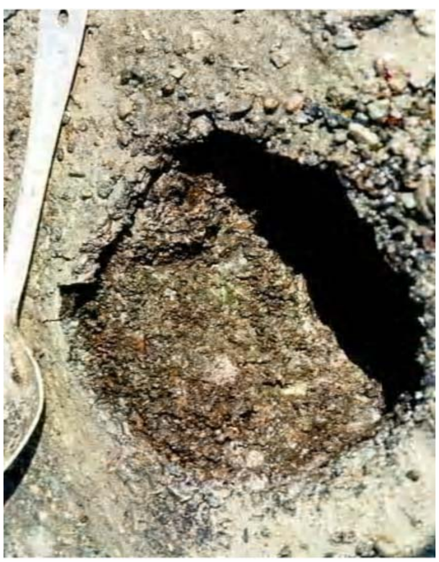
Refine AASHTO T283 Resistance of Compacted Bituminous Mixture to Moisture Induced Damage for Superpave



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for the
Ohio Department of Transportation
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and the
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16. Abstract

Moisture induced damage in asphalt concrete pavements, better known as stripping, is one of primary causes of distresses in the asphalt pavement layers. AASHTO T 283 has historically been used to detect moisture damage potential of asphalt mixes. This method is established for the Marshall mix design process. However, the current hot mix asphalt design calls for the use of Superpave mix design procedure using the Superpave Gyratory Compactor (SGC). The differences in the mix design methods will most likely introduce significant differences in stripping test results. Therefore, to improve the AASHTO T 283 test procedure and to develop the new criterion for the Superpave HMA specimens, this project was conducted to evaluate the applicability of AASHTO T 283 to the Superpave mixes.

A structured laboratory test program was conducted in this research to study the effects of the various factors on the HMA specimen's susceptibility to moisture damage. A complete factorial experimental program for two aggregate sources with virgin asphalt binder was conducted together with a partial factorial experimental program for the other two aggregate sources with polymer modified asphalt binders.

In the data analysis, the effects of different factors on dry tensile strength, freeze-thaw conditioned tensile strength, and tensile strength ratio (TSR) were investigated in this report. The effects of all the factors investigated in this research are summarized in this report. The recommendations for the proposed stripping test procedure for Superpave HMA are given at the end of the report.

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Prepared in cooperation with the Ohio Department of Transportation and the U.S. Department Transportation, Federal Highway Administration.

January 2008

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CHAPTER I

INTRODUCTION

1.1 Problem Statement

Moisture damage in asphalt concrete pavements, better known as stripping, is a primary cause of distresses in the asphalt pavement layers (Hicks, 1991; Pan et al., 1999; and Epps, 2000). The existence of water in asphalt pavement is often one of the major factors affecting the durability of HMA. The water induced damage in HMA layers may be associated with two mechanisms: loss of adhesion and/loss of cohesion (Hicks 1991). In the first mechanism, the water gets between the asphalt and aggregate and strips the asphalt film away, leaving aggregate without asphalt film coverage, as illustrated in Figure1- 1 and Figure1- 2. This is because the aggregates have a greater kinship for water than asphalt binder. The second mechanism includes the interaction of water with the asphalt cement that reduces the cohesion within the asphalt cement. This will lead to a severe reduction in the asphalt mixture strength.

The water sensitivity test methods listed below are national standards and are used by public agencies (AASHTO and ASTM):

- AASHTO T283, "Resistance of Compacted Bituminous Mixture to Moisture Induced Damage"

- ASTM D4867, "Effect of Moisture on Asphalt Concrete Paving Mixtures"

- AASHTO T165/ASTM D1075, "Effect of Water on Compressive Strength of Compacted Bituminous Mixtures"

- ASTM D3625, "Effect of Water on Bituminous-Coated Aggregate Using Boiling Water."

AASHTO T283 is based on research performed by R. P. Lottman under NCHRP Project 4-08(03) and subsequent research performed by D. G. Tunnicliff and R. E. Root under NCHRP Project 10-17. The AASHTO method indicates that it is suitable for testing samples prepared as part of the mixture design process (i.e., laboratory-mixed–laboratory--compacted), as part of the plant control process (i.e., field-mixed–laboratory-compacted) and for cores taken from the roadway (i.e., field-mixed–field-compacted).

The AASHTO procedure ages the mixed, loose HMA for 16 hr at 60 °C. After compaction to an air-void content of 7 percent ±1 percent, the samples are extruded from the compaction mold and allowed to age 24 hours at room temperature. The samples are then placed under water, and a vacuum is used to saturate the samples to a degree of saturation level between 55-80 percent (AASHTO T283-99) or 70-80 percent (AASHTO T283-03). A freeze cycle (16 hr at -18 °C) and a thaw-soak cycle (24 hr at 60 °C) are used to condition the sample prior to indirect tension testing at 25 °C.

The most widely used method for determining HMA moisture resistance is the AASHTO Standard Method of Test T 283, "Resistance of Compacted Bituminous Mixture to Moisture Induced Damage". It is established for the Marshall mix process that uses 4 inch specimens. On the other hand, the Superpave mix design process is being conducted using 6 inch diameter specimens and with a totally different compaction device, Superpave Gyratory Compactor (SGC), for compacting and preparing the specimens. The differences in the mix design methods will most likely introduce significant differences in the moisture resistance test results for the same materials. Currently, SHRP recommended the use of AASHTO T 283 to evaluate the water sensitivity of HMA within the Superpave volumetric mixture design system. Recently, NCHRP 444 (2000) and FHWA/IN/JTRP-97/13 (1997) studies called the public agencies to conduct their own experiments, using their aggregate and asphalt binder sources, before making any modifications to the AASHTO T 283. In 2004 TRB Annual Meeting, Hicks et al. (2004) summarized the road map for mitigating national moisture sensitivity concerns in hot mix pavements, in which they pointed out the need of updating the test method regarding the method of specimen preparation, degree of saturation, air void determination, standardization, and certification.

Ohio Department of Transportation has already implemented Superpave Level I volumetric based design method for developing Job Mix Formula (JMF) for HMA. In the meantime, there has been a lag behind the necessary structured laboratory experiments to ascertain the applicability of current AASHTO T 283 to Ohio's Superpave mixes. This research is to conduct a structured laboratory test program using Ohio typical aggregate and asphalt binder, so that AASHTO T 283 can be either modified or improved to make it suitable for Superpave HMA.

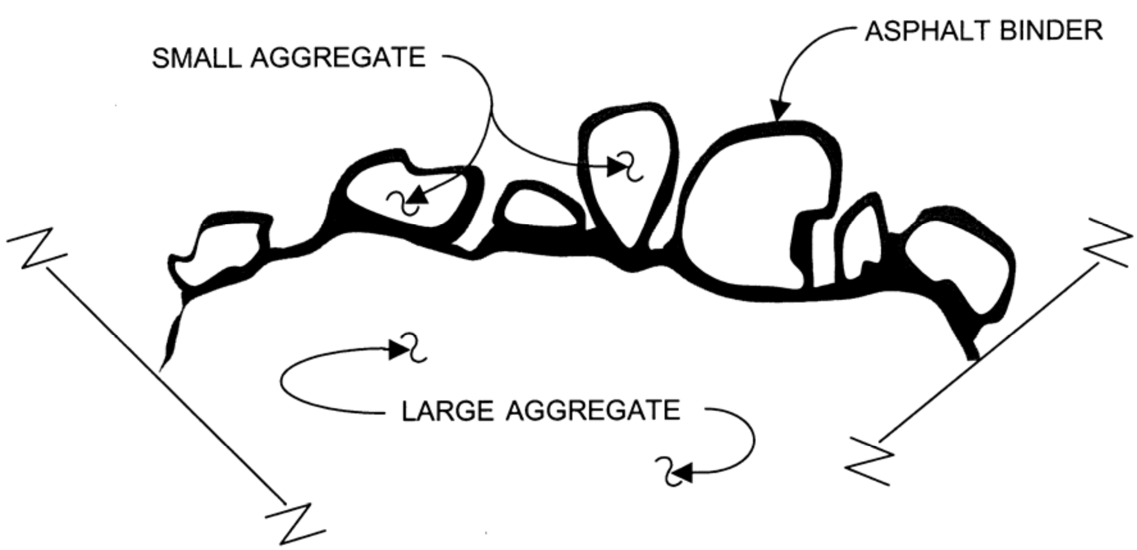

Figure1- 1 HMA at the Time of Mixing (McCann et al., 2001)

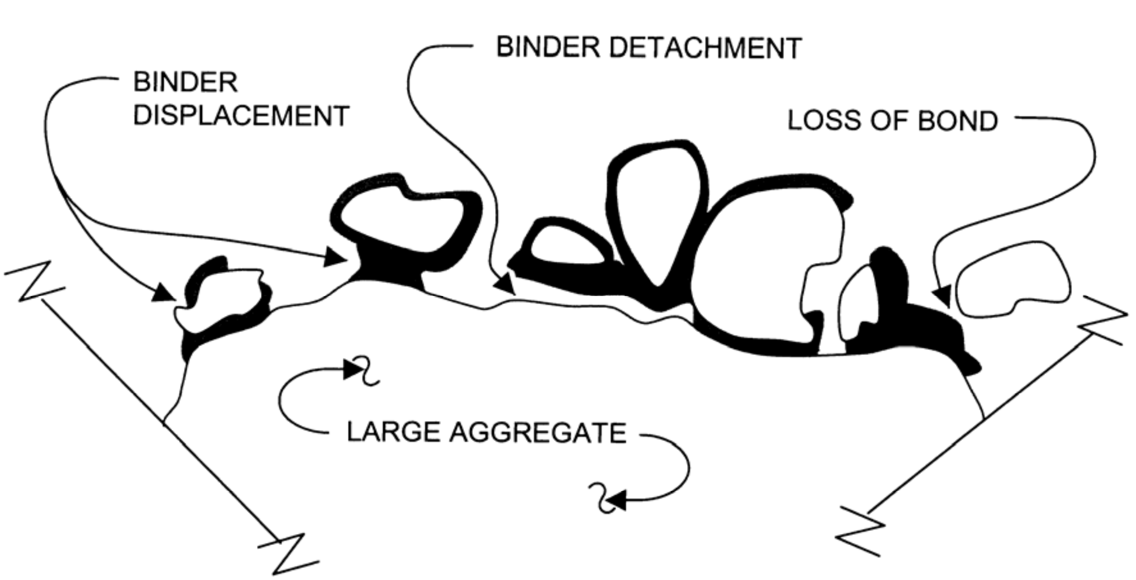

Fig. 1- 2 Displacement and Detachment of Asphalt Binder in the Presence of Moisture (McCann et al., 2001)

1.2 Objectives of the Study

The main objective of this study is to improve and modify the AASHTO T 283, resistance of compacted asphalt mixtures to moisture induced damage, specifically for Superpave HMA in Ohio.

Specific objectives of the study are enumerated below:

- Conduct a structured laboratory experimental study on the various factors affecting dry tensile strength, freeze-thaw tensile strength, and tensile strength ratio (TSR). The factors to be studied include aggregate source, asphalt binder, compaction method, specimen size, aging method, degree of saturation, and freeze-thaw cycle. The laboratory experimental program is divided into two parts: one part is a complete factorial experimental program for two aggregate sources with virgin asphalt binder, the second part is a partial factorial experimental program for the other two aggregate sources with polymer modified asphalt binders. The complete factorial experiment is used to identify and evaluate the influences of the individual factors, along with all the possible interactions among the various factors. The partial factorial experiment program, on the other hand, is used to validate findings from a complete factorial experiment program.

- A comprehensive analysis of test data, using statistical analysis, such as ANOVA (Analysis of Variance) technique and regression analysis technique, is conducted to derive quantitative grouping of the importance of various test variables. This information, in turn, will be used to enable objective modification of current AASHTO and NCHRP (SHRP) test procedures, leading to the development of specific recommendations for AASHTO T 283 test procedures for ODOT.

- Develop test procedures for moisture damage assessment, based on proper modification of AASHTO T283, for ODOT implementation.

1.3 Organization of Report

The organization of this report is as follows:

- Chapter II presents the literature review of current research activities and findings about the water stripping test.
- Chapter III presents the testing plan and test results of the structured laboratory experimental program.
- Chapter IV presents the complete analysis results of the complete factorial test data. Effects of various factors on the water stripping test results are given.
- Chapter V presents analysis of the partial factorial test data and recommended water stripping test procedures for Superpave HMA specimens.
- Chapter VI presents summaries and conclusions of the research work. Also, recommendations for the new moisture damage test procedure are provided.

CHAPTER II

LITEATURE REVIEW

2.1 Background and Significance of Work

In the late 1970s and early 1980s, a significant number of pavements in the United States began to experience distress associated with moisture sensitivity of hot-mix asphalt (HMA) materials. Rutting, raveling, and cracking due to moisture induced damages were observed on many pavements. The causes of this sudden increase in pavement distress because of water sensitivity have not been conclusively identified.

Regardless of the cause of this moisture-related premature distress, methods are needed to identify HMA behavior in the presence of moisture. Test methods and pavement performance prediction tools need to be developed that couple the effects of moisture on the properties of HMA mixtures with performance prediction to estimate the behavior of the mixture in resisting rutting, fatigue, and thermal cracking when it is subjected to moisture under different traffic levels in various climates.

Most state highway agencies have implemented the Superpave (Superior Performing Asphalt Pavement) mix design system developed through the five year research effort of Strategic Highway Research Program (SHRP). This mix design method allows agencies or contractors to design asphalt mixes that meet certain performance requirements as dictated by traffic, environment, and location of the pavement system (Cominsky et al., 1994). Superpave mixes have typically been coarse-graded (gradation passing below the maximum density line) in order to provide a greater volume of stone in the mix to aid in reducing the potential for rutting, fatigue and stripping, and to provide stronger HMA pavement layer than that designed in the conventional methods using Marshall mix design (Hall et al., 2000). The Superpave level I mix design (volumetric based design) is based on gyratory compactor, as shown in Figure 2-1, which typically produces 6 inch diameter specimens.

2.2 AASHTO T-283 Test Method

Several laboratory tests have been developed to assess the moisture susceptibility of HMA. Laboratory testing does not entirely simulate field conditions; however, it can provide useful information. These tests developed for the evaluation of moisture damage either assess the stripping of asphalt from the aggregate surface or the loss in the strength of the compacted HMA specimens.

Currently, AASHTO T 283 Specification is the most widely used method to evaluate the HMA stripping potential. The T 283 procedure consists of preparing 6 HMA samples using Marshall impact compaction method. A picture of the Marshall Impact Compactor is shown in Figure 2-2. The air voids of the prepared samples are between 6 and 8 percent. The required high percentage of air voids helps accelerate moisture damage to the HMA specimens. The samples are divided into two groups: the first group is the control group, or “unconditioned”, while the second group, or “conditioned”, is vacuum-saturated (a picture of the device for sample saturation is shown in Figure 2-3) 55-80 percent (AASHTO T283-99) or 70-80 percent (AASHTO T283-03) with water and then placed in a freezer at 0º F for 16 to 18 hours.

The conditioned specimens are then placed in a water bath (A picture of the device for bathing is shown in Figure 2-4) at 140º F for 24 hours. After the freeze/thaw conditioning is done, the indirect tensile strength (S_t) measured by MTS machine (A picture of MTS machine is shown in Figure 2-5) or a simpler machine is determined for all samples with a loading rate of 2 in/min. The tensile strength of “conditioned” sample $S_{t(Conditioned)}$ is compared to the tensile strength of “unconditioned” sample $S_{t(Control)}$ to determine Tensile Strength Ratio (TSR) as follows:

$$TSR = \frac{S_{t(Conditioned)}}{S_{t(Control)}} \quad \text{(Eq. 1)}$$

A visual (subjective) estimation of the magnitude of stripping of the conditioned sample completes the test procedure. In summary, most agencies use a minimum value of TSR = 80% in the moisture sensitivity test for Superpave HMA mixtures.

Figure 2-1 The Superpave Gyratory Compactor

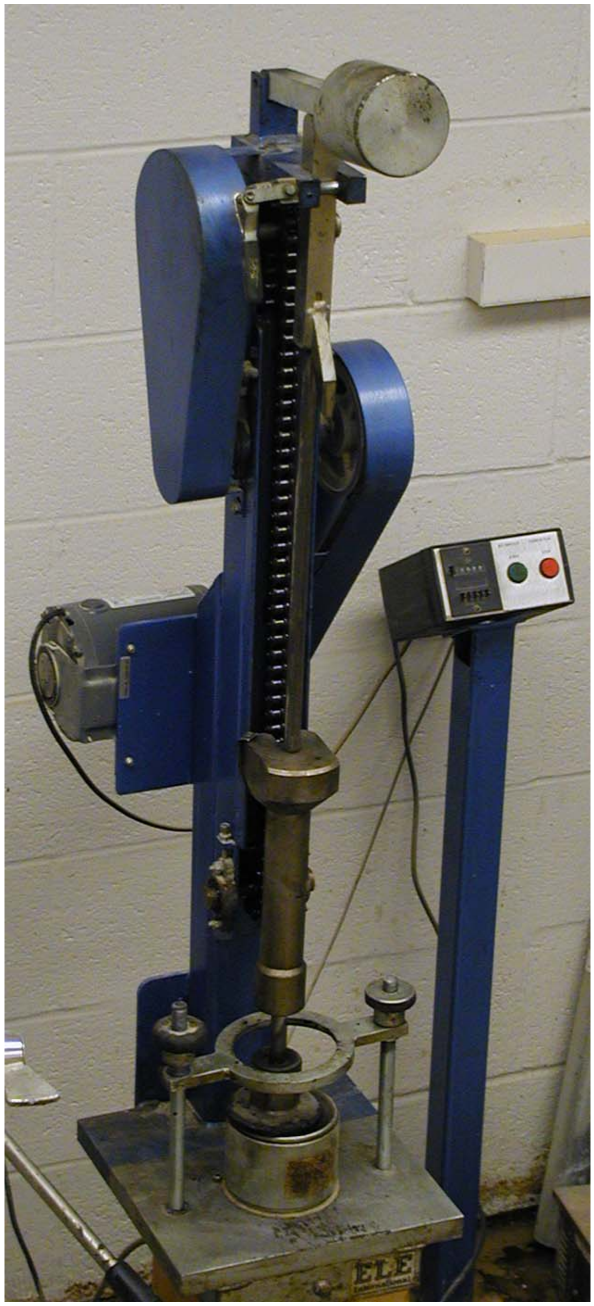

Figure 2-2 The Marshall Impact Compactor

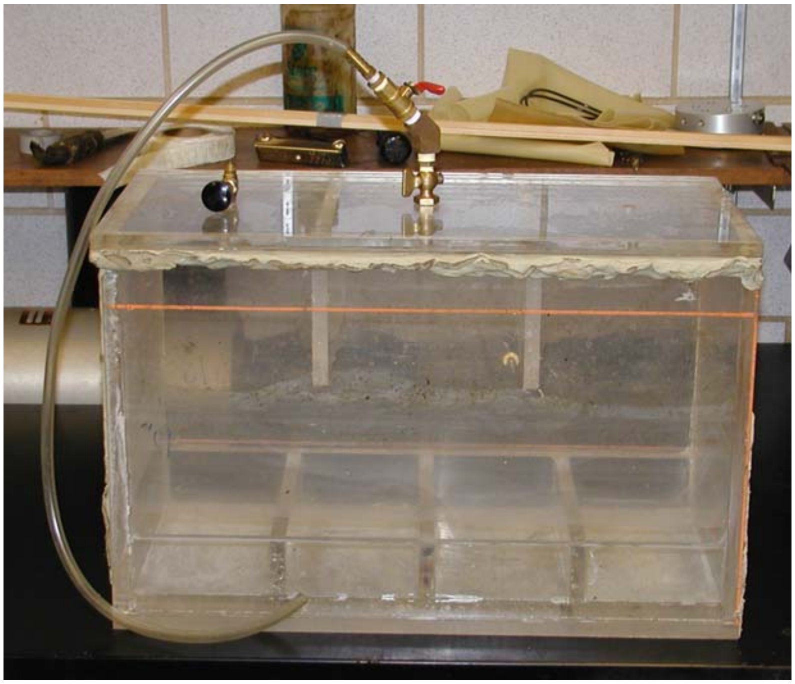

Figure 2-3 The Saturation Chamber

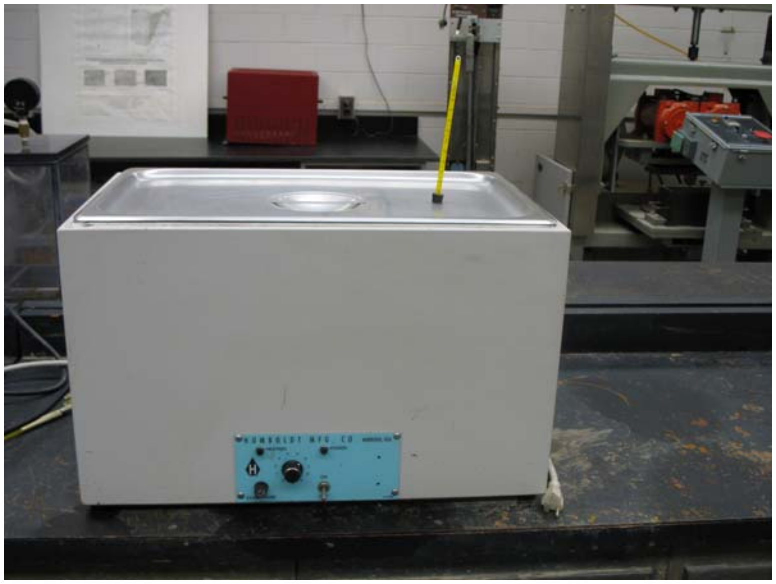

Figure 2-4 Water Bath Container

Fig. 2-5 MTS Machine

2.3 Efforts to Develop Alternative Test Methods

Buchanan et al. (2004) summarized some of the disadvantages of the AASHTO T 283 as follows:

1) Performance of T 283 test is time consuming.
2) The wide range of saturation level (55% - 80%) may result in substantial TSR variability.
3) Uncertainty of test results on the Superpave specimens due to the difference in the Superpave specimen size of 6 inches diameter, as contrast to the 4 inch diameter Marshall samples in the T 283 Specifications.
4) Visual (subjective) examination is required to estimate the magnitude of the conditioned sample stripping.
5) The conditioning procedure in T 283 does not simulate repeated generation of pore pressure under loads, which is believed to be a major cause of stripping in HMA pavements.

As a result, there have been numerous studies focusing on investigating new testing methods or procedures that can characterize the water sensitivity in Superpave HMA, as a substitute to the AASHTO T 283.

Cross et al. (2000) used the loaded wheel tester of Asphalt Pavement Analyzer (APA) to detect moisture susceptible mixtures. Eight different mixes from seven project sites were evaluated with APA. Samples were tested using four different preconditioning procedures: dry, soaked, saturated, and saturated with a freeze cycle. The results were compared with TSR values as well as other aggregate tests. The results indicated that the APA could be utilized to evaluate the moisture susceptibility of asphalt mixes. Additionally, the results indicated that harsh preconditioning of saturation or saturation with a freeze cycle did not result in the increased wet rut depth.

Pan et al. (1998 and 1999) used Purdue Wheel tracking device (PURWheel) to predict the conditions that promote water stripping of HMA specimens. Two major variables were selected for the research, aggregate type and antisripping additive. These variables were used in the experimental designs to characterize the bituminous mixture performance relative to environmental factors such as moisture and temperature. The PURWheel proved to be an effective tool for evaluating HMA mixture stripping potential in a hot/wet environment. The PURWheel also is shown capable of evaluating HMA mixture hot/wet rutting potential. Pan et al. (1998 and 1999) also pointed out that results from AASHTO T283 indicated that moisture conditioning has a significant effect on the stripping potential of the seven mixes tested. The tensile strength of the mixture was reduced after subjected to the environmental conditioning procedures in AASHTO T283 tests. Laboratory wheel tracking test results for all seven types of mixtures indicated that temperature and moisture conditions were significant. It is obvious that damage occurs much faster with wet conditions. Both factors are important in identifying asphalt mixture stripping/rutting potential. Aggregate type has a significant effect on the wheel track test results. Limestone generally provided better performance than other types of aggregate.

McCann et al. (2001) used the ultrasonic moisture accelerated conditioning process to quantify the moisture sensitivity of HMA pavement. A total of 13 HMA mixtures were subjected to ultrasonic moisture accelerated conditioning. The mixtures represented typical Hveem or Superpave mixtures with a 25 mm maximum size aggregate used by the Nevada Department of Transportation. For the laboratory assessment of moisture sensitivity within the mixes, variables included grade of asphalt binder, percent asphalt binder, aggregate type, and mixes with and without lime. Test results from ultrasonic conditioning were then compared to tensile strength ratios derived from the conventional testing procedures. The main conclusion of the research was that the research hypothesis "the loss of material is proportional to the length of time a HMA sample is subjected to ultrasonic conditioning" is found to be true. For the HMA mixes subjected to ultrasonic conditioning and analyzed using linear regression, differences as to aggregate source, type of binder, lime used as an aggregate additive, and the percent asphalt binder within the mix could be detected. The determination for the potential of stripping by ultrasonic moisture accelerated conditioning is analogous to results established by tensile strength testing after 18 cycles of freeze-thaw conditioning.

In Mississippi, Buchanan et al. (2004) evaluated the use of Moisture Induced Stress Tester (MIST) for moisture sensitivity tests and compared its results with that of AASHTO T 283. Basically the MIST simulates HMA pavement stripping mechanism by using compressed air to force water out of the HMA and then by depressuring (creating vacuum) to pull back water into the specimen. By repeating the pressure/depressurization cycles, stripping in a form of emulsification of the asphalt binder and stripping of the fine aggregate from HMA will ensue, resulting in an increase in the turbidity of water. By measuring the scattered/transmitted turbidity ratio, it was shown that the MIST was capable of detecting adhesion failure (stripping).

In Florida, Birgisson et al. (2004) evaluated the use of a new performance-based fracture criterion. The laboratory testing procedures currently available for testing Hot Mix Asphalt moisture susceptibility tend to evaluate effects of moisture damage in the laboratory specimens by measuring the relative change of a single parameter before and after conditioning. The use of a single parameter to evaluate moisture damage must be questioned. Birgisson, et al. (2004) showed that moisture damage has an impact on the fracture resistance of mixtures that is accurately captured by the fundamental parameters of the HAM fracture mechanics model. This means that HAM fracture mechanics can be used to quantify the effects of moisture damage on mixtures. Based on the detailed forensic investigations of 36 field pavement sections of known cracking performance in Florida, a HAM fracture mechanics-based performance specification criterion, termed the “Energy Ratio” (ER), was used to quantify the effects of moisture damage on the fracture resistance of mixtures. Based on Birgisson et al. results the ER was recommended to form the basis of a promising specification criterion for evaluating the effects of moisture damage in mixtures as well as the overall resistance to fracture.

Khosla et al. (2000) investigated an alternative test that evaluates a mixture's fundamental material properties instead of measuring indirect tensile strength ratio. A relative simple test is proposed that measures the cohesion and friction angle for asphalt mixture. The Superpave shear tester was incorporated as a tool in moisture sensitivity evaluation. Based on the tests results, they found that the proposed test apparatus provides a simple method for determining the cohesion and friction angle of a mixture and may be a new way to evaluate the moisture sensitivity of the mixture.

2.4 Pervious Experience in Modifying the AASHTO T 283

2.4.1 NCHRP 444 report "Compatibility of a Test for Moisture-Induced Damage with Superpave Volumetric Mix Design"

This NCHRP 444 project was aimed at evaluating the AASHTO T 283 specification and recommending changes to make it compatible with the Superpave system. Comparisons of the test procedures of ASTM D4867, AASHTO T 283 and Superpave are presented in Table 2-1 (NCHRP 444, 2000; AASHTO Specification Book, 2001; and ASTM Standards, 2001). The differences between T 283 and the Strategic Highway Research Program (SHRP) recommended AASHTO T 283 for Superpave mixtures include the time and temperature of aging and the size of the HMA sample (diameter and height). The SHRP research, however, was deficient due to insufficient testing to establish better understanding of the TSR in relation to sample preparation methods, such as sample conditioning, method of compaction, and size of sample. In general, the TSR ratios of Superpave 6 inch diameter specimens were larger than the Superpave 4 inch specimens. These differences in the TSR are due to the generally higher $S_{t(Control)}$ of dry specimens and lower conditioned $S_{t(Conditioned)}$ obtained on the Superpave 4 inch specimens as compared with the Superpave 6 inch specimens. On the other hand, the TSR for the 4 inch Marshall compacted specimens is similar to the TSR obtained for the Superpave 6 inch specimens. One of the report final conclusions stated that "there is little difference in variability of test results among methods of compaction". A modified AASHTO T 283 method was introduced as a result of this NCHRP study. This method allows the use of both 4 and 6 inch specimens depending on the aggregate size used in the HMA mixture. The saturation level range was expanded to 50-80 %, instead of 55-80 % in the standard AASHTO T 283. The aging of loose mixture and freeze/thaw cycle were recommended as well. Nevertheless, the major recommendation in this study for the state agencies was that they should carry out their own experimental HMA moisture damage testing to determine the comparative behavior of their aggregates and binder sources before switching to the Superpave 6 inch samples.

2.4.2 Specimen size

NCHRP 444 recommends using the Gyratory specimen of both 4 and 6 inch specimens. UTDOT and NCDOT use the Gyratory specimen of the 6 inch-diameter specimens. FDOT uses the 4 inch-diameter specimens, while NYDOT chooses the size based on the nominal maximum aggregate size.

2.4.3 Air void and saturation level

NCHRP 444 recommends that saturation level range should be expanded to 50-80 %, instead of 55-80 % in the standard AASHTO T 283.

Khosla et al. (2000) concluded that a mix at 6% air voids and 55% saturation level may pass TSR requirement, but could fail at a higher level of air voids and degree of saturation, even though both of them are within the AASHTO T-283 specifications. They recommended tightening the standards range for air voids and degree of saturation.

Choubane et al. (2000) investigated the effects of different degrees of saturation on moisture damage. When using AASHTO T283 for moisture susceptibility evaluation of Superpave mixes, it is recommend that the test samples be saturated to more than 90%. It is also suggested that the conditioning phase include the optional freeze-thaw cycle. An appropriate passing TSR limit should be set to no less than 80%. The air void content of test samples should be reduced to 6.5%-7.5%.

Castro-Fernandez et al. (2004) found that after 24 hours of water conditioning process at 140^0 F, the loss in aggregate internal friction and the loss of aggregate-asphalt binder adhesion (retained compressive strength) are more prevalent than the loss of asphalt binder cohesion.

2.4.4 Loose mix aging and compacted mix aging

Most of the modified AASHTO T 283 required loose mix aging and compacted mix aging. The loose mix aging was 2 hours at compaction temperature. The compacted mix aging was 24-96 hours at room temperature, except for UTDOT who used 16 hours at 140 ^{o} F.

2.4.5 Freeze-thaw cycle

Most of the modified AASHTO T 283 required the freeze/thaw cycle.

2.4.6 Minimum TSR

FDOT early experience suggested a minimum TSR value of 85 % for Superpave mixtures (Musselman et al., 1998). Later on, Choubane et al. (2000) recommended the use of minimum TSR value of 80 % for water damage evaluation in FDOT Superpave HMA. Also, Khosla et al. (2000), McGennis et al. (1996), and Pan et al. (1999) suggested a minimum value of TSR = 80%. In summary, most agencies use a minimum value of TSR = 80% in the moisture sensitivity test for Superpave HMA mixtures.

As it was discussed previously, many attempts by state agencies had been made to modify the AASHTO T 283 standards. The collected information about these efforts from different state agencies is summarized in Table 2-2.

Table 2-1 Comparison of Standard Water Sensitivity Tests

Test Parameter	ASTM D4867	AASHTO T 283-99 (AASHTO T 283-03)	Superpave (Recommended by SHRP)
Specimen size	2.5” x 4”	2.5” x 4”	3.75” x 6”
Loose mix aging	None	➢ Cool @ room temp. (2 hrs). ➢ Cure @ 140° F -16 hrs.	275° F – 4 hrs
Compacted HMA curing	0-24 hrs @ room temperature before staring test	24 hrs @ room temp. before starting test	Same as AASHTO T 283
Compaction Temperature	Depends	275° F (2 hrs in oven)	Equiviscous (0.28 Pa.s)
Air voids of compacted specimen	6-8%	6-8% (6.5-7.5%)	6-8%
Saturation	➢ 55-80% ➢ 20 in. Hg for 5 min. ➢ Calculations different from AASHTO T 283	➢ 55-80% (70-80%) ➢ 20 in. Hg for 5 min. ➢ Calculations different from ASTM D4867	Same as in AASHTO T 283
Swell determination	Yes	No	No
Freeze	0 ± 5° F for min. 15 hrs (optional)	0 ± 5° F for min. 16 hrs (optional)	Same as in AASHTO T 283
Water soak	140 + 0.2°F for 24 hrs	140 + 0.2° F for 24 hrs	140 + 0.2° F for 24 hrs
Compaction method	Marshall	Marshall	SGC
Strength property	Indirect Tensile @ room temp	Indirect Tensile @ room temp	Same as in AASHTO T 283

Table 2-2 Summary of state agencies experience in modifying the AASHTO T 283 in different U.S. Departments of Transportation

Specimen Size (in.)	**Compaction method**	**Air voids %**	**Saturation %**	**Loose Mixture Aging**	**Compacted Mixture Aging**	**Freeze/ Thaw**	**Min. TSR%**	**Reference**
4 or 6	Marshall or SGC	Same as in T - 283	Same as in T - 283	Same as in T - 283	0-24 hrs @ room Temp.	Compulsory	80	*NCHRP 444 (2000)*
6	SGC	Same as in T - 283	70-80	2 hrs +- 5 min. @ compaction temp.	16 hrs @ 140 F	Compulsory	N/A	*UTDOT (2003)*
4 or 6	Marshall for 4" or SGC for 6"	4" (same as in T283). 6"(6.5-7.5)	65-80	290+-5 F for 2hrs	24-96 hrs in room temp.	Compulsory (different approaches for 4" and 6")	Visual estimation	*NCDOT (1999)*
4	SGC	Same as in T - 283	70-80	Same as in T - 283	N/A	Compulsory	N/A	*FDOT (2002)*
12 Specimens (4")	CA method similar to Marshall	6.5-7.5	70-80	Same as in T - 283	24-96 hrs @ room temp.	Compulsory	N/A	*CADOT (2003)*
4	Marshall	Same as in T - 283	Same as in T - 283	Short term aging for 2 hrs	Same as in T - 283	Same as in T - 283	80	*INDOT (1999)*
Based on nominal max. agg. size	SGC	Same as in T - 283	Same as in T - 283	Same as in T - 283	Up to 96 hrs @room temp.	Same as in T - 283	80	*NYDOT(2002)*

2.6 Summary

The current Superpave specification uses the AASHTO T 283 moisture susceptibility test for determining moisture sensitivity of HMA specimens. Most state agencies use AASHTO T 283 test, although they still have questions about the accuracy of the test. There is a need to develop a verified test procedure that can be adopted for determining moisture damage resistance of Superpave specimens. The uncertainties surrounding the AASHTO T283 and NCHRP 444 procedures, particularly regarding their impacts on Ohio’s aggregate sources and ODOT Superpave procedures, provided impetus for carrying out this research.

Despite the fact that there are many different test methods for moisture sensitivity of HMA specimens, Hicks et al. (2004) pointed out the need of updating the moisture damage susceptibility test method, particularly regarding the method of specimen preparation, degree of saturation, air void determination, and test procedure standardization. Therefore, a need exists for gaining better understanding of the important factors controlling the accuracy and validity of the stripping test. In this study, a structured laboratory test program is conducted to study the effects of the dominant test variables as well as potential interactions between these test variables on the HMA specimen’s susceptibility to moisture damage. The factors studied include aggregate source, compaction method, specimen size, aging method, saturation level, and freeze-thaw cycle. The effects of these factors on the dry tensile strength, the conditioned tensile strength, and the tensile strength ratio are fully investigated and documented in this report.

CHAPTER III

RESEARCH APPROACH AND TEST RESULTS

3.1 Introduction of Research Approach

A structured laboratory test program is designed and carried out in this research. The factors selected for the test program are based on the literature review. Four aggregate sources are used in the laboratory experimental study: one limestone, one trap rock, and two gravels. Two types of asphalt binders are used: one is virgin binder (PG 64-22), and the other is pre-blended polymer modified asphalt binder (PG 70-22).

The test variables to be included in the test program encompass the following: loose mixture aging (none versus AASHTO T283, 16 hrs @ 140º F, as well as Superpave specifications, 2 hrs @ 275º F or 4 hrs @ 275º F), methods of specimen compaction (Marshall versus Superpave gyratory), specimen sizes (4 inch for Marshall, 4 inch and 6 inch for Superpave gyratory specimens), aging condition of compacted HMA specimens (0-24 hrs @ room temp., versus 72-96 hrs @ room temp.), degree of saturation (three levels: 55, 75, and 90%), and freezing thawing condition (none versus standard one freeze/thaw cycle @ 16 hrs @ 0º F). Previously in Chapter II, Table 2-1 provides details of current ASTM, AASHTO, and Superpave test conditions; these are the basis of test variables identified above.

Each test condition requires testing of triplicate specimens to ensure repeatability of test results.

The test program is divided into two parts: one part is a complete factorial experimental program for two aggregate sources with virgin asphalt binder, the second part is a partial factorial experimental program for the remaining two aggregate sources with modified asphalt binder. Figure 3-1 depicts the independent test variables in a complete factorial laboratory test program. The number of tests to be conducted can be roughly estimated as 3 (replicates) × 2 (aggregate source) × 3 (loose mixture aging condition) × 3 (specimen size) ×4 (degree of saturation) × 2 (w and w/o freeze thaw conditioning) = 864 specimens. The partial factorial experimental program is based on the conclusions from the analysis of the complete factorial experimental program. The partial factorial experimental program and test results are presented in Chapter V.

The complete factorial experiment is used to identify and evaluate the influences of the individual factors, along with all the possible interactions among the various factors. The partial factorial experiment is used to validate findings from a complete factorial experiment test.

3.2 Experimental Program

3.2.1 Materials

Two different aggregates from two districts in Ohio are used in the complete factorial experimental program. One source is the limestone from the Honey Creek Stone Co. in Petersburg, Ohio. The other source is the gravel from Martin Marietta Co. in Ohio. Another two different aggregates from two districts in Ohio are used in the partial factorial experimental tests. One source is Ontario Trap Rock from London, Ontario, Canada. The other source is the gravel from Stocker Sand and Gravel

Co. in Gnadenhutten, Ohio. All the aggregate gradation used is according to ODOT requirements for heavy traffic (Type-1H) as shown in Figure 3-2.

The virgin asphalt binder used in the complete factorial experimental program is a performance grade PG 64-22 (from Tri-State Co.). The Superpave asphalt binder specification (AASHTO MP1-93) for the PG 64-22 is shown in Table 3-1. The modified asphalt binder used in partial factorial experimental test is a performance grade PG 70-22 provided by Marathon Petroleum Company.

