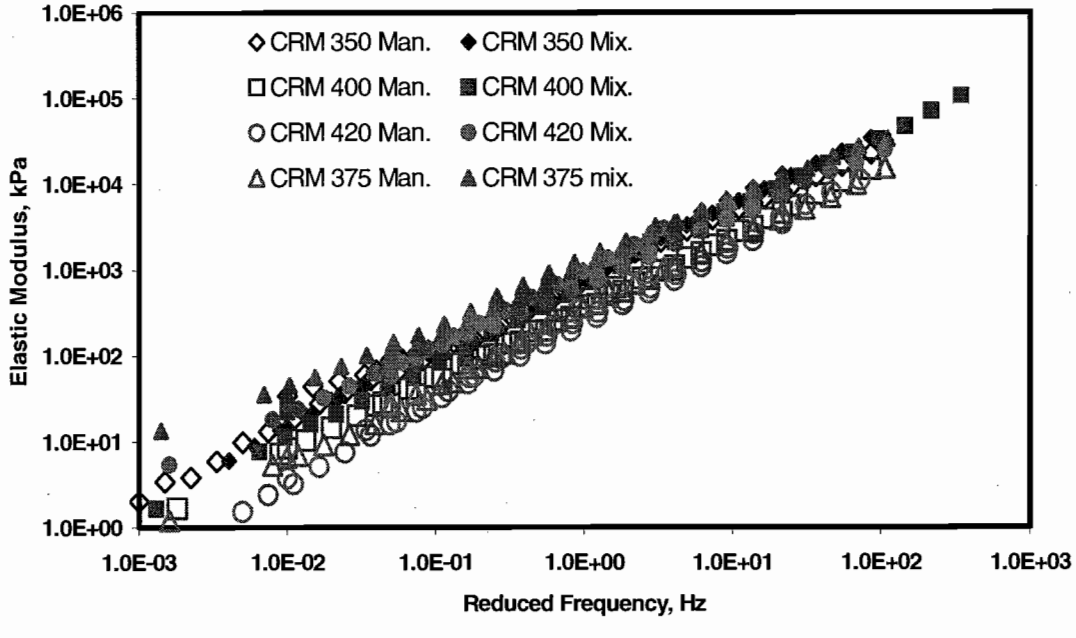

FIGURE 24 Elastic Modulus Master Curve for Different Mixing Methods and Temperatures

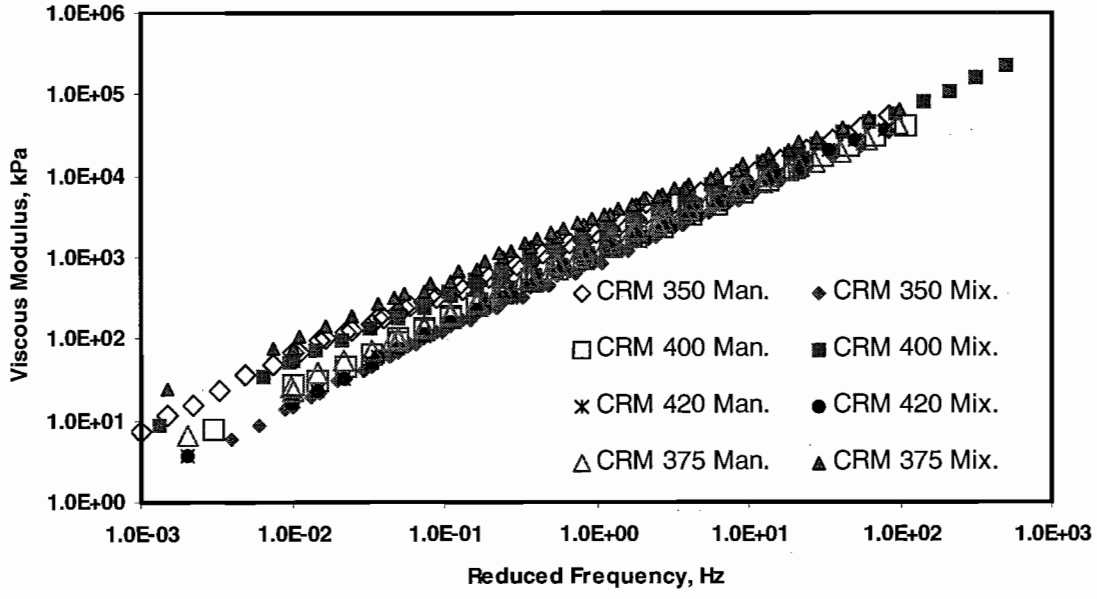

FIGURE 25 Viscous Modulus Master Curve for Different Mixing Methods and Temperatures

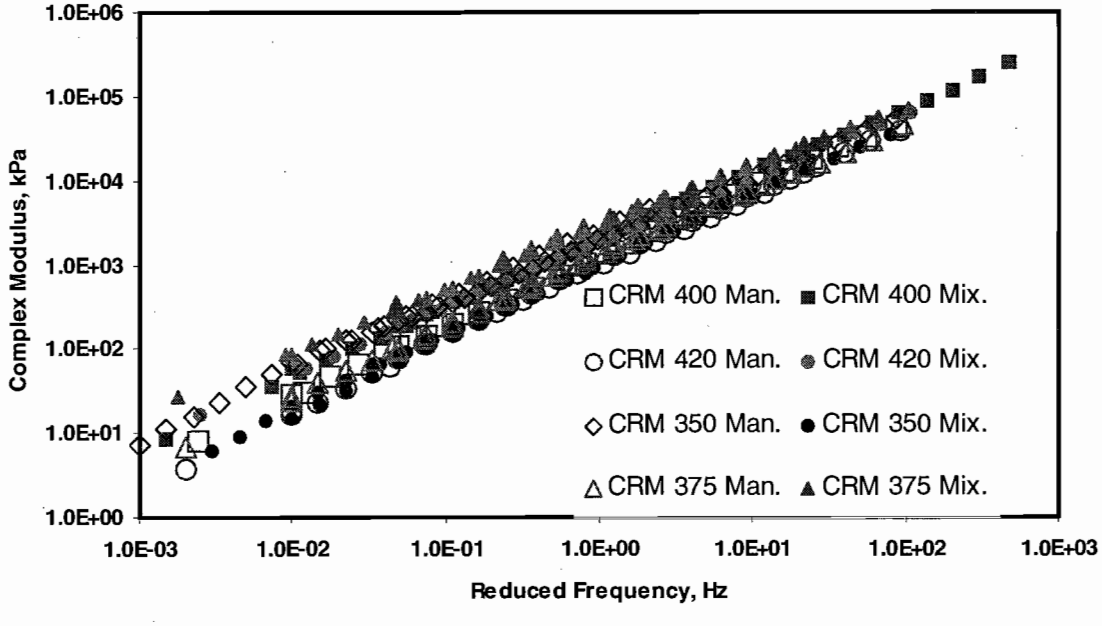

FIGURE 26 Complex Modulus Master Curve for Different Mixing Methods and Temperatures

3.5 Compaction of Crumb Rubber Modified Hot Mix Asphalt Concrete (CRM HMAC)

Although various aspects of the CRM-HMAC constituents were evaluated, the results seem to indicate that the compactability problem of CRM-HMAC mixes may reside with how the specimens are compacted. Therefore, the focus of this section is on various techniques that can be applied to improve the compactability of the CRM-HMAC mixes. Initially, the specimens were compacted using the Texas Gyratory Compactor (TGC); however, problems identified with the device lead us to evaluate the compaction issues using the Superpave Gyratory Compactor (SGC). In the end, the specimens were molded using the TGC with a proposed modified compaction procedure. The steps followed to identify compactability issues are discussed in the following sections:

3.5.1 Unit Weight of Specimens

To ensure that the unit weights of the specimens prepared in the UTEP laboratory (using the TGC or SGC) is similar to the ones prepared by TxDOT, it was decided to gather some specimens prepared by TxDOT laboratory and to measure their unit weights. The specimens prepared in the UTEP laboratory should be of similar unit weights. The molded specimens for the mix design with the Balmorhea screening were obtained from the Odessa District and their unit weights were measured as shown in Table 13. The average unit weight of the specimens is around 134 pcf.

TABLE 13. Unit Weight of Specimens Consisting of Balmorhea Screenings

Specimen ID	Air Voids	Diameter, in.	Length, in.	Unit Weight, pcf
4-1I	3.1	4.0	2.0	133.8
4-1 II	3.0	4.0	2.0	133.8
4-2 I	3.0	4.0	2.0	133.7
4-2 II	2.9	4.0	2.0	133.5
4-2 III	2.7	4.0	2.0	133.6
20-1 I	3.0	4.0	2.0	133.7
20-1 II	3.1	4.0	2.0	133.8
20-1 III	3.2	4.0	2.0	133.7

3.5.2 Initial Investigation of Compactability Using TGC

To ensure that the UTEP research team is proficient with the test method Tex-206-F, and our TGC is working fine, trial tests were carried out using a commonly used Type D material from the El Paso District. The initial compactability results are shown in Table 14. The results of the evaluation indicated that the specimens were compacted to higher than 98% relative density. In addition, the height of the compacted specimens was less than 1.7 in. indicating that the TGC is applying more than desired compactive efforts.