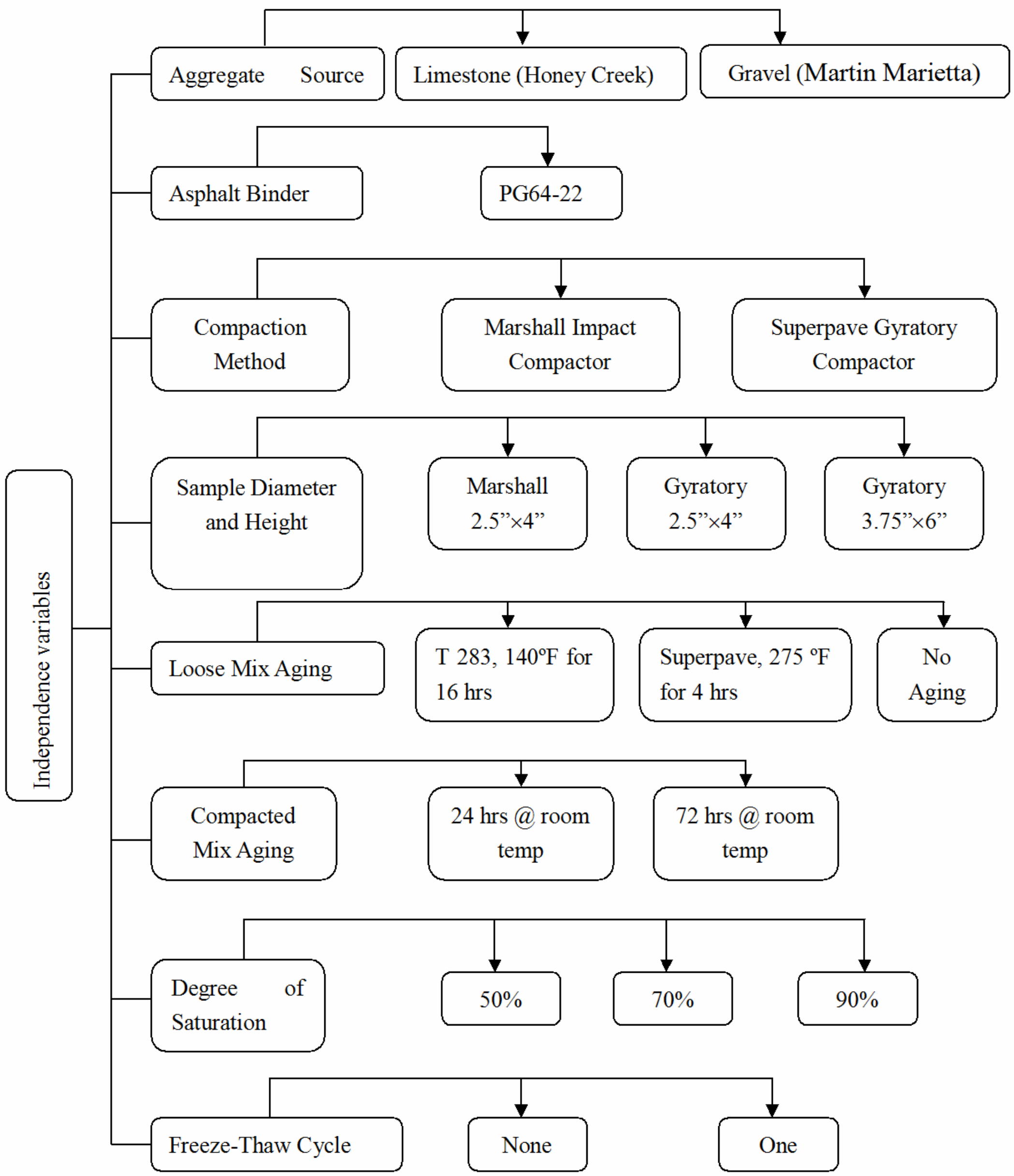

Figure 3-1 Complete Factorial Experimental Test Program

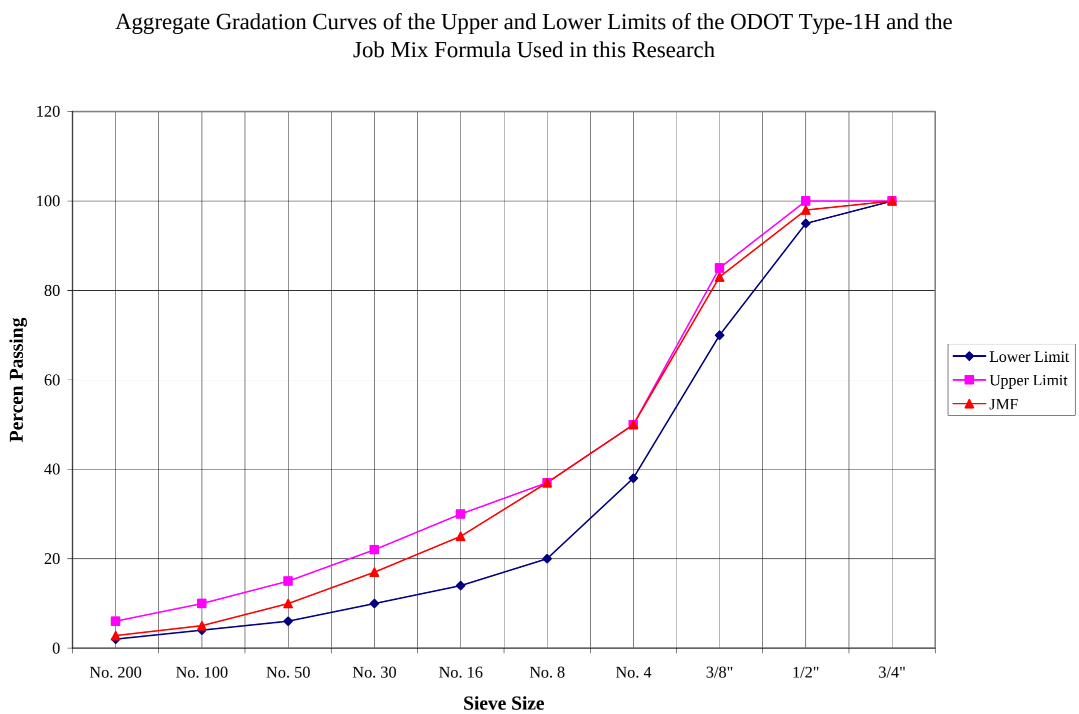

Figure 3- 2 ODOT Requirements for Heavy Traffic (Type-1H)

Table3- 1 Superpave Asphalt Binder Specification for the PG 64-22

Average 7-Day Maximum Pavement Design Temperature (°C).	<64
Minimum Pavement Design Temperature (°C)	>-22
Flash Point Temp. Minimum. (°C)	230
Temperature at Maximum Viscosity of 3000 cP. (°C)	135

3.3 Test Results

The T 283 procedure consists of preparing 6 HMA samples for one set. Each set of specimens is divided into subsets. One subset named “unconditioned” is tested in dry condition for indirect tensile strength. The other subset named “conditioned” is subjected to vacuum saturation and a freeze cycle followed by a warm-water soaking cycle, before being tested for indirect tensile strength. All specimens are tested for indirect-tensile strength at 77º F using a loading rate of 2 in/minute, and the Tensile Strength Ratio (TSR) is determined. A minimum TSR of 0.8 is usually specified.

The indicator of moisture damage susceptibility is the TSR. TSR is obtained from the freeze-thaw (conditioned) tensile strength divided by dry (unconditioned) tensile strength. Thus, values of dry tensile strength, freeze-thaw tensile strength, and tensile strength ratio for all test conditions are listed in this section. The variability of test results is statistically examined via. mean, standard deviation, and coefficient of variation (COV).

The mix designs according to Marshall and Superpave procedures for all four aggregate sources with the associated asphalt binder specifications are summarized in the appendix. Tables 3-2 to 3-10 show the complete factorial experimental program test results for Honey Creek Limestone. Tables 3-11 to 3-19 show the complete factorial experimental program test results for Martin Marietta Gravel.

3.3.1 Complete factorial experimental program test results for Honey Creek Limestone

Table 3-2 Test results for the Marshall 100 specimen with no loose mix aging (Honey Creek Limestone)

Loose mix aging	Saturation level	Compacted mix aging	Sample conditioning	Tensile strength (psi)			Statistics			Tensile strength ratio
				Sample number			Mean	Standard deviation	N samples	
				1	2	3				
No Aging	50	24 h	Dry	87.54	90.83	92.01	90.13	2.32	3	
			F-T	71.09	73.53	66.9	70.51	3.35	3	0.782
		72 h	Dry	105.2	110.93	114.62	110.25	4.75	3	
			F-T	79.82	79.04	80.18	79.68	0.58	3	0.723
	70	24 h	Dry	87.54	90.83	92.01	90.13	2.32	3	
			F-T	57.5	64.14	60.16	60.60	3.34	3	0.672
		72 h	Dry	105.2	110.93	114.62	110.25	4.75	3	
			F-T	69.62	72.94	72.23	71.60	1.75	3	0.649
	90	24 h	Dry	87.54	90.83	92.01	90.13	2.32	3	
			F-T	51.3	50.23	51.4	50.98	0.65	3	0.566
		72 h	Dry	105.2	110.93	114.62	110.25	4.75	3	
			F-T	61.9	68.55	64.81	65.09	3.33	3	0.590

Table 3-3 Test results for the Marshall 100 specimen with 4 hrs loose mix aging (Honey Creek Limestone)

Loose mix aging	Saturation level	Compacted mix aging	Sample conditioning	Tensile strength (psi)			Statistics			Tensile strength ratio
				Sample number			Mean	Standard deviation	N samples	
				1	2	3				
4 hrs Aging	50	24 h	Dry	161.42	167.62	169.89	166.31	4.38	3	
			F-T	167.6	168	171.21	168.94	1.98	3	1.015
		72 h	Dry	187.06	194.47	198.07	193.20	5.61	3	
			F-T	166.34	170.08	162.75	166.39	3.67	3	0.861
	70	24 h	Dry	161.42	167.62	169.89	166.31	4.38	3	
			F-T	129.37	148.2	145.43	141.00	10.17	3	0.847
		72 h	Dry	187.06	194.47	198.07	193.20	5.61	3	
			F-T	150.51	147.88	136.67	145.02	7.35	3	0.750
	90	24 h	Dry	161.42	167.62	169.89	166.31	4.38	3	
			F-T	116.97	123.13	110.74	116.95	6.20	3	0.703
		72 h	Dry	187.06	194.47	198.07	193.20	5.61	3	
			F-T	120.09	116.45	114.02	116.85	3.06	3	0.604

Table 3-4 Test results for the Marshall 100 specimen with 16 hrs loose mix aging (Honey Creek Limestone)

Loose mix aging	Saturation level	Compacted mix aging	Sample conditioning	Tensile strength (psi)			Statistics			Tensile strength ratio
				Sample number			Mean	Standard deviation	N samples	
				1	2	3				
16 hrs Aging	50	24 h	Dry	172.9	166.69	173.28	170.96	3.70	3	
			F-T	150.93	152.75	181.08	161.59	16.91	3	0.945
		72 h	Dry	170.11	180.3	171.29	173.90	5.57	3	
			F-T	156.21	150.59	160.6	155.80	5.02	3	0.896
	70	24 h	Dry	172.9	166.69	173.28	170.96	3.70	3	
			F-T	133.52	149.56	133.75	138.94	9.20	3	0.813
		72 h	Dry	170.11	180.3	171.29	173.90	5.57	3	
			F-T	123.89	124.98	137.65	128.84	7.65	3	0.741
	90	24 h	Dry	172.9	166.69	173.28	170.96	3.70	3	
			F-T	115.27	117.62	128.29	120.39	6.94	3	0.704
		72 h	Dry	170.11	180.3	171.29	173.90	5.57	3	
			F-T	108.54	135.1	97.26	113.63	19.43	3	0.653

Table 3-5 Test results for the Gyratory 100 specimen with no loose mix aging (Honey Creek Limestone)

Loose mix aging	Saturation level	Compacted mix aging	Sample conditioning	Tensile strength (psi)			Statistics			Tensile strength ratio
				Sample number			Mean	Standard deviation	N samples	
				1	2	3				
No Aging	50	24 h	Dry	78.57	80.40	84.50	81.16	3.04	3	
			F-T	73.10	70.20	75.04	72.78	2.44	3	0.897
		72 h	Dry	80.90	88.81	80.97	83.56	4.55	3	
			F-T	75.87	74.90	74.35	75.04	0.77	3	0.898
	70	24 h	Dry	78.57	80.40	84.50	81.16	3.04	3	
			F-T	67.90	73.16	66.86	69.31	3.38	3	0.854
		72 h	Dry	80.90	88.81	80.97	83.56	4.55	3	
			F-T	58.62	66.19	63.12	62.64	3.81	3	0.750
	90	24 h	Dry	78.57	80.40	84.50	81.16	3.04	3	
			F-T	57.40	59.88	59.77	59.02	1.40	3	0.727
		72 h	Dry	80.90	88.81	80.97	83.56	4.55	3	
			F-T	49.86	52.85	54.37	52.36	2.29	3	0.627

Table 3-6 Test results for the Gyratory 100 specimen with 4 hrs loose mix aging (Honey Creek Limestone)

Loose mix aging	Saturation level	Compacted mix aging	Sample conditioning	Tensile strength (psi)			Statistics			Tensile strength ratio
				Sample number			Mean	Standard deviation	N samples	
				1	2	3				
4 hrs Aging	50	24 h	Dry	156.40	169.56	171.05	165.67	8.06	3	
			F-T	144.22	147.22	155.33	148.92	5.75	3	0.899
		72 h	Dry	172.88	166.75	181.58	173.74	7.45	3	
			F-T	152.04	159.64	156.87	156.18	3.85	3	0.899
	70	24 h	Dry	156.40	169.56	171.05	165.67	8.06	3	
			F-T	133.22	123.69	130.95	129.29	4.98	3	0.780
		72 h	Dry	172.88	166.75	181.58	173.74	7.45	3	
			F-T	132.24	141.95	145.74	139.98	6.96	3	0.806
	90	24 h	Dry	156.40	169.56	171.05	165.67	8.06	3	
			F-T	110.56	110.47	112.76	111.26	1.30	3	0.672
		72 h	Dry	172.88	166.75	181.58	173.74	7.45	3	
			F-T	124.60	118.49	125.82	122.97	3.93	3	0.708

Table 3-7 Test results for the Gyratory 100 specimen with 16 hrs loose mix aging (Honey Creek Limestone)

Loose mix aging	Saturation level	Compacted mix aging	Sample conditioning	Tensile strength (psi)			Statistics			Tensile strength ratio
				Sample number			Mean	Standard deviation	N samples	
				1	2	3				
16 hrs Aging	50	24 h	Dry	162.32	162.83	156.3	160.48	3.63	3	
			F-T	135.11	131.9	137.95	134.99	3.03	3	0.841
		72 h	Dry	165.35	174.37	165.1	168.27	5.28	3	
			F-T	150.96	144.85	155.58	150.46	5.38	3	0.894
	70	24 h	Dry	162.32	162.83	156.3	160.48	3.63	3	
			F-T	114.87	136.15	128.05	126.36	10.74	3	0.787
		72 h	Dry	165.35	174.37	165.1	168.27	5.28	3	
			F-T	136.19	138.16	134.52	136.29	1.82	3	0.810
	90	24 h	Dry	162.32	162.83	156.3	160.48	3.63	3	
			F-T	115.8	105.46	103.98	108.41	6.44	3	0.676
		72 h	Dry	165.35	174.37	165.1	168.27	5.28	3	
			F-T	126.54	109.13	111.53	115.73	9.44	3	0.688

Table 3-8 Test results for the Gyratory 150 specimen with no loose mix aging (Honey Creek Limestone)

Loose mix aging	Saturation level	Compacted mix aging	Sample conditioning	Tensile strength (psi)			Statistics			Tensile strength ratio
				Sample number			Mean	Standard deviation	N samples	
				1	2	3				
No Aging	50	24 h	Dry	78.82	84.91	85.10	82.94	3.57	3	
			F-T	70.34	69.62	67.54	69.17	1.45	3	0.834
		72 h	Dry	83.93	84.69	79.52	82.71	2.79	3	
			F-T	72.07	69.37	68.44	69.96	1.89	3	0.846
	70	24 h	Dry	78.82	84.91	85.10	82.94	3.57	3	
			F-T	63.47	55.75	52.94	57.39	5.45	3	0.692
		72 h	Dry	83.93	84.69	79.52	82.71	2.79	3	
			F-T	59.94	55.49	47.06	54.16	6.54	3	0.655
	90	24 h	Dry	78.82	84.91	85.10	82.94	3.57	3	
			F-T	55.83	48.58	49.64	51.35	3.92	3	0.619
		72 h	Dry	83.93	84.69	79.52	82.71	2.79	3	
			F-T	46.90	40.51	45.48	44.30	3.36	3	0.536

Table 3-9 Test results for the Gyratory 150 specimen with 4 hrs loose mix aging (Honey Creek Limestone)

Loose mix aging	Saturation level	Compacted mix aging	Sample conditioning	Tensile strength (psi)			Statistics			Tensile strength ratio
				Sample number			Mean	Standard deviation	N samples	
				1	2	3				
4 hrs Aging	50	24 h	Dry	121.18	135.88	125.96	127.67	7.50	3	
			F-T	118.59	122.48	127.52	122.86	4.48	3	0.962
		72 h	Dry	137.60	149.46	143.53	143.53	5.93	3	
			F-T	136.72	126.2	132.85	131.92	5.32	3	0.919
	70	24 h	Dry	121.18	135.88	125.96	127.67	7.50	3	
			F-T	112.33	112.04	111.03	111.80	0.68	3	0.876
		72 h	Dry	137.60	149.46	143.53	143.53	5.93	3	
			F-T	112.76	121.76	113.57	116.03	4.98	3	0.808
	90	24 h	Dry	121.18	135.88	125.96	127.67	7.50	3	
			F-T	99.13	94.94	89.95	94.67	4.60	3	0.742
		72 h	Dry	137.60	149.46	143.53	143.53	5.93	3	
			F-T	109.45	114.89	106.32	110.22	4.34	3	0.768

Table 3-10 Test results for the Gyratory 150 specimen with 16 hrs loose mix aging (Honey Creek Limestone)

Loose mix aging	Saturation level	Compacted mix aging	Sample conditioning	Tensile strength (psi)			Statistics			Tensile strength ratio
				Sample number			Mean	Standard deviation	N samples	
				1	2	3				
16 hrs Aging	50	24 h	Dry	146.15	130.37	148.54	141.69	9.87	3	
			F-T	141.75	142.95	138.36	141.02	2.38	3	0.995
		72 h	Dry	161.22	177.77	175.9	171.63	9.06	3	
			F-T	150.67	154.99	153.5	153.05	2.19	3	0.892
	70	24 h	Dry	146.15	130.37	148.54	141.69	9.87	3	
			F-T	121.96	115.24	115.75	117.65	3.74	3	0.830
		72 h	Dry	161.22	177.77	175.9	171.63	9.06	3	
			F-T	125.7	137.68	129.87	131.08	6.08	3	0.764
	90	24 h	Dry	146.15	130.37	148.54	141.69	9.87	3	
			F-T	102.2	101.78	104.59	102.86	1.52	3	0.726
		72 h	Dry	161.22	177.77	175.9	171.63	9.06	3	
			F-T	120.28	122.24	116.16	119.56	3.10	3	0.697

3.3.2 Complete factorial experimental program test results for Martin Marietta Gravel

Table 3-11 Test results for the Marshall 100 specimen with no loose mix aging (Martin Marietta Gravel)

Loose mix aging	Saturation level	Compacted mix aging	Sample conditioning	Tensile strength (psi)			Statistics			Tensile strength ratio
				Sample number			Mean	Standard deviation	N samples	
				1	2	3				
No Aging	50	24 h	Dry	83.92	89.20	85.01	86.04	2.78	3	
			F-T	81.29	81.68	82.62	81.86	0.68	3	0.95
		72 h	Dry	89.20	92.30	93.87	91.79	2.38	3	
			F-T	89.53	87.37	88.98	88.63	1.12	3	0.97
	70	24 h	Dry	83.92	89.20	85.01	86.04	2.78	3	
			F-T	65.53	72.60	73.58	70.57	4.39	3	0.82
		72 h	Dry	89.20	92.30	81.81	87.77	5.39	3	
			F-T	86.45	67.53	71.77	75.25	9.93	3	0.86
	90	24 h	Dry	83.92	89.20	85.01	86.04	2.78	3	
			F-T	70.91	70.87	68.85	70.21	1.18	3	0.82
		72 h	Dry	89.20	92.30	81.81	87.77	5.39	3	
			F-T	67.62	66.59	64.87	66.36	1.39	3	0.76

Table 3-12 Test results for the Marshall 100 specimen with 4 hrs loose mix aging (Martin Marietta Gravel)

Loose mix aging	Saturation level	Compacted mix aging	Sample conditioning	Tensile strength (psi)			Statistics			Tensile strength ratio
				Sample number			Mean	Standard deviation	N samples	
				1	2	3				
4 hrs Aging	50	24 h	Dry	180.77	164.51	171.05	172.11	8.18	3	
			F-T	123.18	129.68	148.52	133.80	13.16	3	0.777
		72 h	Dry	191.22	175.39	195.27	187.29	10.51	3	
			F-T	156.83	137.66	156.45	150.31	10.96	3	0.803
	70	24 h	Dry	180.77	164.51	171.05	172.11	8.18	3	
			F-T	134.61	146.18	147.43	142.74	7.07	3	0.829
		72 h	Dry	191.22	175.39	195.27	187.29	10.51	3	
			F-T	158.32	157.57	166.38	160.76	4.88	3	0.858
	90	24 h	Dry	180.77	164.51	171.05	172.11	8.18	3	
			F-T	157.04	165.42	159.72	160.73	4.28	3	0.934
		72 h	Dry	191.22	175.39	195.27	187.29	10.51	3	
			F-T	157.04	164.68	157.77	159.83	4.22	3	0.853

Table 3-13 Test results for the Marshall 100 specimen with 16 hrs loose mix aging (Martin Marietta Gravel)

Loose mix aging	Saturation level	Compacted mix aging	Sample conditioning	Tensile strength (psi)			Statistics			Tensile strength ratio
				Sample number			Mean	Standard deviation	N samples	
				1	2	3				
16 hrs Aging	50	24 h	Dry	138.04	129.96	133.47	133.83	4.05	3	
			F-T	171.95	162.02	163.60	165.86	5.33	3	1.239
		72 h	Dry	150.77	160.93	165.25	158.99	7.43	3	
			F-T	138.53	136.92	157.10	144.18	11.21	3	0.907
	70	24 h	Dry	138.04	129.96	133.47	133.83	4.05	3	
			F-T	184.18	159.84	154.37	166.13	15.87	3	1.241
		72 h	Dry	150.77	160.93	165.25	158.99	7.43	3	
			F-T	165.20	158.21	150.24	157.88	7.48	3	0.993
	90	24 h	Dry	138.04	129.96	133.47	133.83	4.05	3	
			F-T	151.51	146.24	142.22	146.66	4.66	3	1.096
		72 h	Dry	150.77	160.93	165.25	158.99	7.43	3	
			F-T	153.37	145.06	142.38	146.94	5.73	3	0.924

Table 3-14 Test results for the Gyratory 100 specimen with no loose mix aging (Martin Marietta Gravel)

Loose mix aging	Saturation level	Compacted mix aging	Sample conditioning	Tensile strength (psi)			Statistics			Tensile strength ratio
				Sample number			Mean	Standard deviation	N samples	
				1	2	3				
No Aging	50	24 h	Dry	80.00	78.59	78.32	78.97	0.91	3	
			F-T	75.09	69.26	70.20	71.51	3.13	3	0.906
		72 h	Dry	78.79	77.93	78.49	78.40	0.44	3	
			F-T	68.98	68.52	66.86	68.12	1.11	3	0.869
	70	24 h	Dry	80.00	78.59	78.32	78.97	0.91	3	
			F-T	67.64	67.14	69.77	68.18	1.40	3	0.863
		72 h	Dry	78.79	77.93	78.49	78.40	0.44	3	
			F-T	59.99	67.37	67.25	64.87	4.23	3	0.827
	90	24 h	Dry	80.00	78.59	78.32	78.97	0.91	3	
			F-T	67.75	60.18	63.71	63.88	3.79	3	0.809
		72 h	Dry	78.79	77.93	78.49	78.40	0.44	3	
			F-T	71.66	71.12	68.90	70.56	1.47	3	0.900

Table 3-15 Test results for the Gyratory 100 specimen with 4 hrs loose mix aging (Martin Marietta Gravel)

Loose mix aging	Saturation level	Compacted mix aging	Sample conditioning	Tensile strength (psi)			Statistics			Tensile strength ratio
				Sample number			Mean	Standard deviation	N samples	
				1	2	3				
4 hrs Aging	50	24 h	Dry	148.30	153.83	152.11	151.41	2.83	3	
			F-T	145.22	130.30	140.99	138.84	7.69	3	0.917
		72 h	Dry	145.07	142.78	146.00	144.62	1.65	3	
			F-T	132.92	123.58	134.72	130.41	5.98	3	0.902
	70	24 h	Dry	148.30	153.83	152.11	151.41	2.83	3	
			F-T	144.33	135.90	145.94	142.06	5.40	3	0.938
		72 h	Dry	145.07	142.78	146.00	144.62	1.65	3	
			F-T	127.26	132.57	162.48	140.77	18.99	3	0.973
	90	24 h	Dry	148.30	153.83	152.11	151.41	2.83	3	
			F-T	155.79	135.06	147.16	146.00	10.42	3	0.964
		72 h	Dry	145.07	142.78	146.00	144.62	1.65	3	
			F-T	156.66	129.31	157.20	147.72	15.95	3	1.021

Table 3-16 Test results for the Gyratory 100 specimen with 16 hrs loose mix aging (Martin Marietta Gravel)

Loose mix aging	Saturation level	Compacted mix aging	Sample conditioning	Tensile strength (psi)			Statistics			Tensile strength ratio
				Sample number			Mean	Standard deviation	N samples	
				1	2	3				
16 hrs Aging	50	24 h	Dry	127.57	146.06	146.69	140.10	10.86	3	
			F-T	151.70	157.53	155.54	154.92	2.96	3	1.106
		72 h	Dry	137.93	143.18	161.34	147.48	12.28	3	
			F-T	159.75	153.56	147.89	153.73	5.93	3	1.042
	70	24 h	Dry	127.57	146.06	146.69	140.10	10.86	3	
			F-T	129.37	141.81	114.53	128.57	13.66	3	0.918
		72 h	Dry	137.93	143.18	161.34	147.48	12.28	3	
			F-T	133.69	132.58	148.40	138.22	8.83	3	0.937
	90	24 h	Dry	127.57	146.06	146.69	140.10	10.86	3	
			F-T	133.10	112.86	132.01	125.99	11.38	3	0.899
		72 h	Dry	137.93	143.18	161.34	147.48	12.28	3	
			F-T	161.91	135.91	144.32	147.38	13.26	3	0.999

Table 3-17 Test results for the Gyratory 150 specimen with no loose mix aging (Martin Marietta Gravel)

Loose mix aging	Saturation level	Compacted mix aging	Sample conditioning	Tensile strength (psi)			Statistics			Tensile strength ratio
				Sample number			Mean	Standard deviation	N samples	
				1	2	3				
No Aging	50	24 h	Dry	59.96	64.80	50.45	58.40	7.30	3	
			F-T	64.37	61.76	58.28	61.47	3.06	3	1.053
		72 h	Dry	70.28	71.19	73.25	71.57	1.52	3	
			F-T	61.45	66.55	68.90	65.63	3.81	3	0.917
	70	24 h	Dry	59.96	64.80	50.45	58.40	7.30	3	
			F-T	34.71	44.85	39.78	39.78	5.07	3	0.681
		72 h	Dry	70.28	71.19	73.25	71.57	1.52	3	
			F-T	52.90	58.76	58.21	56.62	3.24	3	0.791
	90	24 h	Dry	59.96	64.80	50.45	58.40	7.30	3	
			F-T	42.64	44.91	49.04	45.53	3.25	3	0.780
		72 h	Dry	70.28	71.19	73.25	71.57	1.52	3	
			F-T	54.87	47.55	50.93	51.12	3.67	3	0.714

Table 3-18 Test results for the Gyratory 150 specimen with 4 hrs loose mix aging (Martin Marietta Gravel)

Loose mix aging	Saturation level	Compacted mix aging	Sample conditioning	Tensile strength (psi)			Statistics			Tensile strength ratio
				Sample number			Mean	Standard deviation	N samples	
				1	2	3				
4 hrs Aging	50	24 h	Dry	168.60	160.74	174.39	167.91	6.85	3	
			F-T	139.21	158.25	168.20	155.22	14.73	3	0.924
		72 h	Dry	153.18	142.73	144.98	146.96	5.50	3	
			F-T	112.70	128.71	122.37	121.26	8.07	3	0.825
	70	24 h	Dry	168.60	160.74	174.39	167.91	6.85	3	
			F-T	167.58	161.02	175.97	168.19	7.50	3	1.002
		72 h	Dry	153.18	142.73	144.98	146.96	5.50	3	
			F-T	121.50	127.10	122.62	123.74	2.96	3	0.842
	90	24 h	Dry	168.60	160.74	174.39	167.91	6.85	3	
			F-T	153.33	171.58	161.19	162.03	9.15	3	0.965
		72 h	Dry	153.18	142.73	144.98	146.96	5.50	3	
			F-T	112.66	104.80	121.59	113.01	8.40	3	0.769

Table 3-19 Test results for the Gyratory 150 specimen with 16 hrs loose mix aging (Martin Marietta Gravel)

Loose mix aging	Saturation level	Compacted mix aging	Sample conditioning	Tensile strength (psi)			Statistics			Tensile strength ratio
				Sample number			Mean	Standard deviation	N samples	
				1	2	3				
16 hrs Aging	50	24 h	Dry	133.11	124.14	138.80	132.02	7.39	3	
			F-T	109.28	129.76	120.40	119.81	10.25	3	0.908
		72 h	Dry	149.89	152.77	150.07	150.91	1.61	3	
			F-T	147.84	145.31	140.78	144.64	3.58	3	0.958
	70	24 h	Dry	133.11	124.14	138.80	132.02	7.39	3	
			F-T	161.40	154.03	170.87	162.10	8.44	3	1.228
		72 h	Dry	149.89	152.77	150.07	150.91	1.61	3	
			F-T	112.35	128.93	139.07	126.78	13.49	3	0.840
	90	24 h	Dry	133.11	124.14	138.80	132.02	7.39	3	
			F-T	130.87	140.06	142.37	137.77	6.08	3	1.044
		72 h	Dry	149.89	152.77	150.07	150.91	1.61	3	
			F-T	104.29	132.30	144.76	127.12	20.73	3	0.842

CHAPTER IV

FACTORS AFFECTING WATER STRIPPING TEST RESULTS

4.1 Introduction

The objectives of this study are to evaluate AASHTO T283, "Resistance of Compacted Bituminous Mixture to Moisture Induced Damage," and to recommend changes to make it compatible with the Superpave mix design procedures. The central issue of the study is to determine the influences of the compaction method and size of sample on the results of the AASHTO T283 method of test. Comparisons of indirect tensile strength test results have been made among the 150-mm-diameter Superpave gyratory HMA samples, 100-mm-diameter Superpave gyratory HMA samples, and 100-mm-diameter Marshall HMA samples. The influences of compaction method and sample size are analyzed in terms of dry tensile strength, freeze-thaw conditioned tensile strength, and tensile strength ratio.

In the data analysis, "pair-wise" comparisons are used to compare the impact of each individual factor while maintaining all other factors at a constant level. This type of analysis is an excellent tool to identify the effects of each individual factor in terms of direction (increase or decrease) and magnitude. For example, using the pair-wise analysis, an engineer can assess whether the dry tensile strength of G150 samples is equal to, lower than, or higher than the dry tensile strength of M100 samples. Criterion of 95% confidence is used in data analysis. The significance value less than 0.05 is considered statistically different.

(ANOVA) test and regression analysis technique are used in analyzing test data as well. The analysis of variance (ANOVA) technique is used to conduct the statistical analysis of the overall data generated from the complete factorial experiments. The contributions of the main factors to the water stripping test results and their interactions are identified by ANOVA analysis techniques. The magnitude of the F-statistics is used to rank the relative importance of the influencing factors and their interactions. Regression analysis technique is used to evaluate the tensile strength ratio for different compaction methods.

4.2 Dry Tensile Strength

4.2.1 Comparison of three compaction methods

This section provides analysis on the effect of compaction method and sample size on the dry tensile strengths.

Tables 4-1, 4-2, and 4-3 show statistical comparisons of samples prepared with the Marshall 100-mm specimen, Gyratory 100-mm specimen, and Gyratory 150-mm specimen, respectively. Observations based on three tables are summarized below.

- M100 Samples versus G100 Samples

Table 4-1 indicates that the dry tensile strengths of HMA samples compacted by the M100 compactor is statistically the same as those samples compacted by the G100 compactor. This is true for both aggregate sources.

- M100 Samples versus G150 Samples

Table 4-2 indicates that the dry tensile strengths of samples compacted by the M100 compactor are statistically larger than those samples compacted by the G150 compactor for limestone. The dry tensile strength is statistically the same for gravel.

- G100 Samples versus G150 Samples

Table 4-3 indicates that the dry tensile strengths of samples compacted by the G100 compactor are statistically larger than those samples compacted by the G150 compactor for limestone. The dry tensile strength is statistically the same for gravel.

Table 4-1 Statistical Comparison of 100-mm Diameter Marshall Compacted Samples and 100-mm Diameter Superpave Gyratory Compacted Samples

Sample conditioning	Source	Larger*	Same*	Smaller*
Dry	Honey Creek Limestone		√	
	Martin Marietta Gravel		√	

Table 4-2 Statistical Comparison of 100-mm Diameter Marshall Compacted Samples and 150-mm Diameter Superpave Gyratory Compacted Samples

Sample conditioning	Source	Larger*	Same*	Smaller*
Dry	Honey Creek Limestone	√		
	Martin Marietta Gravel		√	

Table 4-3 Statistical Comparison of 100-mm and 150-mm Diameter Superpave Gyratory Compacted Samples

Sample conditioning	Source	Larger*	Same*	Smaller*
Dry	Honey Creek Limestone	√		
	Martin Marietta Gravel		√	

4.2.2 Dry tensile strength subjected to loose mix aging and compacted mix aging

Tables 4-4 and 4-5 show the influence of loose mix aging on the dry tensile strength for the Honey Creek Limestone and Martin Marietta Gravel, respectively. Tables 4-6 and 4-7 show the influence of compacted mix aging on the dry tensile strength for the Honey Creek Limestone and Martin Marietta Gravel, respectively. For Honey Creek Limestone, Table 4-4 indicates that loose mix aging increases the dry tensile strength in all six cases considered. Table 4-6 shows that compacted mix aging increases the dry tensile strength in 2 of 9 possible conditions. In 7 of 9 comparisons, the dry tensile strengths are the same. For Martin Marietta Gravel, Table 4-5 indicates that loose mix aging increases the dry tensile strength in all six cases considered. Table 4-7 shows that compacted mix aging increases the dry tensile strength in 2 of 9 test conditions. In 5 of 9 comparisons, the dry tensile strengths are the same. In 2 of 9 conditions, compacted mix aging tends to decrease the dry tensile strength.

Table 4-4 Statistical Comparison of Dry Tensile Strength for Mixtures Subjected to Loose Mix Aging (Honey Creek Limestone)

Compaction Method	Compacted Mix Aging Hrs	Increase*	Same*	Decrease*
Marshall 100	24	√		
	72	√		
Gyratory 100	24	√		
	72	√		
Gyratory 150	24	√		
	72	√		
Total	All	6		

Table 4-5 Statistical Comparison of Dry Tensile Strength for Mixtures Subjected to Loose Mix Aging (Martin Marietta Gravel)

Compaction Method	Compacted Mix Aging Hrs	Increase*	Same*	Decrease*
Marshall 100	24	√		
	72	√		
Gyratory 100	24	√		
	72	√		
Gyratory 150	24	√		
	72	√		
Total	All	6		

Table 4-6 Statistical Comparison of Dry Tensile Strength for Mixtures Subjected to Compacted Mix Aging (Honey Creek Limestone)

Compaction Method	Loose Mix Aging Hrs	Increase*	Same*	Decrease*
Marshall 100	0		√	
	4		√	
	16		√	
Gyratory 100	0		√	
	4		√	
	16		√	
Gyratory 150	0		√	
	4	√		
	16	√		
Total	All	2	7	

Table 4-7 Statistical Comparison of Dry Tensile Strength for Mixtures Subjected to Compacted Mix Aging (Martin Marietta Gravel)

Compaction Method	Loose Mix Aging Hrs	Increase*	Same*	Decrease*
Marshall 100	0		√	
	4		√	
	16			√
Gyratory 100	0		√	
	4		√	
	16		√	
Gyratory 150	0	√		
	4			√
	16	√		
Total	All	2	5	2

4.2.3 ANOVA analysis of dry tensile strength

4.2.3.1 ANOVA analysis of dry tensile strength for Honey Creek Limestone

Tables 4-8, 4-9, and 4-10 show the results of ANOVA analysis of the dry tensile strength of Marshall 100-mm specimen, ANOVA analysis of the dry tensile strength of Gyratory 100-mm specimen, and ANOVA analysis of the dry tensile strength of Gyratory 150-mm specimen, respectively. Table 4-11 provides the summary and comparison results of ANOVA analysis results for different compaction methods for Honey Creek Limestone.

It can be seen from Tables 4-8, 4-9, 4-10 and 4-11 that the loose mix aging is the most important factor to influence the dry tensile strength. Furthermore, compacted mix aging is the second important factor. The above observations are true for the Marshall 100-mm specimen, Gyratory 100-mm specimen, and Gyratory 150-mm specimen for Honey Creek Limestone.

Table 4-8 ANOVA Analysis of the Dry Tensile Strength (Marshall 100-mm specimen)

Rank	Source	F Value	Pr>F	Significant
1	LMA	564.211	0.000	Y
2	CMA	60.677	0.000	Y
3	LMA*CMA	11.116	0.000	Y

Table 4-9 ANOVA Analysis of the Dry Tensile Strength (Gyratory 100-mm specimen)

Rank	Source	F Value	Pr>F	Significant
1	LMA	450.665	0.000	Y
2	CMA	5.223	0.041	Y
3	LMA*CMA	.479	0.631	N

Table 4-10 ANOVA Analysis of the Dry Tensile Strength (Gyratory 150-mm specimen)

Rank	Source	F Value	Pr>F	Significant
1	LMA	178.604	0.000	Y
2	CMA	21.367	0.000	Y
3	LMA*CMA	7.036	0.001	Y

Table 4-11 Summarizing Comparison ANOVA Analysis for the Dry Tensile Strength

Rank	Compaction Method	Source	F Value	Pr>F	Significant
1	M100	LMA	564.211	0.000	Y
	G100	LMA	450.665	0.000	Y
	G150	LMA	178.604	0.000	Y
2	M100	CMA	60.677	0.000	Y
	G100	CMA	5.223	0.041	Y
	G150	CMA	21.367	0.000	Y
3	M100	LMA*CMA	11.116	0.000	Y
	G100	LMA*CMA	.479	0.631	N
	G150	LMA*CMA	7.036	0.001	Y

4.2.3.2 ANOVA analysis of dry tensile strength for Martin Marietta Gravel

Tables 4-12, 4-13, and 4-14 show the results of ANOVA analysis of the dry tensile strength of Marshall 100-mm specimen, ANOVA analysis of the dry tensile strength of Gyratory 100-mm specimen, and ANOVA analysis of the dry tensile strength of Gyratory 150-mm specimen, respectively. Table 4-15 provides the summary and comparison results of ANOVA analysis for different compaction methods for Martin Marietta Gravel.

As can be seen from Tables 4-12, 4-13, 4-14 and 4-15, the loose mix aging is the most important factor to influence the dry tensile strength. In addition, compacted mix aging is the second important factor. The above observation is valid for the Marshall 100-mm specimen, Gyratory 100-mm specimen, and Gyratory 150-mm specimen for Martin Marietta Gravel.