TABLE 14. Initial Evaluation Using Type D Mix

Specimen ID	G_{mb}	G_{mm}	Air Voids
1	2.423	2.457	1.38
2	2.44	2.457	0.69
3	2.423	2.457	1.38
4	2.437	2.457	0.81
5	2.439	2.457	0.73

Since the heights of the specimens were less than the desired 2 in., the mold was marked for a height of 2 in., and the compactive effort was adjusted accordingly to make sure that the specimen is not compacted beyond that height. As shown in Table 15, the specimens prepared in that manner exhibited extremely low air voids and their heights were still less than, 2 in. Since it was difficult to obtain the desired heights for the specimens, this approach was abandoned.

TABLE 15. Trial Runs for Maintaining Constant Height

Specimen ID	G_{mb}	G_{mm}	Air Voids
1	2.427	2.457	1.22
2	2.439	2.457	0.73
3	2.417	2.457	1.63
4	2.431	2.457	1.06

As per test method Tex-206-F, a stress of 2,500 psi should be applied to the specimen. The height of the specimen typically reduced significantly from the original height when this load was applied. To avoid further changes in the height of the specimen, this stress was not applied. The volumetric information about the specimens prepared in this manner is shown in Table 16. The specimens' exhibit air voids more than 3%, indicating that the process of eliminating the stress is not appropriate. With the UTEP gyratory compactor, it was difficult to prepare specimens of desired density and the prepared specimens were not consistent (Tables 14 through 16). The Jobe Concrete's TGC equipment was then used to mold specimens. Specimens with desired heights and VTM's could easily be prepared using that TGC. This indicated that the UTEP's TGC required modification and calibration. During the repair and calibration of UTEP TGC, the compactability of the materials was carried out using a SGC. The results are reported in the following section.

TABLE 16. Influence of Eliminating 2,500 psi Stress Step of Test Method Tex-206-F

Specimen ID	G_{mb}	G_{mm}	Air Voids
1	2.331	2.457	5.13
2	2.374	2.457	3.38
3	2.368	2.457	3.62

3.5.3 Specimen Preparation Using SGC

To prepare specimens using the SGC, it is necessary to determine three parameters, namely N_{ini}, N_{des}, and N_{max}. An N_{des} value of 74, which is recommended for average design high temperature of less than 40 °C (104 °F) and traffic levels of less than 0.3 million ESAL's, was initially used. To ensure similarity in densities between specimens molded with the SGC and TGC, similar unit weights were used. Representative amounts of material were mixed and compacted to a nominal unit weight of 134 pcf. The results of the initial sample preparation are presented in Table 18. The air voids of the specimens were substantially greater than 3% with 74 gyrations. Although on the target unit weight was 134 pcf, the actual unit weights were less than 130 pcf. A loss of material during mixing and compacting was determined as the source of this problem.

TABLE 17. First Step in Modifying the Mixing and Compaction Procedure

Specimen	Unit Weight, pcf	No. of Gyrations	Height, mm (in.)	G_{mb}	G_{mm}	Air Voids
1	130	74	117 (4.606)	2.056	2.255	8.8
2	128	74	119 (4.685)	2.034	2.255	9.8
3	127	74	120 (4.724)	2.002	2.255	11.2

3.5.4 Handling of CRM HMAC Mix and Specimen

As indicated before, several issues had to be addressed during the compaction of the specimens. These issues include the horizontal expansion of the specimen, the loss of temperature during compaction, and the loss of material during mixing and compaction.

To minimize the horizontal expansion after the removal of the mold and to ensure that the specimen would not collapse, the specimen was maintained inside the mold for 45 minutes to minimize the expansion. In addition, the specimens were placed in a PVC pipe after the removal from the mold to further minimize the horizontal expansion, as shown in Figure 8.

The change in the height of a specimen with the number of gyrations for a typical specimen is shown in Table 18. The rate in change of the height of the specimen decreased as the number of gyrations increased. For instance, the change in height was 0.090 in. when the number of gyrations increased from 20 to 30, while the change in height was 0.002 in. from 140 to 150 gyrations. The increase in the number of gyrations beyond 150 may not significantly impact the density of the molded specimens. The reduction in the rate of change in height can be attributed to the loss of temperature, amongst other parameters. Since the loss of temperature is significant and rapid, it can lead to the increase in the viscosity of the CRM blend as the number of gyrations increases. To minimize the loss of temperature, the mold was kept inside an oven set at the specified temperature for 15 minutes after the loose mix was placed inside the mold.

To minimize the loss of materials during mixing and compacting, the mixing pans are sprayed with a small amount of WD40. If an excessive amount of WD40 is sprayed, it can be wiped using a paper towel before mixing the CRM blend with the aggregates. The amounts of weight losses for a number of specimens before and after using the WD40 are shown in Table 19. A significant amount of the material is lost during mixing process without spraying the pans. For example, up to 140 grams (3.5%) of 4,000 grams of the materials was lost during mixing without spraying the pans. The loss of materials is less than 30 grams (0.6%) when WD40 is sprayed on the pans.

3.5.5 Influence of Compaction Temperature and Load

Although proposed changes increased the relative density of the molded specimens, the specimens could not be prepared to a 97% relative density. The results of the specimens prepared with modified procedure are included in Figure 27. It was impossible to achieve a relative density of more than 88%, even if the number of gyrations was increased to 1,000.

Finally, the compaction temperature was increased from 375 °F to 385 °F. As shown in Figure 28, the relative density increased from 88% to 93%, but it was still less than desired 97%. The temperature was further increased to 400 °F and a stress of 600 kPa was maintained on the specimen after compaction as suggested by Natu and Tayebali (1999). To maintain the stress, the stop button of the SGC is pushed after the specimen is compacted to the desired height. These two measures further increased the relative density of the specimens, as shown in Figure 29. The constant load applied after compaction increased the density from 93% to 96%, while the increase in temperature from 385 °F to 400 °F further increased the relative density to the target value of 97%.

TABLE 18. Influence of No. of Gyrations on Compactability of Mix

No. of Gyrations	Height, in.	No. of Gyrations	Height, in.	No. of Gyrations	Height, in.
0	5.866	121	4.756	154	4.720
1	5.685	122	4.756	155	4.720
9	5.291	123	4.752	156	4.720
10	5.268	124	4.752	157	4.717
11	5.244	125	4.752	158	4.717
12	5.224	126	4.748	159	4.717
13	5.209	127	4.748	160	4.717
14	5.189	128	4.748	161	4.717
15	5.173	129	4.748	162	4.713
16	5.157	130	4.744	163	4.713
17	5.146	131	4.744	164	4.713
18	5.134	132	4.744	165	4.713
19	5.122	133	4.740	166	4.713
20	5.110	134	4.740	167	4.709
30	5.020	135	4.740	168	4.709
40	4.957	136	4.740	169	4.709
50	4.909	137	4.736	170	4.709
60	4.874	138	4.736	171	4.709
70	4.846	139	4.736	172	4.705
80	4.823	140	4.732	173	4.705
90	4.803	141	4.732	174	4.705
100	4.783	142	4.732	175	4.705
108	4.772	143	4.732	176	4.705
111	4.768	144	4.728	177	4.701
112	4.768	145	4.728	178	4.701
113	4.768	146	4.728	179	4.701
114	4.764	147	4.728		
115	4.764	148	4.728		
116	4.764	149	4.724		
117	4.760	150	4.724		
118	4.760	151	4.724		
119	4.760	152	4.724		
120	4.756	153	4.720		

TABLE 19. Influence of WD 40 on Weight Loss During Mixing and Compaction

Mixing Loss			Compaction Loss		
Weight Before Mixing (gms)	**Weight After Mixing (gms)**	**Loss During Mixing (gms)**	**Weight Before Compaction (gms)**	**Weight of specimen after Compaction (gms)**	**Loss During Compaction (gms)**
Without WD 40					
4000	3859.2	140.8	3824.5	3815.9	8.6
4000	3863.1	136.9	3824.5	3820.6	3.9
4000	3861.4	138.6	3824.5	3819.3	5.2
4600	4466.2	133.8	4398.2	4393.7	4.5
4600	4545.5	54.5	4398.2	4392.9	5.3
After Using WD 40					
4600	4575.4	24.6	4353	4350.1	2.9
4600	4569.8	30.2	4220.6	4216.5	4.1

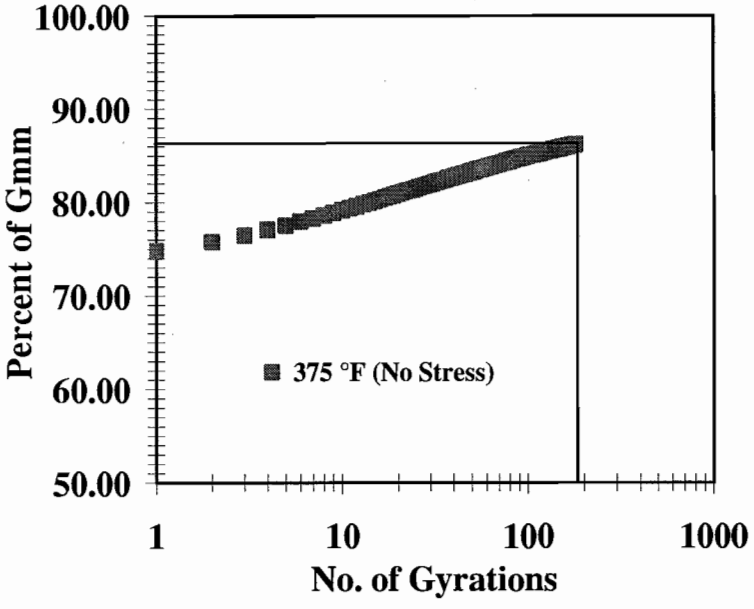

FIGURE 27 Percent G_{mm} versus Number of Gyrations for Compaction Temperature of 375 °F