Table 4-12 ANOVA Analysis of the Dry Tensile Strength (Marshall 100-mm specimen)

Rank	Source	F Value	Pr>F	Significant
1	LMA	289.328	0	Y
2	LMA * CMA	15.274	0.001	Y
3	CMA	0.204	0.659	N

Table 4-13 ANOVA Analysis of the Dry Tensile Strength (Gyratory 100-mm specimen)

Rank	Source	F Value	Pr>F	Significant
1	LMA	193.825	0	Y
2	CMA	5.223	0.041	Y
3	LMA * CMA	0	0.998	N

Table 4-14 ANOVA Analysis of the Dry Tensile Strength (Gyratory 150-mm specimen)

Rank	Source	F Value	Pr>F	Significant
1	LMA	462.676	0	Y
2	CMA	21.981	0	Y
3	LMA * CMA	1.952	0.188	N

Table 4-15 Summarizing comparison ANOVA Analysis for the dry tensile strength

Rank	Compaction Method	Source	F Value	Pr>F	Significant
1	M100	LMA	289.328	0.000	Y
	G100	LMA	193.825	0.000	Y
	G150	LMA	462.676	0.000	Y
2	M100	LMA*CMA	15.274	0.001	Y
	G100	CMA	5.223	0.041	Y
	G150	CMA	21.981	0	Y
3	M100	CMA	0.204	0.659	N
	G100	LMA * CMA	0	0.998	N
	G150	LMA * CMA	1.952	0.188	N

4.2.3.3 Complete factorial ANOVA analysis for dry tensile strength

An analysis of variance (ANOVA) is performed to determine the significance of the various factors and interactions of these factors to the dry tensile strength. Table 4-16 and Table 4-17 show the test results of dry tensile strength at different conditions for limestone and gravel, respectively. The class level information is explained in Table 4-18. Table 4-19 provideds a summary of data analysis. Independent variables in the analysis are the source of aggregate (SOURCE), compaction method (COMP), loose mix aging (LMA), compacted mix aging (CMA). The dependent variable is dry tensile strength. The ANOVA analysis indicates that loose mix aging is the most important factor affecting the dry tensile strength. The analysis also shows that both source of aggregate and compaction method have some effects on the dry tensile strength. Figure 4-1 and 4-2 show the dry tensile strength at different conditions for limestone and gravel, respectively. From the Figures 4-1 and 4-2, one can observe that both 4 hours loose mix aging and 16 hours loose mix aging increase the dry tensile strength in all cases. Dry tensile strength with 24 hours compacted mix aging and with 72 hours compacted mix aging are about the same, indicating that compacted mix aging is not an important factor affecting the dry tensile strength. For both aggregate sources, the 150-mm diameter specimens have lower tensile strength than the 100-mm diameter specimens. It should be noted that the loading rate (2-inches per minute) is the same for both sizes of specimens; therefore, the strain rate for 150-mm diameter specimens is 50% lower than that for the 100-mm diameter specimens. A lower loading strain rate usually produces a lower tensile strength. One can also observe that the dry tensile strengths of limestone are larger than the dry tensile strengths of gravel, indicating the influence of the aggregate source.

Table 4-16 Results Summary of Dry Tensile Strength for the Limestone

Loose Mix Aging	Compacted Mix Aging	Condition Designation No.	Mean Value for Limestone (psi)		
			Marshall 100	Gyratory 100	Gyratory 150
No Aging	24 h	1	90.13	81.16	82.94
	72 h	2	110.25	83.56	82.71
4 Hrs Aging	24 h	3	166.31	165.67	127.67
	72 h	4	193.20	173.74	143.53
16 Hrs Aging	24 h	5	170.96	160.48	141.69
	72 h	6	173.90	168.27	171.63

Table 4- 17 Results Summary of Dry Tensile Strength for the Gravel

Loose Mix Aging	Compacted Mix Aging	Condition Designation No.	Mean Value for Gravel (psi)		
			Marshall 100	Gyratory 100	Gyratory 150
No Aging	24 h	1	86.04	78.96	58.40
	72 h	2	91.79	78.40	71.57
4 Hrs Aging	24 h	3	172.10	151.41	167.90
	72 h	4	187.29	144.61	146.96
16 Hrs Aging	24 h	5	133.82	140.10	132.01
	72 h	6	158.98	147.48	150.91

Table 4-18 Class level Information for Dry Tensile Strength

Parameters	Level of Variations
Loose Mix Aging (LMA)	1. No aging
	2. 4 hrs@275°F
	3. 16hrs@140°F
Compacted Mix Aging (CMA)	1. 24 hrs@ room temp
	2. 72 hrs@ room temp
Source of Aggregate (SOURCE)	1. Limestone
	2. Gravel
Compaction Method (COMP)	1. Marshall
	2. Gyratory 4 in
	3. Gyratory 6 in

Table 4-19 ANOVA Analysis of Dry Tensile Strength

Dependent Variable: Dry Tensile Strength			
Factors	Mean Square	F	Sig.
LMA	67919.85	1825.43	2.05E-62
COMP	4210.88	113.17	5.94E-23
SOURCE	2976.16	79.99	2.66E-13
CMA	1213.95	32.63	2.34E-07
SOURCE * LMA	958.95	25.77	3.62E-09
SOURCE * CMA	951.91	25.58	3.12E-06
COMP * LMA * CMA	724.69	19.48	6.74E-11
SOURCE * COMP * LMA	665.98	17.9	3.05E-10
COMP * LMA	412.92	11.1	4.56E-07
R Squared = .984 (Adjusted R Squared = .976)			

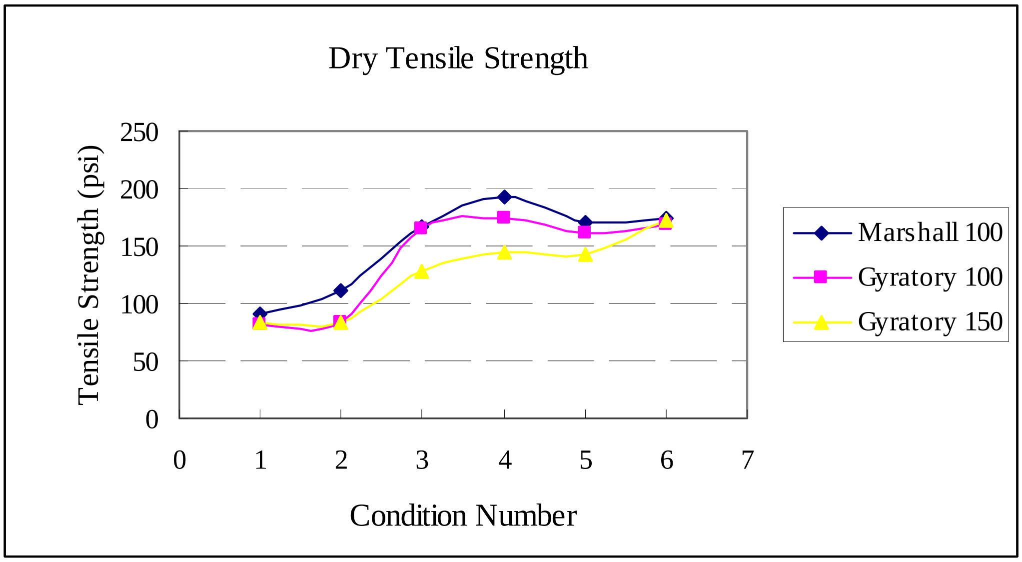

Figure 4- 1 Distribution of Dry Tensile Strength for Honey Creek Limestone

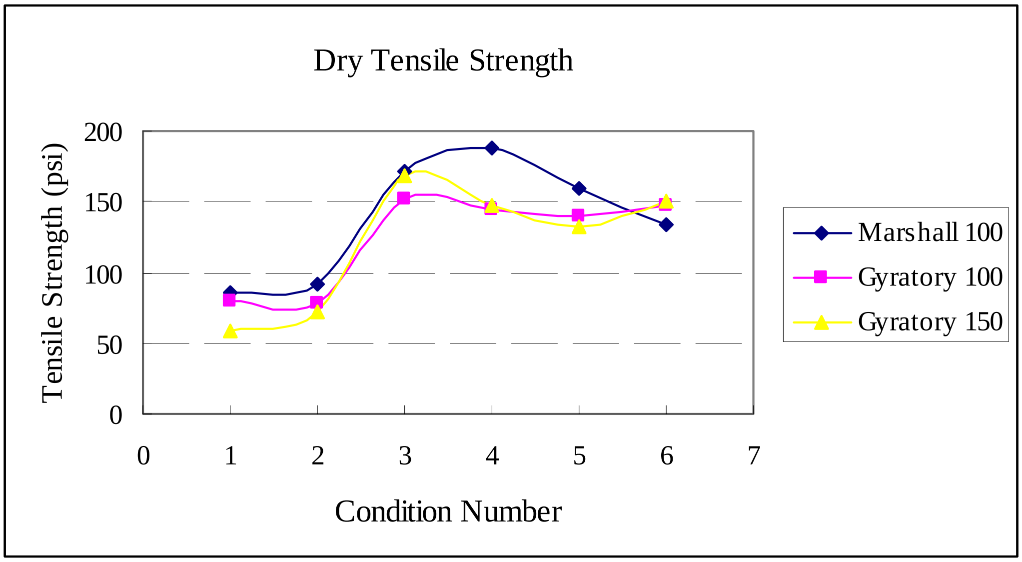

Figure 4- 2 Distribution of Dry Tensile Strength for Martin Marietta Gravel

4.3 Freeze-Thaw Tensile Strength:

4.3.1 Comparison of three compaction methods

The effects of compaction method and sample size on the freeze-thaw tensile strengths are analyzed in this section. Tables 4-20, 4-21, and 4-22 show statistical comparisons of freeze-thaw tensile strength for the Marshall 100-mm HMA specimens, the Gyratory 100-mm HMA specimens, and Gyratory 150-mm HMA specimens, respectively. Based on these tables, some observations are summarized below.

- M100 Samples versus G100 Samples

Table 4-20 indicates that the freeze-thaw tensile strength of samples compacted by the M100 compactor is statistically the same as those samples compacted by the G100 compactor for both aggregate sources.

- M100 Samples versus G150 Samples

Table 4-21 indicates that the freeze-thaw tensile strength of samples compacted by the M100 compactor is statistically larger than those samples compacted by the G150 compactor for both aggregate sources.

- G100 Samples versus G150 Samples

Table 4-22 indicates that the freeze-thaw tensile strength of samples compacted by the G100 compactor is statistically larger than those samples compacted by the G150 compactor for Honey Creek Limestone, but statistically the same for Martin Marietta Gravel.

Table 4-20 Statistical Comparison of 100-mm Diameter Marshall Compacted Samples and 100-mm Diameter Superpave Gyratory Compacted Samples

Sample conditioning	Source	Larger*	Same*	Smaller*
Freeze-Thaw	Honey Creek Limestone		√	
	Martin Marietta Gravel		√	

Table 4-21 Statistical Comparison of 100-mm Diameter Marshall Compacted Samples and 150-mm Diameter Superpave Gyratory Compacted Samples

Sample conditioning	Source	Larger*	Same*	Smaller*
Freeze-Thaw	Honey Creek Limestone	√		
	Martin Marietta Gravel	√		

Table 4-22 Statistical Comparison of 100-mm and 150-mm Diameter Superpave Gyratory Compacted Samples

Sample conditioning	Source	Larger*	Same*	Smaller*
Freeze-Thaw	Honey Creek Limestone	√		
	Martin Marietta Gravel		√	

4.3.2 Freeze-Thaw tensile strength subjected to loose mix aging and compacted mix aging

Tables 4-23 and 4-24 show the statistical analysis results for the influence of loose mix aging and compacted mix aging on the freeze-thaw tensile strength for the Honey Creek Limestone. Tables 4-25 and 4-26 show the statistical analysis results for the influences of loose mix aging and compacted mix aging on the freeze-thaw tensile strength for the Martin Marietta Gravel. For Honey Creek Limestone, Table 4-23 indicates that loose mix aging increases the freeze thaw tensile strength in 18 of 18 conditions. Table 4-24 shows that compacted mix aging increases the freeze thaw tensile strength in 10 of 27 possible comparisons. In 17 of 27 possible comparisons, the freeze-thaw tensile strength are same. For Martin Marietta Gravel, Table 4-25 indicates that loose mix aging increases the freeze-thaw tensile strength in 18 of 18 conditions. Table 4-26 shows that compacted mix aging increases the freeze-thaw tensile strength in 11 of 27 possible comparisons. In 16 of 27 comparisons, the freeze-thaw tensile strengths are the same.

Table 4-23 Statistical Comparison of Freeze-Thaw Tensile Strength for Mixtures Subjected to Loose Mix Aging (Honey Creek Limestone)

Compaction Method	Compacted Mix Aging Hrs	Saturation Level	Increase*	Same*	Decrease*
Marshall 100	24	50	√		
		70	√		
		90	√		
	72	50	√		
		70	√		
		90	√		
Gyratory 100	24	50	√		
		70	√		
		90	√		
	72	50	√		
		70	√		
		90	√		
Gyratory 150	24	50	√		
		70	√		
		90	√		
	72	50	√		
		70	√		
		90	√		
Marshall			6		
Gyratory			12		
Total			18		

Table 4-24 Statistical Comparison of Freeze-Thaw Tensile Strength for Mixtures Subjected to Compacted Mix Aging (Honey Creek Limestone)

Compaction Method	Loose Mix Aging Hrs	Saturation Level	Increase*	Same*	Decrease*
Marshall 100	No aging	50	√		
		70	√		
		90	√		
	4 hrs aging	50		√	
		70		√	
		90		√	
	16 hrs aging	50		√	
		70		√	
		90		√	
Gyratory 100	No aging	50		√	
		70		√	
		90	√		
	4 hrs aging	50		√	
		70		√	
		90	√		
	16 hrs aging	50	√		
		70		√	
		90		√	
Gyratory 150	No aging	50		√	
		70		√	
		90		√	
	4 hrs aging	50		√	
		70		√	
		90	√		
	16 hrs aging	50	√		
		70	√		
		90	√		
Marshall			3	6	
Gyratory			7	11	
Total			10	17	

Table 4-25 Statistical Comparison of Freeze-Thaw Tensile Strength for Mixtures Subjected to Loose Mix Aging (Martin Marietta Gravel)

Compaction Method	Compacted Mix Aging Hrs	Saturation Level	Increase*	Same*	Decrease*
Marshall 100	24	50	√		
		70	√		
		90	√		
	72	50	√		
		70	√		
		90	√		
Gyratory 100	24	50	√		
		70	√		
		90	√		
	72	50	√		
		70	√		
		90	√		
Gyratory 150	24	50	√		
		70	√		
		90	√		
	72	50	√		
		70	√		
		90	√		
Marshall			6		
Gyratory			12		
Total			18		

Table 4-26 Statistical Comparison of Freeze-Thaw Tensile Strength for Mixtures Subjected to Compacted Mix Aging (Martin Marietta Gravel)

Compaction Method	Loose Mix Aging Hrs	Saturation Level	Increase*	Same*	Decrease*
Marshall 100	No aging	50	√		
		70		√	
		90	√		
	4 hrs aging	50		√	
		70	√		
		90		√	
	16 hrs aging	50	√		
		70		√	
		90		√	
Gyratory 100	No aging	50		√	
		70		√	
		90	√		
	4 hrs aging	50		√	
		70		√	
		90		√	
	16 hrs aging	50		√	
		70		√	
		90		√	
Gyratory 150	No aging	50		√	
		70	√		
		90		√	
	4 hrs aging	50	√		
		70	√		
		90	√		
	16 hrs aging	50	√		
		70	√		
		90		√	
Marshall			4	5	
Gyratory			7	11	
Total			11	16	

4.3.3 ANOVA analysis of freeze-thaw conditioned tensile strength

4.3.3.1 ANOVA analysis of freeze-thaw conditioned tensile strength for Honey Creek Limestone

Tables 4-27, 4-28, and 4-29 show the results of ANOVA analysis of the freeze-thaw tensile strength of Marshall 100-mm specimen, Gyratory 100-mm specimen, and Gyratory 150-mm specimen, respectively. Table 4-30 provides the summary and comparison results of ANOVA analysis for the freeze-thaw tensile strength with different compaction methods for Honey Creek Limestone.

Tables 4-27, 4-28, 4-29 and 4-30 indicate that the loose mix aging is the most important factor to influence the freeze-thaw conditioned tensile strength and saturation level is the second important factor for all of Marshall 100-mm specimen, Gyratory 100-mm specimen, and Gyratory 150-mm specimen, respectively. For Gyratory 100-mm specimen and Gyratory 150-mm specimen, the compacted mix aging is ranked 3, after loose mix aging and saturation level. For Marshall specimen, the compacted mix aging is ranked 5, after loose mix aging, saturation level, and combined effects of loose mix aging and saturation level.

Table 4-27 ANOVA Analysis of the Complete Factorial Experiment for the Freeze-Thaw Tensile Strength (Marshall 100 –mm specimen)

Rank	Source	F Value	Pr>F	Significant
1	LMA	509.339	0.000	Y
2	SATLEV	94.861	0.000	Y
3	LMA * SATLEV	7.393	0.000	Y
4	LMA * CMA	6.452	.004	Y
5	CMA	.446	.509	N
6	LMA * SATLEV * CMA	.223	.924	N
7	SATLEV * CMA	.083	.920	N

Table 4-28 ANOVA Analysis of the Complete Factorial Experiment for the Freeze-Thaw Tensile Strength (Gyratory 100-mm specimen)

Rank	Source	F Value	Pr>F	Significant
1	LMA	1034.555	0.000	Y
2	SATLEV	138.149	0.000	Y
3	CMA	16.991	0.000	Y
4	LMA * CMA	11.560	.000	Y
5	LMA * SATLEV	4.925	.003	Y
6	LMA * SATLEV * CMA	.973	.434	N
7	SATLEV * CMA	.915	.410	N

Table 4-29 ANOVA Analysis of the Complete Factorial Experiment for the Freeze-Thaw Tensile Strength (Gyratory 150-mm specimen)

Rank	Source	F Value	Pr>F	Significant
1	LMA	1531.931	0.000	Y
2	SATLEV	213.162	0.000	Y
3	CMA	38.926	0.000	Y
4	LMA * CMA	22.184	.000	Y
5	LMA * SATLEV	5.481	.001	Y
6	LMA * SATLEV * CMA	2.002	.115	N
7	SATLEV * CMA	.936	.401	N

Table 4-30 Comparison ANOVA Analysis for the F-T Tensile Strength

Rank	Compaction Method	Source	F Value	Pr>F	Significant
1	M100	LMA	509.339	0.000	Y
	G100	LMA	1034.555	0.000	Y
	G150	LMA	1531.931	0.000	Y
2	M100	SATLEV	94.861	0.000	Y
	G100	SATLEV	138.149	0.000	Y
	G150	SATLEV	213.162	0.000	Y
3	M100	LMA * SATLEV	7.393	0.000	Y
	G100	CMA	16.991	0.000	Y
	G150	CMA	38.926	0.000	Y
4	M100	LMA * CMA	6.452	.004	Y
	G100	LMA * CMA	11.560	.000	Y
	G150	LMA * CMA	22.184	.000	Y
5	M100	CMA	.446	.509	N
	G100	LMA * SATLEV	4.925	.003	Y
	G150	LMA * SATLEV	5.481	.001	Y
6	M100	LMA * SATLEV * CMA	.223	.924	N
	G100	LMA * SATLEV * CMA	.973	.434	N
	G150	LMA * SATLEV * CMA	2.002	.115	N
7	M100	SATLEV * CMA	.083	.920	N
	G100	SATLEV * CMA	.915	.410	N
	G150	SATLEV * CMA	.936	.401	N

4.3.3.2 ANOVA analysis of freeze-thaw tensile strength for Martin Marietta Gravel

Tables 4-31, 4-32, and 4-33 show the results of ANOVA analysis of the freeze-thaw conditioned tensile strength of Marshall 100-mm specimen, Gyratory 100-mm specimen, and Gyratory 150-mm specimen, respectively. Table 4-34 shows the summary and comparison of ANOVA analysis results for the freeze-thaw tensile strength with different compaction methods for Martin Marietta Gravel. Tables 4-31, 4-32, 4-33 and 4-34 indicate that the loose mix aging is the most important factor to influence the freeze-thaw conditioned tensile strength, while saturation level is the second important factor for all of Marshall 100-mm specimen, Gyratory 100-mm specimen, and Gyratory 150mm specimen. For all the Marshall 100-mm specimen, Gyratory 100-mm specimen, and Gyratory 150-mm specimen, the compacted mix aging is ranked 3, after the loose mix aging and saturation level.

Table 4-31 ANOVA Analysis of the Freeze-Thaw Conditioned Tensile Strength (Marshall 100-mm specimen)

Rank	Source	F Value	Pr>F	Significant
1	LMA	623.103	0	Y
2	SATLEV	14.454	0.001	Y
3	CMA	10.729	0	Y
4	LMA * SATLEV	5.738	0.007	Y
5	LMA * CMA	1.698	0.197	N
6	SATLEV * CMA	1.124	0.336	N
7	LMA * SATLEV * CMA	0.558	0.695	N

Table 4-32 ANOVA Analysis of the Freeze-Thaw Conditioned Tensile Strength

(Gyratory 100-mm specimen)

Rank	Source	F Value	Pr>F	Significant
1	LMA	385.32	0	Y
2	SATLEV	5.08	0.002	Y
3	CMA	2.756	0.077	N
4	LMA * SATLEV	2.375	0.107	N
5	LMA * CMA	1.816	0.177	N
6	SATLEV * CMA	0.947	0.337	N
7	LMA * SATLEV * CMA	0.308	0.871	N

Table 4-33 ANOVA Analysis of the Freeze-Thaw Conditioned Tensile Strength

(Gyratory 150-mm specimen)

Rank	Source	F Value	Pr>F	Significant
1	LMA	550.805	0	Y
2	SATLEV	39.318	0	Y
3	CMA	31.363	0	Y
4	LMA * SATLEV	6.612	0	Y
5	LMA * CMA	6.165	0.005	N
6	SATLEV * CMA	4.207	0.007	N
7	LMA * SATLEV * CMA	2.872	0.07	N

Table 4-34 Comparison ANOVA Analysis for the F-T Tensile Strength

Rank	Compaction Method	Source	F Value	Pr>F	Significant
1	M100	LMA	623.103	0	Y
	G100	LMA	385.32	0	Y
	G150	LMA	550.805	0	Y
2	M100	SATLEV	14.454	0.001	Y
	G100	SATLEV	5.08	0.002	Y
	G150	SATLEV	39.318	0	Y
3	M100	CMA	10.729	0	Y
	G100	CMA	2.756	0.077	N
	G150	CMA	31.363	0	Y
4	M100	LMA * SATLEV	5.738	0.007	Y
	G100	LMA * SATLEV	2.375	0.107	N
	G150	LMA * SATLEV	6.612	0	Y
5	M100	LMA * CMA	1.698	0.197	N
	G100	LMA * CMA	1.816	0.177	N
	G150	LMA * CMA	6.165	0.005	N
6	M100	SATLEV * CMA	1.124	0.336	N
	G100	SATLEV * CMA	0.947	0.337	N
	G150	SATLEV * CMA	4.207	0.007	N
7	M100	LMA * SATLEV * CMA	0.558	0.695	N
	G100	LMA * SATLEV * CMA	0.308	0.871	N
	G150	LMA * SATLEV * CMA	2.872	0.07	N

4.3.3.3 Complete factorial ANOVA analysis for freeze-thaw tensile strength

Table 4-35 and Table 4-36 show the test results of freeze-thaw tensile strength at different conditions for limestone and gravel, respectively. Table 4-37 provides a summary of ANOVA analysis results. Independent variables in the analysis are the source of aggregate (SOURCE), compaction method (COMP), loose mix aging (LMA), compacted mix aging (CMA), and saturation level (SATLEV). The dependent variable is freeze-thaw tensile strength. The ANOVA analysis indicates that loose mix aging is the most important factor affecting the freeze-thaw tensile strength. Source of aggregate, compaction method and saturation level are also important. Compacted mix aging is not an important factor. Figures 4-3 and 4-4 show the freeze-thaw tensile strength at different conditions for limestone and gravel, respectively. The condition numbers are explained in Tables 4-35 and 4-36. From Figures 4-3 and 4-4, one can see that both 4 hours and 16 hours loose mix aging increase the freeze-thaw conditioned tensile strength. Compacted mix aging shows very little influence on the freeze-thaw conditioned tensile strength. For both aggregate sources, the 150mm diameter specimens have lower freeze-thaw conditioned tensile strength than the 100mm diameter specimens. The data also indicates that freeze-thaw tensile strength decreases with the increase of the level of saturation.

Table 4-35 Results Summary of Freeze-Thaw Tensile Strength for the Limestone

Loose Mix Aging	Saturation Level	Compacted Mix Aging	Condition Designation No.	Mean Value for limestone		
				Marshall 100	Gyratory 100	Gyratory 150
No Aging	50	24 h	1	70.51	72.78	69.17
		72 h	2	79.68	75.04	69.96
	70	24 h	3	60.60	69.31	57.39
		72 h	4	71.60	62.64	54.16
	90	24 h	5	50.98	59.02	51.35
		72 h	6	65.09	52.36	44.30
4 hrs Aging	50	24 h	7	168.94	148.92	122.86
		72 h	8	166.39	156.18	131.92
	70	24 h	9	141.00	129.29	111.80
		72 h	10	145.02	139.98	116.03
	90	24 h	11	116.95	111.26	94.67
		72 h	12	116.85	122.97	110.22
16 hrs Aging	50	24 h	13	181.08	134.99	141.02
		72 h	14	160.60	150.46	153.05
	70	24 h	15	133.75	126.36	117.65
		72 h	16	137.65	136.29	131.08
	90	24 h	17	128.29	108.41	102.86
		72 h	18	97.26	115.73	119.56

Table 4-36 Results Summary of Freeze-Thaw Tensile Strength for the Gravel

Loose Mix Aging	Saturation Level	Compacted Mix Aging	Condition Designation No.	Mean value for gravel		
				Marshall 100	Gyratory 100	Gyratory 150
No Aging	50	24 h	1	81.86	71.51	61.47
		72 h	2	88.63	68.12	65.63
	70	24 h	3	70.57	68.18	39.78
		72 h	4	75.25	64.87	56.62
	90	24 h	5	70.21	63.88	45.53
		72 h	6	66.36	70.56	51.12
4 hrs Aging	50	24 h	7	133.80	138.84	155.22
		72 h	8	150.31	130.41	121.26
	70	24 h	9	142.74	142.06	168.19
		72 h	10	160.76	140.77	123.74
	90	24 h	11	160.73	146.00	162.03
		72 h	12	159.83	147.72	113.01
16 hrs Aging	50	24 h	13	144.18	154.92	119.81
		72 h	14	165.86	153.73	144.64
	70	24 h	15	157.88	128.57	162.10
		72 h	16	166.13	138.22	126.78
	90	24 h	17	146.94	125.99	137.77
		72 h	18	146.66	147.38	127.12

Table 4-37 ANOVA Analysis of Freeze-Thaw Conditioned Tensile Strength

Dependent Variable: F-T Conditioned Tensile Strength			
Source	Mean Square	F	Sig.
LMA	192711.89	3545.35	6.9E-166
SATLEV	7855.23	144.51	1.46E-40
SOURCE	7756.53	142.70	1.39E-25
COMP	7023.02	129.20	1.25E-37
SOURCE * SATLEV	5051.03	92.92	7.62E-30
SOURCE * COMP * CMA	1244.46	22.89	9.6E-10
SOURCE * LMA	1088.71	20.03	1.05E-08
SOURCE * COMP * LMA * CMA	1055.82	19.42	1.15E-13
SOURCE * LMA * SATLEV	948.30	17.45	2.02E-12
SOURCE * LMA * CMA	780.19	14.35	1.4E-06
SOURCE * COMP * LMA	741.01	13.63	6.3E-10
SOURCE * CMA	668.53	12.30	0.000551
COMP * LMA * CMA	599.69	11.03	3.68E-08
COMP * CMA	538.84	9.91	7.6E-05
LMA * CMA	381.34	7.02	0.001117
SOURCE * COMP * LMA * SATLEV	341.27	6.28	2.62E-07
SOURCE * COMP * SATLEV * CMA	278.30	5.12	0.000584
CMA	259.13	4.77	0.030083
LMA * SATLEV	253.71	4.67	0.00124
Corrected Total			
R Squared = .975 (Adjusted R Squared = .963)			

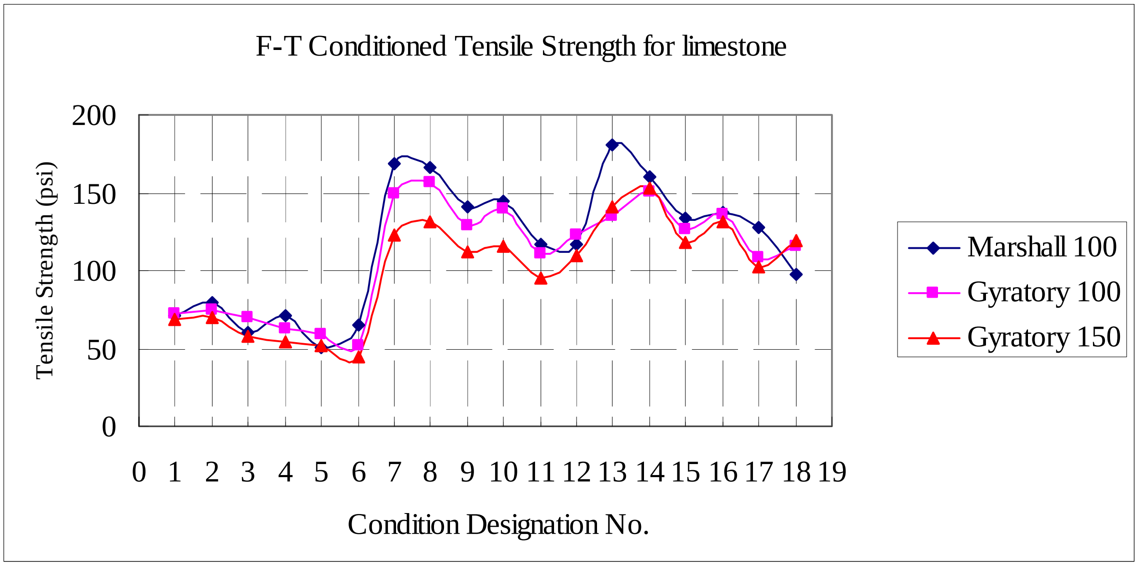

Figure 4- 3 Distribution of Freeze-Thaw Conditioned Tensile Strength for Limestone

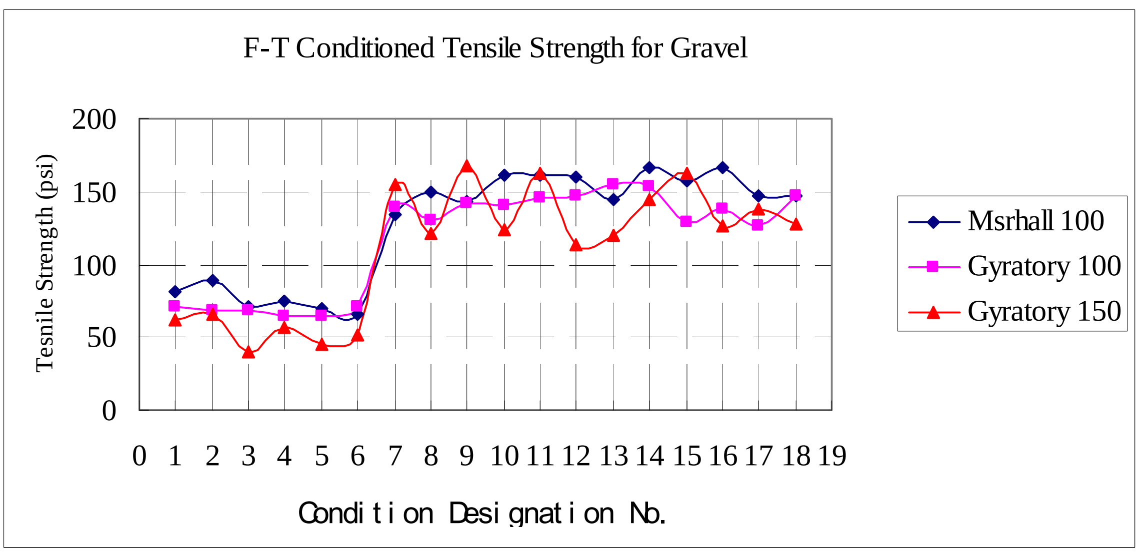

Figure 4- 4 Distribution of Freeze-Thaw Conditioned Tensile Strength for Gravel

4.4 Dry tensile strength versus freeze-thaw tensile strength

4.4.1 Comparison of three compaction methods

The water conditioning of HMA samples by vacuum saturation, soaking, and a freeze-thaw cycle normally decreases the tensile strength. Statistical comparisons have been made among groups of sample dry (without conditioning) and after water conditioning with vacuum saturation and a freeze-thaw cycle.

This section provides information about the effect of compaction method and sample size on the comparison results between dry tensile strength and freeze-thaw tensile strength. The variable included in this analysis is mixture source (Honey Creek Limestone Vs. Martin Marietta Gravel).

Table 4-38 shows statistical comparisons of samples for Honey Creek Limestone, while Table 4-39 shows statistical comparisons of samples for Martin Marietta Gravel. Based on analysis presented in these two tables, the following observations can be made.

For Honey Creek Limestone

- M100 Samples

Table 4-38 indicates that the freeze-thaw tensile strengths are statistically the same as the dry tensile strengths for 2 of 18 conditions. In 16 of 18 comparisons, the freeze thaw tensile strengths are statistically lower than the dry tensile strengths.

- G100 and G150 Samples

Table 4-38 indicates that the freeze-thaw tensile strengths are statistically the same as the dry tensile strengths for 2 of 36 conditions. In 34 of 36 comparisons, the freeze-thaw tensile strengths are statistically lower than the dry tensile strengths.

For Martin Marietta Gravel

- M100 Samples

Table 4-39 indicates that the freeze-thaw tensile strengths are statistically the same as the dry tensile strengths for 3 of 9 conditions. In 6 of 9 comparisons, the freeze-thaw tensile strengths are statistically lower than the dry tensile strengths.

- G100 and G150 Samples

Table 4-39 indicates that the freeze thaw tensile strengths were statistically the same as the dry tensile strengths for 17 of 36 conditions. In 17 of 36 comparisons, the freeze-thaw tensile strengths are statistically lower than the dry tensile strengths. In 2 of 36 comparisons, the freeze-thaw tensile strengths are statistically larger than the dry tensile strengths.

Table 4-38 Statistical Comparison of Dry Tensile Strength and Freeze-Thaw Tensile Strength (Honey Creek Limestone)

Compaction Method	Loose Mix Aging Hrs	Compacted Mix Aging Hrs	Increase*	Same*	Decrease*
Marshall 100	No aging	24			3
		72			3
	4 hrs aging	24		1	2
		72			3
	16 hrs aging	24		1	2
		72			3
Gyratory 100	No aging	24			3
		72			3
	4 hrs aging	24			3
		72			3
	16 hrs aging	24			3
		72			3
Gyratory 150	No aging	24			3
		72			3
	4 hrs aging	24		1	2
		72			3
	16 hrs aging	24		1	2
		72			3
Marshall				2	16
Gyratory				2	34
Total				4	50

Table 4-39 Statistical Comparison of Dry Tensile Strength and Freeze-Thaw Tensile Strength (Martin Marietta Gravel)

Compaction Method	Loose Mix Aging Hrs	Compacted Mix Aging Hrs	Increase*	Same*	Decrease*
Marshall 100	No aging	24		1	2
		72		1	2
	4 hrs aging	24		1	2
		72			3
	16 hrs aging	24		3	
		72	3		
Gyratory 100	No aging	24			3
		72			3
	4 hrs aging	24		3	
		72		2	1
	16 hrs aging	24	1	1	1
		72		3	
Gyratory 150	No aging	24		1	2
		72		1	2
	4 hrs aging	24		3	
		72			3
	16 hrs aging	24	1	2	
		72		1	2
Marshall			3	6	9
Gyratory			2	17	17
Total			5	23	26

4.4.2 Comparisons of dry tensile strength and freeze-thaw tensile strength

In theory the conditioned tensile strength is expected to be lower than the dry tensile strength, because conditioning in water according to the AASHTO T 283 can lead to moisture damage. Figures 4-5, 4-6, and 4-7 show the comparisons of the dry tensile strength versus freeze-thaw tensile strength at different conditions for Honey Creek Limestone. Figures 4-8, 4-9, and 4-10 show the comparisons of the dry tensile strength versus freeze-thaw tensile strength at different conditions for Martin Marietta Gravel. The condition numbers indicated in these figures are defined in Tables 4-35 and 4-36 for Honey Creek Limestone and Martin Marietta Gravel, respectively. The results show that freeze-thaw tensile strengths are lower than the dry tensile strengths for both Honey Creek Limestone and Martin Marietta Gravel. For all the HMA specimens, including Marshall 100-mm specimen, Gyratory 100-mm specimen and Gyratory 150-mm specimen, the same trend is observed in these figures. It is clear that freeze-thaw conditioning is crucial in the conditioning process. One freeze-thaw cycle should be included in the proposed water stripping test procedure.

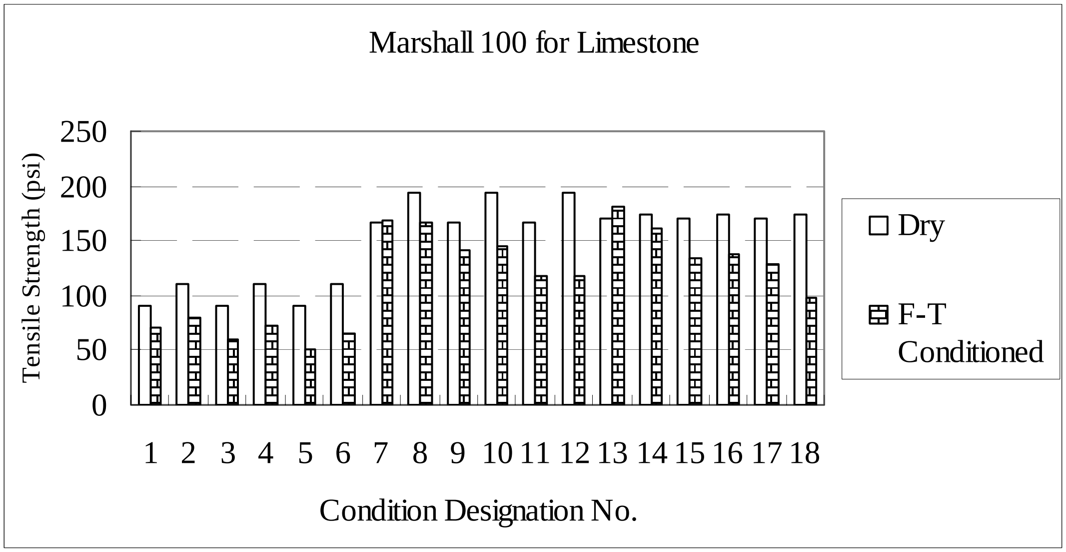

Figure 4- 5 Comparisons of Dry Tensile Strength and Freeze-Thaw Tensile Strength for Honey Creek Limestone (Marshall 100-mm Diameter Specimen)

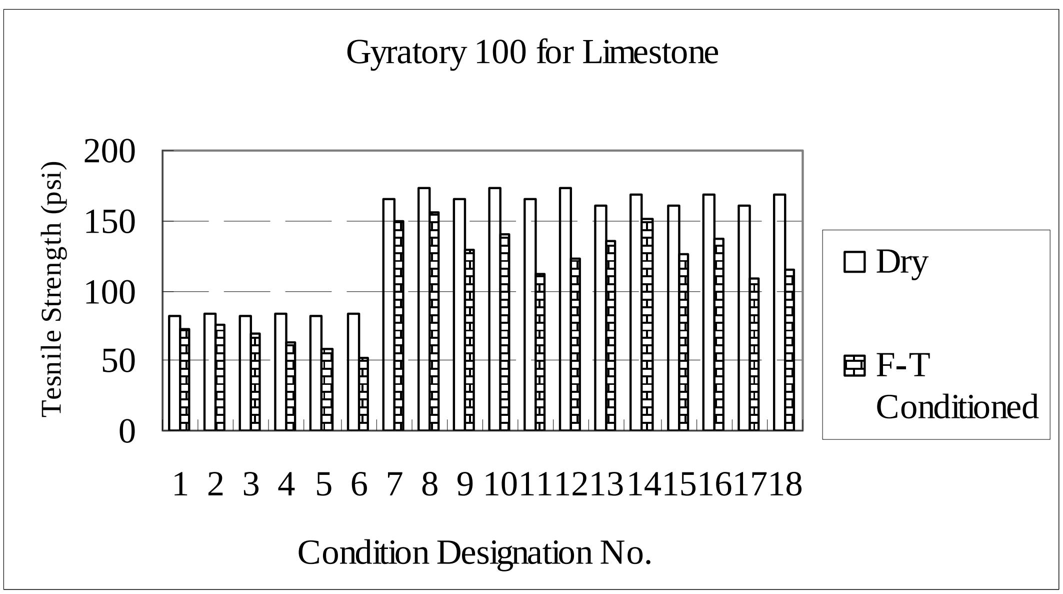

Figure 4- 6 Comparisons of Dry Tensile Strength and Freeze-Thaw Tensile Strength for Honey Creek Limestone (Gyratory100-mm Diameter Specimen)

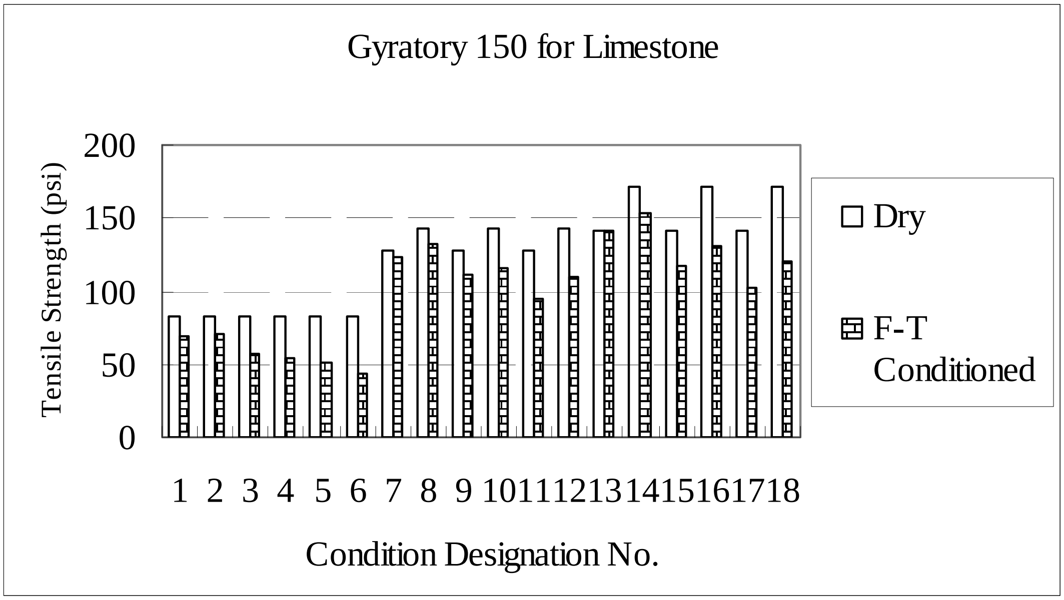

Figure 4- 7 Comparisons of Dry Tensile Strength and Freeze-Thaw Tensile Strength for Honey Creek Limestone (Gyratory 150-mm Diameter Specimen)

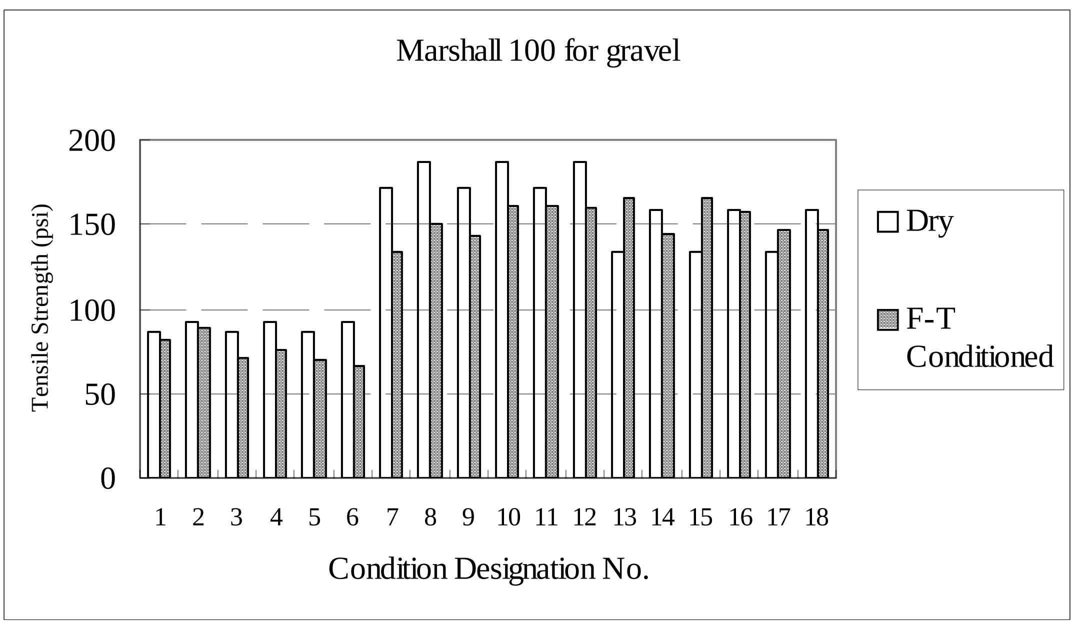

Figure 4- 8 Comparisons of Dry Tensile Strength and Freeze-Thaw Tensile Strength for Martin Marietta Gravel (Marshall 100-mm Diameter Specimen)

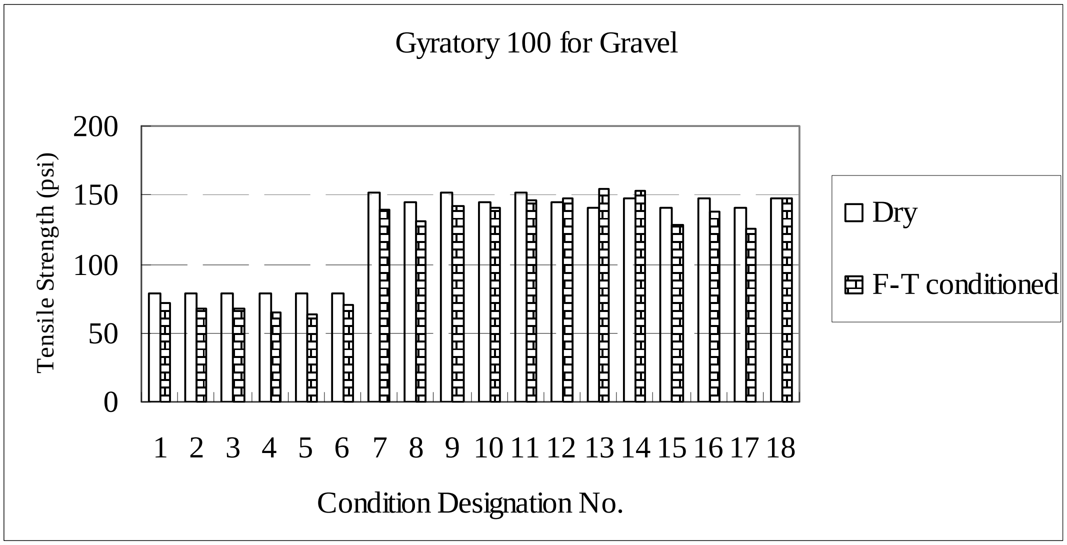

Figure 4- 9 Comparisons of Dry Tensile Strength and Freeze-Thaw Tensile Strength for Martin Marietta Gravel (Gyratory100-mm Diameter Specimen)

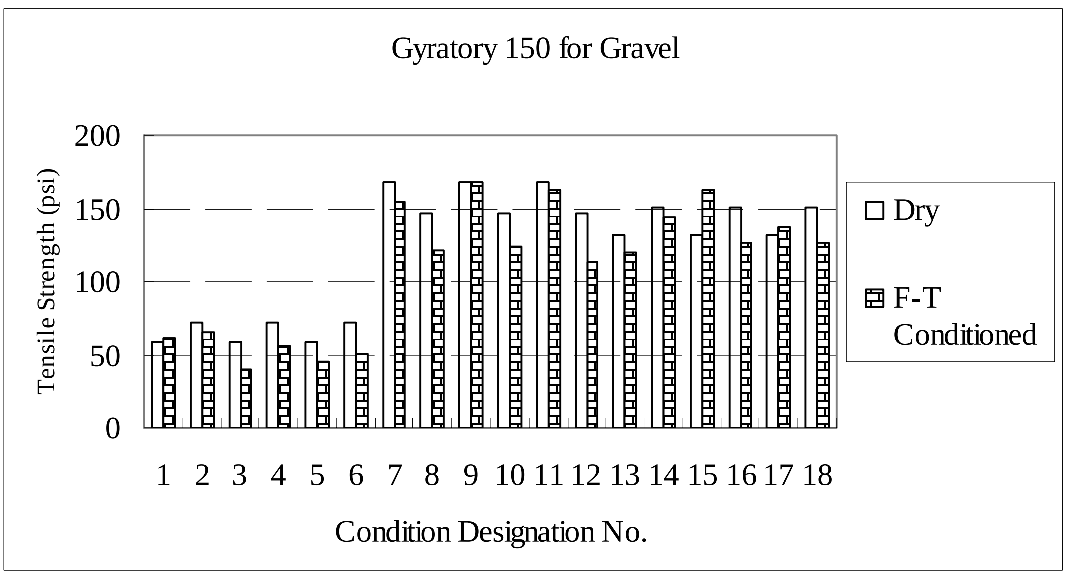

Figure 4- 10 Comparisons of Dry Tensile Strength and Freeze-Thaw Tensile Strength for Martin Marietta Gravel (Gyratory 150-mm Diameter Specimen)

4.5 Level of Saturation

The experimental program includes saturation level at 50, 70, and 90 percent for both Honey Creek Limestone and Martin Marietta Gravel. Tables 4-40, 4-41, and 4-42 show the statistical comparison results of the influence of level of saturation on freeze-thaw tensile strength for the Honey Creek Limestone. Tables 4-43, 4-44, and 4-45 are results for Martin Marietta Gravel. For both Honey Creek Limestone and Martin Marietta Gravel, the freeze-thaw tensile strength decreases with the increase of saturation level in most cases.

From the ANOVA analysis (Table 4-37) for the freeze-thaw tensile strength, the saturation level is an important factor. Figure 4-11 shows the relationship of freeze-thaw conditioned tensile strength with saturation level for limestone at the 24 hrs compacted mix aging. The results show that freeze-thaw tensile strength decreases with the increase of saturation level in all cases. A good correlation exists between freeze-thaw conditioned tensile strength and saturation level. For the 72 hrs compacted mix aging, the similar trend of relationship is obtained. The test results also indicate that freeze-thaw tensile strength of HMA specimens saturated to the lower end of range may be significantly different than those of the same HMA specimens saturated to the upper end for a similar air void content. As a result, the TSR values could also be significantly different since the dry tensile strength is the same.

Table 4-40 Statistical Comparison of Freeze-Thaw Tensile Strength subjected to different Levels of Saturation: 70% vs. 50% (Honey Creek Limestone)

Compaction Method	Loose Mix Aging Hrs	Compacted Mix Aging Hrs	Increase*	Same*	Decrease*
Marshall 100	No aging	24			√
		72			√
	4 hrs aging	24			√
		72			√
	16 hrs aging	24			√
		72			√
Gyratory 100	No aging	24		√	
		72			√
	4 hrs aging	24			√
		72			√
	16 hrs aging	24		√	
		72			√
Gyratory 150	No aging	24			√
		72			√
	4 hrs aging	24			√
		72			√
	16 hrs aging	24			√
		72			√
Marshall				0	6
Gyratory				2	10
Total				2	16

Table 4-41 Statistical Comparison of Freeze-Thaw Tensile Strength subjected to different Levels of Saturation: 90% vs. 50% (Honey Creek Limestone)

Compaction Method	Loose Mix Aging Hrs	Compacted Mix Aging Hrs	Increase*	Same*	Decrease*
Marshall 100	No aging	24			√
		72			√
	4 hrs aging	24			√
		72			√
	16 hrs aging	24			√
		72			√
Gyratory 100	No aging	24			√
		72			√
	4 hrs aging	24			√
		72			√
	16 hrs aging	24			√
		72			√
Gyratory 150	No aging	24			√
		72			√
	4 hrs aging	24			√
		72			√
	16 hrs aging	24			√
		72			√
Marshall				0	6
Gyratory				0	12
Total				0	18

Table 4-42 Statistical Comparison of Freeze-Thaw Tensile Strength subjected to different Levels of Saturation: 90% vs. 70% (Honey Creek Limestone)

Compaction Method	Loose Mix Aging Hrs	Compacted Mix Aging Hrs	Increase*	Same*	Decrease*
Marshall 100	No aging	24			√
		72			√
	4 hrs aging	24			√
		72			√
	16 hrs aging	24			√
		72			√
Gyratory 100	No aging	24			√
		72			√
	4 hrs aging	24			√
		72			√
	16 hrs aging	24			√
		72			√
Gyratory 150	No aging	24		√	
		72			√
	4 hrs aging	24			√
		72		√	
	16 hrs aging	24			√
		72		√	
Marshall				0	6
Gyratory				2	10
Total				2	16

Table 4-43 Statistical Comparison of Freeze-Thaw Tensile Strength subjected to different Levels of Saturation: 70% vs. 50% (Martin Marietta Gravel)

Compaction Method	Loose Mix Aging Hrs	Compacted Mix Aging Hrs	Increase*	Same*	Decrease*
Marshall 100	No aging	24			√
		72			√
	4 hrs aging	24		√	
		72		√	
	16 hrs aging	24		√	
		72		√	
Gyratory 100	No aging	24		√	
		72		√	
	4 hrs aging	24		√	
		72		√	
	16 hrs aging	24			√
		72		√	
Gyratory 150	No aging	24			√
		72			√
	4 hrs aging	24		√	
		72		√	
	16 hrs aging	24	√		
		72		√	
Marshall				4	2
Gyratory			1	8	3
Total			1	12	5

Table 4-44 Statistical Comparison of Freeze-Thaw Tensile Strength subjected to different Levels of Saturation: 90% vs. 50% (Martin Marietta Gravel)

Compaction Method	Loose Mix Aging Hrs	Compacted Mix Aging Hrs	Increase*	Same*	Decrease*
Marshall 100	No aging	24			√
		72			√
	4 hrs aging	24	√		
		72		√	
	16 hrs aging	24		√	
		72			√
Gyratory 100	No aging	24		√	
		72		√	
	4 hrs aging	24		√	
		72		√	
	16 hrs aging	24			√
		72		√	
Gyratory 150	No aging	24			√
		72			√
	4 hrs aging	24		√	
		72		√	
	16 hrs aging	24		√	
		72		√	
Marshall			1	2	3
Gyratory				9	3
Total			1	11	6

Table 4-45 Statistical Comparison of Freeze-Thaw Tensile Strength subjected to different Levels of Saturation: 90% vs. 70% (Martin Marietta Gravel)

Compaction Method	Loose Mix Aging Hrs	Compacted Mix Aging Hrs	Increase*	Same*	Decrease*
Marshall 100	No aging	24		√	
		72			√
	4 hrs aging	24	√		
		72		√	
	16 hrs aging	24		√	
		72			√
Gyratory 100	No aging	24		√	
		72		√	
	4 hrs aging	24		√	
		72		√	
	16 hrs aging	24		√	
		72		√	
Gyratory 150	No aging	24		√	
		72		√	
	4 hrs aging	24		√	
		72		√	
	16 hrs aging	24			√
		72		√	
Marshall			1	3	2
Gyratory				11	1
Total			1	14	3

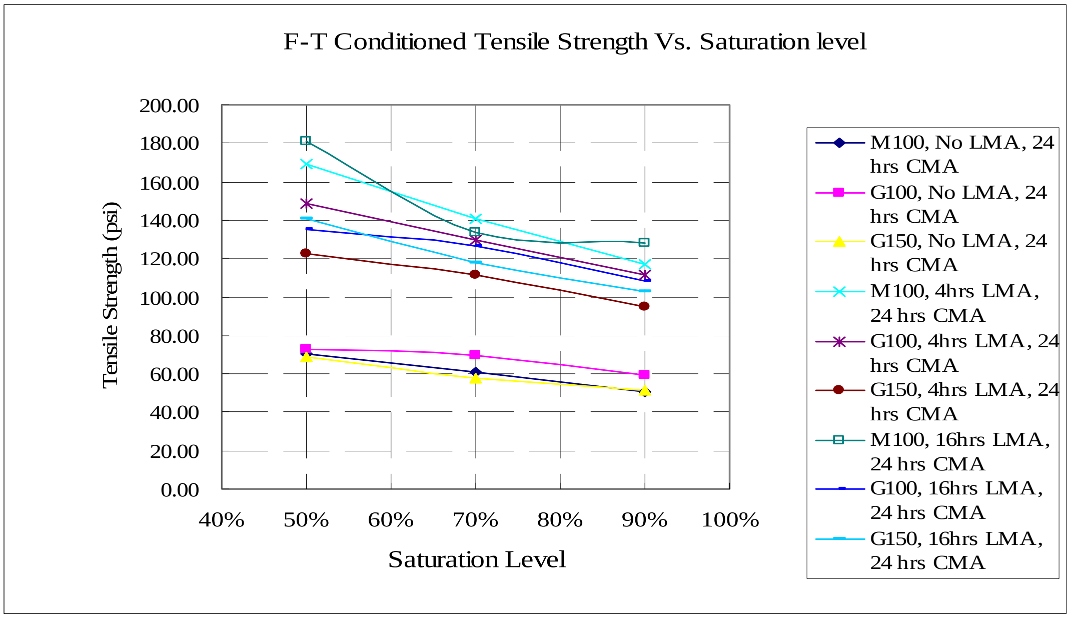

Figure 4- 11 Relationship of the F-T Tensile Strength Versus. Saturation Level

4.6 Water Sensitivity

Tensile strength ratios of 70 to 80 percent are typically used as acceptance levels for the AASHTO T 283 method of test. Tensile strength ratios from portions of this study are shown in Tables 4-46, 4-47, and 4-48.

Table 4-46 shows the sources of the materials, type of compaction, and conditioning associated with 70 and 80 percent minimum tensile strength ratios for this portion of the study. The mixtures prepared with the Honey Greek Limestone and Martin Marietta Gravel would pass the 70 and 80 criteria for the most conditions.

For Honey Greek Limestone, almost all the tensile strength ratio passed the 80% at the saturation of 50%. At the saturation of 70%, 6 of 14 conditions passed the TSR of 70%, while 8 of 14 passed 80%. At the saturation of 90%, just half of these conditions can pass the TSR of 70%, the other tensile strength ratios are below the TSR of 70%.

For Martin Marietta Gravel, at the saturation of 50%, almost all the tensile strength ratio passed the TSR of 80%. The same observation can be made at the saturation of 70%. At the saturation of 90%, 4 of 18 conditions passed the TSR of 70%, 14 of 18 passed TSR of 80%.

Tables 4-47 and 4-48 also show that Marshall 100-mm specimen fails the TSR of 80% at high saturation level while Gyratory 150-mm specimen pass TSR of 80% at the same saturation level for both sources of aggregates. This indicates that Marshall 100-mm specimen has a lower tensile strength ratio than the Gyratory 150-mm specimen at the same saturation level.

Table 4-46 Acceptable Mixtures

Mixtures	Conditioning	Method of Compaction		
Honey Greek Limestone	F-T	M100	G100	G150
Martin Marietta Gravel	F-T	70*, 80	70*, 80	70*, 80

Table 4-47 Tensile Strength Ratio for Freeze-Thaw Conditioning

(Honey Greek Limestone)

Compaction Method	Loose Mix Aging Hrs	Compacted Mix Aging Hrs	Saturation Level					
			50		70		90	
			70%	80%	70%	80%	70%	80%
Marshall 100	No aging	24	√					
		72	√					
	4 hrs aging	24		√		√	√	
		72		√	√			
	16 hrs aging	24		√		√	√	
		72		√	√			
Gyratory 100	No aging	24		√		√	√	
		72		√	√			
	4 hrs aging	24		√	√			
		72		√		√	√	
	16 hrs aging	24		√	√			
		72		√		√		
Gyratory 150	No aging	24		√				
		72		√				
	4 hrs aging	24		√		√	√	
		72		√		√	√	
	16 hrs aging	24		√		√	√	
		72		√	√			
Marshall			2	4	2	2	2	0
Gyratory				12	4	6	5	0
Total			2	16	6	8	7	0

*Note: * Meet 70% or 80% retained tensile strength ratio.

Table 4-48 Tensile Strength Ratio for Freeze-Thaw Conditioning

(Martin Marietta Gravel)

Compaction Method	Loose Mix Aging Hrs	Compacted Mix Aging Hrs	Saturation Level					
			50		70		90	
			70%	80%	70%	80%	70%	80%
Marshall 100	No aging	24		√		√		√
		72		√		√	√	
	4 hrs aging	24	√			√		√
		72		√		√		√
	16 hrs aging	24		√		√		√
		72		√		√		√
Gyratory 100	No aging	24		√		√		√
		72		√		√		√
	4 hrs aging	24		√		√		√
		72		√		√		√
	16 hrs aging	24		√		√		√
		72		√		√		√
Gyratory 150	No aging	24		√			√	
		72		√	√		√	
	4 hrs aging	24		√		√		√
		72		√		√	√	
	16 hrs aging	24		√		√		√
		72		√		√		√
Marshall			1	5	0	6	1	5
Gyratory				12	1	10	3	9
Total			1	17	1	16	4	14

*Note: * Meet 70% or 80% retained tensile strength ratio.

4.7 Tensile Strength Ratio

Table 4-49 and Table 4-50 show the results of TSR at different conditions for Honey Creek Limestone and Martin Marietta Gravel, respectively. Table 4-51 shows the ANOVA analysis of the tensile strength ratio from the complete factorial experiment for Honey Creek Limestone,. Table 4-52 shows the ANOVA analysis of the tensile strength ratio from complete factorial experiment for Martin Marietta Gravel. The results show that the loose mix aging, saturation level and compaction method are important factors influencing the tensile strength ratio. Compacted mix aging ranks behind these three dominant factors.

Figure 4-12 shows Tensile Strength Ratio of Marshall 100-mm specimen, Gyratory 100-mm specimen, and Gyratory 100-mm specimen at different conditions for Honey Creek Limestone. The figure shows that Tensile Strength Ratio decreases with the saturation level for all the Marshall 100-mm, Gyratory 100-mm, and gyratory 150-mm specimens. The TSR value is higher for the specimens with 4 hours loose mix aging and 16 hours loose mix aging at the condition when other testing parameters are the same.

Figure 4-13 shows Tensile Strength Ratio of Marshall 100-mm specimen, Gyratory 100-mm specimen, and Gyratory 100-mm specimen at different conditions for Martin Marietta Gravel. The figure shows that Tensile Strength Ratio changes a little with the different compacted mix aging. The TSR value is higher for the specimens with 4 hours loose mix aging than the specimen with 16 hours loose mix aging when other test parameters are the same.

Table 4-49 Comparison of TSR of M100, G100 and G150 at Different Conditions (Honey Greek Limestone)

Loose Mix Aging Hrs	Compacted Mix Aging Hrs	Saturation Level	Condition Number	TSR		
				M100	G100	G150
No aging	24	50%	1	0.782	0.897	0.834
	72	50%	2	0.723	0.898	0.846
	24	70%	3	0.672	0.854	0.692
	72	70%	4	0.649	0.750	0.655
	24	90%	5	0.566	0.727	0.619
	72	90%	6	0.590	0.627	0.536
4 hrs aging	24	50%	7	1.016	0.899	0.962
	72	50%	8	0.861	0.899	0.919
	24	70%	9	0.848	0.780	0.876
	72	70%	10	0.751	0.806	0.808
	24	90%	11	0.703	0.672	0.742
	72	90%	12	0.605	0.708	0.768
16 hrs aging	24	50%	13	0.945	0.841	0.995
	72	50%	14	0.896	0.894	0.892
	24	70%	15	0.813	0.787	0.830
	72	70%	16	0.741	0.810	0.764
	24	90%	17	0.704	0.676	0.726
	72	90%	18	0.653	0.688	0.697

Table 4-50 Comparison of TSR of M100, G100 and G150 at Different Conditions

(Martin Marietta Gravel)

Loose Mix Aging Hrs	Compacted Mix Aging Hrs	Saturation Level	Condition Number	TSR		
				M100	G100	G150
No aging	24	50%	1	0.950	0.906	1.053
	72	50%	2	0.970	0.869	0.917
	24	70%	3	0.820	0.863	0.681
	72	70%	4	0.860	0.827	0.791
	24	90%	5	0.820	0.809	0.780
	72	90%	6	0.760	0.900	0.714
4 hrs aging	24	50%	7	0.777	0.917	0.924
	72	50%	8	0.803	0.902	0.825
	24	70%	9	0.829	0.938	1.002
	72	70%	10	0.858	0.973	0.842
	24	90%	11	0.934	0.964	0.965
	72	90%	12	0.853	1.021	0.769
16 hrs aging	24	50%	13	1.239	1.106	0.908
	72	50%	14	0.907	1.042	0.958
	24	70%	15	1.241	0.918	1.228
	72	70%	16	0.993	0.937	0.840
	24	90%	17	1.096	0.899	1.044
	72	90%	18	0.924	0.999	0.842

Table 4-51 ANOVA Analysis of the Tensile Strength Ratio for Limestone

Dependent Variable: TSR			
Source	Mean Square	F	Sig.
SATLEV	0.67	415.97	1.81E-51
LMA	0.14	87.56	2.51E-23
CMA	0.06	36.57	2.15E-08
COMP * LMA	0.04	23.74	4.21E-14
COMP	0.02	15.52	1.19E-06
COMP * LMA * CMA	0.01	7.89	1.28E-05
COMP * CMA	0.01	7.39	0.000982
COMP * LMA * SATLEV	0.00	2.59	0.01252
COMP * SATLEV	0.00	1.85	0.123704
R Squared = .922 (Adjusted R Squared = .883)			

Table 4-52 ANOVA Analysis of the Tensile Strength Ratio for Gravel

Dependent Variable: TSR			
Source	Mean Square	F	Sig.
LMA	0.36	91.43	5.84E-24
COMP * CMA	0.14	36.17	9.48E-13
LMA * SATLEV	0.06	16.39	1.6E-10
COMP * LMA * CMA	0.05	13.88	3.61E-09
COMP * LMA	0.05	11.63	6.83E-08
SATLEV	0.03	8.42	0.0004
COMP * LMA * SATLEV	0.02	6.23	1.31E-06
COMP	0.02	5.85	0.003888
CMA	0.00	0.66	0.419461
Error	0.00		
R Squared = .845 (Adjusted R Squared = .770)			

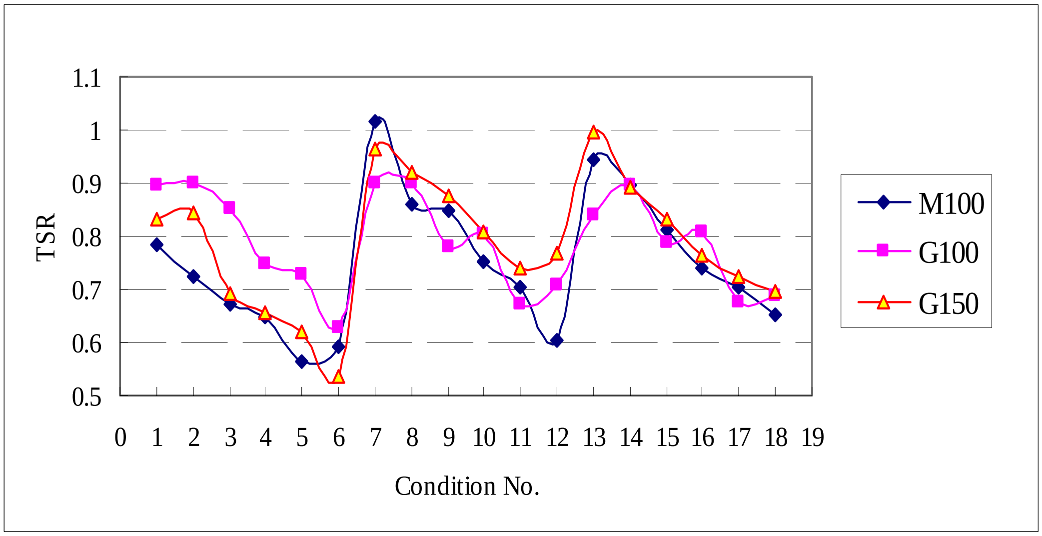

Figure 4- 12 TSR distributions of M100, G100 and G150 at different conditions (Honey Creek Limestone)

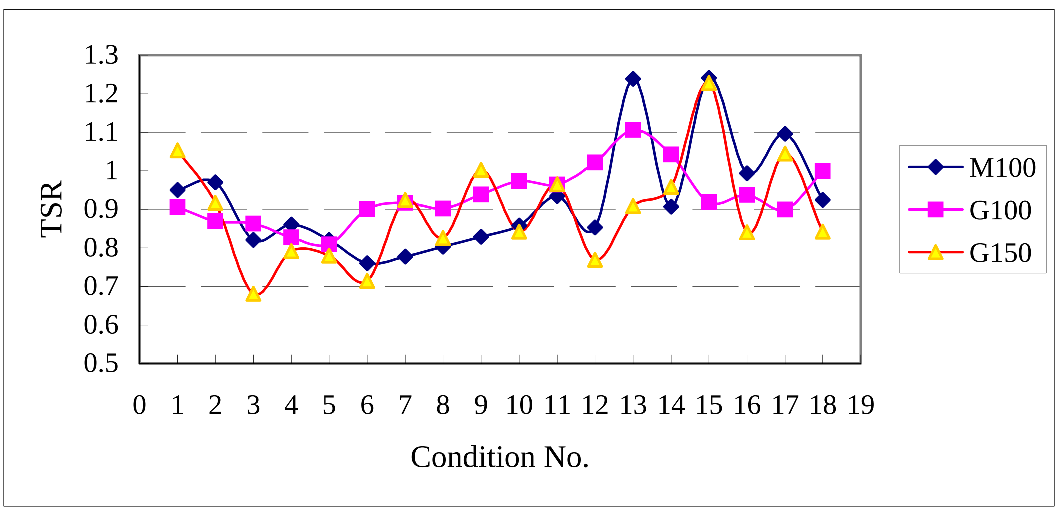

Figure 4- 13 TSR distributions of M100, G100 and G150 at different conditions (Martin Marietta Gravel)

4.8 Summary

Based on the test performed and data analysis presented in this chapter, the following observations can be made.

1. Loose mix aging is the most important factor affecting the dry tensile strength. Both sources of aggregate and compaction method have an effect on the dry tensile strength. Compacted mix aging is not as an important factor as the above mentioned factors.

2. Loose mix aging is the most important factor affecting the freeze-thaw tensile strength. Source of aggregate, compaction method, and saturation level are also important to freeze-thaw tensile strength. Compacted mix aging is not as an important factor as the above mentioned factors.

3. Freeze-thaw tensile strengths are lower than the dry tensile strengths for both limestone and gravel, indicating that freeze-thaw cycle is crucial in the conditioning process. One freeze-thaw cycle should be included in the proposed water stripping test procedure.

4. Freeze-thaw tensile strength decreases with the increase of saturation level. Based on Tables 4-49 and 4-50, Marshall 100-mm specimen has a lower tensile strength ratio than the Gyratory 150-mm specimen at the same saturation level. The saturation level could be increased to 80%-90% for the Gyratory 150-mm, based on the

analysis of test results presented in this chapter, in order for the TSR values to be even closer between Marshall 100-mm specimens and Gyratory 150-mm specimens.

5. Loose mix aging, saturation level, and compaction method are important factors influencing the tensile strength ratio. Compacted mix aging ranks behind these three dominant factors in affecting the tensile strength ratio.

CHAPTER V

DEVELOPMENT OF STRIPPING TEST PROCEDURE FOR SUPERPAVE SPECIMENS

5.1 Introduction

Based on the analysis of various factors affecting the stripping test results from the complete factorial experimental test program presented in chapter IV, regression analysis technique is used to evaluate the relationship of the tensile strength ratio among Marshall 100-mm specimen, Gyratory 100-mm specimen, and Gyratory 150-mm specimen. Based on regression analysis results, the proposed sample conditioning procedure is developed. Furthermore, a partial factorial test program is carried out on HMA mixtures using polymer modified binder. The test results from partial factorial test program are shown to validate the findings from the complete factorial test program.

5.2 Analysis of Tensile Strength Ratio

Figures 5-1 and 5-2 show the TSR regression simulation between Marshall 100-mm specimen and Gyratory 100-mm specimen for Honey Creek Limestone and Martin Marietta Gravel, respectively. Figures 5-3 and 5-4 show the TSR regression simulation between Marshall 100-mm specimen and Gyratory 150-mm specimen for Honey Creek Limestone and Martin Marietta Gravel, respectively.

The tensile strength ratios of Gyratory 150-mm compacted samples are similar to the tensile strength ratios of Marshall 100-mm compacted samples. The R-square is 0.83 for Honey Creek Limestone and 0.63 for Martin Marietta Gravel, respectively. On the contrary, no relationship can be found between Gyratory 100-mm specimen and Marshall 100-mm specimen, since the R-square is 0.478 for Honey Creek Limestone and 0.011 for Martin Marietta Gravel, respectively. It is recommended that Gyratory 150-mm compacted samples should be used in the proposed procedure.

In previous analysis presented in Chapter IV, (i.e., Table 4-51 and Table 4-52), it was found that the loose mix aging, saturation level, and compaction method are three important factors affecting the tensile strength ratio. The values of TSR are different for specimens conditioned with different loose mix aging procedure. Therefore, loose mix aging is required in the proposed procedure. The TSR values of Marshall 100-mm specimen at standard loose mix aging (16hrs) condition are compared with the TSR values of Gyratory 150-mm specimen at different loose mix aging conditions for Honey Creek Limestone and Martin Marietta Gravel in Figures 5-5 and 5-6, respectively. It is seen that the TSR values of Gyratory 150mm specimen at four hours loose mix aging are about the same as the TSR values of Marshall 100mm specimen at standard loose mix aging condition for both Honey Creek Limestone and Martin Marietta Gravel. The four hours loose mix aging for Gyratory 150-mm specimens is similar to sixteen hours loose mix aging on Marshall 100-mm specimen. It is recommended that the four hours loose mix aging for Gyratory 150-mm compacted samples should be used in the proposed procedure.

Based on the analysis of dry tensile strength, freeze-thaw conditioned tensile strength and tensile strength ratio for both Honey Creek Limestone and Martin Marietta Gravel, compacted loose mix aging is not an important factor for the stripping test. Dry tensile strength, freeze-thaw conditioned tensile strength and tensile strength ratio are not significantly changed by different compacted mix aging procedure, (i.e., Table 4-19, Table 4-37, Table 4-51, and Table 4-52) between 24 hours compacted mix aging and 72 hours compacted mix aging. It is recommended that 24 hours compacted mix aging to be used in the proposed test procedures.

Linear regression analysis is performed to investigate the relationships between the TSR values and the degree of saturation. The results are summarized in Table 5-1 and plotted in Figure 5-7. The slopes and intercepts for the regression lines are presented in the table along with the R-square values. The R-square values ranged from 0.85 to 0.99, suggesting a strong correlation between the TSR values and the level of saturation. All the regression lines have relatively low but negative slopes, indicating a reduction in TSR values with an increase of degree of saturation. TSR values of specimens saturated to the lower end of range are significantly higher than the same specimens saturated to the upper end of range. Figure 5-8 shows a comparison of TSR values between Marshall 100-mm specimens with 16 hours aging and Gyratory 150-mm specimens with 4 hours aging at different saturation level. The TSR values of G150 are a little higher than the M100 at the same saturation level. It is recommended that the saturation level be increased to a range of 80%-90% in the proposed test procedure.

Based on the ANOVA analysis for both Honey Creek Limestone and Martin Marietta Gravel presented in Chapter IV, one cycle freeze-thaw condition is an important factor that needs to be included in the proposed test procedures. The proposed test procedure is shown in Table 5-2, in which the suggested conditioning procedure is marked.