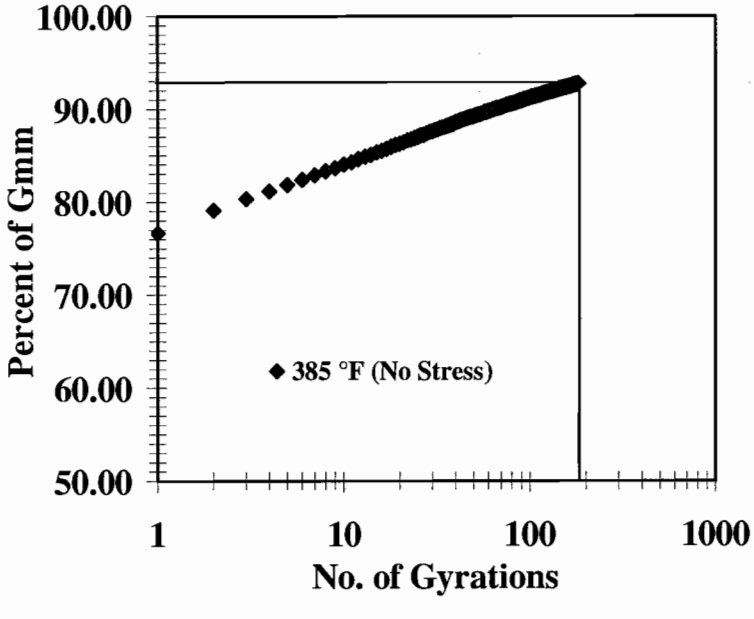

FIGURE 28 Percent G_{mm} versus Number of Gyrations for Compaction Temperature of 385 °F

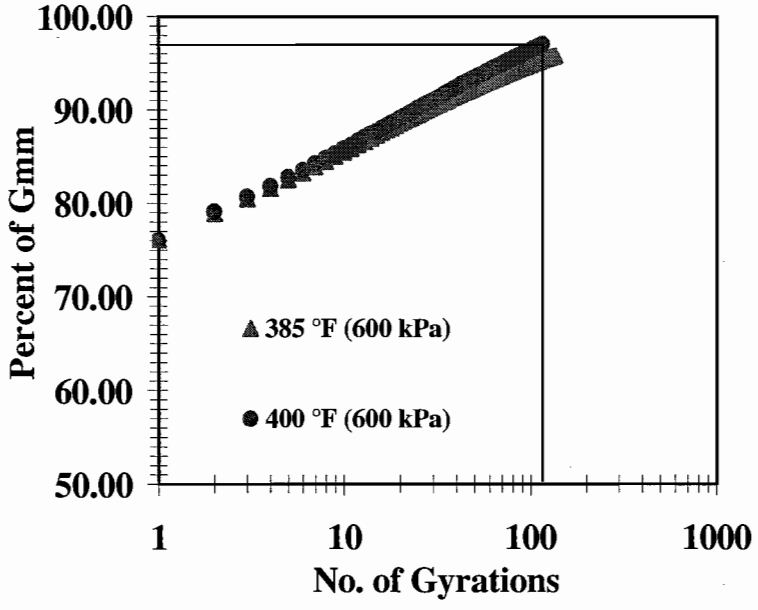

FIGURE 29 Percent G_{mm} versus Number of Gyrations for Different Compaction Temperatures

The data presented in Figure 29 suggests that the compaction temperature should be increased to 400 °F and a stress of 600 kPa should to be maintained after the compaction to achieve the desired relative density. To verify the newly proposed method of compaction, specimens were prepared from two additional CRM-HMAC mixes such that the G_{mb} of the specimens were similar to that of the mix design and the air voids at the end of compaction were around 3%. The results of this evaluation are presented in Table 20. The specimens could be prepared to desired relative densities; however, the number of gyrations varied between 98 and 105, which is not very different. Since for the Superpave Level I mix design for a traffic of 3 to 10 million ESAL's and a design temperature of 40 °C the number of gyrations should be 106, it is proposed that the future specimens be prepared using an N_{des} of 106.

TABLE 20. Compactability of CRM-HMAC Mixes

Specimen ID	No. of Gyrations	Height, mm	Gmm	Gmb	Air Voids
Rankine	98	114.4	2.286	2.221	2.8
CRM-HMAC (O)	100	114.5	2.301	2.231	3.01
CRM-HMAC (N)	105	115.5	2.305	2.234	3.08

3.5.6 Verification of the Procedure Using TGC

Since TxDOT mix designs are based on the TGC, it is essential that the modified mixing and compaction procedure be verified using the TGC. The four mixes were compacted using the TGC as well and the results are presented in Table 21. The results suggest that the specimens can be prepared to the desired density of 97% using the modified procedure.

TABLE 21. Specimens Prepared Using TGC

Specimen ID	Gmm	Gmb	Air Voids
Rankine	2.286	2.22	2.9
Balmorhea	2.274	2.204	3.1
CRM-HMAC (O)	2.301	2.232	2.9
CRM-HMAC (N)	2.305	2.233	3.1

Based on this study, a modified procedure has been proposed in Appendix B.

CHAPTER 4 CONCLUSIONS AND RECOMMENDATIONS

To improve the performance of hot-mix asphalt concrete at high temperatures, crumb-rubber is typically used. Although hot-mix asphalt concrete consisting of crumb-rubber has been successfully placed and have performed well over the years, the laboratory design and preparation of specimens are sometimes problematic. The current mix design procedure (Tex-232-F) is cumbersome and requires preparing a large number of laboratory specimens to carry out an appropriate mix design. The purpose of this research project is to identify the problems with and provide solutions to the current procedure. In addition, the mix design procedure using Superpave Gyratory Compactor has also been developed.

Based on the evaluation results of Tex-232-F, the following modifications have been proposed:

1. An analytical tool has been developed to optimize the gradation of the CRM-HMAC.
2. The asphalt binder should be heated to 375 °F before mixing of the CRM; however, the blend of CRM and asphalt should be maintained at 350 °F.
3. To minimize the loss in material during mixing and compaction, a small amount of WD40 should be sprayed on the mixing bowls and pans.
4. After mixing and before compaction, the loose mix should be heated to 400 °F for 2 hours. In addition, the mold should also be maintained at 400 °F.
5. After the placement of the mix in the compaction mold, the mold together with the mix should be placed in the oven for 15 minutes prior to compaction.
6. After the desired number of gyrations, the SGC should be stopped and a stress of 600 kPa should be applied for 45 minutes.
7. After the removal of the specimen from the mold, the specimen should be enclosed in a PVC mold overnight before measuring its air void.

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APPENDIX A: TEX-232-F, MIXTURE DESIGN PROCEDURE FOR CRUMB RUBBER MODIFIED ASPHALTIC CONCRETE

Section 1. Overview

Use this procedure to determine the proper proportions of approved aggregates and rubber-asphalt blend which, when combined, will produce a mixture that will satisfy the specification requirements. Typical examples for design are provided.

Units of Measurement

The values given in parentheses (if provided) are not considered to be standard and may not be exact mathematical conversions. Each system of units shall be used independently of the other. Combining values from the two systems may result in non-conformance with the standard.

Section 2. Definitions

The following term is referenced in this test method:

- Binder - Binder is a blend of asphalt and ground rubber.

Section 3. Apparatus

The following apparatus is required:

- apparatus listed in the following test methods.
  - "Tex-200-F, Sieve Analysis of Fine and Coarse Aggregates"
  - "Tex-201-F, Bulk Specific Gravity and Water Absorption of Aggregate"
  - "Tex-202-F, Apparent Specific Gravity of Material Finer than 180 □m (No. 80) Sieve"
  - "Tex-205-F, Laboratory Method of Mixing Bituminous Mixtures"
  - "Tex-206-F, Compacting Test Specimens of Bituminous Mixtures"
  - "Tex-207-F, Determining Density of Compacted Bituminous Mixtures"
  - "Tex-227-F, Theoretical Maximum Specific Gravity of Bituminous mixtures."

Section 4. Part I, Determining Optimum Gradation

Use this method to determine the optimum gradation.

Procedure

Follow these steps to determine optimum gradation.