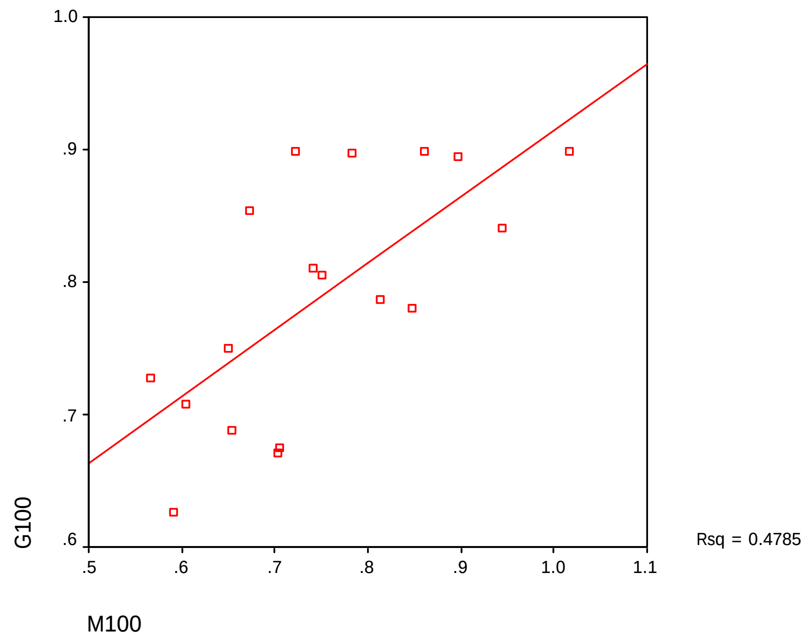

Figure 5- 1 TSR Regression Simulations for Honey Creek Limestone (M100 Vs. G100)

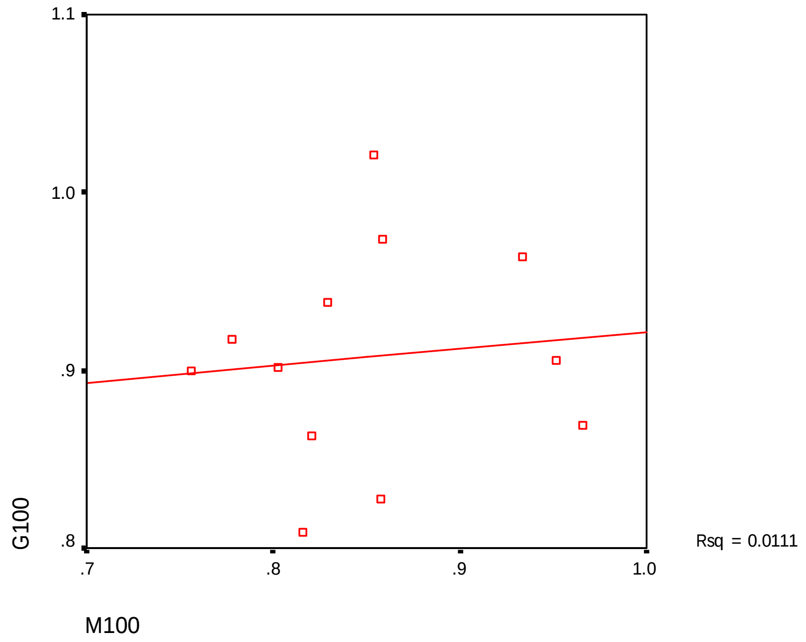

Figure 5- 2 TSR Regression Simulations for Martin Marietta Gravel (M100 Vs. G100)

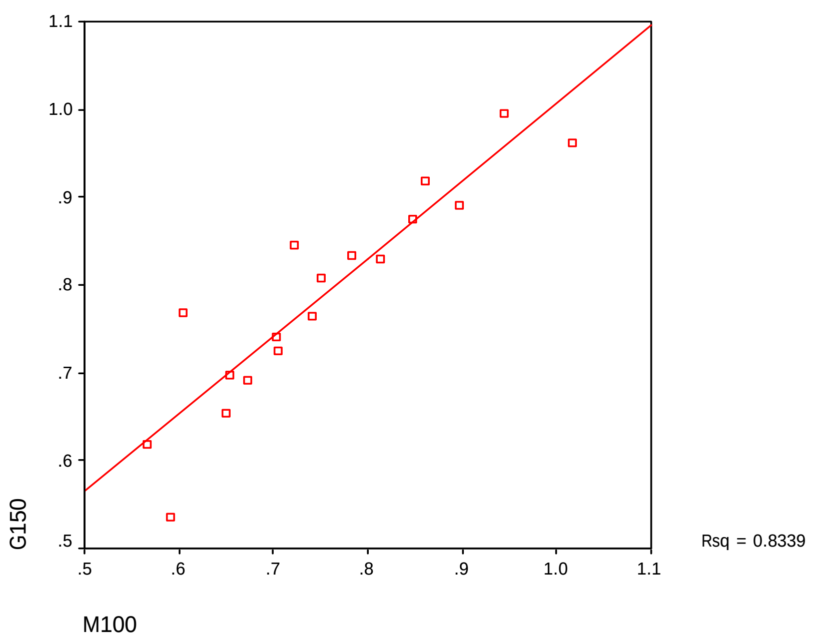

Figure 5- 3 TSR Regression Simulations for Honey Creek Limestone (M100 Vs. G150)

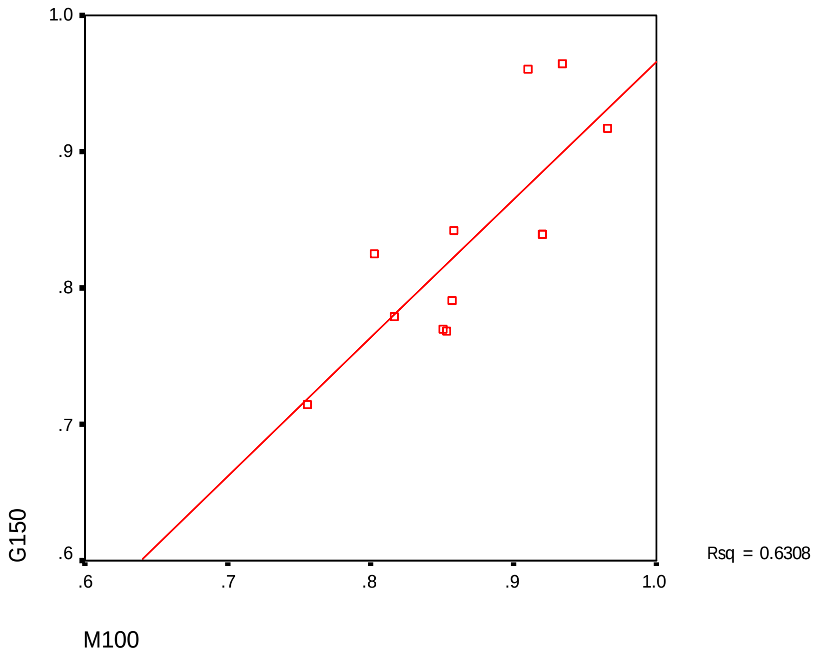

Figure 5- 4 TSR Regression Simulations for Martin Marietta Gravel (M100 Vs. G150)

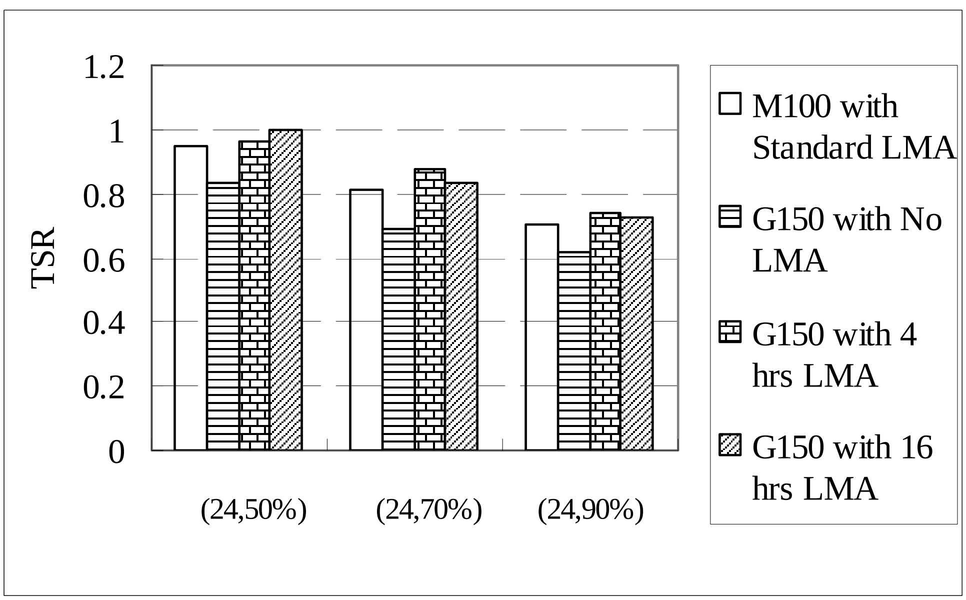

Figure 5- 5 Comparisons of TSR Values of M100 at Standard Loose Mix Aging Condition with G150 at different Loose Mix Aging Condition (Honey Creek Limestone)

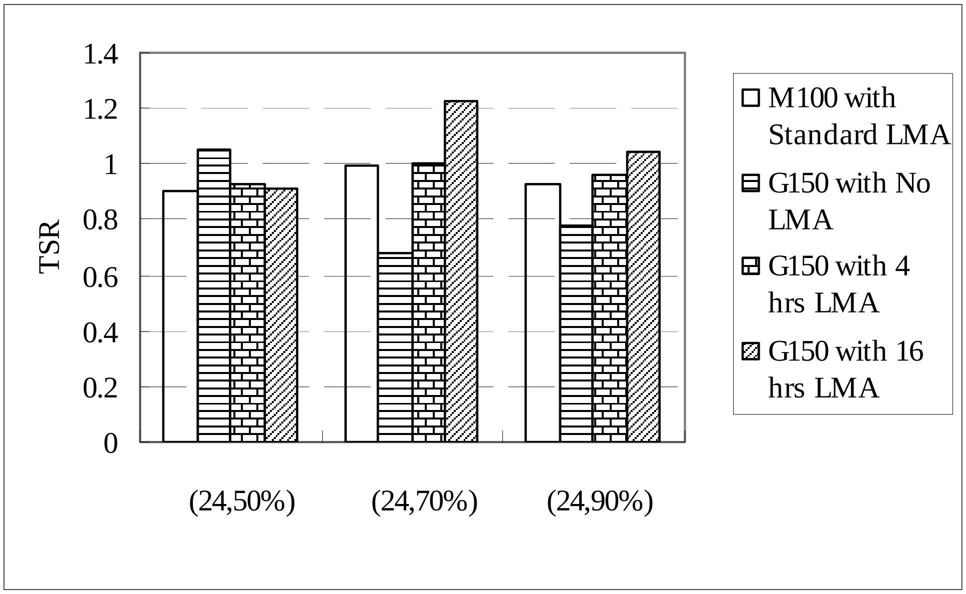

Figure 5- 6 Comparisons of TSR Values of M100 at Standard Loose Mix Aging Condition with G150 at different Loose Mix Aging Condition (Martin Marietta Gravel)

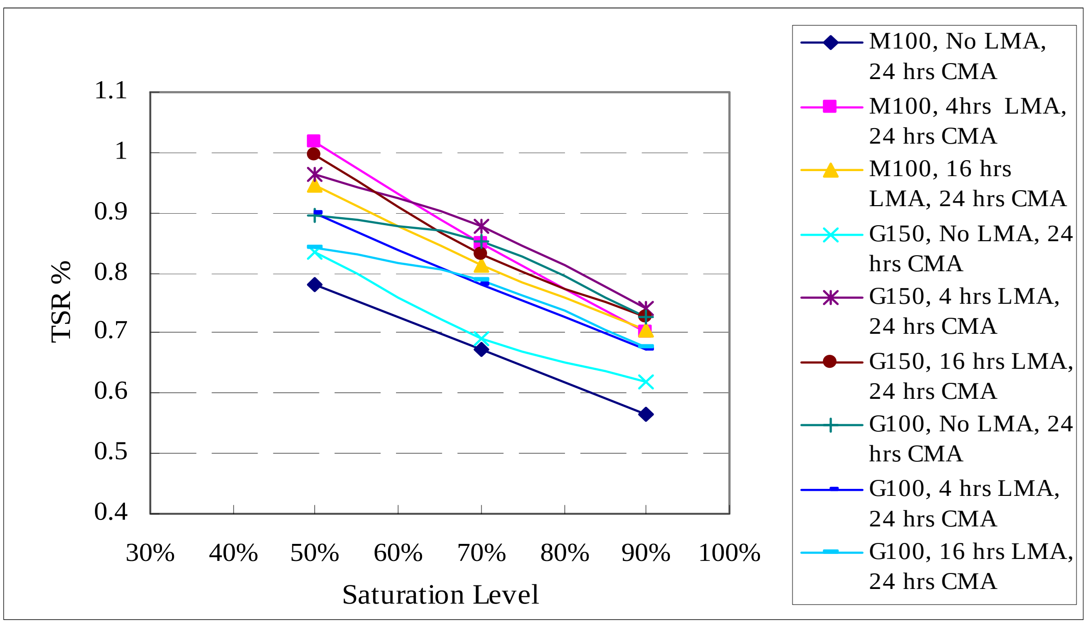

Figure 5- 7 Relationship of TSR and Saturation Level for Honey Creek Limestone

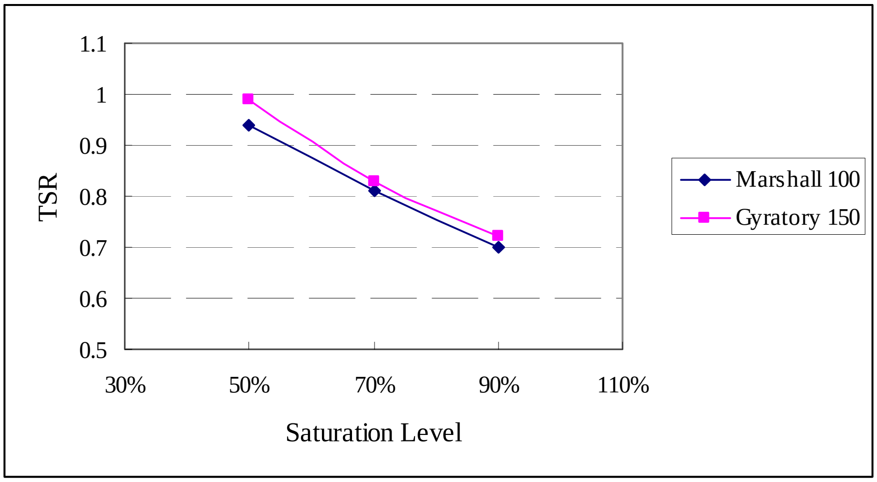

Figure 5- 8 TSR Values of M100 and G150 with Different Saturation Level

Table 5- 1 Summary of Regression between TSR values and the Degree of Saturation

Sample Type	Loose Mix Aging	Slope	Intercept	R-square
M100	No	-0.005	1.053	0.99
	4	-0.008	1.403	0.996
	16	-0.006	1.242	0.993
G100	No	-0.005	1.091	0.933
	4	-0.006	1.246	0.97
	16	-0.007	1.322	0.96
G150	No	-0.004	1.123	0.85
	4	-0.006	1.181	0.99
	16	-0.004	1.508	0.921

5.3 Partial Factorial Test Program

The partial factorial test program for the Ontario Trap Rock and Stocker Sand is depicted in Figure 5-9. The purpose of the partial factorial program is two fold: (a) to validate the conclusions and proposed test procedures using the two new aggregate sources, and (b) to validate the applicability of the test procedure for polymer modified binders.

Table 5- 2 Summary of the Suggested Test Procedure for Gyratory 150-mm (G150) Specimen

Factors Investigated	Level of Variations	Suggested
Loose Mix Aging	1. No aging	
	2. 4 hrs@275°F	√
	3. 16hrs@140°F	
Compacted Mix Aging	1. 24 hrs@ room temp	√
	2. 72 hrs@ room temp	
Freeze-Thaw Cycle	1. None	
	2. One	√
Compaction Method	1. Marshall	
	2. Gyratory 4 in	
	3. Gyratory 6 in	√
Saturation Level	1. 50%	
	2. 70%	
	3. 90%	√

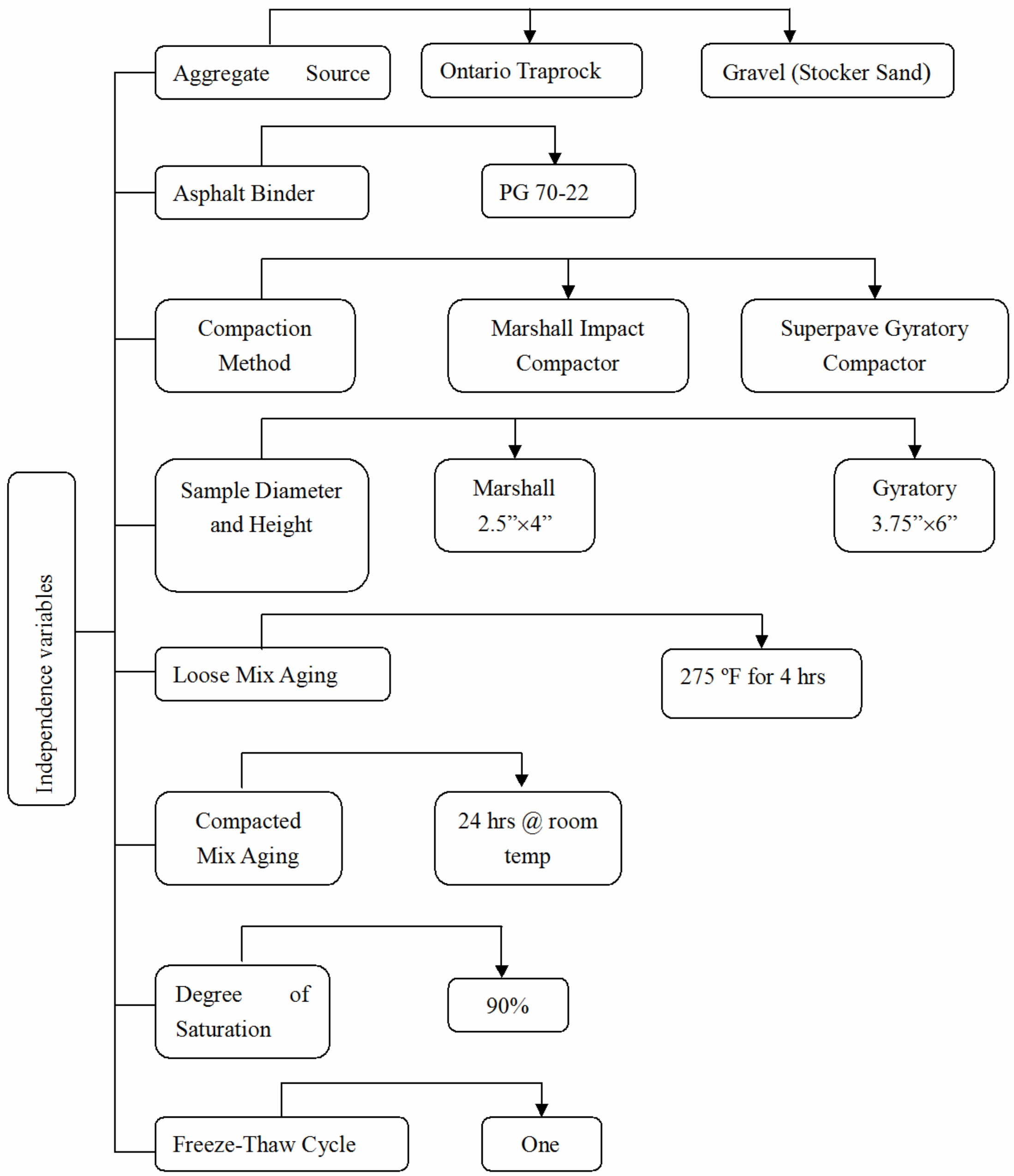

Figure 5-9 Partial Factorial Experimental Test Program

5.4 The Partial Factorial Test Results and Validation of Proposed Test Procedure

The complete mix design details are presented in Appendix for two aggregates sources using polymer modified binder PG 70-22. Table 5-3 shows comparison of the values of Tensile Strength Ratio between Marshall 100-mm specimen using standard AASHTO T283 procedure and Gyratory 150-mm specimen using the proposed procedure for both Ontario Trap Rock and Stocker Sand Gravel.

The mean and standard deviation of tensile strength ratio values for the Marshall 100-mm specimen using standard procedure and for Gyratory 150-mm specimen using the proposed procedure are shown in Table 5-3. The mean value of Gyratory 150-mm specimen using the proposed procedure is almost the same as the Marshall 100-mm specimen using standard procedure for both sources of aggregate. Therefore, the test results of the partial factorial test program validate the proposed test procedure. The TSR values of Ontario Trap Rock and Stocker Sand and gravel are higher than that of Honey Creek Limestone and Martin Marietta Gravel. This is because the modified asphalt binder is used in the partial factorial experimental test, which improved the moisture damage resistance for the specimens.

Table 5-3 Comparison of TSR of M100 at standard procedure and G150 at proposed procedure

Aggregate Source	Loose Mix Aging	Compacted Mix Aging	Saturation Level	Sample Number	TSR Value		Statistics	
					Marshall 100	Gyratory 150	Mean	Standard deviation
Ontario Trap Rock	16 hrs Aging	24 h	70%	1	0.829		0.929	0.133
				2	0.879			
				3	1.080			
	4 hrs Aging	24 h	90%	1		0.909	0.944	0.096
				2		1.052		
				3		0.870		
Stocker Sand Gravel	16 hrs Aging	24 h	70%	1	1.023		0.922	0.089
				2	0.883			
				3	0.859			
	4 hrs Aging	24 h	90%	1		0.945	0.944	0.051
				2		0.893		
				3		0.995		

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary of the Work Completed

A structured laboratory test program was conducted in this study to investigate the effects of the various factors on the HMA specimen's resistance to moisture damage. The experimental test program includes two parts: one part is a complete factorial experimental program, the second part is a partial factorial experimental program. The factors investigated in the complete factorial experimental program include aggregate sources (Honey Creek Limestone and Martin Marietta Gravel), compaction methods (Marshall and Gyratory), specimen size (4 inch and 6 inch), loose mix aging methods (none versus AASHTO T283(03), 16 hrs @ 140º F, as well as Superpave specifications, 4 hrs @ 275º F), saturation level (three levels: 55, 75, and 90%), and freeze-thaw cycle (none versus standard one freeze/thaw cycle @ 16 hrs @ 0º F). The factors selected are based on the literature review. Honey Creek Limestone and Martin Marietta Gravel are mixed with virgin asphalt binder PG 64-22 to prepare HMA specimens for the complete factorial experimental program. The partial factorial experimental program is based on the conclusions from the analysis of the complete factorial experimental program. The factors investigated in the partial factorial experiment tests include aggregate sources (Ontario Trap Rock and Stocker Sand and Gravel), compaction methods (Marshall and Gyratory), specimen size (4 inch and 6 inch), loose mix aging methods (AASHTO T283, 16 hrs @ 140º F versus Superpave specifications, 4 hrs @ 275º F), saturation level (90%), and freeze-thaw cycle (one freeze/thaw cycle @ 16 hrs @ 0º F). Ontario Trap Rock and Stocker Sand and Gravel are aggregate sources which are mixed with the modified asphalt binder PG 70-22 to prepare HMA specimens for the partial factorial experimental program.

The appendix at the end of the report provides the test results of the Marshall and Gyratory mix design for four sources of aggregate. Chapter III provides the test results of the complete factorial experimental program including dry tensile strength, freeze-thaw conditioned tensile strength, and tensile strength ratio. The partial factorial experimental test results are presented in Chapter V.

In the data analysis, the results of the complete factorial experimental program are useful in identifying and evaluating the contributions of the individual factors, along with all the possible interactions among the various factors. The results of the partial factorial experimental program, on the other hand, are useful for validating findings from the complete factorial experimental results.

In this report, the effects of different factors on dry tensile strength, freeze-thaw conditioned tensile strength, and tensile strength ratio (TSR) are investigated. The indicator of moisture damage susceptibility is the TSR. Thus, the variability of test results is statistically examined via. mean, standard deviation, and coefficient of variation (COV). Analysis based on “Pair-wise” comparisons is used to compare the impact of two individual factors while maintaining all other factors at a constant level. The ANOVA (Analysis of Variance) technique is used to perform F-tests (Type III S: partial sum sequences) to identify the contribution of the main test variables and their interactions. Regression analysis technique is used to (1) evaluate the tensile strength ratio relationship between different compaction methods, and (2) evaluate the relationship between tensile strength ratio and saturation level. The effects of all the factors investigated in this research are summarized in this report. The recommendations and proposed test procedure are given based on the test results and the accompanied analysis.

6.2 Conclusions and Recommendations

6.2.1 Main conclusions & recommendations

Based on the analysis of test data conducted on the HMA specimens prepared using four different aggregate sources and two different asphalt binders, it can be concluded that aggregate source, method of compaction, specimen size, loose mix aging, compacted HMA aging, freeze-thaw conditioning, and saturation level can exert influences on the outcome of test results in terms of dry tensile strength, freeze-thaw conditioned tensile strength, and tensile strength ratio (TSR).

Based on the premise that TSR for the Superpave HMA specimens be compatible with TSR for the Marshall HMA specimens under current AASHTO T 283, the key steps in the proposed test procedure for moisture induced damage for Superpave HMA specimens include the following.

1. Use of Gyratory 150 mm specimen is recommended as the specimen size for water stripping test.
2. After mixing the aggregate and asphalt binder, age the loose HMA for 4 hours at 275 ºF.
3. Heat the loose mixtures to the required compaction temperature before compacting.
4. After compacting the loose mixture to the air-void content of 7 percent ± 1 percent, the HMA samples are extruded from the compaction mold and allowed to aging for 24 hours at room temperature.
5. Place the HMA samples into water and saturate the samples to a saturation level between 80 and 90 percent.
6. Condition the sample for a freeze cycle (16 hr at 0 ºF) and a thaw-soak cycle (24 hr at 140 ºF).
7. Put the sample into the water bath at room temperature for 2 hrs prior to commencing the indirect tension test.

6.2.2 Implementation Recommendations

The recommended test procedure for determining the moisture damage potential of Superpave HMA is established based on the premise that TSR produced by the new procedure with the 6 inch Superpave specimens would be compatible with TSR for the 4 inch Marshall specimens. Thus, it is important to keep in mind that current study is assuming the applicability of the AASHTO T283 for the 4 inch Marshall specimens.

Implementation of the proposed test procedure for Superpave HMA specimens requires that ODOT engineers continue to monitor field performance of the same HMA specimens tested in the lab. In addition, establishing minimum tensile strength and tensile strength ratio values based on traffic level, allowable rutting depth, and expected fatigue life is a key issue that needs to be further addressed for full implementation of the moisture induced damage test as an integral part of ODOT Superpave HMA design protocol.

The implementation of the research findings in the form of modification of the pertinent section of ODOT Construction and Materials Specifications may result in benefits, including more confidence in the mix design for resisting moisture induced damage. In addition, the proposed test procedure shortens the test duration due to a reduction of aging time to four (4) hours for the loose mix.

6.2.3 Secondary observations of experimental results

This section provides a brief summary of secondary observations, as they are not the main objective of the present study. It should also be cautioned that these observations should not be generalized or interpreted outside the context that these are secondary observations.

6.2.3.1 Aggregate source

The aggregate source has an effect on the dry tensile strength, freeze-thaw tensile strength, and tensile strength ratio based on the ANOVA analysis presented in chapter IV. The limestone has higher dry tensile strength than the gravel. For the F-T conditioned tensile strength, the limestone is similar to the gravel. However, when the modified asphalt binder is used in compacting the HMA specimens, the influence of aggregate source on the tensile strength ratio decreases. This observation is in contradiction with ODOT past experiences. More aggregates sources need to be tested before this observation can be further substantiated.

6.2.3.2 Method of compaction

The compaction method has an effect on the dry tensile strength, freeze-thaw tensile strength, and tensile strength ratio based on the ANOVA analysis presented in chapter IV. No tensile strength ratio relationship can be found between the Marshall 100-mm compacted specimen and Gyratory 100-mm specimen. This indicates that in order to test Gyratory compacted HMA for moisture damage resistance, different Gyratory specimen size (150-mm) may be needed to produce similar results as the Marshall 100-mm specimens.

6.2.3.3 Specimen size

Gyratory 150-mm specimen is recommended to be used in the proposed test procedure. The tensile strength ratio of Gyratory 150-mm compacted specimen exhibits a strong correlation with the tensile strength ratio of Marshall 100-mm compacted specimen.

6.2.3.4 Loose mix aging method

The loose mix aging is the most important factor for the dry tensile strength, freeze-thaw conditioned tensile strength and tensile strength ratio. TSR values of Gyratory 150-mm specimen at 4 hours loose mix aging are about the same as the TSR values of Marshall 100-mm specimen at standard loose mix aging condition for both limestone and gravel. Therefore, 4 hours loose mix aging is recommended in the proposed test procedure based on the comparisons with the 16 hours aging.

6.2.3.5 Compacted mix aging method

The compacted mix aging is not an important factor for the dry tensile strength, freeze-thaw conditioned tensile strength, and tensile strength ratio. Therefore, 24 hours of compacted mix aging could be used in the proposed test procedure, since dry tensile strength, freeze-thaw conditioned tensile strength and tensile strength ratio with 24 hours compacted mix aging are statistically the same as those with 72 hours compacted mix aging.

6.2.3.6 Conditioning procedure

The freeze-thaw conditioning is an important factor for the freeze-thaw tensile strength, and tensile strength ratio. Freeze-thaw conditioned tensile strengths are lower than the dry tensile strengths for both limestone and gravel, indicating that freeze-thaw cycle is crucial in the conditioning process. One freeze-thaw cycle should be included in the proposed test procedure.

6.2.3.7 Saturation level

The saturation level is an important factor for the freeze-thaw tensile strength and tensile strength ratio. Freeze-thaw conditioned tensile strength decreases with the increases of saturation level. From Figures 4-12 and 4-13, it can be seen that some specimens at 50% saturation level pass TSR requirement, but fail at a 70% or 90% level of saturation, even though 50% saturation is within the AASHTO T 283(99) specifications. Figure 5-8 provides a validation that the saturation level for the Gyratory compacted specimens should be increased. It is recommended that the saturation level be increased to 80%-90% in the proposed test procedure.

6.3 Recommendations for Future Study

1. Effects of polymer modified asphalt binder and anti-stripping additives on the moisture resistance of the various HMA are encouraged to be completely investigated, since they are an economical and effective way to improve the HMA's resistance to the moisture damage.

2. It is important to incorporate indirect tensile strength as a design and evaluation tool for Superpave mixture and establish minimum tensile strength and tensile strength ratio based on traffic level, allowable rutting depth, and expected fatigue life. The minimum tensile strength criteria could be used along with the tensile strength ratio values as a part of the Superpave mix design criteria. There is a need to set up a simple, reasonable and dependable method for mix design and performance evaluation system for Superpave mixtures.

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APPENDIX A OPTIMUM ASPHALT CONTENT MIX DESIGN

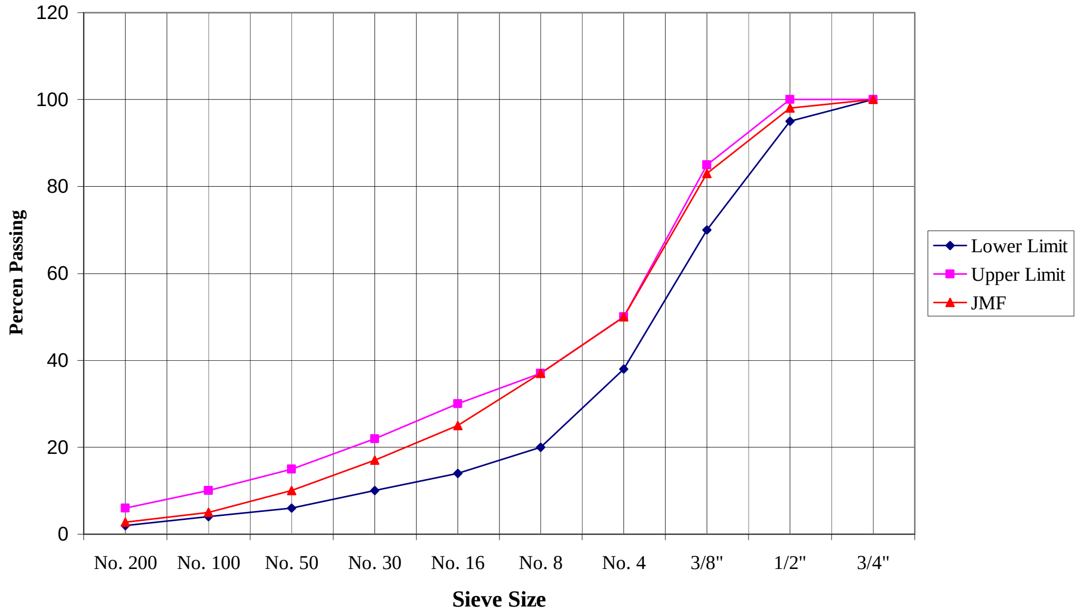
1. Honey Creek Limestone
    - Marshall mix design
    - Gyratory 4 inch mix design
    - Gyratory 6 inch mix design
2. Martin Marietta Gravel
    - Marshall mix design
    - Gyratory 4 inch mix design
    - Gyratory 6 inch mix design
3. Ontario Trap Rock
    - Marshall mix design
    - Gyratory 6 inch mix design
4. Stocker Sand Gravel
    - Marshall mix design
    - Gyratory 6 inch mix design

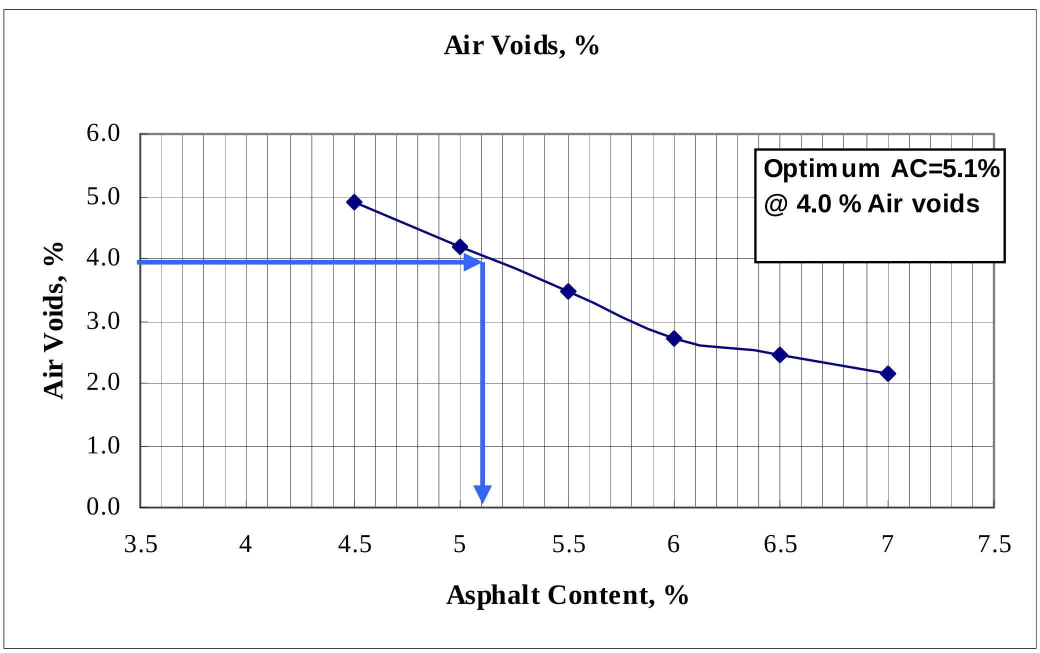
A.1 Honey Creek Limestone

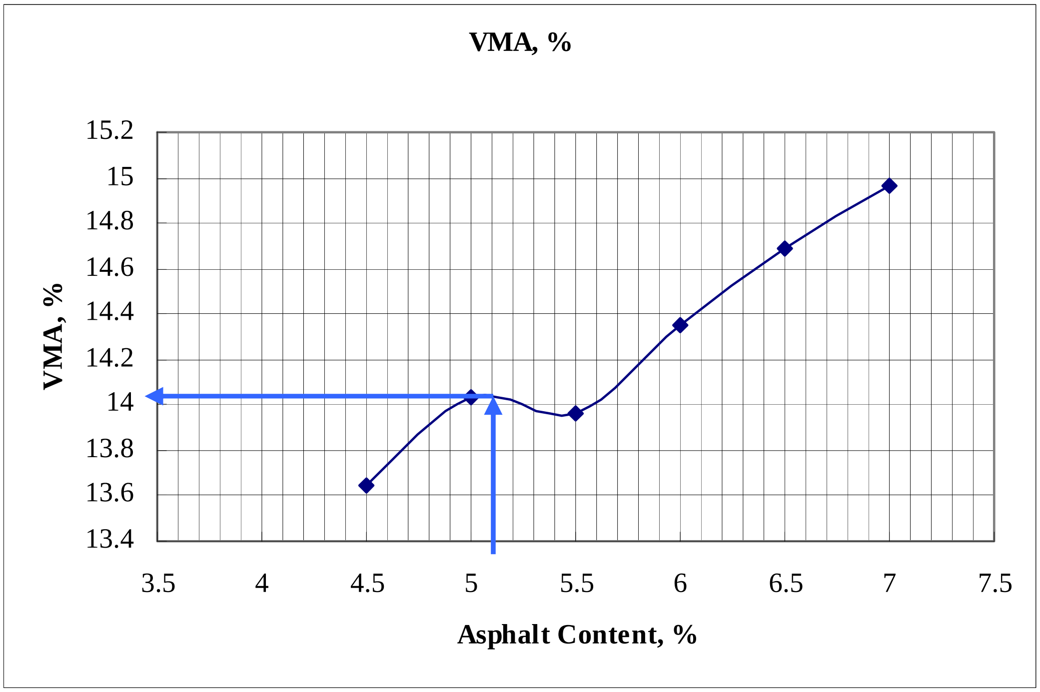
- Marshall mix design

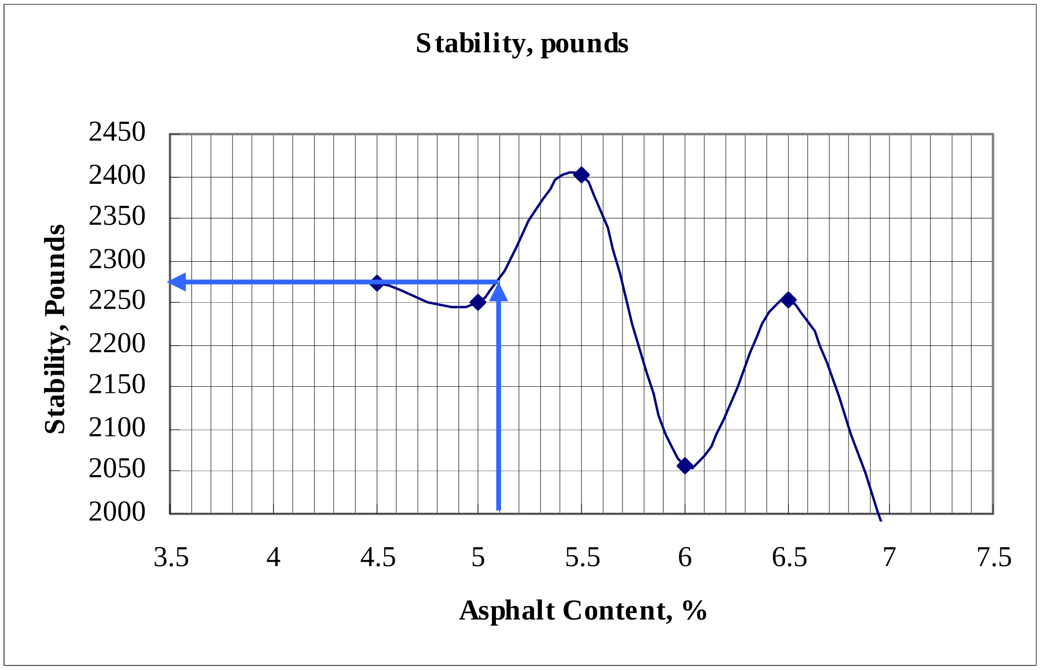
Honey Creek Limestone						
% AC by wt. of mix.	Unit Weight, Pcf, (Mg/m3)	% Air Voids	% VMA	% VFA	Stability, lbs(N)	Flow 0.01 in. (0.25 mm)
4.5	149.53	4.91	13.64	64.02	2274	11.3
5	149.64	4.19	14.03	70.12	2250	11.6
5.5	150.54	3.46	13.97	75.24	2403	12.1
6	150.67	2.72	14.35	81.06	2057	12.5
6.5	150.87	2.47	14.69	83.20	2253	13.3
7	151.19	2.14	14.97	85.68	1962	13.7

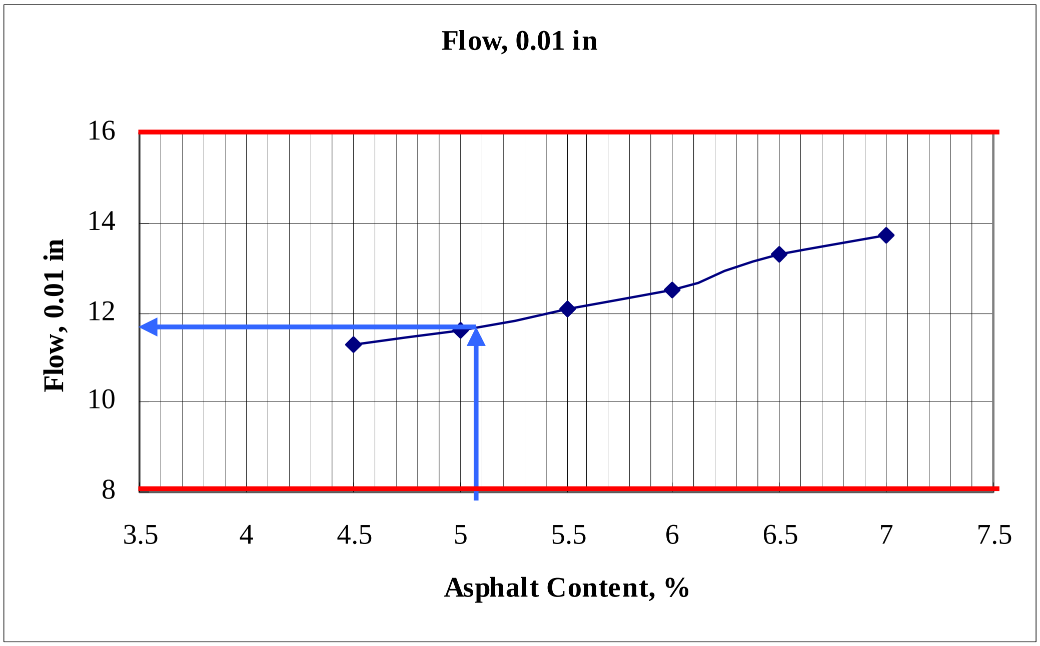
Aggregate Gradation Curves of the upper and lower limits of the ODOT Type-1H and the Job Mix Formula Used in this Research



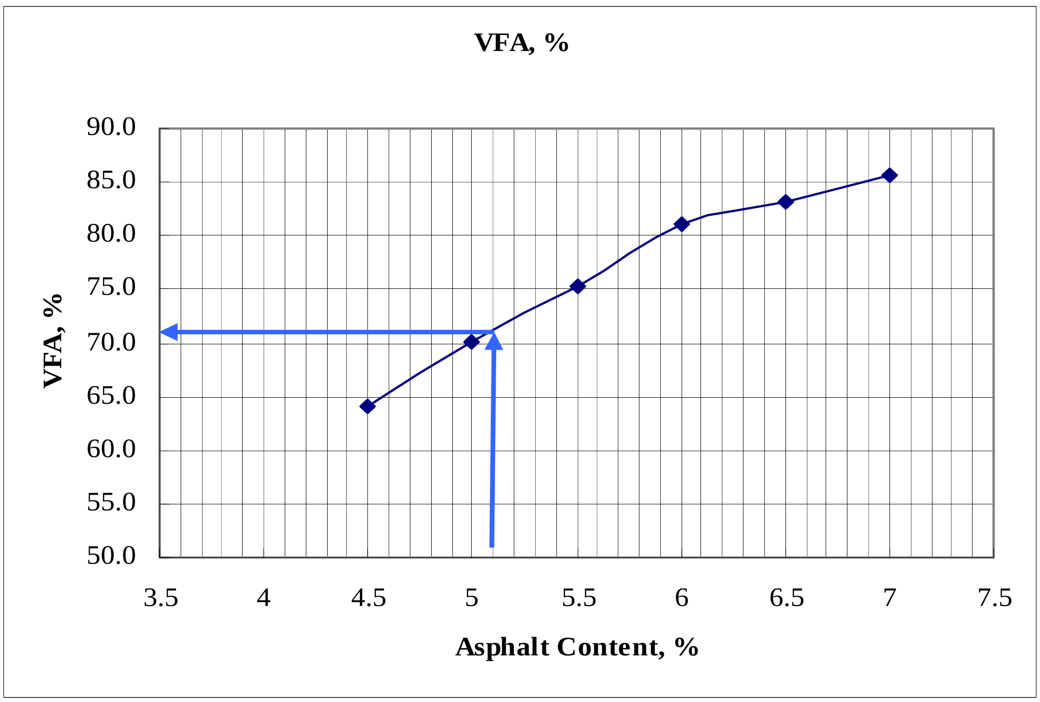



VMA, %
15.2
15
14.8
14.6
14.4
14.2
14
13.8
13.6
13.4
VMA, %
3.5
4
4.5
5
5.5
6
6.5
7
7.5
Asphalt Content, %

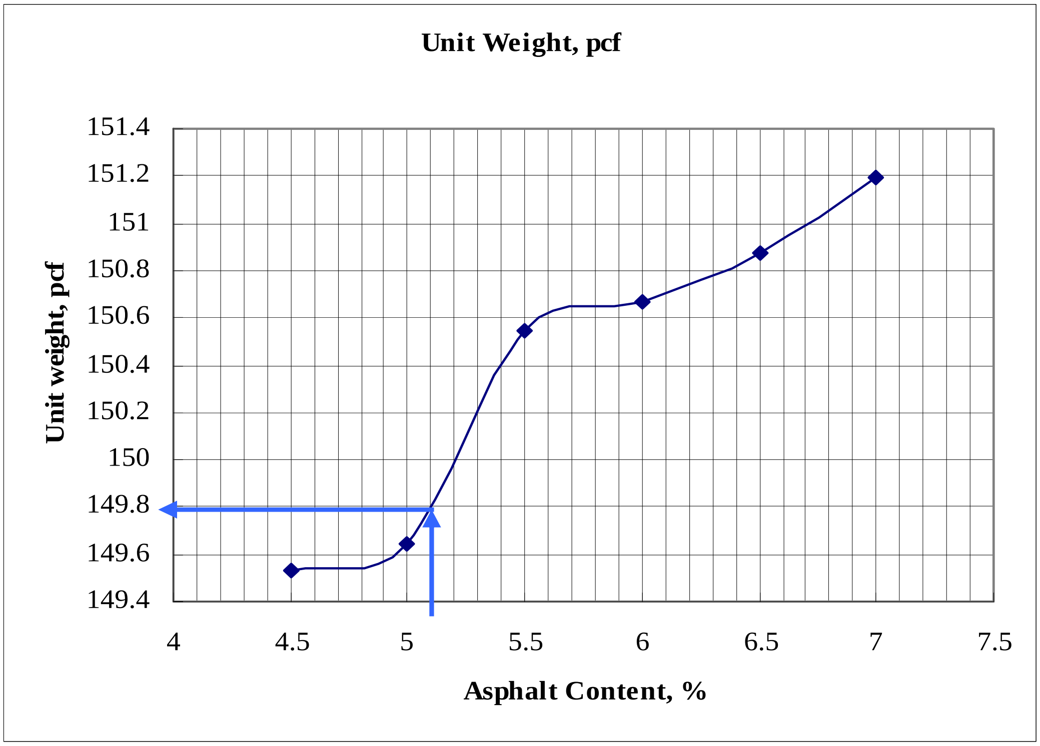

Stability, pounds
2450
2400
2350
2300
2250
2200
2150
2100
2050
2000
Stability, Pounds
3.5
4
4.5
5
5.5
6
6.5
7
7.5
Asphalt Content, %



Flow, 0.01 in
16
14
12
10
8
Flow, 0.01 in
3.5
4
4.5
5
5.5
6
6.5
7
7.5
Asphalt Content, %



VFA, %
90.0
85.0
80.0
75.0
70.0
65.0
60.0
55.0
50.0
VFA, %
3.5
4
4.5
5
5.5
6
6.5
7
7.5
Asphalt Content, %


Unit Weight, pcf
151.4
151.2
151
150.8
150.6
150.4
150.2
150
149.8
149.6
149.4
Unit weight, pcf
4
4.5
5
5.5
6
6.5
7
7.5
Asphalt Content, %

- Gyratory 4 inch optimum asphalt mix design

Densification Data @ 5.0 % Asphalt Content											
Gmm(means) =		2.492									
Gyrations	Specimen 1					Specimen 2					Avg
	Ht, mm	Volume, cm3	Gmb(est)	Gmb(corr)	%Gmm	Ht, mm	Volume, cm3	Gmb(est)	Gmb(corr)	%Gmm	%Gmm
5	71.6	562.345	2.072	2.128	85.4	72.1	566.272	2.109	2.164	86.9	86.114
7	70.6	554.491	2.102	2.158	86.6	71.2	559.203	2.136	2.192	88.0	87.268
10	69.5	545.851	2.135	2.192	88.0	70.1	550.564	2.169	2.226	89.3	88.643
20	67.4	529.358	2.201	2.260	90.7	68.2	535.641	2.230	2.288	91.8	91.258
30	66.2	519.933	2.241	2.301	92.3	67.1	527.002	2.266	2.326	93.3	92.832
40	65.5	514.435	2.265	2.326	93.3	66.3	520.719	2.294	2.354	94.5	93.889
50	64.9	509.723	2.286	2.347	94.2	65.7	516.006	2.315	2.375	95.3	94.752
60	64.4	505.796	2.304	2.365	94.9	65.3	512.865	2.329	2.390	95.9	95.409
65	64.2	504.225	2.311	2.373	95.2	65.1	511.294	2.336	2.397	96.2	95.704
70	64	502.654	2.318	2.380	95.5	64.9	509.723	2.343	2.405	96.5	96.001
80	63.7	500.298	2.329	2.391	96.0	64.6	507.367	2.354	2.416	96.9	96.450
90	63.5	498.727	2.337	2.399	96.3	64.3	505.011	2.365	2.427	97.4	96.828
99	63.1	495.586	2.351	2.414	96.9	64	502.654	2.376	2.438	97.8	97.361
Weight (gm) =		1165.3					1194.3				
Gmb(means)=		2.414					2.438				
CF=		1.027					1.026				

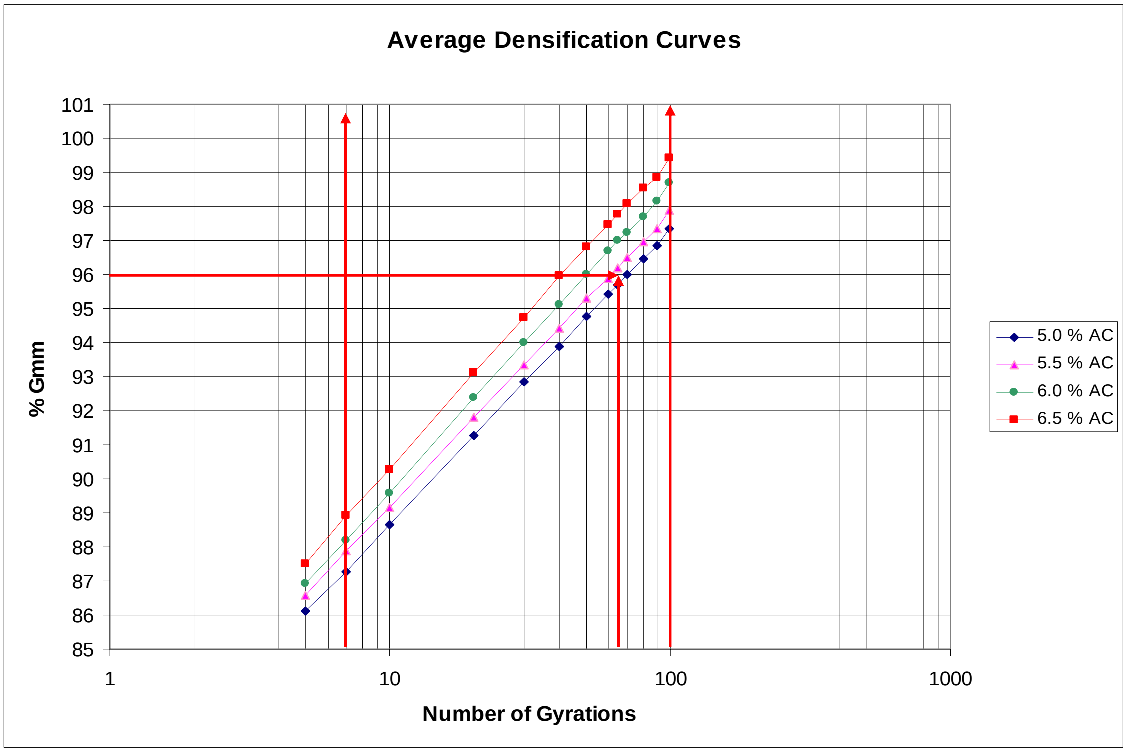
Densification Data @ 5.5 % Asphalt Content											
Gmm(means) =		2.491									
Gyrations	Specimen 1					Specimen 2					Avg
	Ht, mm	Volume, cm3	Gmb(est)	Gmb(corr)	%Gmm	Ht, mm	Volume, cm3	Gmb(est)	Gmb(corr)	%Gmm	%Gmm
5	71.5	561.559	2.104	2.156	86.532	70.5	553.705	2.105	2.158	86.623	86.577
7	70.3	552.134	2.140	2.192	88.009	69.6	546.637	2.132	2.186	87.743	87.876
10	69.4	545.066	2.168	2.221	89.151	68.5	537.997	2.166	2.221	89.152	89.151
20	67.4	529.358	2.232	2.287	91.796	66.5	522.289	2.231	2.288	91.833	91.815
30	66.3	520.719	2.269	2.325	93.319	65.4	513.650	2.269	2.326	93.378	93.348
40	65.5	514.435	2.297	2.353	94.459	64.7	508.152	2.293	2.351	94.388	94.423
50	64.9	509.723	2.318	2.375	95.332	64.1	503.440	2.315	2.373	95.271	95.302
60	64.5	506.581	2.332	2.389	95.923	63.7	500.298	2.329	2.388	95.870	95.896
65	64.3	505.011	2.340	2.397	96.222	63.5	498.727	2.337	2.396	96.172	96.197
70	64.1	503.440	2.347	2.404	96.522	63.3	497.157	2.344	2.403	96.476	96.499
80	63.8	501.084	2.358	2.416	96.976	63	494.800	2.355	2.415	96.935	96.955
90	63.5	498.727	2.369	2.427	97.434	62.8	493.230	2.363	2.422	97.244	97.339
99	63.2	496.371	2.380	2.439	97.896	62.4	490.088	2.378	2.438	97.867	97.882
Weight (gm) =		1181.5					1165.3				
Gmb(means)=		2.439					2.438				
CF=		1.025					1.025				

Densification Data @ 6.0 % Asphalt Content											
Gmm(means) =		2.468									
Gyrations	Specimen 1					Specimen 2					Avg
	Ht, mm	Volume, cm3	Gmb(est)	Gmb(corr)	%Gmm	Ht, mm	Volume, cm3	Gmb(est)	Gmb(corr)	%Gmm	%Gmm
5	71.2	559.203	2.086	2.141	86.757	71.6	562.345	2.086	2.150	87.122	86.939
7	70.2	551.349	2.116	2.172	87.993	70.6	554.491	2.116	2.181	88.356	88.174
10	69.1	542.710	2.150	2.206	89.394	69.5	545.851	2.149	2.215	89.754	89.574
20	67	526.216	2.217	2.275	92.195	67.4	529.358	2.216	2.284	92.550	92.373
30	65.9	517.577	2.254	2.313	93.734	66.2	519.933	2.257	2.326	94.228	93.981
40	65.1	511.294	2.282	2.342	94.886	65.4	513.650	2.284	2.354	95.381	95.133
50	64.5	506.581	2.303	2.364	95.769	64.8	508.938	2.305	2.376	96.264	96.016
60	64	502.654	2.321	2.382	96.517	64.4	505.796	2.320	2.391	96.862	96.689
65	63.8	501.084	2.328	2.390	96.820	64.2	504.225	2.327	2.398	97.164	96.992
70	63.7	500.298	2.332	2.393	96.972	64	502.654	2.334	2.405	97.467	97.219
80	63.4	497.942	2.343	2.405	97.430	63.7	500.298	2.345	2.417	97.926	97.678
90	63.1	495.586	2.354	2.416	97.894	63.4	497.942	2.356	2.428	98.390	98.142
99	62.7	492.444	2.369	2.431	98.518	63.1	495.586	2.368	2.440	98.857	98.688
Weight (gm) =		1166.6					1173.3				
Gmb(means)=		2.431					2.440				
CF=		1.026					1.031				

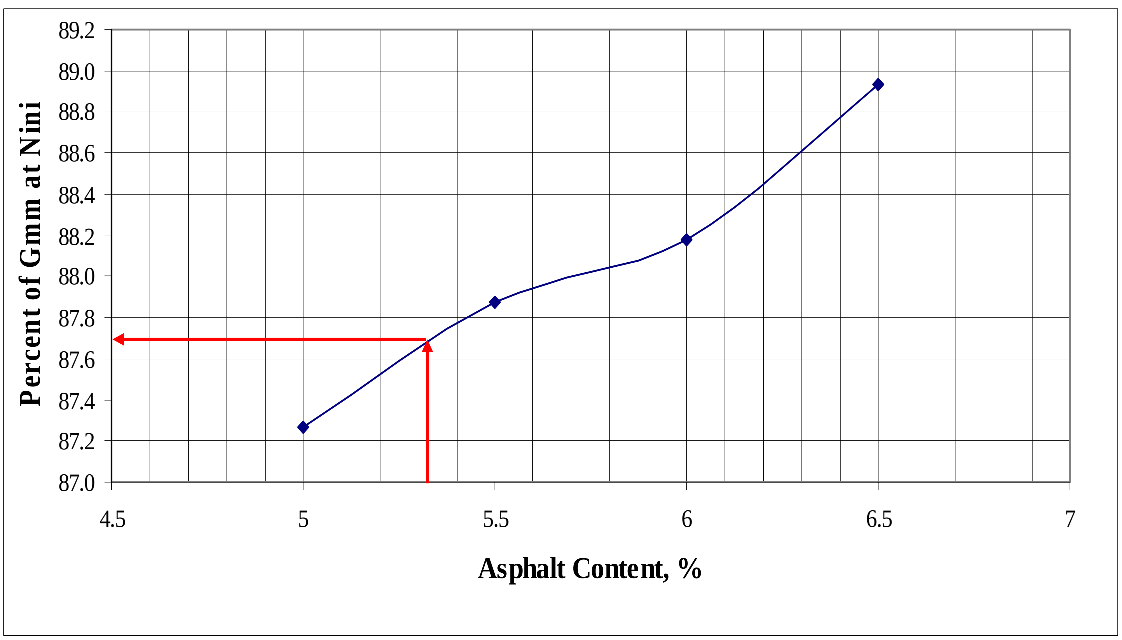
Densification Data @ 6.5 % Asphalt Content											
Gmm(means) =		2.461									
Gyrations	Specimen 1					Specimen 2					Avg
	Ht, mm	Volume, cm3	Gmb(est)	Gmb(corr)	%Gmm	Ht, mm	Volume, cm3	Gmb(est)	Gmb(corr)	%Gmm	%Gmm
5	72.1	566.272	2.116	2.156	87.599	70.7	555.276	2.110	2.151	87.407	87.503
7	70.8	556.061	2.155	2.195	89.207	69.7	547.422	2.140	2.182	88.662	88.934
10	69.8	548.207	2.186	2.227	90.485	68.6	538.783	2.175	2.217	90.083	90.284
20	67.8	532.500	2.251	2.293	93.154	66.4	521.504	2.247	2.290	93.068	93.111
30	66.6	523.075	2.291	2.334	94.833	65.3	512.865	2.284	2.329	94.636	94.734
40	65.8	516.792	2.319	2.362	95.986	64.4	505.796	2.316	2.362	95.958	95.972
50	65.2	512.079	2.340	2.384	96.869	63.9	501.869	2.334	2.380	96.709	96.789
60	64.8	508.938	2.355	2.399	97.467	63.4	497.942	2.353	2.399	97.472	97.469
65	64.6	507.367	2.362	2.406	97.769	63.2	496.371	2.360	2.406	97.780	97.775
70	64.4	505.796	2.370	2.414	98.072	63	494.800	2.368	2.414	98.091	98.082
80	64.1	503.440	2.381	2.425	98.531	62.7	492.444	2.379	2.426	98.560	98.546
90	63.9	501.869	2.388	2.432	98.840	62.5	490.873	2.387	2.433	98.875	98.858
99	63.6	499.513	2.399	2.444	99.306	62.1	487.732	2.402	2.449	99.512	99.409
Weight (gm) =		1198.5					1171.6				
Gmb(means)=		2.444					2.449				
CF=		1.019					1.020				

Number of Gyration	% Gmm, 5.0 AC	% Gmm, 5.5 AC	%Gmm,6.0AC	%Gmm, 6.5 AC
5	86.114	86.577	86.939	87.503
7	87.268	87.876	88.174	88.934
10	88.643	89.151	89.574	90.284
20	91.258	91.815	92.373	93.111
30	92.832	93.348	93.981	94.734
40	93.889	94.423	95.133	95.972
50	94.752	95.302	96.016	96.789
60	95.409	95.896	96.689	97.469
65	95.704	96.197	96.992	97.775
70	96.001	96.499	97.219	98.082
80	96.450	96.955	97.678	98.546
90	96.828	97.339	98.142	98.858
99	97.361	97.882	98.688	99.409

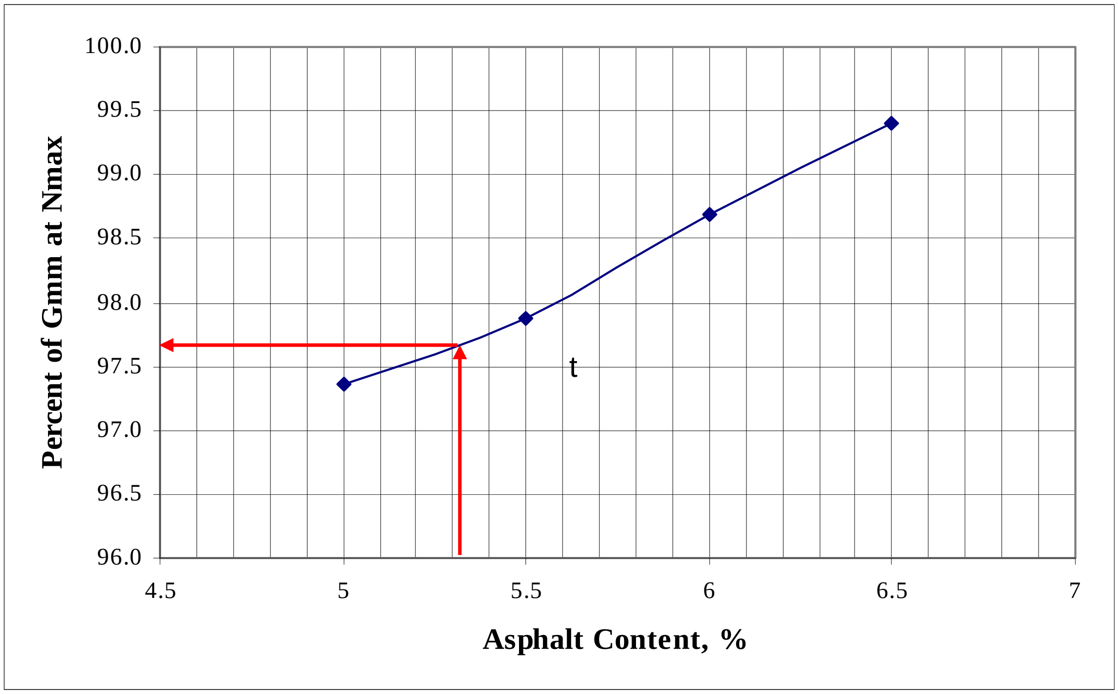
AC %	% Gmm @N=7	% Gmm @N=65	% Gmm @N=99	Air Void, %, @ Ndes	Gsb	Ps	Gmm	% VMA	% VFA
5	87.268	95.704	97.361	4.296	2.65	0.95	2.492	14.497	70.369
5.5	87.876	96.197	97.882	3.803	2.65	0.945	2.491	14.537	73.836
6	88.174	96.992	98.688	3.008	2.65	0.94	2.468	15.094	80.069
6.5	88.934	97.775	99.409	2.225	2.65	0.935	2.461	15.100	85.262

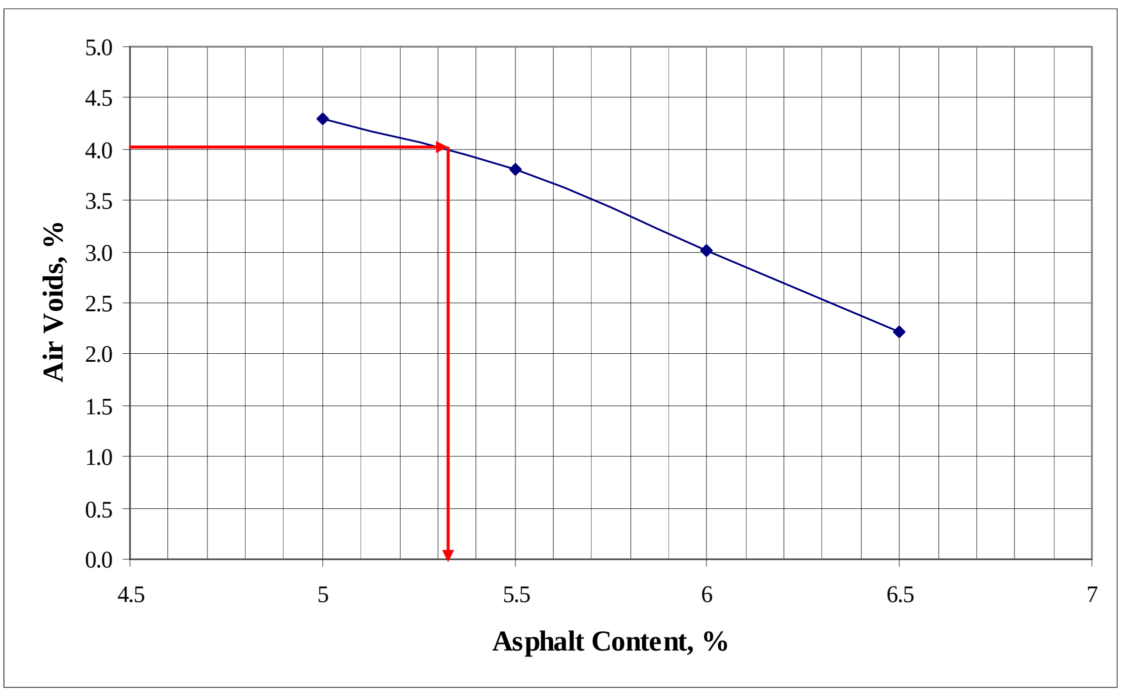


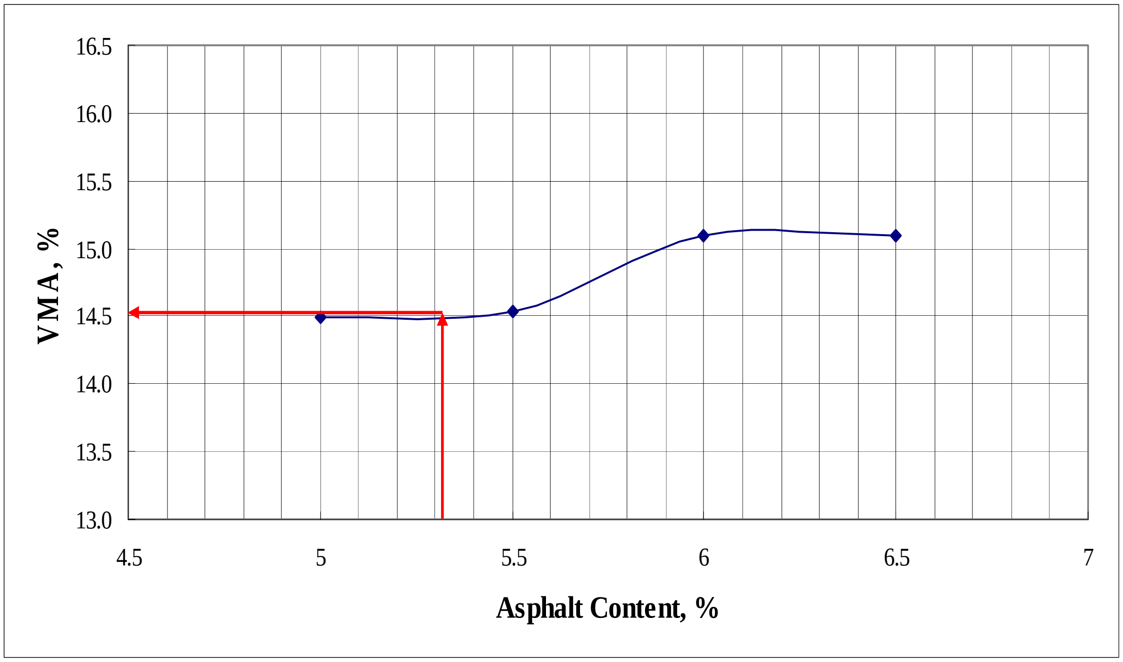
Average Densification Curves
% Gmm
Number of Gyrations
5.0 % AC
5.5 % AC
6.0 % AC
6.5 % AC



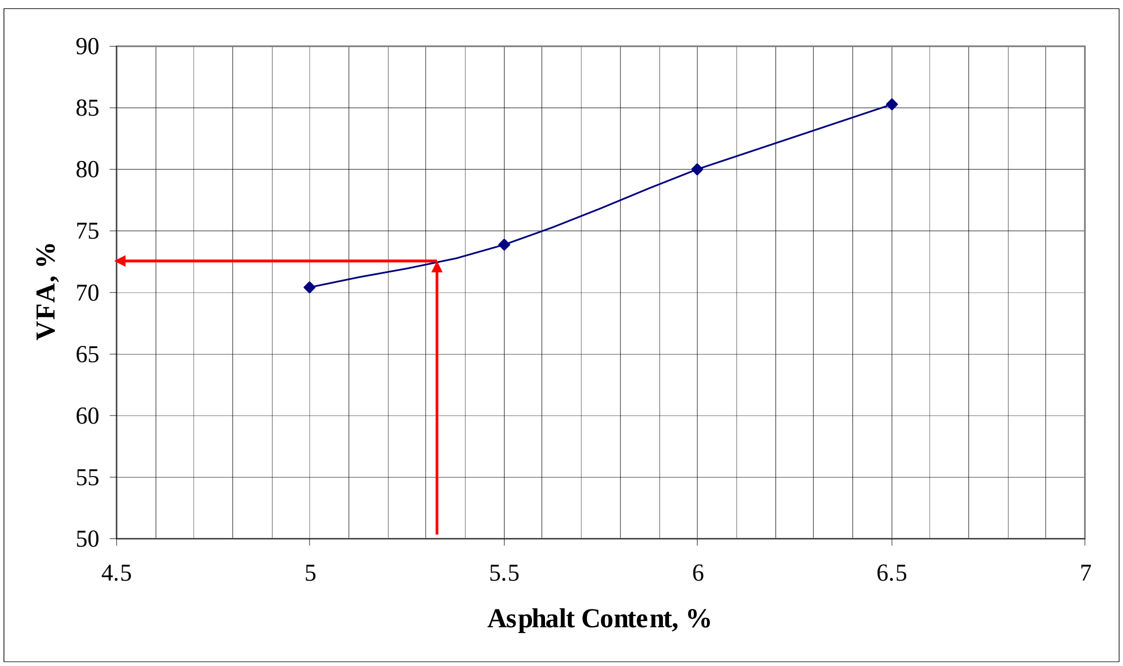
Percent of Gmm at Nini
Asphalt Content, %


100.0
99.5
99.0
98.5
98.0
97.5
97.0
96.5
96.0
Percent of Gmm at Nmax
t
4.5
5
5.5
6
6.5
7
Asphalt Content, %


5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Air Voids, %
4.5
5
5.5
6
6.5
7
Asphalt Content, %



16.5
16.0
15.5
15.0
14.5
14.0
13.5
13.0
VMA, %
4.5
5
5.5
6
6.5
7
Asphalt Content, %



90
85
80
75
70
65
60
55
50
VFA, %
4.5
5
5.5
6
6.5
7
Asphalt Content, %

- Gyratory 6 inch specimen mix design

Densification Data @ 4.0 % Asphalt Content											
Gmm(means) =		2.561									
Gyrations	Specimen 1					Specimen 2					Avg
	Ht, mm	Volume, cm3	Gmb(est)	Gmb(corr)	%Gmm	Ht, mm	Volume, cm3	Gmb(est)	Gmb(corr)	%Gmm	%Gmm
5	130.4	2304.356	2.114	2.153	84.1	129.9	2295.521	2.104	2.162	84.4	84.240
7	128.6	2272.548	2.143	2.183	85.3	128.2	2265.479	2.132	2.190	85.5	85.388
10	126.7	2238.972	2.175	2.216	86.5	126.4	2233.670	2.162	2.221	86.7	86.636
20	123.1	2175.355	2.239	2.281	89.1	122.9	2171.820	2.224	2.285	89.2	89.136
30	121	2138.245	2.278	2.321	90.6	121	2138.245	2.259	2.321	90.6	90.609
40	119.6	2113.505	2.304	2.348	91.7	119.6	2113.505	2.285	2.348	91.7	91.670
50	118.6	2095.833	2.324	2.368	92.4	118.6	2095.833	2.304	2.368	92.4	92.443
60	117.8	2081.696	2.340	2.384	93.1	117.8	2081.696	2.320	2.384	93.1	93.071
65	117.4	2074.627	2.348	2.392	93.4	117.4	2074.627	2.328	2.392	93.4	93.388
70	117.1	2069.326	2.354	2.398	93.6	117.1	2069.326	2.334	2.398	93.6	93.627
80	116.6	2060.490	2.364	2.408	94.0	116.6	2060.490	2.344	2.408	94.0	94.029
90	116.1	2051.655	2.374	2.418	94.4	116.1	2051.655	2.354	2.418	94.4	94.434
99	115.4	2039.285	2.388	2.433	95.0	115.4	2039.285	2.368	2.433	95.0	95.006
Weight (gm) =		4870.5					4829.3				
Gmb(means)=		2.433					2.433				
CF=		1.019					1.027				

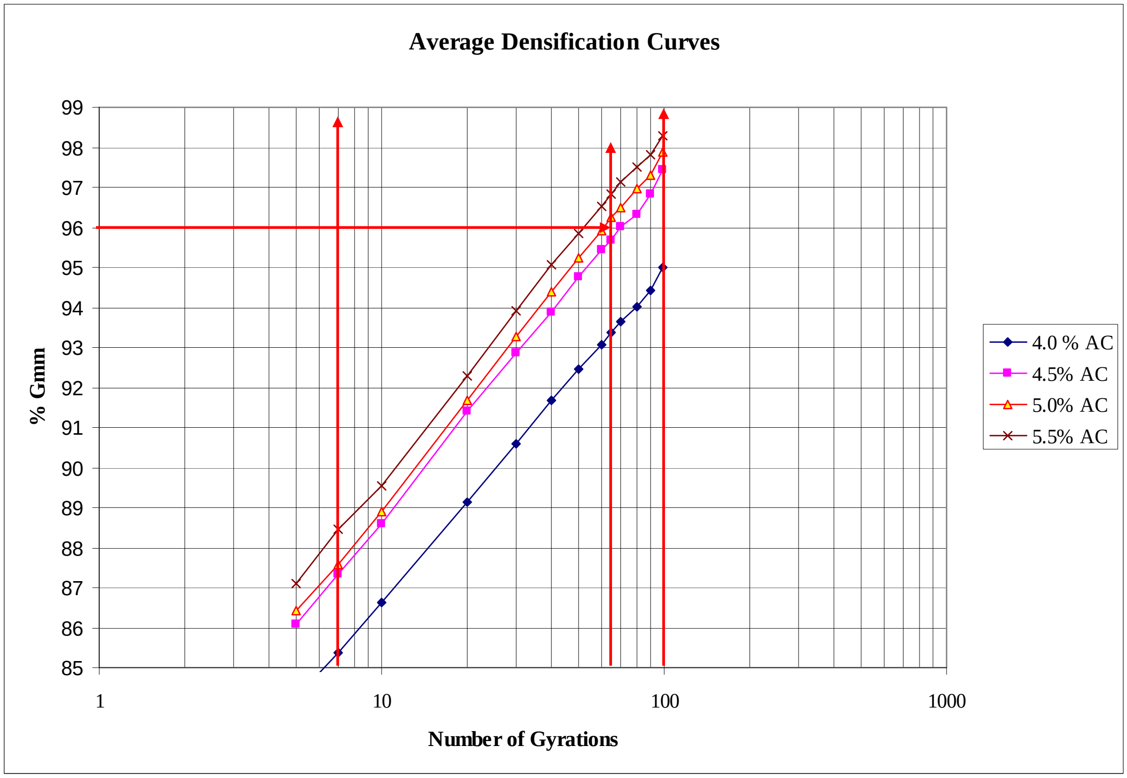
Densification Data @ 4.5 % Asphalt Content											
Gmm(means) =		2.524									
Gyrations	Specimen 1					Specimen 2					Avg
	Ht, mm	Volume, cm3	Gmb(est)	Gmb(corr)	%Gmm	Ht, mm	Volume, cm3	Gmb(est)	Gmb(corr)	%Gmm	%Gmm
5	129.1	2281.383	2.142	2.175	86.176	129.4	2286.685	2.138	2.170	85.999	86.087
7	127.3	2249.575	2.172	2.206	87.394	127.5	2253.109	2.170	2.203	87.280	87.337
10	125.5	2217.766	2.204	2.237	88.648	125.7	2221.300	2.201	2.234	88.530	88.589
20	121.8	2152.382	2.271	2.305	91.341	121.7	2150.615	2.273	2.308	91.440	91.390
30	119.8	2117.039	2.309	2.344	92.866	119.8	2117.039	2.309	2.344	92.890	92.878
40	118.5	2094.066	2.334	2.369	93.884	118.5	2094.066	2.334	2.370	93.909	93.897
50	117.4	2074.627	2.356	2.392	94.764	117.4	2074.627	2.356	2.392	94.789	94.777
60	116.6	2060.490	2.372	2.408	95.414	116.6	2060.490	2.372	2.409	95.440	95.427
65	116.3	2055.189	2.378	2.414	95.660	116.3	2055.189	2.379	2.415	95.686	95.673
70	115.9	2048.120	2.386	2.422	95.990	115.9	2048.120	2.387	2.423	96.016	96.003
80	115.5	2041.052	2.394	2.431	96.323	115.5	2041.052	2.395	2.432	96.348	96.336
90	114.9	2030.449	2.407	2.444	96.826	114.9	2030.449	2.408	2.444	96.852	96.839
99	114.2	2018.079	2.422	2.459	97.419	114.2	2018.079	2.422	2.459	97.445	97.432
Weight (gm) =		4893.1					4890.5				
Gmb(meas)=		2.459					2.459				
CF=		1.015					1.015				

Densification Data @ 5.0 % Asphalt Content											
Gmm(meas) =		2.516									
Gyrations	Specimen 1					Specimen 2					Avg
	Ht, mm	Volume, cm3	Gmb(est)	Gmb(corr)	%Gmm	Ht, mm	Volume, cm3	Gmb(est)	Gmb(corr)	%Gmm	%Gmm
5	129.3	2284.918	2.129	2.173	86.394	129.3	2284.918	2.130	2.175	86.451	86.422
7	127.6	2254.876	2.158	2.202	87.545	127.6	2254.876	2.158	2.204	87.603	87.574
10	125.7	2221.300	2.190	2.236	88.868	125.7	2221.300	2.191	2.237	88.927	88.897
20	121.9	2154.149	2.259	2.305	91.638	121.9	2154.149	2.259	2.307	91.699	91.669
30	119.8	2117.039	2.298	2.346	93.244	119.8	2117.039	2.299	2.347	93.307	93.276
40	118.4	2092.299	2.325	2.373	94.347	118.4	2092.299	2.326	2.375	94.410	94.378
50	117.4	2074.627	2.345	2.394	95.151	117.3	2072.860	2.348	2.397	95.295	95.223
60	116.5	2058.723	2.363	2.412	95.886	116.5	2058.723	2.364	2.414	95.950	95.918
65	116.1	2051.655	2.372	2.420	96.216	116.1	2051.655	2.372	2.422	96.280	96.248
70	115.8	2046.353	2.378	2.427	96.465	115.8	2046.353	2.378	2.428	96.530	96.498
80	115.3	2037.517	2.388	2.437	96.884	115.2	2035.750	2.391	2.441	97.032	96.958
90	114.9	2030.449	2.396	2.446	97.221	114.8	2028.682	2.399	2.449	97.371	97.296
99	114.2	2018.079	2.411	2.461	97.817	114.1	2016.312	2.414	2.464	97.968	97.892
Weight (gm) =		4894.5					4877.1				
Gmb(meas)=		2.461					2.464				
CF=		1.021					1.021				

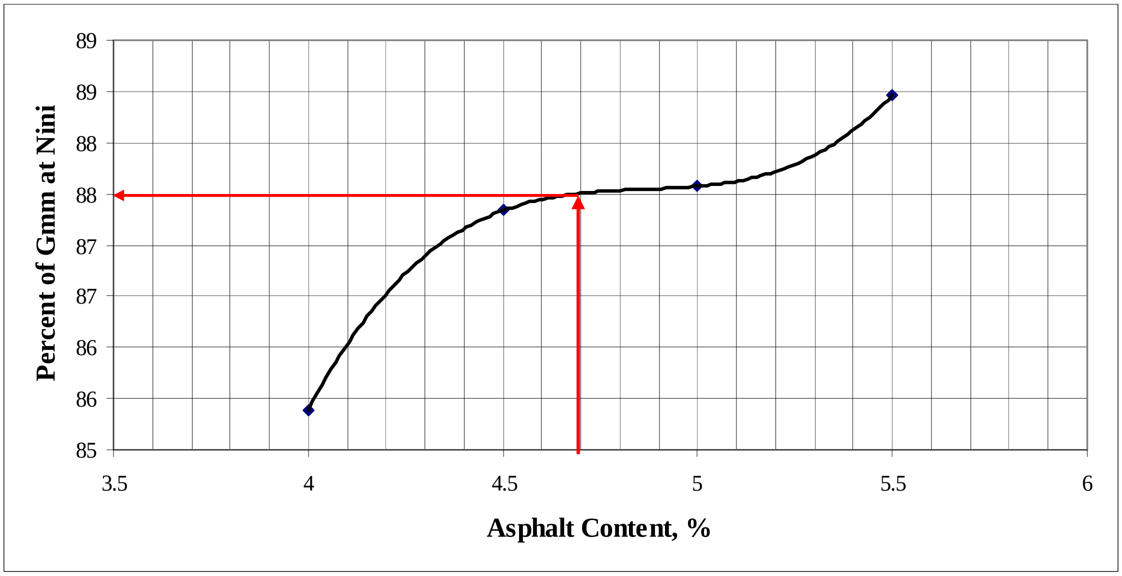
Densification Data @ 5.5 % Asphalt Content											
Gmm(meas) =		2.493									
Gyrations	Specimen 1					Specimen 2					Avg
	Ht, mm	Volume, cm3	Gmb(est)	Gmb(corr)	%Gmm	Ht, mm	Volume, cm3	Gmb(est)	Gmb(corr)	%Gmm	%Gmm
5	128.6	2272.548	2.170	2.204	87.604	123.2	2177.122	2.137	2.178	86.588	87.096
7	126.5	2235.438	2.206	2.240	89.059	121.4	2145.313	2.168	2.210	87.871	88.465
10	124.9	2207.163	2.234	2.269	90.200	120	2120.573	2.194	2.236	88.897	89.548
20	121.1	2140.012	2.305	2.340	93.030	116.5	2058.723	2.259	2.303	91.567	92.299
30	119	2102.902	2.345	2.382	94.672	114.5	2023.380	2.299	2.344	93.167	93.919
40	117.6	2078.162	2.373	2.410	95.799	113.1	1998.640	2.327	2.373	94.320	95.059
50	116.7	2062.257	2.391	2.428	96.537	112.1	1980.969	2.348	2.394	95.161	95.849
60	115.9	2048.120	2.408	2.445	97.204	111.3	1966.832	2.365	2.411	95.845	96.525
65	115.6	2042.819	2.414	2.452	97.456	110.9	1959.763	2.374	2.420	96.191	96.824
70	115.3	2037.517	2.420	2.458	97.710	110.5	1952.695	2.382	2.429	96.539	97.124
80	114.9	2030.449	2.429	2.467	98.050	110	1943.859	2.393	2.440	96.978	97.514
90	114.6	2025.147	2.435	2.473	98.306	109.6	1936.790	2.402	2.448	97.332	97.819
99	114.2	2018.079	2.444	2.482	98.651	108.9	1924.420	2.417	2.464	97.958	98.304
Weight (gm) =		4931.8					4651.5				
Gmb(meas)=		2.482					2.464				
CF=		1.015					1.019				