Determining Optimum Gradation	
Step	**Action**
1	☐ Obtain representative samples of each processed aggregate proposed for use according to Test Method "Tex-221-F, Sampling Aggregate for Bituminous Mixtures, Aggregate for Surface Treatment, and Limestone Rock Asphalt." ☐ Approximately 45 kg (100 lb.) of each aggregate stockpile will be required.
2	Dry the aggregate in an oven at a temperature between 38 □C (100 □F) and 150 □C (302 □F).
3	☐ Obtain the average gradation of each proposed aggregate stockpile according to 'Part II, Washed Sieve Analysis' of Test Method "Tex-200-F, Sieve Analysis of Fine and Coarse Aggregates." ☐ Use samples taken from several locations in the stockpile and average the results. (When this is not possible, the aggregate samples received in the laboratory may be quartered and used for the sieve analysis.)
4	Determine the 24-hour water absorption and specific gravity of each size of each aggregate according to test methods "Tex-201-F, Bulk Specific Gravity and Water Absorption of Aggregate" and "Tex-202-F, Apparent Specific Gravity of Material Finer than 180 □m (No. 80) Sieve." NOTE: (Normally, specific gravities are not determined for size fractions consisting of less than 15 % of the individual aggregate. Smaller size fractions are assigned the water absorption and specific gravity of the next adjacent size fraction for which values were determined.)
5	☐ Calculate the initial desired combined gradation from the gradations of the stockpiles proposed for use. ☐ As a guideline, keep a ratio of 1.5 to 2.0 between the two coarsest sieves on which aggregate is retained. (Use this initial gradation only to determine aggregate grading factors.) ☐ In the 'Trial Gradations' table the initial gradation has a coarse to fine aggregate ratio of 80/20 and a 1.67 ratio between the two coarsest sieves.
6	☐ Prepare 5000 g batches with 4.0% asphalt for each of the coarse-to-fine aggregate ratios (see 'Calculations'). ☐ Follow Test Method "Tex-205-F, Laboratory Method of Mixing Bituminous Mixtures."
7	Mold three samples of mix from each of the batches according to Test Method "Tex-206-F, Compacting Test Specimens of Bituminous Mixtures."
8	Determine the bulk specific gravity of each of the compacted specimens according to Test Method "Tex-207-F, Determining Density of Compacted Bituminous Mixtures."
9	Determine the theoretical maximum specific gravity of each of the batches according to Test Method "Tex-227-F, Theoretical Maximum Specific Gravity of Bituminous Mixtures."
10	Calculate the density of each of the molded specimens according to Test Method "Tex-207-F, Determining Density of Compacted Bituminous Mixtures."
11	☐ Plot the average volumetric proportion of total retained on the 2.00 mm (No. 10) sieve for each set of molded specimens versus their average density. ☐ See the example in 'Density vs. Volume + No.10.'
12	☐ Pick the point that gives the maximum density on the curve in 'Density vs. Volume + No.10.' ☐ Draw a line from the peak down to where it intersects the x-axis and read the total volume of + 2.00 mm (No. 10).

	☐ Example in 'Density vs. Volume + No.10.' ☐ The optimum density occurs at a density of 97.3% and a volume of 66.0% retained on the 2.00 mm (No. 10) sieve.
13	☐ Add 2.5% to the total volume retained on the 2.00 mm (No. 10) sieve. ☐ This value will be the new target used in 'Part II, Determining Optimum Asphalt Content.' ☐ Example in 'Density vs. Volume + No.10.' ☐ The new target gradation will be 68.5% by volume retained on the 2.00 mm (No. 10) sieve.

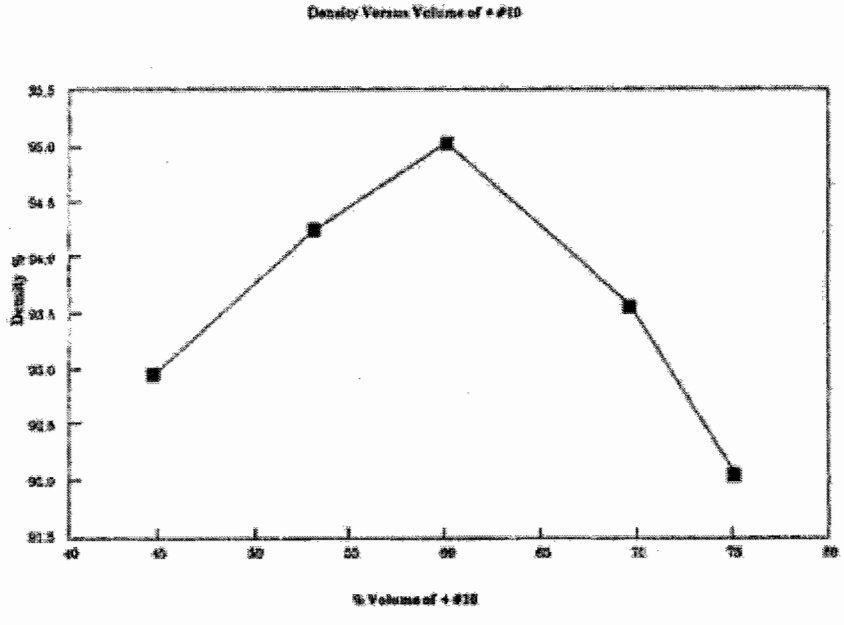

Figure 29-1. Density vs. Volume + No. 10.

Calculations

☐ Determine grading factors for coarse aggregate:

$$Grading\ factor = \frac{individual\ \%\ retained\ on\ each\ sieve}{total\ \%\ retained\ on\ 2.00\ mm\ (No.\ 10)\ sieve}$$

Example from the 'Trial Gradations' table:

The amount passing the 9.5 mm (3/8 in.) and retained on 4.75 mm (No. 4) sieve = 50%. The total retained on the 2.00 mm (No. 10) sieve = 80%.
The grading factor = 50/80 = 0.625 for the 9.5 mm - 4.75 mm (3/8 in.- 4.75 mm (No. 4)) fraction.

- Determine grading factors for fine aggregate:

$$Grading\ factor = \frac{individual\ \%\ retained\ on\ each\ sieve}{total\ \%\ passing\ 2.00\ mm\ (No.\ 10) - 6.0\%}$$

Example from the 'Trial Gradations' table:

The amount passing the 2.00 mm (No. 10) sieve and retained on the 425 □m (No. 40) sieve = 10% and the total % passing the 2.00 mm (No. 10) sieve = 20%.

The grading factor = 10/(20-6) = 0.714 for the 2.00 mm- 425 □m (No.10-no. 40) size fraction.

- Calculate combined gradations for coarse-to-fine aggregate ratios of 60/40, 65/35, 70/30, 75/25, 80/20, and 85/15. Use the grading factors determined in Steps 2 and 3 of the 'Determining Optimum Gradation' procedure to keep the same aggregate proportions.

Example from the 'Trial Gradations' table:

For a coarse-to-fine aggregate ratio of 60/40, the % passing the 9.5 mm (3/8 in.) sieve and retained on the 4.75 mm (No. 4) sieve will be (0.625)(60%) = 37.5%. The % passing the 2.00 mm (No. 10) and retained on the 425 □m (No. 40) will be (.714)(34%) = 24.2%.

- Calculate volume of total retained on the 2.00 mm (No. 10) sieve for each set of molded specimens:

$$\%V_{2.00\ mm\ (+No.10)} = (V_{2.00\ mm\ (+No.10)} / V_s) \times 100$$

Where:

- $V_{2.00\ mm\ (+10)} = W_{2.00\ mm\ (+No.\ 10)} / G_{2.00\ mm\ (+No.\ 10)}$ = Volume of aggregate retained on 2.00 mm (No. 10) sieve
- V_s = Volume of molded specimen = W_s/G_s
- W_s = Weight of dry molded specimen, Test Method "Tex-207-F, Determining Density of Compacted Bituminous Mixtures"
- W_{ar} = Weight of binder in molded specimen
- $W_{-2.00\ mm\ (-10)}$ = Weight of aggregate passing 2.00 mm (No. 10) sieve
- $W_{2.00\ (+10)}$ = Weight of aggregate retained on 2.00 mm (No. 10) sieve
- V_{air} = Volume of air
- V_{ar} = Volume of binder = W_{ar}/G_{ar}
- VMA = $V_{air} + V_{ar}$

- $V_{-2.00\ mm\ (-10)} = W_{-2.00\ mm\ (-No.\ 10)}/G_{-2.00\ mm\ (-No.\ 10)}$ = Volume of aggregate passing 2.00 mm (No. 10) sieve
- G_s = Bulk specific gravity of molded specimen, Test Method "Tex-207-F, Determining Density of Compacted Bituminous Mixtures"
- $G_{2.00\ mm\ (+10)}$ = Bulk specific gravity of aggregate retained on 2.00 mm (No. 10) sieve, test method "Tex-201-F, Bulk Specific Gravity and Water Absorption of Aggregate"
- $G_{-2.00\ mm\ (-10)}$= Specific gravity of aggregate passing 2.00 mm (No. 10) sieve, test methods "Tex-201-F, Bulk Specific Gravity and Water Absorption of Aggregate" and "Tex-202-F, Apparent Specific Gravity of Material Finer than 180 □m (No. 80) Sieve"
- G_{ar} = Specific gravity of binder at 20 □C (68 □F).

A graphical representation of components of a molded specimen is shown in 'Volumetric Analysis of Molded Specimens.'

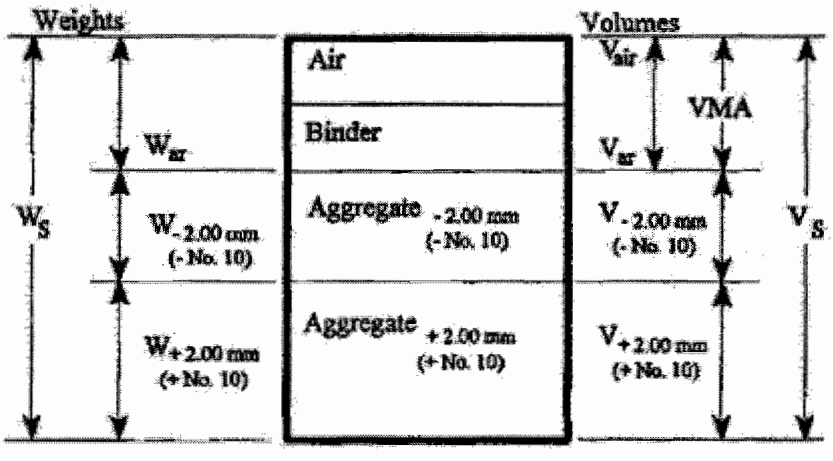

Figure 29-2. Volumetric Analysis of Molded Specimens.

NOTE: The sum of the volumetric proportions ($V_{2.00\ mm\ (+No.\ 10)} + V_{-2.00\ mm\ (-No.\ 10)} + V_{ar} + V_{air}$) may not total 100%, caused by errors in determining aggregate specific gravity. Check errors greater than □ 3%.

Trial Gradations								
Sieve Size	Initial Gradation	Grading Factor	% Retained on 2.00 mm (No. 10)/% Passing 2.00 mm (No. 10)					
			60/40	65/35	70/30	75/25	80/20	85/15

12.5 mm - 9.5 mm (1/2 in. - 3/8 in.)	0							
9.5 mm - 4.75 mm (3/8-4.75 mm [No.4])	50.0	50/80 = .625	37.5	40.6	43.8	46.9	50.0	53.1
4.75 mm (No. 4)-2.00 mm (No. 10)	30.0	30/80 = .375	22.5	24.4	26.3	28.1	30.0	31.9
2.00 mm (No. 10)-425 □m (No. 40)	10.0	10/(20-6) =.714	24.2	20.8	17.1	13.6	10.0	6.4
425 □m (No. 40)-180 □m (No. 80)	2.0	2/(20-6) = .143	4.9	4.1	3.4	2.7	2.0	1.3
180 □m (No. 80)-No. 200	2.0	2/(20-6) = .143	4.9	4.1	3.4	2.7	2.0	1.3
Pass No. 200	6.0	N/A	6.0	6.0	6.0	6.0	6.0	6.0
TOTAL	100.0		100.0	100.0	100.0	100.0	100.0	100.0

Section 5. Part II, Determining Optimum Asphalt Content

Use this method to determine optimum asphalt content.

Procedure

Follow these steps, referring to the calculations and tables that follow, to determine optimum asphalt content.

Determining Optimum Asphalt Content	
Step	Action
1	□ Weigh enough aggregate, asphalt, and crumb rubber to make a 5000 g batch of mix using the stockpile percentages in 'Calculations' (#5). □ Use the binder content determined in the 'Ratios of Volume to Weight in % of Total' table.
2	Heat the aggregate to a minimum temperature of 190 □C (375 □F).
3	Heat the asphalt and crumb rubber to 190 □C (375 □F).
4	Blend together thoroughly and place in the 190 □C (375 □F) oven for approximately 30 minutes.
5	Stir thoroughly and leave the blend for another 30 minutes at the same temperature.
6	Remove from the oven at the end of one hour and measure the viscosity using a Haake viscometer. □ If the viscosity meets the required specification, proceed with Step 10. □ If the viscosity is below the minimum requirement, stir the binder thoroughly and return it to the 190 □C (375 □F) oven for 30 minute increments until it reaches a satisfactory viscosity.
7	Thoroughly stir the heated binder and add the appropriate amount to the heated aggregate.
8	Mix with a mechanical mixer according to Test Method "Tex-205-F, Laboratory Method of Mixing Bituminous Mixtures."
9	□ Weigh three separate 1000 g samples of the mix for molding. □ Save the remaining mix for determining the theoretical maximum specific gravity.
10	Cure all four samples in an oven preheated to 121 □C (250 □ 5 □F) for 2 hours.

11	Mold the three 1000 g specimens according to Test Method "Tex-206-F, Compacting Test Specimens of Bituminous Mixtures." □ Heights must be 50.8 □ 2.5 mm (2 □ 0.1 in.).
12	Leave the samples in the molds until they are cool to the touch.
13	Determine the maximum specific gravity according to Test Method "Tex-227-F, Theoretical Maximum Specific Gravity of Bituminous Mixtures."
14	Determine the bulk specific gravity and relative density of molded specimens according to Test Method "Tex-207-F, Determining Density of Compacted Bituminous Mixtures."
15	Calculate the density of the molded specimens using the theoretical maximum specific gravity determined from Test Method "Tex-227-F, Theoretical Maximum Specific Gravity of Bituminous Mixtures."
16	If the molded density is equal to 97 □ 0.2%, determine the creep properties of the mixture according to Test Method "Tex-231-F, Static Creep Test."
17	□ If the density is greater than 97.2 %, perform the 'Molded Density Greater than 97.2%' procedure. □ If the molded density is less than 96.8%, perform the 'Molded Density Less than 96.8%' procedure.

Calculations

1. Determine the first estimated volume of air, asphalt, and - 2.00 mm (- No. 10) aggregate:

$$V_{+2.00\,mm\,(+No.10)} + V_{-2.00\,mm\,(-No.10)} + V_{ar} + V_{air} = 100\%$$

- From Part I:

$$V + 2.00\ mm\ (+\ No.10) = 68.5\%$$

- V_{air} = 3% (as set in the specification)
- VMA = minimum 20 (as set in the specification)
- V_{ar} = VMA - V_{air} =20-3=17% minimum
- $V_{-200mm(-No.\ 10)}$ = 100% -68.5%-17%-3%=11.5%.

2. Calculate the combined aggregate gravities from the bulk gravities of individual sizes. For the example proportions determined in Calculation No. 1, the following gravities are calculated:

$$G_{b\,+2.00\,mm\,(+No.10)} = 2.565,\ G_{b-2.00\,mm\,(-No.10)} = 2.678$$

- The gravity of the binder (G_{ar}) is 1.02.

Calculate the weight of each of the volumes determined in Calculation No. 1 by multiplying the volume times its gravity.

- Assume the total volume of the molded specimen to be 100 mL (3.5 fl. oz.).
- For the proportions determined in Calculation No. 1, the weight of the + 2.00 mm (No. 10) portion of the aggregate is:

$$68.5 \times 2.565 = 175.7g$$

- Refer to the 'Ratios of Volume to Weight in % of Total' table for the weight conversions of the other components. The total weight of a 100 mL (3.5 fl. oz.) molded specimen using these aggregates is 223.8 g.

4. Calculate the percent by weight of total mix of each of the components calculated in Calculation No. 3 by dividing the component weight by the total molded specimen weight. For the weights determined, the % by weight retained on the 2.00 mm (No. 10) sieve is:

$$\left(175.7/223.8\right) x\ 100 = 78.5$$

5. Calculate the percentages of each stockpile necessary to obtain the total weight percentages of +2.00 mm (+No. 10), -2.00 mm (-No. 10) , and binder calculated in the 'Ratios of Volume to Weight in % of Total' table.

Ratios of Volume to Weight in % of Total			
	Volume	Weight (g)	% of Total
Retained 2.00 mm (No.10)	68.5 mL (2.3 fl. oz.)	68.5 x 2.565 = 175.7 g	175.7/223.8 x 100 = 78.5%
Passing 2.00 mm (No. 10)	11.5 mL (0.4 fl. oz.)	11.5 x 2.678 = 30.8 g	30.8/223.8 x 100 = 13.8%
Binder	17.0 mL (0.6 fl. oz.)	17.0 x 1.02 = 17.3 g	17.3/223.8 x 100 = 7.7%
Air	3.0 mL (0.11 fl. oz)		
TOTAL	100.0 mL (3.5 fl. oz.)	223.8 g	100.0 %

Molded Density Greater than 97.2%

Use these steps for molded density greater than 97.2%.

Molded Density Greater Than 97.2%	
Step	Action
1	Add 5.0% to the total volume retained on the 2.00 mm (No. 10) sieve.
2	Subtract 5.0% from the volume passing the 2.00 mm (No.10) sieve.
3	- Determine new batch proportions in 'Calculations.' - Calculate new weight proportions as shown in the 'Mix Ratios if Molded Density is Greater than 97.2%' table.
4	Mix a 5000 g batch using mix proportions determined in 'Calculations' and the 'Mix Ratios if Molded Density is Greater than 97.2%' table.
5	Repeat Steps 1 through 15 of the 'Determining Optimum Asphalt Content' procedure.
6	- Plot density versus volume retained on the 2.00 mm (No. 10) sieve on the same graph with the first set of molds made in 'Part II, Determining Optimum Asphalt Content.' - Example is shown in 'Density vs. Volume of +#10 (Example).'
7	Interpolate to find the volume retained on the 2.00 mm (No.10) sieve where the density = 97.0%.