Number of Gyration	% Gmm, 4.0 AC	% Gmm, 4.5 AC	% Gmm, 5.0 AC	% Gmm, 5.5 AC
5	84.240	86.087	86.422	87.096
7	85.388	87.337	87.574	88.465
10	86.636	88.589	88.897	89.548
20	89.136	91.390	91.669	92.299
30	90.609	92.878	93.276	93.919
40	91.670	93.897	94.378	95.059
50	92.443	94.777	95.223	95.849
60	93.071	95.427	95.918	96.525
65	93.388	95.673	96.248	96.824
70	93.627	96.003	96.498	97.124
80	94.029	96.336	96.958	97.514
90	94.434	96.839	97.296	97.819
99	95.006	97.432	97.892	98.304

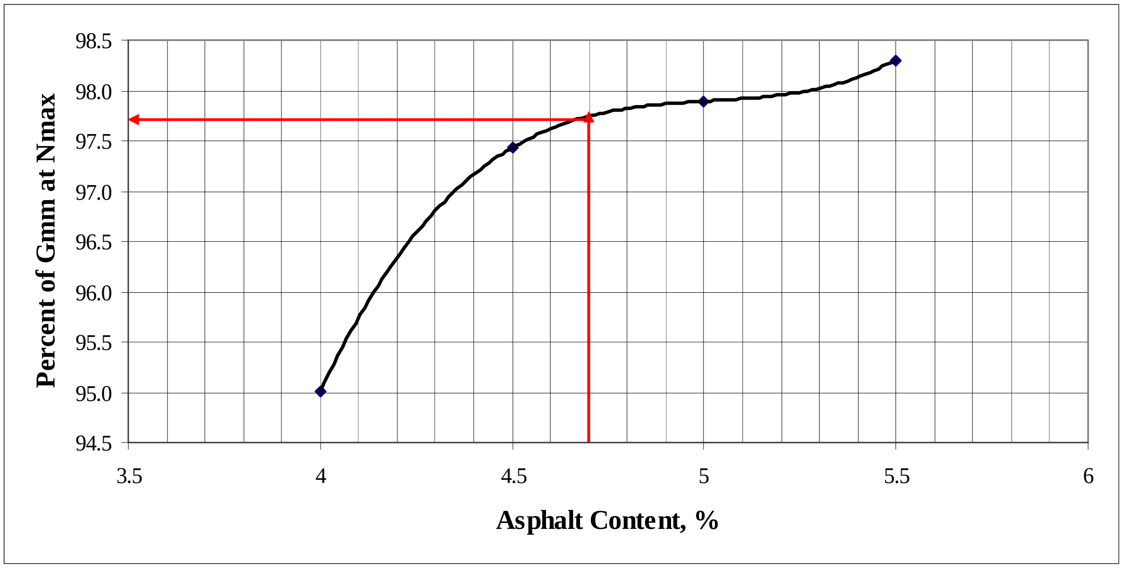
AC %	% Gmm @N=7	% Gmm @N=65	% Gmm @N=99	Air Void, %, @ Ndes	Gsb	Ps	Gmm	% VMA	% VFA
4	85.388	93.388	95.006	6.612	2.65	0.96	2.561	13.359	50.503
4.5	87.337	95.673	97.432	4.327	2.65	0.955	2.523	13.011	66.743
5	87.574	96.248	97.892	3.752	2.65	0.95	2.515	13.222	71.624
5.5	88.465	96.824	98.304	3.176	2.65	0.945	2.493	13.923	77.185

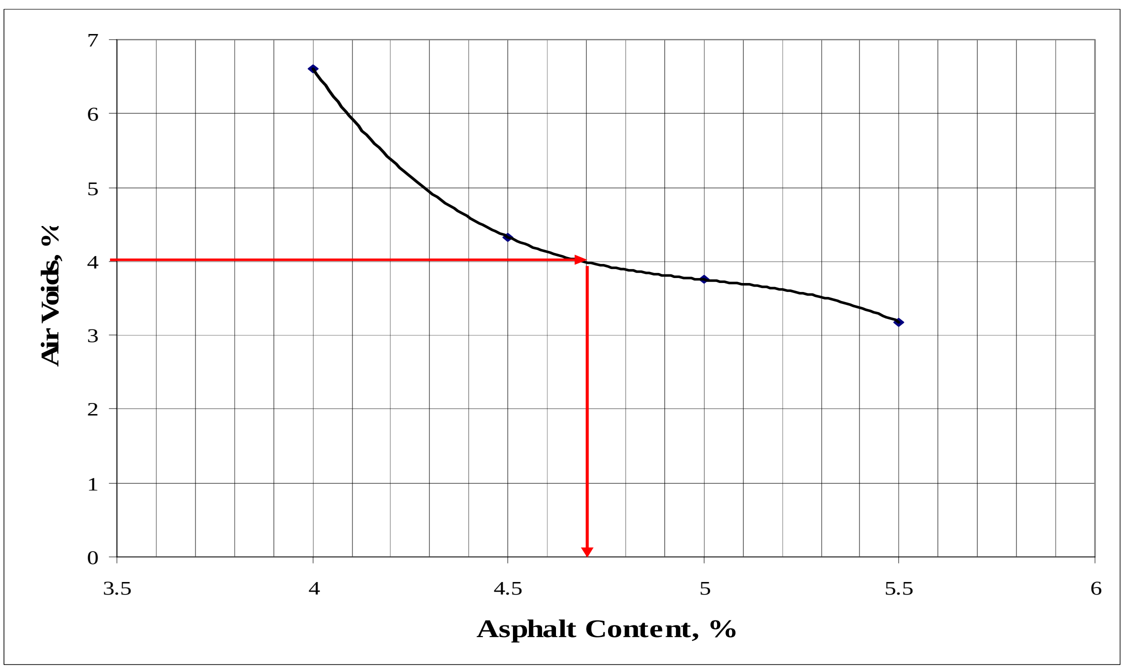


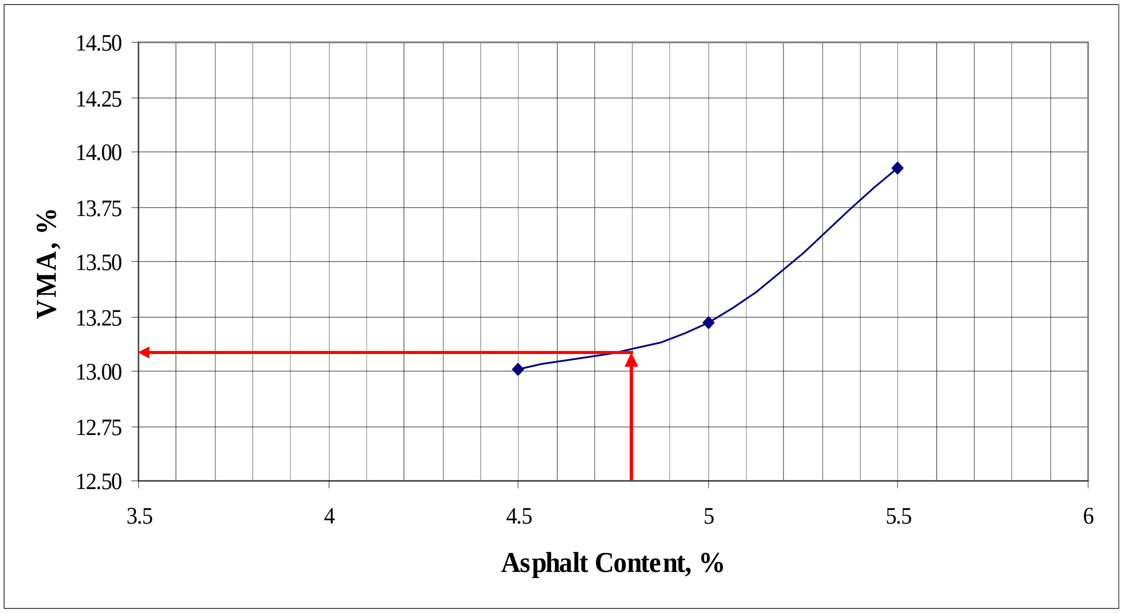
Average Densification Curves
% Gmm
Number of Gyrations
4.0 % AC
4.5% AC
5.0% AC
5.5% AC



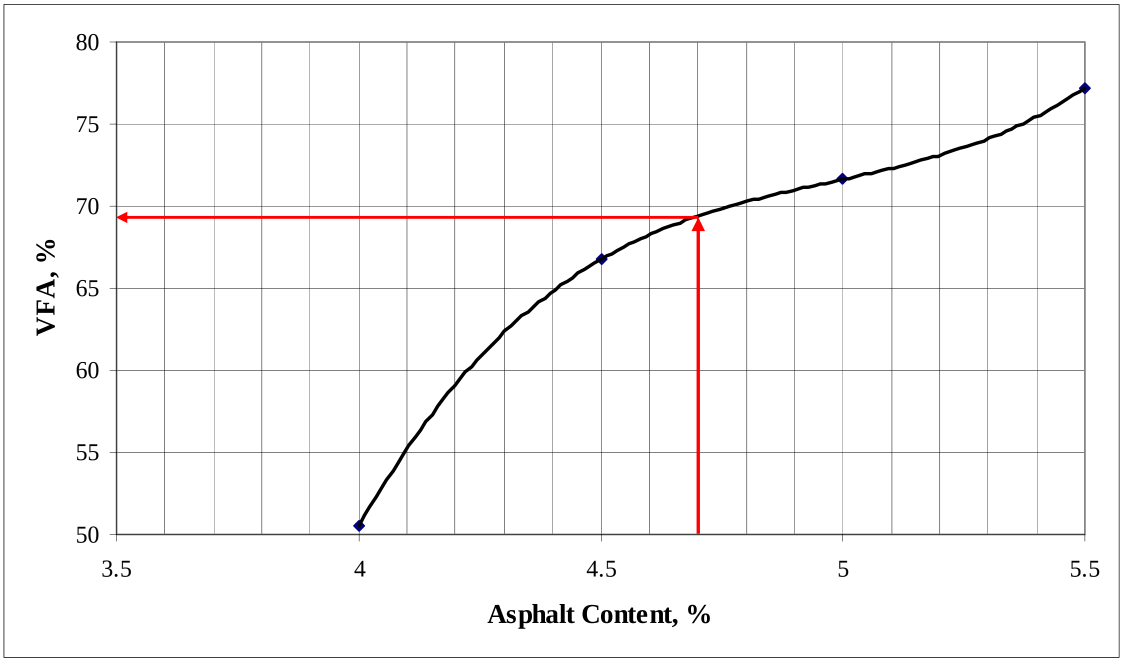
Percent of Gmm at Nini
Asphalt Content, %


98.5
98.0
97.5
97.0
96.5
96.0
95.5
95.0
94.5
Percent of Gmm at Nmax
3.5
4
4.5
5
5.5
6
Asphalt Content, %


7
6
5
4
3
2
1
0
Air Voids, %
3.5
4
4.5
5
5.5
6
Asphalt Content, %



14.50
14.25
14.00
13.75
13.50
13.25
13.00
12.75
12.50
VMA, %
3.5
4
4.5
5
5.5
6
Asphalt Content, %

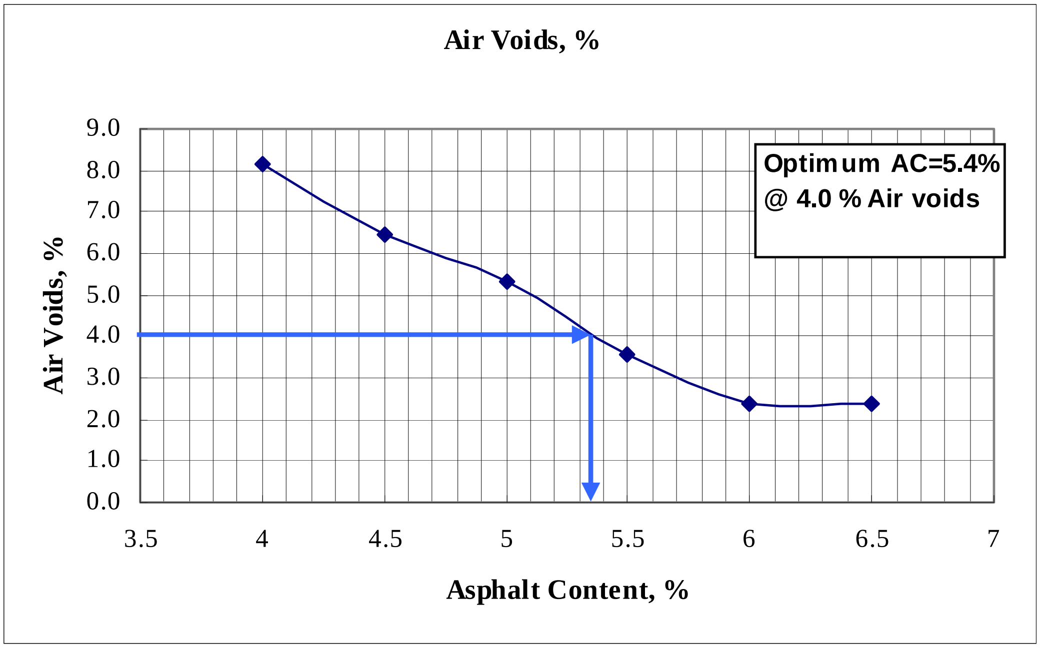


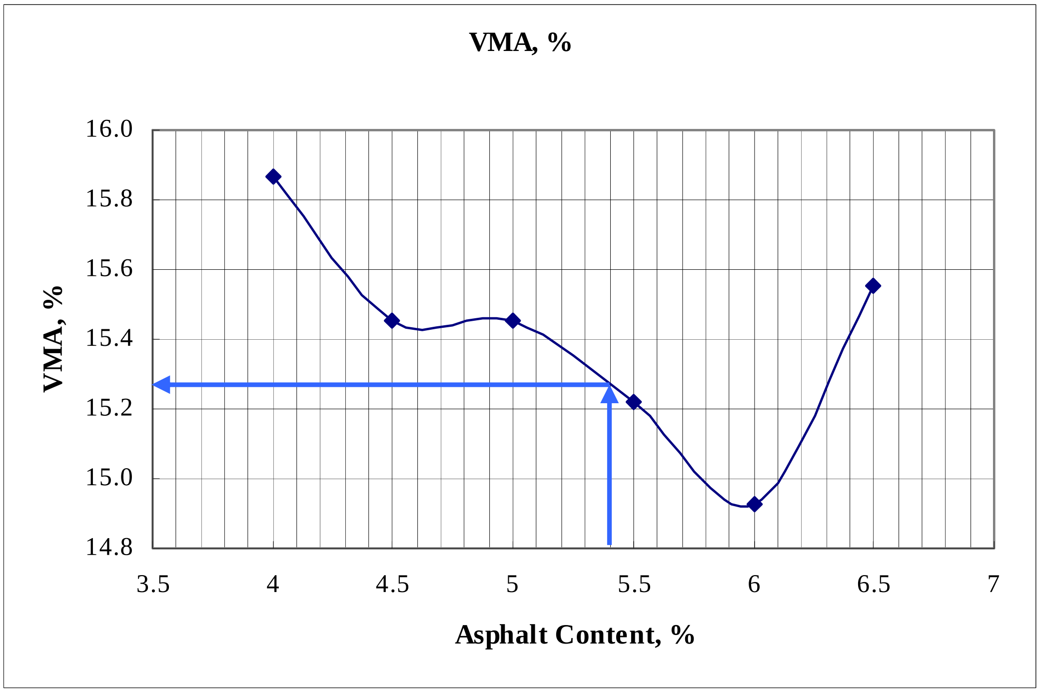
80
75
70
65
60
55
50
VFA, %
3.5
4
4.5
5
5.5
Asphalt Content, %

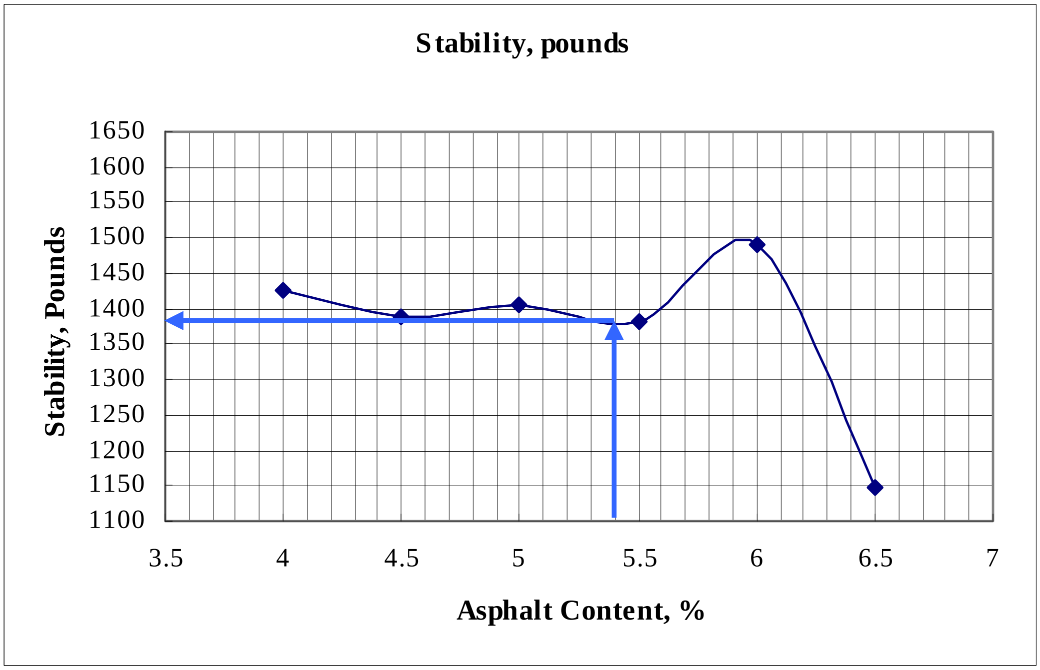
A.2 Martin Marietta Gravel

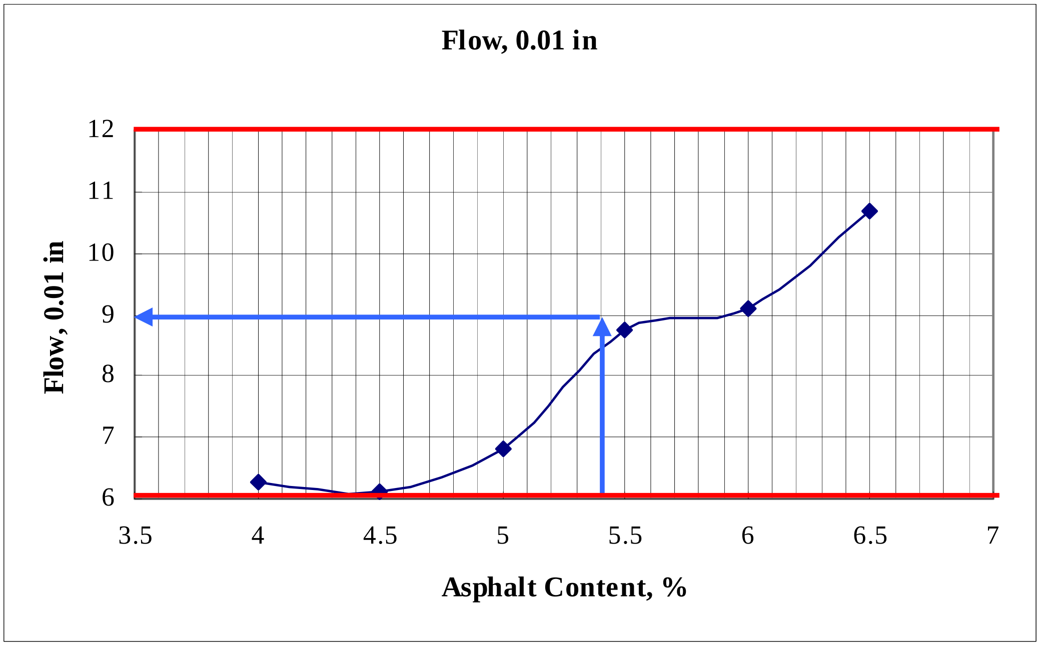
➢ Marshall specimen mix design

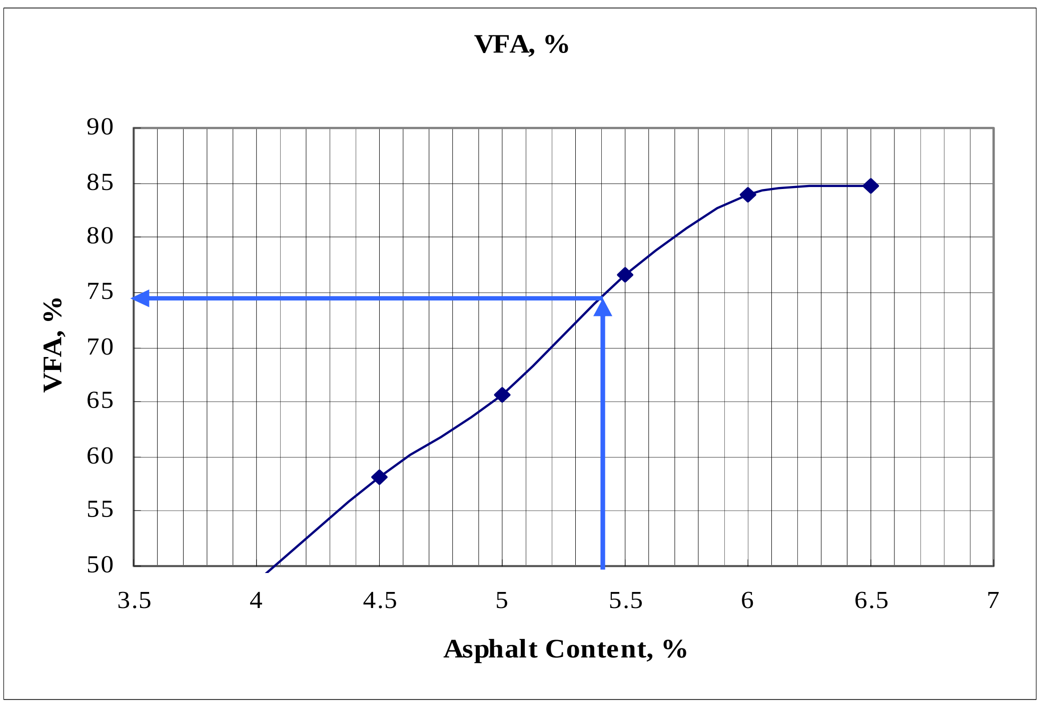
Martin Marietta Co						
% AC by wt. of mix.	Unit Weight, pcf (Mg/m3)	% Air Voids	% VMA	% VFA	Stability (lb)	Flow 0.01 in.
4	140.88	8.15	15.86	48.62	1427	6.3
4.5	142.30	6.46	15.45	58.20	1389	6.1
5	143.06	5.30	15.45	65.68	1405	6.8
5.5	144.21	3.55	15.22	76.69	1382	8.7
6	144.70	2.39	14.93	84.00	1491	9.1
6.5	143.65	2.39	15.55	84.65	1147	10.7

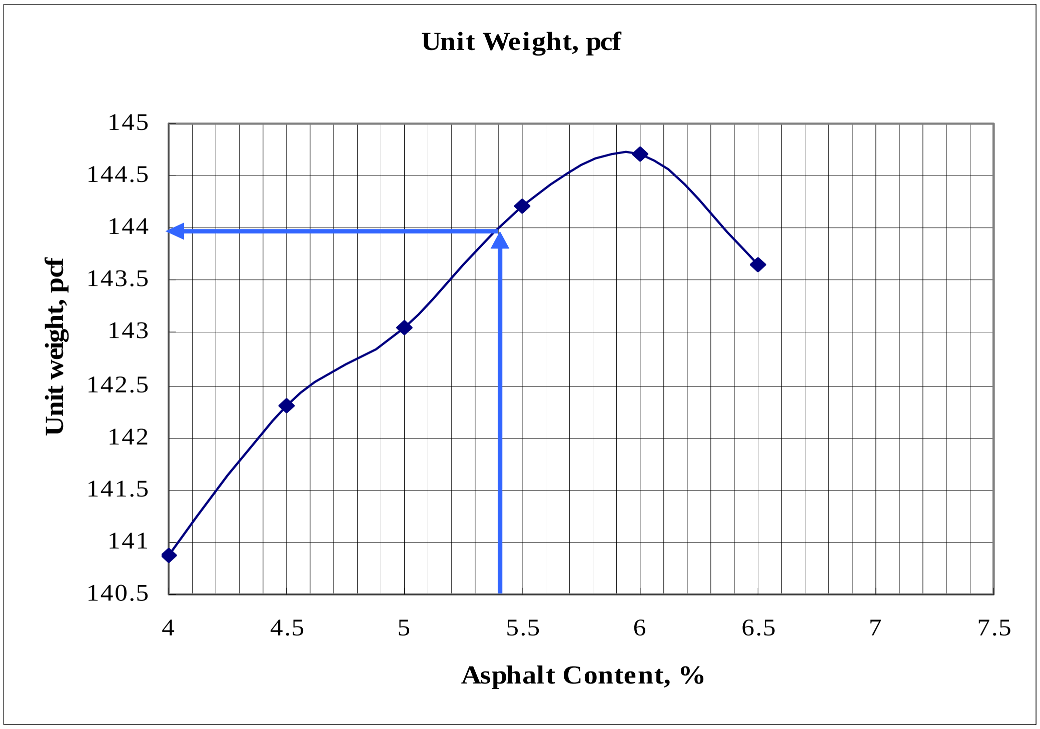



VMA, %
16.0
15.8
15.6
15.4
15.2
15.0
14.8
VMA, %
3.5
4
4.5
5
5.5
6
6.5
7
Asphalt Content, %


Stability, pounds
1650
1600
1550
1500
1450
1400
1350
1300
1250
1200
1150
1100
Stability, Pounds
3.5
4
4.5
5
5.5
6
6.5
7
Asphalt Content, %


Flow, 0.01 in
12
11
10
9
8
7
6
3.5
4
4.5
5
5.5
6
6.5
7
Flow, 0.01 in
Asphalt Content, %


VFA, %
90
85
80
75
70
65
60
55
50
3.5
4
4.5
5
5.5
6
6.5
7
VFA, %
Asphalt Content, %


Unit Weight, pcf
Unit weight, pcf
145
144.5
144
143.5
143
142.5
142
141.5
141
140.5
4
4.5
5
5.5
6
6.5
7
7.5
Asphalt Content, %

- Gyratory 4 inch specimen mix design

Densification Data @ 5.0 % Asphalt Content											
Gmm(meas) =		2.414									
Gyrations	Specimen 1					Specimen 2					Avg
	Ht, mm	Volume, cm3	Gmb(est)	Gmb(corr)	%Gmm	Ht, mm	Volume, cm3	Gmb(est)	Gmb(corr)	%Gmm	%Gmm
5	69.2	543.496	2.078	2.125	88.0	68.9	541.139	2.086	2.146	88.9	88.460
7	68.5	537.998	2.100	2.146	88.9	68.3	536.427	2.104	2.165	89.7	89.300
10	67.8	532.500	2.121	2.169	89.8	67.7	531.715	2.123	2.184	90.5	90.157
20	66.5	522.290	2.163	2.211	91.6	66.5	522.290	2.161	2.224	92.1	91.851
30	65.8	516.792	2.186	2.235	92.6	65.8	516.792	2.184	2.247	93.1	92.828
40	65.4	513.650	2.199	2.248	93.1	65.3	512.865	2.201	2.264	93.8	93.468
50	65.1	511.294	2.209	2.259	93.6	65	510.509	2.211	2.275	94.2	93.899
60	64.8	508.938	2.220	2.269	94.0	64.7	508.153	2.222	2.285	94.7	94.334
65	64.6	507.367	2.226	2.276	94.3	64.6	507.367	2.225	2.289	94.8	94.552
70	64.6	507.367	2.226	2.276	94.3	64.5	506.582	2.228	2.292	95.0	94.626
80	64.4	505.796	2.233	2.283	94.6	64.3	505.011	2.235	2.300	95.3	94.920
90	64.2	504.226	2.240	2.290	94.9	64.1	503.440	2.242	2.307	95.6	95.216
99	63.9	501.869	2.251	2.301	95.3	63.9	501.869	2.249	2.314	95.9	95.588
Weight (gm) =		1129.6					1128.9				
Gmb(meas)=		2.301					2.314				
CF=		1.022					1.029				

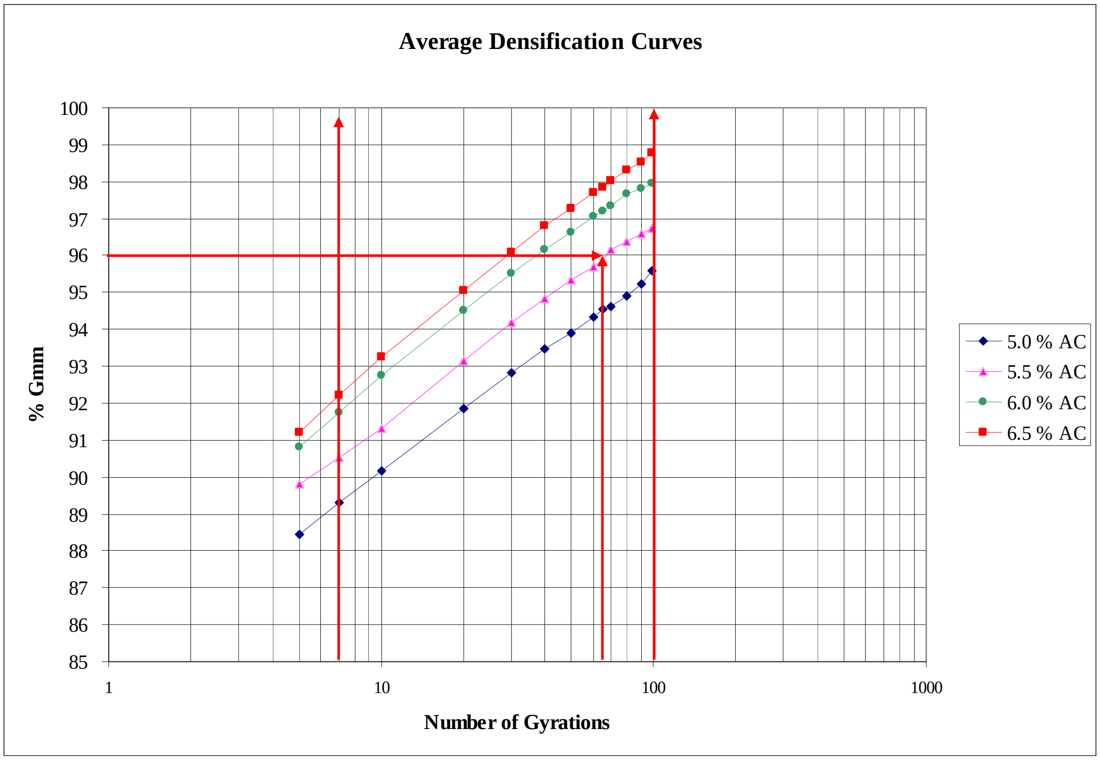
Densification Data @ 5.5 % Asphalt Content											
Gmm(meas) =		2.398									
Gyrations	Specimen 1					Specimen 2					Avg
	Ht, mm	Volume, cm3	Gmb(est)	Gmb(corr)	%Gmm	Ht, mm	Volume, cm3	Gmb(est)	Gmb(corr)	%Gmm	%Gmm
5	69.9	548.993	2.094	2.158	89.987	69.5	545.852	2.098	2.149	89.624	89.806
7	69.5	545.852	2.106	2.170	90.505	68.8	540.354	2.119	2.171	90.536	90.521
10	69	541.925	2.122	2.186	91.161	68.1	534.856	2.141	2.193	91.467	91.314
20	67.6	530.929	2.166	2.231	93.049	66.8	524.646	2.182	2.236	93.247	93.148
30	66.9	525.431	2.188	2.255	94.022	66	518.363	2.209	2.263	94.377	94.200
40	66.4	521.504	2.205	2.272	94.730	65.6	515.221	2.222	2.277	94.953	94.842
50	66.1	519.148	2.215	2.282	95.160	65.2	512.080	2.236	2.291	95.535	95.348
60	65.8	516.792	2.225	2.292	95.594	65	510.509	2.243	2.298	95.829	95.712
65	65.7	516.007	2.228	2.296	95.740	64.9	509.723	2.246	2.302	95.977	95.858
70	65.5	514.436	2.235	2.303	96.032	64.7	508.153	2.253	2.309	96.273	96.153
80	65.4	513.650	2.238	2.306	96.179	64.5	506.582	2.260	2.316	96.572	96.375
90	65.2	512.080	2.245	2.313	96.474	64.4	505.796	2.264	2.319	96.722	96.598
99	65.1	511.294	2.249	2.317	96.622	64.3	505.011	2.267	2.323	96.872	96.747
Weight (gm) =		1149.8					1144.95				
Gmb(meas)=		2.317					2.323				
CF=		1.030					1.025				

Densification Data @ 6.0 % Asphalt Content											
Gmm(meas) =		2.385									
Gyrations	Specimen 1					Specimen 2					Avg
	Ht, mm	Volume, cm3	Gmb(est)	Gmb(corr)	%Gmm	Ht, mm	Volume, cm3	Gmb(est)	Gmb(corr)	%Gmm	%Gmm
5	69.5	545.852	2.107	2.160	90.5784	69.1	542.710	2.112	2.172	91.078	90.828
7	68.8	540.354	2.128	2.182	91.5	68.4	537.212	2.133	2.194	92.010	91.755
10	68	534.071	2.153	2.208	92.5765	67.7	531.715	2.155	2.217	92.961	92.769
20	66.7	523.861	2.195	2.251	94.3808	66.5	522.290	2.194	2.257	94.639	94.510
30	66	518.363	2.219	2.275	95.3818	65.8	516.792	2.218	2.281	95.646	95.514
40	65.5	514.436	2.236	2.292	96.1099	65.4	513.650	2.231	2.295	96.231	96.170
50	65.2	512.080	2.246	2.303	96.5521	65.1	511.294	2.241	2.306	96.674	96.613
60	64.9	509.723	2.256	2.313	96.9984	64.8	508.938	2.252	2.316	97.122	97.060
65	64.8	508.938	2.260	2.317	97.1481	64.7	508.153	2.255	2.320	97.272	97.210
70	64.7	508.153	2.263	2.321	97.2983	64.6	507.367	2.259	2.324	97.422	97.360
80	64.5	506.582	2.270	2.328	97.6	64.4	505.796	2.266	2.331	97.725	97.662
90	64.4	505.796	2.274	2.331	97.7515	64.3	505.011	2.269	2.334	97.877	97.814
99	64.3	505.011	2.277	2.335	97.9036	64.2	504.226	2.273	2.338	98.029	97.966
Weight (gm) =		1150.1					1146				
Gmb(meas)=		2.335					2.338				
CF=		1.025					1.029				

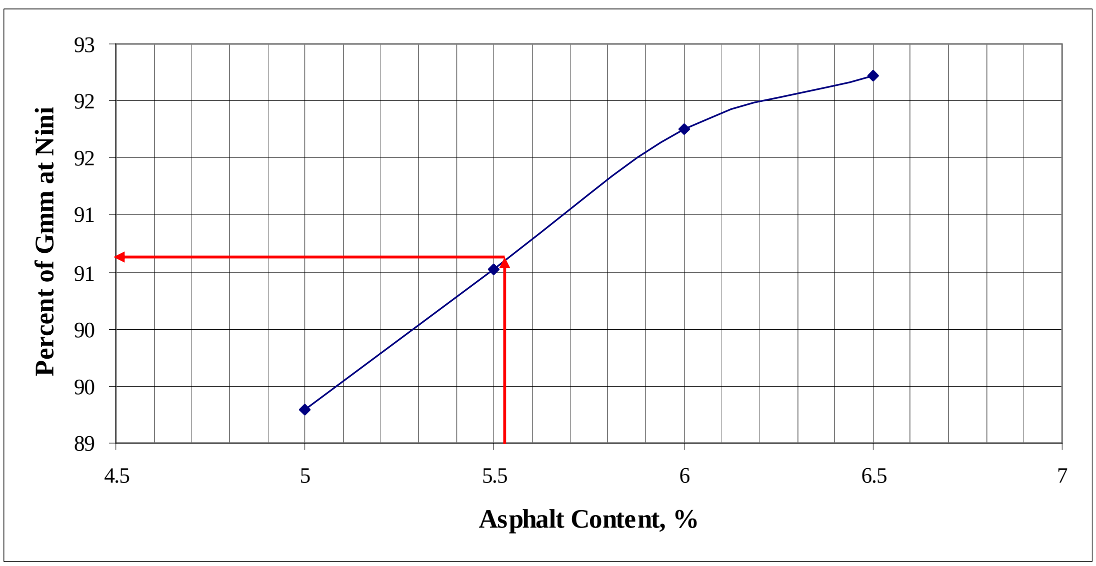
Densification Data @ 6.5 % Asphalt Content											
Gmm(meas) =		2.369									
Gyrations	Specimen 1					Specimen 2					Avg
	Ht, mm	Volume, cm3	Gmb(est)	Gmb(corr)	%Gmm	Ht, mm	Volume, cm3	Gmb(est)	Gmb(corr)	%Gmm	%Gmm
5	69.5	545.852	2.105	2.158	91.087	69.1	542.710	2.122	2.164	91.356	91.221
7	68.8	540.354	2.127	2.180	92.014	68.3	536.427	2.147	2.190	92.426	92.220
10	68	534.071	2.152	2.205	93.097	67.6	530.929	2.169	2.212	93.383	93.240
20	66.7	523.861	2.194	2.248	94.911	66.3	520.719	2.212	2.256	95.214	95.062
30	66	518.363	2.217	2.272	95.918	65.6	515.221	2.235	2.280	96.230	96.074
40	65.5	514.436	2.234	2.290	96.650	65.1	511.294	2.252	2.297	96.969	96.809
50	65.2	512.080	2.244	2.300	97.095	64.8	508.938	2.263	2.308	97.418	97.256
60	64.9	509.723	2.255	2.311	97.543	64.5	506.582	2.273	2.319	97.871	97.707
65	64.8	508.938	2.258	2.314	97.694	64.4	505.796	2.277	2.322	98.023	97.858
70	64.7	508.153	2.262	2.318	97.845	64.3	505.011	2.280	2.326	98.175	98.010
80	64.5	506.582	2.269	2.325	98.148	64.1	503.440	2.288	2.333	98.482	98.315
90	64.3	505.011	2.276	2.332	98.454	64	502.655	2.291	2.337	98.636	98.545
99	64.2	504.226	2.279	2.336	98.607	63.8	501.084	2.298	2.344	98.945	98.776
Weight (gm) =		1149.2					1151.65				
Gmb(meas)=		2.336					2.344				
CF=		1.025					1.020				