8	Mix and mold a set of specimens at the interpolated +2.00 mm (+No. 10) volume from Step 7.
9	Test for creep properties according to Test Method "Tex-231-F, Static Creep Test."

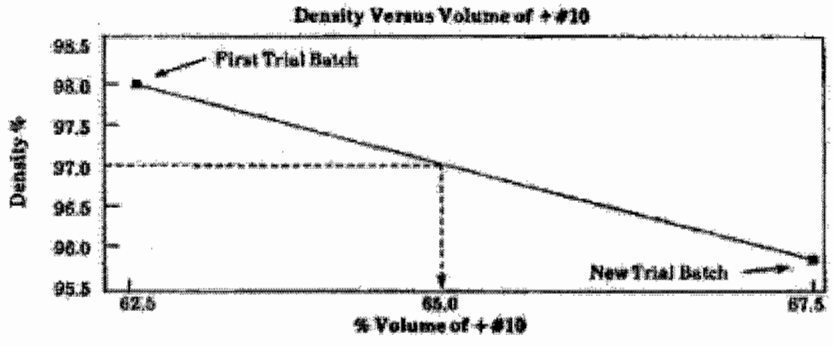

Figure 29-3. Density vs. Volume of + #10 (Example).

Calculations

Determine new batch proportions:

- Volume retained on 2.00 mm (No. 10) = 68.5 + 5.0 = 73.5%
- Volume passing 2.00 mm (No. 10) = 11.5 - 5.0 = 6.5%
- Volume of binder = 17.0%
- Volume of air = 3.0%.

Calculate new weight proportions in this ratio table.

Mix Ratios if Molded Density is Greater than 97.2%			
	Volume	Weight	Mix Proportion
Retained 2.00 mm (#10)	73.5 mL (2.5 fl. oz.)	73.5 x 2.565 = 188.5 g	(188.5/223.2) x 100 = 84.4%
Passing 2.00 mm (#10)	6.5 mL (0.22 fl. oz.)	6.5 x 2.678 = 17.4 g	(17.4/223.2) x 100 = 7.8 %
Binder	17.0 mL (0.6 fl. oz.)	17.0 x 1.02 = 17.3 g	(17.3/233.2) x 100 = 7.8 %
Air	mL (0.11 fl. oz.)		
TOTAL	100.0 mL (3.5 fl. oz.)	223.2 g	100.0%

Molded Density Less Than 96.8%

Follow these steps, referring to the calculations and tables that follow, to determine optimum asphalt content if molded density is less than 96.8%.

Molded Density Less Than 96.8%	
Step	Action
1	Add 2.0% to the volume of the binder.
2	Subtract 2.0% from the volume passing the 2.00 mm (No. 10) sieve.
3	Use 'Calculations' data and 'Mix Ratio if Molded Density is less than 96.8%' table to calculate new weight proportions.
4	Mix a 5000 g batch using the proportions determined in 'Calculations' and the 'Mix Ratios if Molded Density is Less than 96.8%' table.
5	Repeat Steps 1 through 15 of the 'Determining Optimum Asphalt Content' procedure.
6	☐ Plot density versus % volume of binder for the initial binder content and the second binder content. ☐ Example is shown in 'Density vs. Volume of Binder.'
7	Interpolate to find the volume of binder at a density of 97.0%.
8	☐ Mix and mold a set of specimens at the interpolated binder content from Step 7. ☐ Determine creep properties according to Test Method "Tex-231-F, Static Creep Test."

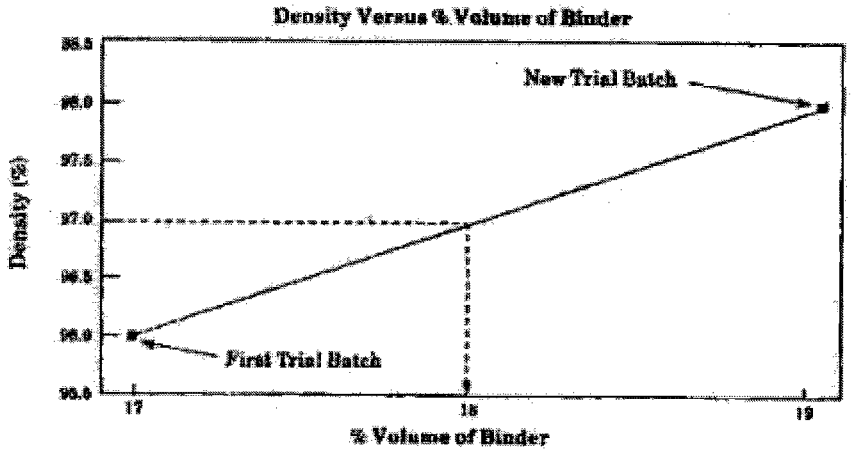

Figure 29-4 Density vs. Volume of Binder.

Calculations

Determine new trial batch proportions as shown by this example:

☐ Volume retained on 2.00 mm (No. 10) sieve = 68.5 %

- Volume passing 2.00 mm (No. 10) sieve = 11.5 - 2.0 = 9.5 %
- Volume of binder = 17.0 + 2.0 = 19.0 %
- Volume of air = 3.0 %.

Use this table to calculate new weight proportions.

Mix Ratios if Molded Density is Less than 96.8%			
	Volume	Weight	Total Mix Proportion
Retained 2.00 mm (No.10)	68.5 mL (2.3 fl. oz.)	68.5 x 2.565 = 175.7 g	(175.7/220.5) x 100 = 79.7%
Passing 2.00 mm (No. 10)	9.5 mL (0.32 fl. oz.)	9.5 x 2.678 = 25.4 g	(25.4/220.5) x 100 = 11.5%
Binder	19.0 mL (0.64 fl. oz.)	19.0 x 1.02 = 19.4 g	(19.4/220.5) x 100 = 8.8%
Air	3.0 mL (0.11 fl. oz.)		
Total	100.0 mL (3.5 fl. oz.)	220.5 g	100.0%

APPENDIX B: MODIFIED TEX-232-F, MIXTURE DESIGN PROCEDURE FOR CRUMB RUBBER MODIFIED ASPHALTIC CONCRETE

Section 1: **Overview**
Use this procedure to determine the proper proportions of approved aggregates and rubber-asphalt blend which, when combined, will produce a mixture that will satisfy the specification requirements.

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

Section 2: **Definitions**
The following term is referenced in this test method

- Binder - Binder is a blend of asphalt and ground rubber.

Section 3: **Apparatus**
The following apparatus is required:

► Apparatus listed in the following test methods

- "Tex-200-F, Sieve Analysis of Fine and Coarse Aggregates"
- "Tex-201-F, Bulk Specific Gravity and Water Absorption of Aggregate"
- "Tex-202-F, Apparent Specific Gravity of Material Finer than 180 mm (No. 80) Sieve"
- "Tex-205-F, Laboratory Method of Mixing Bituminous Mixtures"
- "Tex-206-F, Compacting Test Specimens of Bituminous Mixtures"
- "Tex-207-F, Determining Density of Compacted Bituminous Mixtures"
- "Tex-227-F, Theoretical Maximum Specific Gravity of Bituminous Mixtures."
- "Tex-241-F, Superpave Gyratory Compacting of Test Specimens of Bituminous Mixtures."

Section 4: Part I, Determining Optimum Gradation

Use this method to determine the optimum gradation

Procedure
Follow these steps to determine optimum gradation.

Determining Optimum Gradation	
Step	**Action**
1.	• Obtain representative samples of each processed aggregate lot proposed for use according to Test Method "Tex-221-F, Sampling Aggregate for Bituminous Mixtures, Aggregate for Surface Treatment, and Limestone Rock Asphalt." • Approximately 100 lb. (45 kg) of each aggregate stockpile will be required.
2.	Dry the aggregate in an oven at a temperature between 100 °F (38 °C) and 302 °F (150 °C).
3.	• Obtain the average gradation of each proposed aggregate stockpile according to 'Part II, Washed Sieve Analysis' of Test Method "Tex-200-F, Sieve Analysis of Fine and Coarse Aggregates." • Use samples taken from several locations in the stockpile and average the results. (When this is not possible, the aggregate samples received in the laboratory may be quartered and used for the sieve analysis.).
4.	Determine the 24-hour water absorption and specific gravity of each size of each aggregate according to test methods "Tex-201-F, Bulk Specific Gravity and Water Absorption of Aggregate" and "Tex-202-F, Apparent Specific Gravity of Material Finer than No. 80 (180 mm) Sieve." NOTE: (Normally, specific gravities are not determined for size fractions consisting of less than 15 % of the individual aggregate. Smaller size fractions are assigned the water absorption and specific gravity of the next adjacent size fraction for which values were determined.)
5.	Calculate the initial desired combined gradation using the solver program (Excel Sheet). As a guideline, keep a ratio of 1.5 to 2.0 between the two coarsest sieves on which aggregate is retained. (Use this initial gradation only to determine aggregate grading factors). • Use Solver Tool of Excel Sheet. • Third parameter is target cell. • Enter average gradation of each proposed aggregates, found in step 3 in appropriate cells. • Give any number for the percentage of stockpiles and then start iteration on any value by clicking on solver button until gradation is within specified limits.

- After finding the gradation prepare 2 G_{mb} and 2 G_{mm} with 4% neat asphalt using TGC for the volumetric analysis (Calculations). Determine percent volume retained on the 2.00 mm (No. 10) sieve for example it is 66.0 %.
- Add 2.5 % to the total volume retained on 2.00 mm (No. 10) sieve. The new target gradation will be 68.5% by volume retained on the 2.00 mm (No.10) sieve.

Calculations I:

Calculate volume of total retained on the 2.00 mm (No. 10) sieve for each set of molded specimens:

$$\%\ (V)_{2.00\ mm\ (+No.10)} = (V_{2.00\ mm\ (+No.10)} / V_s) \times 100$$

Where:

- $V_{2.00\ mm\ (+10)} = W_{2.00\ mm\ (+No.\ 10)}/G_{2.00\ mm\ (+No.\ 10)}$ = Volume of aggregate retained on 2.00 mm (No. 10) sieve
- V_s = Volume of molded specimen = W_s/G_s
- Ws = Weight of dry molded specimen, Test Method "Tex-207-F, Determining Density of Compacted Bituminous Mixtures"
- W_{ar} = Weight of binder in molded specimen
- $W_{-2.00\ mm\ (-10)}$ = Weight of aggregate passing 2.00 mm (No. 10) sieve
- $W_{2.00\ (+10)}$ = Weight of aggregate retained on 2.00 mm (No. 10) sieve
- V_{air} = Volume of air
- V_{ar} = Volume of binder = W_{ar}/G_{ar}
- VMA = $V_{air} + V_{ar}$
- $V_{-2.00\ mm\ (-10)} = W_{-2.00\ mm\ (-No.\ 10)}/G_{-2.00\ mm\ (-No.\ 10)}$ = Volume of aggregate passing 2.00 mm (No.10) sieve
- G_s = Bulk specific gravity of molded specimen, Test Method "Tex-207-F. Determining Density of Compacted Bituminous Mixtures"
- $G_{2.00\ mm\ (+10)}$ = Bulk specific gravity of aggregate retained on 2.00 mm (No. 10) sieve, test method "Tex-201-F, Bulk Specific Gravity and Water Absorption of Aggregate"
- $G_{-2.00\ mm\ (-10)}$= Specific gravity of aggregate passing 2.00 mm (No. 10) sieve, test methods "Tex-201-F, Bulk Specific Gravity and Water Absorption of Aggregate" and "Tex-202-F, Apparent Specific Gravity of Material Finer than 180 µm (No.80) Sieve"
- G_{ar} = Specific gravity of binder at 68 °F (20 °C).

A graphical representation of components of a molded specimen is shown in 'Volumetric Analysis of Molded Specimens.'

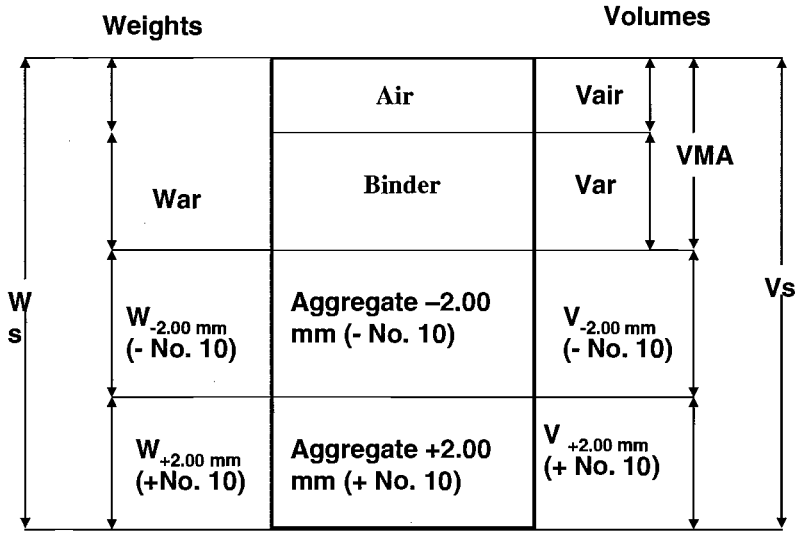

Figure: Volumetric Analysis of Molded Specimens

Section 5: Part II, Determining Optimum Asphalt Content

Determining Optimum Asphalt Content	
Step	**Action**
1.	• Weigh enough aggregate, asphalt, and crumb rubber to make an 11 lb. (5,000 g) for TGC and 37.5 lb. (17,000 g) for SGC using batch of mix using the stockpile percentages shown in "calculations II". • Use the binder content determined in the '*Ratio of Volume to Weight in % of Total*' table.
2.	Heat the aggregate to a minimum temperature of 375 °F (190 °C).
3.	Blend asphalt rubber by heating a known quantity of asphalt cement to 375 °F and adding specified crumb rubber based on total weight, to the heated asphalt. Stir the mixture slowly until all rubber particles become wet with asphalt and place the sample in 350 °F oven. Stir the mixture again in 30 minutes and place back in 350 °F oven.
4.	Remove from the oven at the end of one hour and measure the viscosity using a Haake viscometer. • If the viscosity meets the required specification, proceed with Step 5. • If the viscosity is below the minimum requirement, stir the binder thoroughly and return it to the 350 °F oven for 30-minute increments until it reaches a satisfactory

	viscosity.
5.	Thoroughly stir the heated binder and add the appropriate amount to the heated aggregate.
6.	Mix with a mechanical mixer according to method "Tex-205- F, Laboratory Method of Mixing Bituminous Mixtures." The hot mix is very sticky so spray little bit of WD 40 in mixer prior to mixing. Keep the hot mix in the oven at 400°F for short-term aging. Keep the mold and its plates also in the oven at 400°F.
7.	• Weigh three separate 2.2 lb. (1,000 g) samples of the mix for molding using TGC and three separate 11.01 lb (5000 g) samples of the mix for molding using SGC. • Save the remaining mix for determining the theoretical maximum specific gravity.
8.	Cure all four samples in an oven preheated to 400 °F (205 °C) for 2 hours
9.	Mold the three 2,200 lb. (1,000 g) specimens according to Test Method "Tex-206-F, Compacting Test Specimens of Bituminous Mixtures. Mold the three 11.01 lb (5000 g) specimens according to Test Method "Tex-241-F, Superpave Gyratory Compacting of Test Specimens of Bituminous Mixtures." • To avoid temperature loss, after pouring hot mix in the mold keep mold inside the oven for 15 minutes. • Heights must be 2 ± 0.1 in. (50.8 ± 2.5 mm) for TGC and 4.5 ± 0.2 in. (115 ± 5 mm) for SGC (some important steps for the compaction of specimen using SGC is in step 10). • Leave the samples in the molds until they are cool to touch for TGC specimens.
10.	In addition to test method Tex-241-F there are some additional steps for compacting specimen using SGC are following:- • To avoid temperature loss, after pouring hot mix in the mold keep mold inside the oven for 15 minutes. • N_{des} for the compaction is 106 gyrations. • After compacting hot mix till desired gyrations press the emergency stop in SGC machine so that 87 psi. (600 kPa) stresses will be on specimen and leave the mold with specimen inside SGC for 45 minutes. Application of stress after compaction is to restrain the axial expansion. • After 45 minutes remove specimen from mold and tie in PVC pipe to restrain horizontal expansion. • If height of specimen at 106 gyrations is more than 4.724 in. or less than 4.331 in. (120 mm or less than 110 mm), decrease or increase the weight of hot mix to obtain height within the specified range.

11.	Determine the maximum specific gravity according to Test Method "Tex-227-F, Theoretical Maximum Specific Gravity of Bituminous Mixtures.
12.	Determine the bulk specific gravity and relative density of molded specimens according to Test Method "Tex-207-F, Determining Density of Compacted Bituminous Mixtures."
13.	Calculate the density of the molded specimens using the theoretical maximum specific gravity determined from Test Method "Tex-227-F, Theoretical Maximum Specific Gravity of Bituminous Mixtures.
14.	If the molded density is equal to 97 ± 0.2%, determine the creep properties of the mixture according to Test Method "Tex-231-F, Static Creep Test."
15.	• If the density is greater than 97.2 %, perform the 'Molded Density Greater than 97.2%' procedure. • If the molded density is less than 96.8%, perform the 'Molded Density Less than 96.8%' procedure.

Calculations II:

- Determine the first estimated volume of air, asphalt, and - 2.00 mm (- No. 10) aggregate:

$V_{+2.00\ mm\ (+No.\ 10)} + V_{-\ 2.00\ mm\ (-No.\ 10)} + V_{ar} + V_{air} = 100\%$

- From part I: $V_{+2.00\ mm\ (+No.\ 10)} = 68.5$
- $V_{air} = 3\%$ (as set in the specification)
- VMA = minimum 20 (as set in the specification)
- $V_{ar} = VMA - V_{air} = 20-3=17\%$ minimum
- $V_{-2.00\ mm\ (-No.\ 10)} = 100\% - 68.5\% - 17\% - 3\% = 11.5\%$.

Calculate the combined aggregate gravities from the bulk gravities of individual sizes. For the example proportions determined in Calculation No. 1, the following gravities are calculated:

- $G_{b + 2.00\ mm\ (+No.\ 10)} = 2.565$
- $G_{b- 2.00\ mm\ (-No.\ 10)} = 2.678$
- The gravity of the binder (G_{ar}) is 1.02.
- Calculate the weight of each of the volumes determined in Calculation No. 1 by multiplying the volume times its gravity.
- Assume the total volume of the molded specimen to be 100 mL (3.5 fl. oz.).
- For the proportions determined in Calculation No. 1, the weight of the + 2.00 mm (No. 10) portion of the aggregate is:

$$68.5*2.565 = 175.7 \text{ grams}$$

- Refer to the 'Ratios of Volume to Weight in % of Total' table for the weight conversions of the other components. The total weight of a 100 mL (3.5 fl. oz.) molded specimen using these aggregates is 223.8 g.

- Calculate the percent by weight of total mix of each of the components calculated in Calculation No. 3 by dividing the component weight by the total molded specimen weight. For the weights determined, the % by weight retained on the 2.00 mm (No. 10) sieve is:

$$(175.7/223.8)*100 = 78.5$$

- Calculate the percentages of each stockpile necessary to obtain the total weight percentages of +2.00 mm (+No. 10), -2.00 mm (-No. 10) , and binder calculated in the 'Ratios of Volume to Weight in % of Total' table.

Ratio of Volume to Weight in % of Total			
	Volume	**Weight (g)**	**% of Total**
Retained 2.00 mm (No.10)	68.5 ml (2.3 fl. oz.)	68.5 × 2.565 = 175.7	175.7/223.8 × 100 = 78.5 %
Passing 2.00 mm (No.10)	11.5 ml (0.4 fl. oz.)	11.5 × 2.678 = 30.8	30.8/223.8 × 100 = 13.8 %
Binder	17.0 ml (0.6 fl. oz.)	17.0 × 1.02 = 17.3 g	17.3/223.8 × 100 = 7.7 %
Air	3.0 ml (0.11 fl. oz.)	--	--
TOTAL	100.0 ml (3.5 fl. oz.)	223.8 g	100 %

Molded Density Greater than 97.2%

Use these steps for molded density greater than 97.2%.

Molded Density Greater Than 97.2%	
Step	**Action**
1.	Add 5.0% to the total volume retained on the 2.00 mm (No. 10) sieve.
2.	Subtract 5.0% from the volume passing the 2.00 mm (No.10) sieve.
3.	• Determine new batch proportions (calculations III). • Calculate new weight proportions if Molded Density is Greater than 97.2%' table.
4.	Mix a 5000 g batch using mix proportions determined if Molded Density is Greater than 97.2%' table.
5.	Repeat Steps 1 through 15 of the 'Determining Optimum Asphalt Content' procedure.
6.	• Plot density versus volume retained on the 2.00 mm (No. 10) sieve on the same graph with the first set of molds made in 'Part II, Determining Optimum Asphalt Content. • Example is shown in 'Density vs. Volume of +#10 (Example).
7.	Interpolate to find the volume retained on the 2.00 mm (No.10) sieve where the density = 97.0%.
8.	Mix and mold a set of specimens at the interpolated +2.00 mm (+No. 10) volume from Step 7.
9.	Test for creep properties according to Test Method "Tex-231-F, Static Creep Test.".

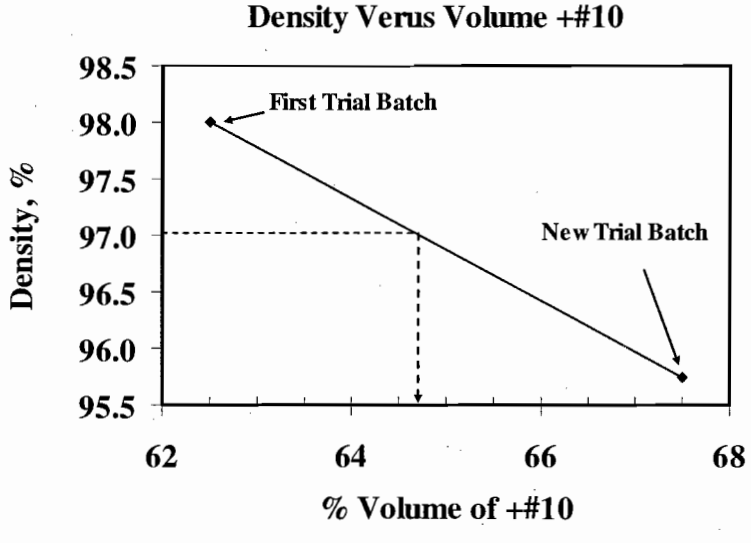

Figure . Density vs. Volume of + #10 (Example).

Calculations III:

Determine new batch proportions:

- Volume retained on 2.00 mm (No. 10) = 68.5 + 5.0 = 73.5%.
- Volume passing 2.00 mm (No. 10) = 11.5 - 5.0 = 6.5 %
- Volume of binder = 17.0 %
- Volume of air = 3.0 %

Mix Ratios if Molded Density is Greater than 97.2 %			
	Volume	**Weight (g)**	**% of Total**
Retained 2.00 mm (No.10)	73.5 ml (2.5 fl. oz.)	73.5 × 2.565 = 188.5 g	188.5/223.2 × 100 = 84.4 %
Passing 2.00 mm (No.10)	6.5 ml (0.22 fl. oz.)	6.5 × 2.678 = 17.4 g	17.4/223.2 × 100 = 7.8 %
Binder	17.0 ml (0.6 fl. oz.)	17.0 × 1.02 = 17.3 g	17.3/223.2 × 100 = 7.8 %
Air	3.0 ml (0.11 fl. oz.)	--	--
TOTAL	100.0 ml (3.5 fl. oz.)	223.2 g	100 %

Molded Density Less Than 96.8%

Follow these steps, referring to the calculations and tables that follow, to determine optimum asphalt content if molded density is less than 96.8%.

Molded Density Less Than 96.8%	
Step	**Action**
1.	Add 2.0% to the volume of the binder.
2.	Subtract 2.0% from the volume passing the 2.00 mm (No. 10) sieve.
3.	Use 'calculations IV' data and "Mix ratio if Molded Density is less than 96.8 %"
4.	Mix a 5000 g batch using mix proportions determined if Molded Density is Less than 96.8%'.
5.	Repeat Steps 1 through 15 of the 'Determining Optimum Asphalt Content' procedure.
6.	• Plot density versus % volume of binder for the initial binder content and the second binder content. • Example is shown in 'Density vs. Volume of Binder.'
7.	Interpolate to find the volume of binder at a density of 97.0%.
8.	• Mix and mold a set of specimens at the interpolated binder content from Step 7. • Determine creep properties according to Test Method "Tex-231-F, Static Creep Test.".

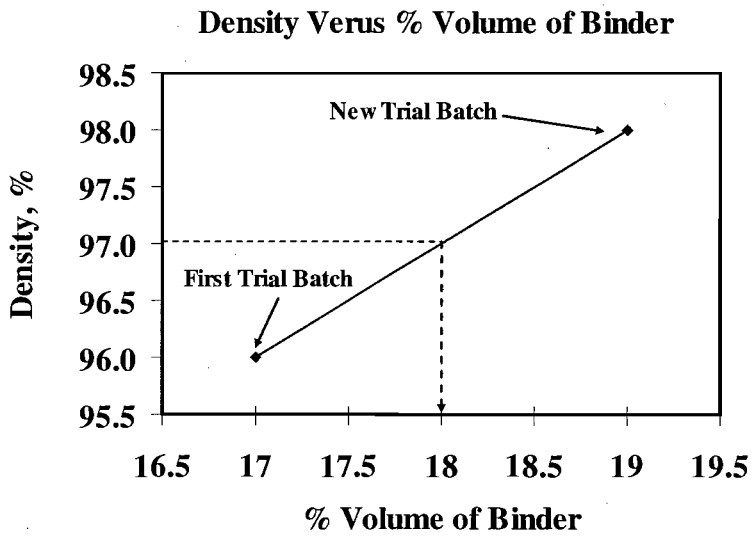

Figure . Density vs. Volume of Binder (Example).

Calculations IV:

- Volume retained on 2.00 mm (No. 10) = 68.5 %.
- Volume passing 2.00 mm (No. 10) = 11.5 – 2.0 = 9.5 %
- Volume of binder = 17.0 + 2.0 = 19.0 %
- Volume of air = 3.0 %

Mix Ratios if Molded Density is Less than 96.8 %			
	Volume	**Weight (g)**	**% of Total**
Retained 2.00 mm (No.10)	68.5 ml (2.5 fl. oz.)	68.5 × 2.565 = 175.7 g	175.7/220.5 × 100 = 79.7 %
Passing 2.00 mm (No.10)	9.5 ml (0.32 fl. oz.)	9.5 × 2.678 = 25.4 g	25.4/220.5 × 100 = 11.5 %
Binder	19.0 ml (0.64 fl. oz.)	19.0 × 1.02 = 19.4 g	19.4/220.5 × 100 = 8.8 %
Air	3.0 ml (0.11 fl. oz.)	--	--
TOTAL	100.0 ml (3.5 fl. oz.)	220.5 g	100 %