Number of Gyration	% Gmm, 5.0 AC	% Gmm, 5.5 AC	% Gmm, 6.0 AC	% Gmm, 6.5 AC
5	88.460	89.806	90.828	91.221
7	89.300	90.521	91.755	92.220
10	90.157	91.314	92.769	93.240
20	91.851	93.148	94.510	95.062
30	92.828	94.200	95.514	96.074
40	93.468	94.842	96.170	96.809
50	93.899	95.348	96.613	97.256
60	94.334	95.712	97.060	97.707
65	94.552	95.858	97.210	97.858
70	94.626	96.153	97.360	98.010
80	94.920	96.375	97.662	98.315
90	95.216	96.598	97.814	98.545
99	95.588	96.747	97.966	98.776

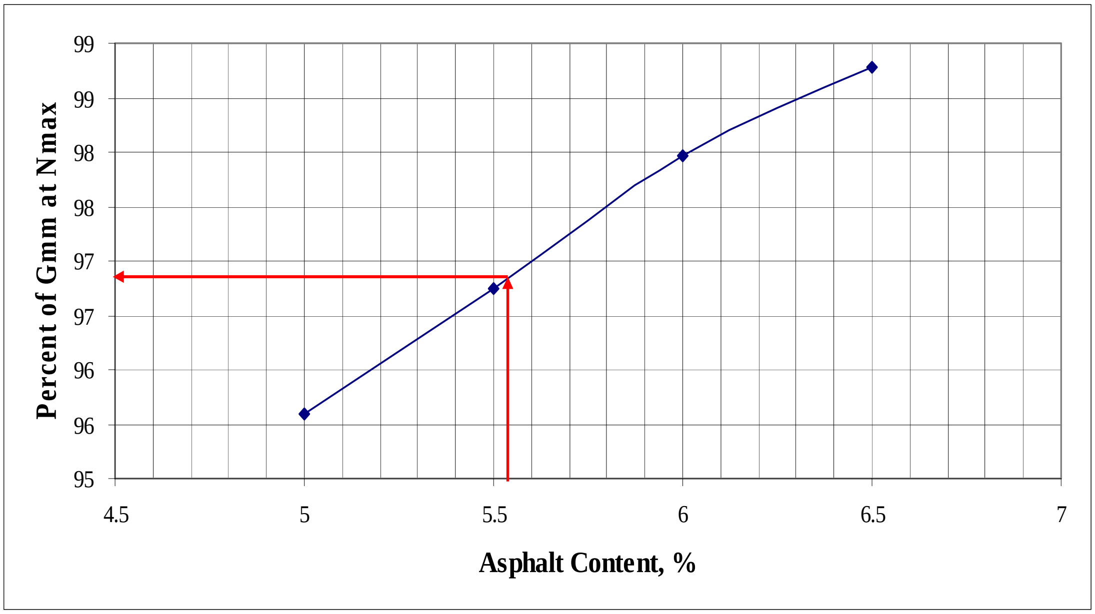
AC %	% Gmm @N=7	% Gmm @N=65	% Gmm @N=99	Air Void, %, @ Ndes	Gsb	Ps	Gmm	% VMA	% VFA
5	89.300	94.552	95.588	5.448	2.576	0.95	2.426	15.41	64.64
5.5	90.521	95.858	96.747	4.142	2.576	0.945	2.413	15.15	72.65
6	91.755	97.210	97.966	2.790	2.576	0.94	2.391	15.19	81.63
6.5	92.220	97.858	98.776	2.142	2.576	0.935	2.383	15.36	86.06



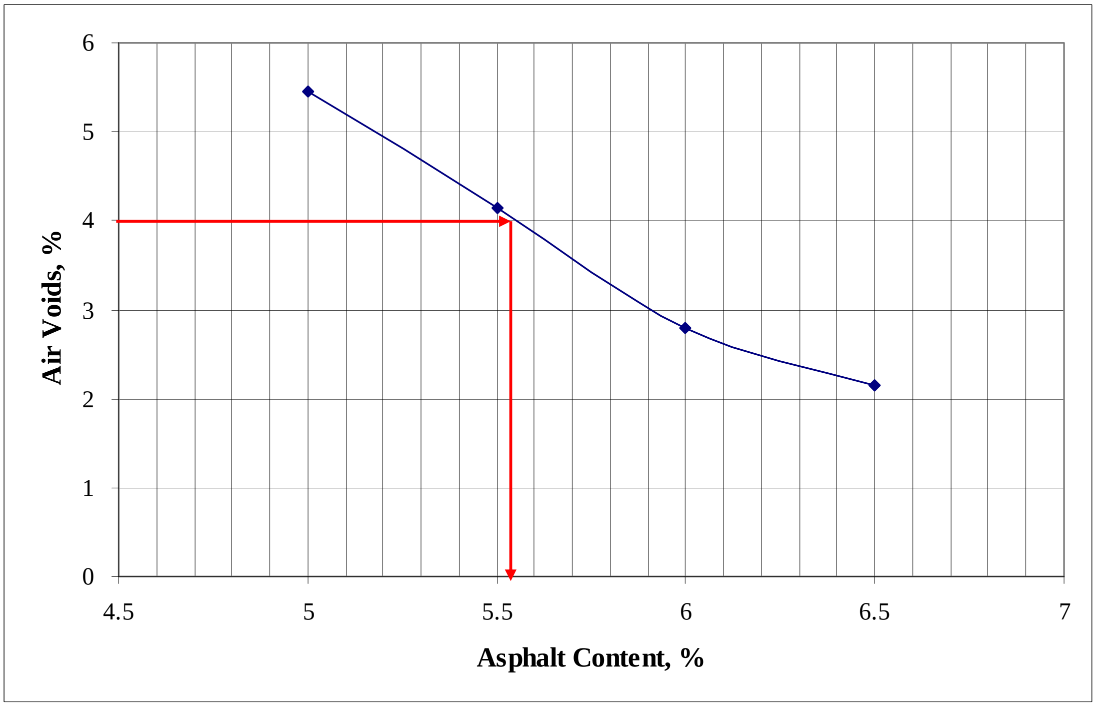
Average Densification Curves
% Gmm
Number of Gyrations
100
99
98
97
96
95
94
93
92
91
90
89
88
87
86
85
1
10
100
1000
5.0 % AC
5.5 % AC
6.0 % AC
6.5 % AC



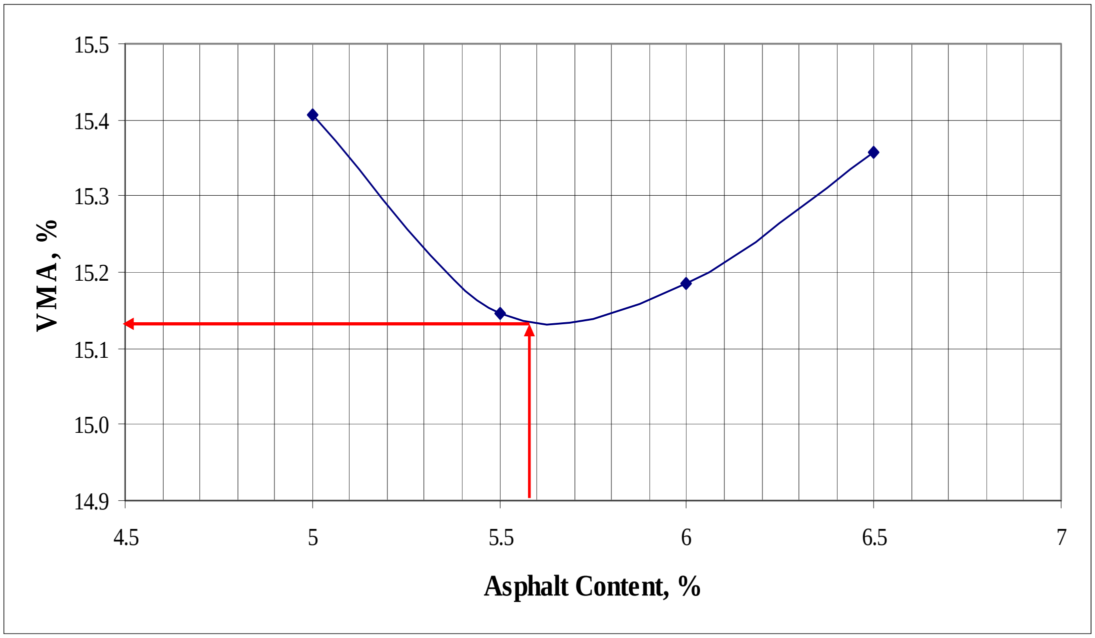
Percent of Gmm at Nini
Asphalt Content, %
93
92
92
91
91
90
90
89
4.5
5
5.5
6
6.5
7

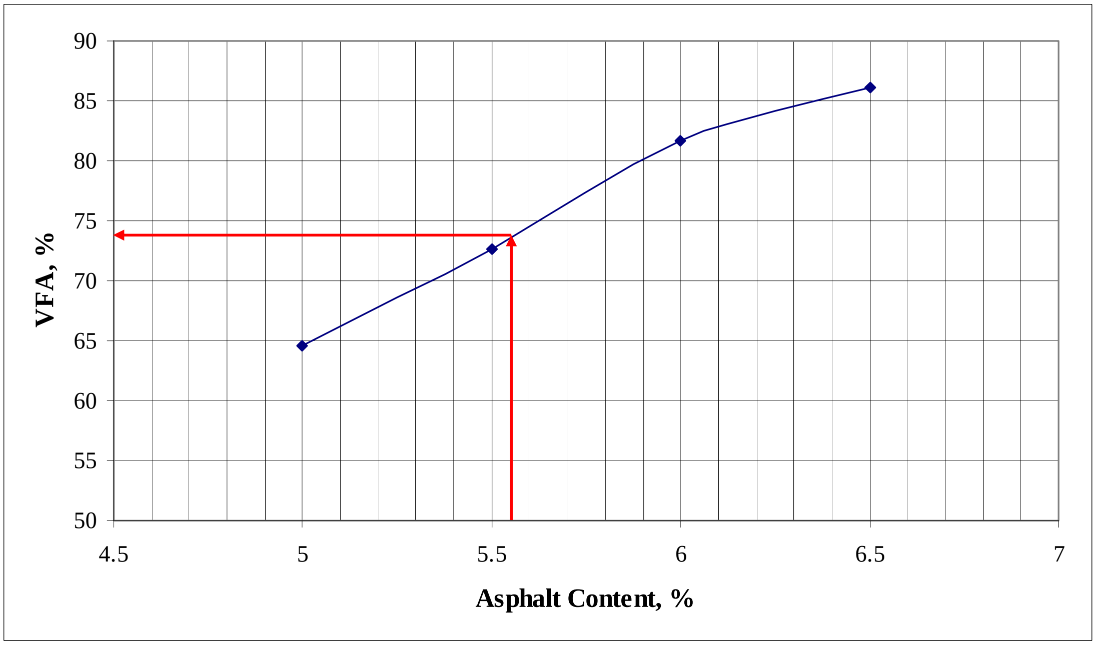


99
99
98
98
97
97
96
96
95
4.5
5
5.5
6
6.5
7
Percent of Gmm at Nmax
Asphalt Content, %



6
5
4
3
2
1
0
4.5
5
5.5
6
6.5
7
Air Voids, %
Asphalt Content, %


15.5
15.4
15.3
15.2
15.1
15.0
14.9
VMA, %
4.5
5
5.5
6
6.5
7
Asphalt Content, %


90
85
80
75
70
65
60
55
50
VFA, %
4.5
5
5.5
6
6.5
7
Asphalt Content, %

- Gyratory 6 inch specimen mix design

Densification Data @ 4.0 % Asphalt Content											
Gmm(meas) =		2.452									
Gyrations	Specimen 1					Specimen 2					Avg
	Ht, mm	Volume, cm3	Gmb(est)	Gmb(corr)	%Gmm	Ht, mm	Volume, cm3	Gmb(est)	Gmb(corr)	%Gmm	%Gmm
5	125.2	2212.467	2.092	2.135	87.1	125.9	2224.837	2.088	2.139	87.2	87.150
7	123.9	2189.494	2.114	2.157	88.0	124.7	2203.631	2.108	2.160	88.1	88.027
10	122.5	2164.754	2.138	2.182	89.0	123.5	2182.425	2.129	2.181	88.9	88.957
20	120.4	2127.644	2.175	2.220	90.5	121.2	2141.781	2.169	2.222	90.6	90.577
30	119.2	2106.438	2.197	2.242	91.4	120.1	2122.342	2.189	2.243	91.5	91.448
40	118.4	2092.301	2.212	2.257	92.1	119.3	2108.205	2.204	2.258	92.1	92.063
50	117.8	2081.698	2.223	2.269	92.5	118.7	2097.602	2.215	2.269	92.5	92.531
60	117.4	2074.629	2.231	2.276	92.8	118.3	2090.534	2.222	2.277	92.8	92.845
65	117.2	2071.095	2.234	2.280	93.0	118.1	2086.999	2.226	2.280	93.0	93.002
70	117.1	2069.328	2.236	2.282	93.1	118	2085.232	2.228	2.282	93.1	93.082
80	116.8	2064.026	2.242	2.288	93.3	117.6	2078.164	2.235	2.290	93.4	93.359
90	116.5	2058.725	2.248	2.294	93.6	117.4	2074.629	2.239	2.294	93.6	93.559
99	116.3	2055.191	2.252	2.298	93.7	117.2	2071.095	2.243	2.298	93.7	93.719
Weight (gm) =		4627.7					4645.5				
Gmb(meas)=		2.298					2.298				
CF=		1.021					1.025				

Densification Data @ 4.5 % Asphalt Content											
Gmm(meas) =		2.426									
Gyrations	Specimen 1					Specimen 2					Avg
	Ht, mm	Volume, cm3	Gmb(est)	Gmb(corr)	%Gmm	Ht, mm	Volume, cm3	Gmb(est)	Gmb(corr)	%Gmm	%Gmm
5	125.6	2219.535	2.106	2.146	88.473	125.6	2219.535	2.100	2.144	88.358	88.415
7	124.3	2196.562	2.128	2.169	89.398	124.4	2198.329	2.121	2.164	89.210	89.304
10	123.1	2175.357	2.149	2.190	90.269	123.1	2175.357	2.143	2.187	90.152	90.211
20	120.8	2134.712	2.189	2.232	91.988	120.8	2134.712	2.184	2.229	91.869	91.928
30	119.5	2111.739	2.213	2.256	92.989	119.6	2113.506	2.206	2.251	92.791	92.890
40	118.7	2097.602	2.228	2.271	93.616	118.8	2099.369	2.221	2.266	93.415	93.515
50	118.1	2086.999	2.239	2.283	94.091	118.2	2088.766	2.232	2.278	93.890	93.990
60	117.7	2079.931	2.247	2.290	94.411	117.7	2079.931	2.241	2.287	94.288	94.350
65	117.5	2076.396	2.251	2.294	94.572	117.5	2076.396	2.245	2.291	94.449	94.510
70	117.3	2072.862	2.255	2.298	94.733	117.3	2072.862	2.249	2.295	94.610	94.671
80	117	2067.561	2.261	2.304	94.976	117	2067.561	2.255	2.301	94.853	94.914
90	116.7	2062.259	2.266	2.310	95.220	116.7	2062.259	2.261	2.307	95.096	95.158
99	116.5	2058.725	2.270	2.314	95.383	116.5	2058.725	2.265	2.311	95.260	95.322
Weight (gm) =		4673.8					4662				
Gmb(meas)=		2.314					2.311				
CF=		1.019					1.021				

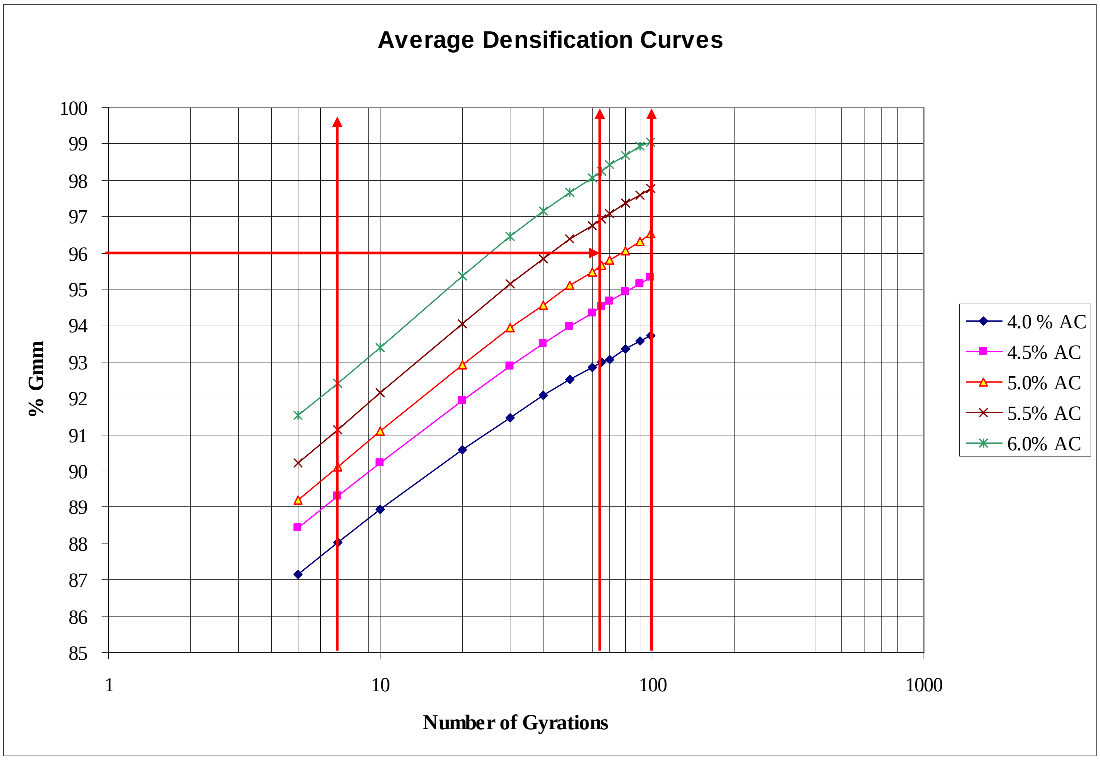
Densification Data @ 5.0 % Asphalt Content											
Gmm(meas) =		2.414									
Gyrations	Specimen 1					Specimen 2					Avg
	Ht, mm	Volume, cm3	Gmb(est)	Gmb(corr)	%Gmm	Ht, mm	Volume, cm3	Gmb(est)	Gmb(corr)	%Gmm	%Gmm
5	125.5	2217.768	2.105	2.146	88.907	125	2208.932	2.119	2.160	89.493	89.200
7	124.2	2194.795	2.127	2.169	89.837	123.8	2187.727	2.139	2.181	90.361	90.099
10	122.8	2170.055	2.151	2.193	90.862	122.5	2164.754	2.162	2.204	91.320	91.091
20	120.4	2127.644	2.194	2.237	92.673	120.1	2122.342	2.205	2.249	93.144	92.909
30	119	2102.904	2.220	2.263	93.763	118.9	2101.136	2.227	2.271	94.084	93.924
40	118.2	2088.766	2.235	2.279	94.398	118.1	2086.999	2.243	2.287	94.722	94.560
50	117.5	2076.396	2.248	2.292	94.960	117.4	2074.629	2.256	2.300	95.287	95.123
60	117	2067.561	2.258	2.302	95.366	117	2067.561	2.264	2.308	95.612	95.489
65	116.8	2064.026	2.262	2.306	95.529	116.8	2064.026	2.268	2.312	95.776	95.653
70	116.6	2060.492	2.265	2.310	95.693	116.6	2060.492	2.271	2.316	95.940	95.817
80	116.3	2055.191	2.271	2.316	95.940	116.3	2055.191	2.277	2.322	96.188	96.064
90	116	2049.889	2.277	2.322	96.188	116	2049.889	2.283	2.328	96.437	96.312
99	115.7	2044.588	2.283	2.328	96.437	115.8	2046.355	2.287	2.332	96.603	96.520
Weight (gm) =		4667.8					4680.2				
Gmb(meas)=		2.328					2.332				
CF=		1.020					1.020				

Densification Data @ 5.5 % Asphalt Content											
Gmm(meas) =		2.398									
Gyrations	Specimen 1					Specimen 2					Avg
	Ht, mm	Volume, cm3	Gmb(est)	Gmb(corr)	%Gmm	Ht, mm	Volume, cm3	Gmb(est)	Gmb(corr)	%Gmm	%Gmm
5	125.5	2217.768	2.121	2.153	90.268	125.2	2212.467	2.132	2.165	90.775	90.521
7	124.3	2196.562	2.141	2.174	91.140	123.9	2189.494	2.154	2.188	91.727	91.433
10	122.9	2171.822	2.166	2.198	92.178	122.5	2164.754	2.179	2.213	92.775	92.477
20	120.5	2129.411	2.209	2.242	94.014	120	2120.575	2.224	2.259	94.708	94.361
30	119.1	2104.671	2.235	2.269	95.119	118.6	2095.835	2.250	2.285	95.826	95.473
40	118.3	2090.534	2.250	2.284	95.762	117.7	2079.931	2.268	2.303	96.559	96.161
50	117.6	2078.164	2.263	2.298	96.332	117.1	2069.328	2.279	2.315	97.054	96.693
60	117.1	2069.328	2.273	2.307	96.744	116.7	2062.259	2.287	2.323	97.386	97.065
65	116.9	2065.794	2.277	2.311	96.909	116.4	2056.958	2.293	2.329	97.637	97.273
70	116.7	2062.259	2.281	2.315	97.075	116.3	2055.191	2.295	2.331	97.721	97.398
80	116.4	2056.958	2.287	2.321	97.325	115.9	2048.122	2.303	2.339	98.059	97.692
90	116.1	2051.656	2.293	2.327	97.577	115.7	2044.588	2.307	2.343	98.228	97.902
99	115.9	2048.122	2.297	2.331	97.745	115.4	2039.286	2.313	2.349	98.483	98.114
Weight (gm) =		4701.1					4705.8				
Gmb(meas)=		2.34					2.35				
CF=		1.019					1.016				

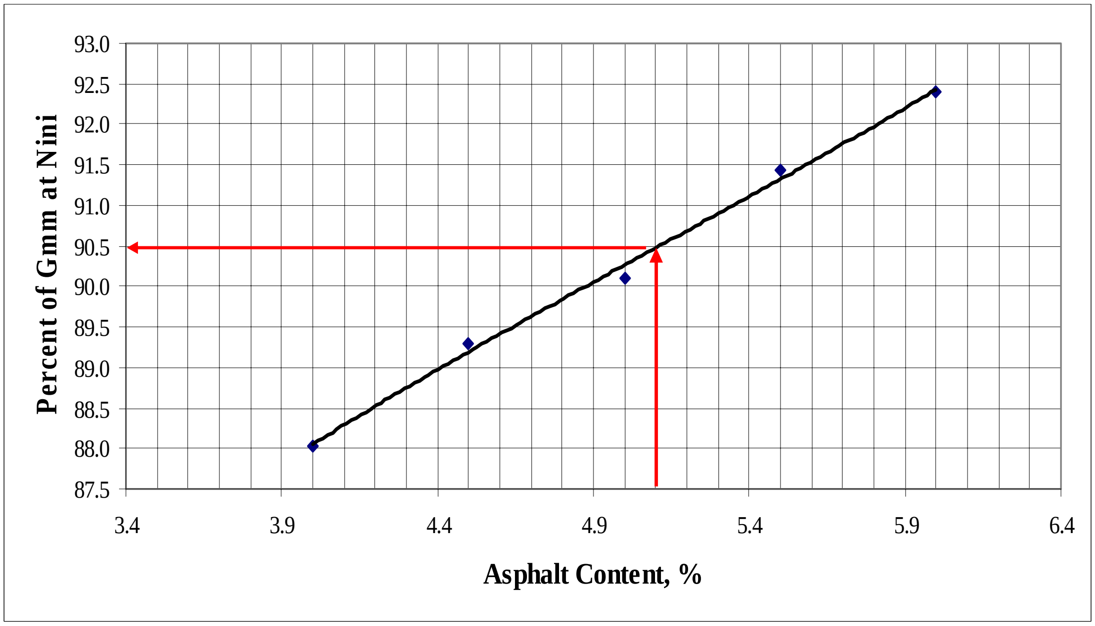
Densification Data @ 6.0 % Asphalt Content											
Gmm(meas) =		2.385									
Gyrations	Specimen 1					Specimen 2					Avg
	Ht, mm	Volume, cm3	Gmb(est)	Gmb(corr)	%Gmm	Ht, mm	Volume, cm3	Gmb(est)	Gmb(corr)	%Gmm	%Gmm
5	123.2	2177.124	2.161	2.193	91.953	124.7	2203.631	2.140	2.174	91.139	91.546
7	122.2	2159.452	2.178	2.211	92.706	123.4	2180.658	2.163	2.197	92.099	92.402
10	120.9	2136.479	2.202	2.235	93.703	122.1	2157.685	2.186	2.220	93.079	93.391
20	118.4	2092.301	2.248	2.282	95.681	119.6	2113.506	2.232	2.266	95.025	95.353
30	117.1	2069.328	2.273	2.307	96.744	118.2	2088.766	2.258	2.293	96.151	96.447
40	116.3	2055.191	2.289	2.323	97.409	117.3	2072.862	2.275	2.311	96.888	97.149
50	115.7	2044.588	2.301	2.335	97.914	116.7	2062.259	2.287	2.323	97.386	97.650
60	115.2	2035.752	2.311	2.345	98.339	116.2	2053.423	2.297	2.333	97.805	98.072
65	115	2032.218	2.315	2.349	98.510	116	2049.889	2.301	2.337	97.974	98.242
70	114.8	2028.683	2.319	2.354	98.682	115.8	2046.355	2.305	2.341	98.143	98.413
80	114.5	2023.382	2.325	2.360	98.940	115.5	2041.053	2.311	2.347	98.398	98.669
90	114.2	2018.081	2.331	2.366	99.200	115.2	2035.752	2.317	2.353	98.654	98.927
99	114.1	2016.313	2.333	2.368	99.287	115	2032.218	2.321	2.357	98.826	99.057
Weight (gm) =		4703.9					4716.4				
Gmb(meas)=		2.368					2.357				
CF=		1.015					1.016				

Number of Gyration	% Gmm, 4.0 AC	% Gmm, 4.5 AC	% Gmm, 5.0 AC	% Gmm, 5.5 AC	% Gmm, 6.0 AC
5	87.150	88.415	89.200	90.222	91.546
7	88.027	89.304	90.099	91.131	92.402
10	88.957	90.211	91.091	92.171	93.391
20	90.577	91.928	92.909	94.049	95.353
30	91.448	92.890	93.924	95.157	96.447
40	92.063	93.515	94.560	95.842	97.149
50	92.531	93.990	95.123	96.373	97.650
60	92.845	94.350	95.489	96.744	98.072
65	93.002	94.510	95.653	96.951	98.242
70	93.082	94.671	95.817	97.076	98.413
80	93.359	94.914	96.064	97.369	98.669
90	93.559	95.158	96.312	97.579	98.927
99	93.719	95.322	96.520	97.790	99.057

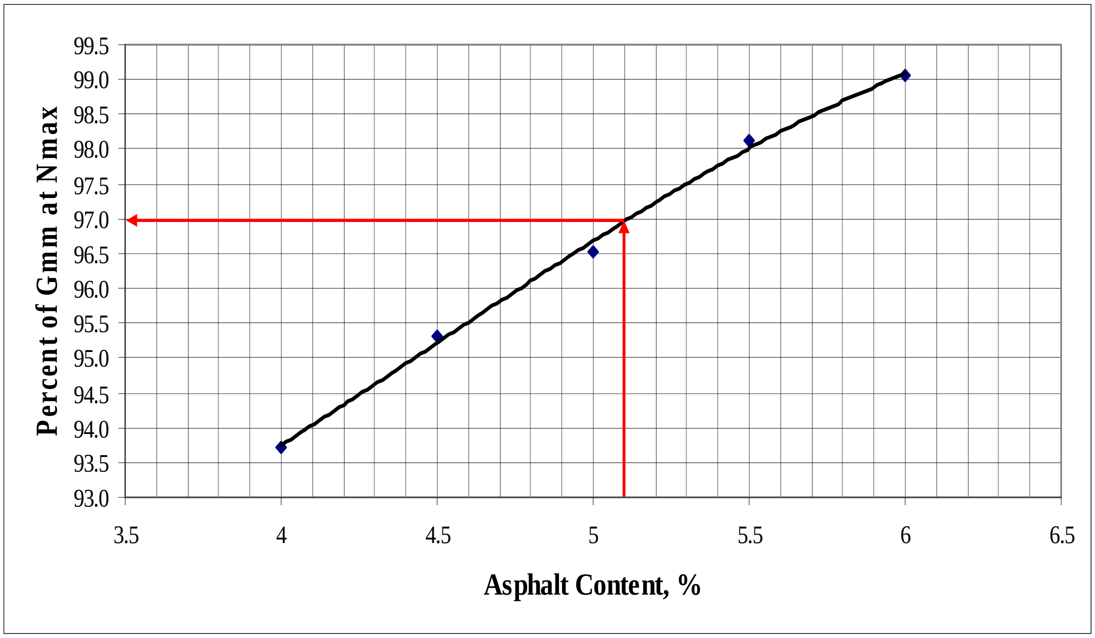
AC %	% Gmm @N=7	% Gmm @N=65	% Gmm @N=99	Air Void, %, @ Ndes	Gsb	Ps	Gmm	% VMA	% VFA
4	88.027	93.002	93.719	6.998	2.576	0.96	2.452	15.015	53.398
4.5	89.304	94.510	95.322	5.490	2.576	0.955	2.426	14.998	63.398
5	90.099	95.653	96.520	4.347	2.576	0.95	2.414	14.845	70.714
5.5	91.433	97.273	98.114	2.727	2.576	0.945	2.398	14.429	81.102
6	92.402	98.242	99.057	1.758	2.576	0.94	2.379	14.715	88.054

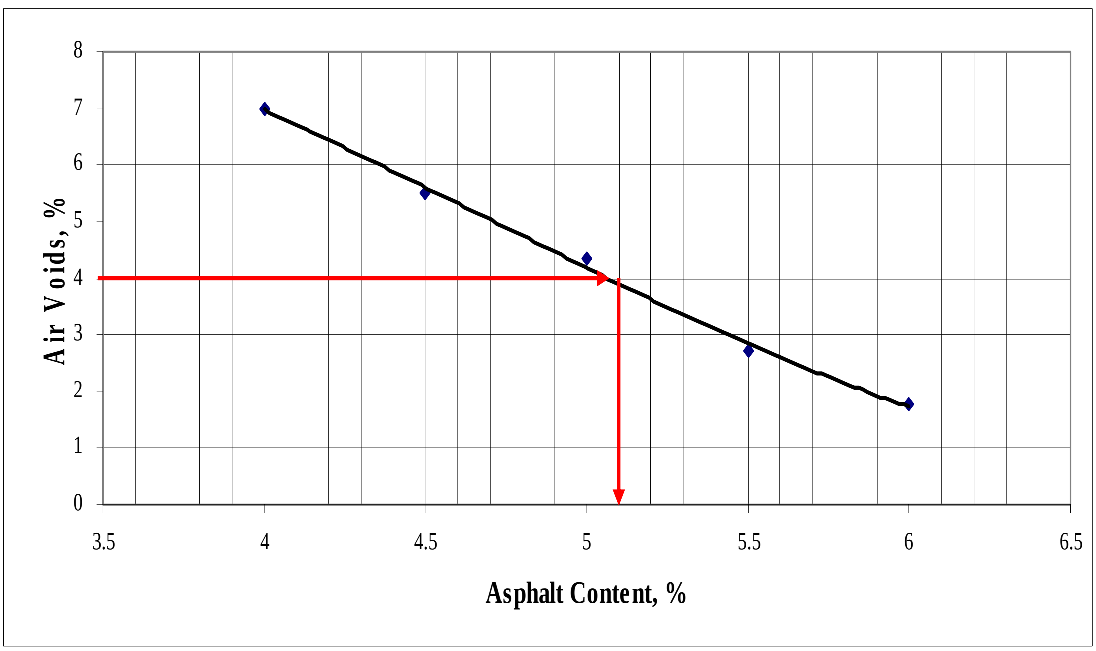


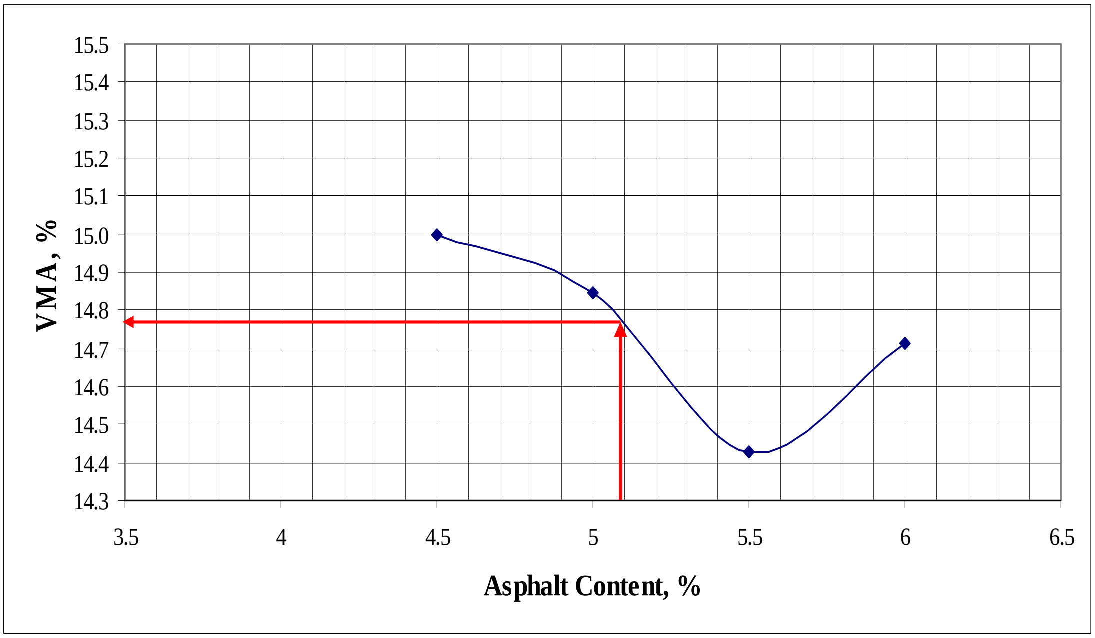
Average Densification Curves
% Gmm
Number of Gyrations
100
99
98
97
96
95
94
93
92
91
90
89
88
87
86
85
1
10
100
1000
4.0 % AC
4.5% AC
5.0% AC
5.5% AC
6.0% AC



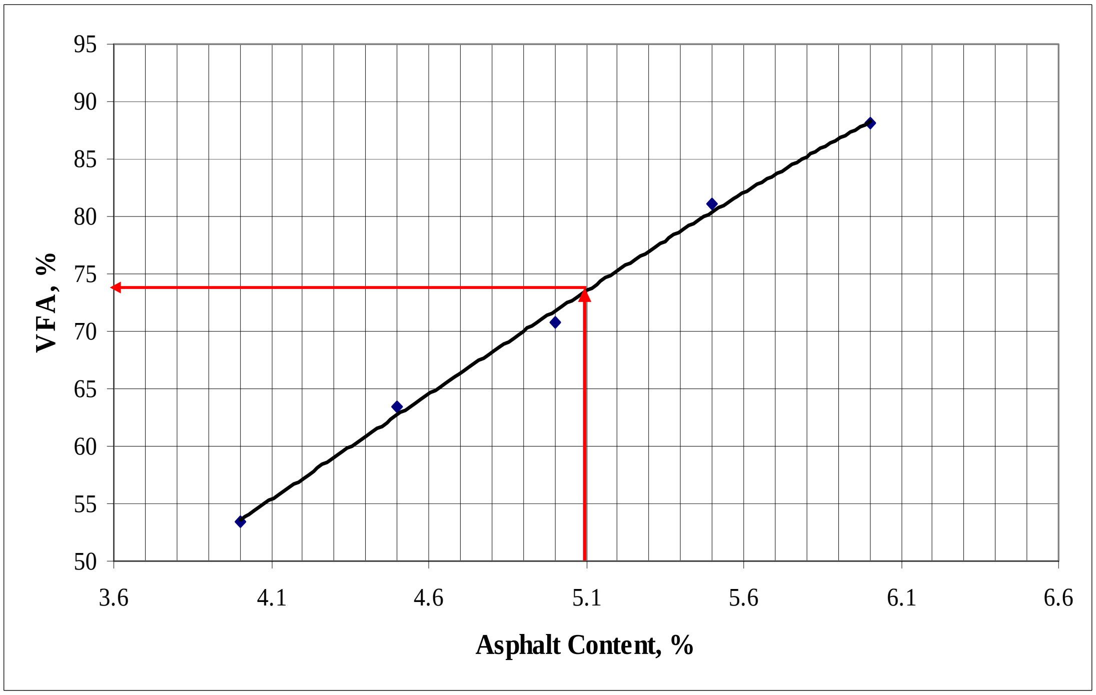
Percent of Gmm at Nini
Asphalt Content, %
93.0
92.5
92.0
91.5
91.0
90.5
90.0
89.5
89.0
88.5
88.0
87.5
3.4
3.9
4.4
4.9
5.4
5.9
6.4


99.5
99.0
98.5
98.0
97.5
97.0
96.5
96.0
95.5
95.0
94.5
94.0
93.5
93.0
Percent of Gmm at Nmax
3.5
4
4.5
5
5.5
6
6.5
Asphalt Content, %


8
7
6
5
4
3
2
1
0
Air Voids, %
3.5
4
4.5
5
5.5
6
6.5
Asphalt Content, %



15.5
15.4
15.3
15.2
15.1
15.0
14.9
14.8
14.7
14.6
14.5
14.4
14.3
VMA, %
3.5
4
4.5
5
5.5
6
6.5
Asphalt Content, %

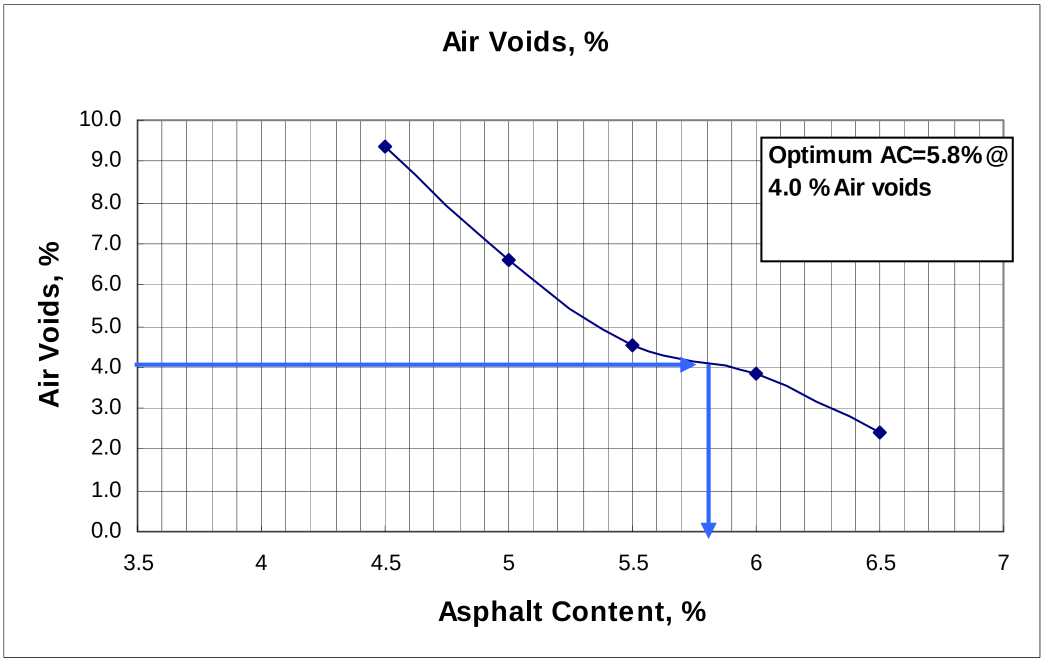


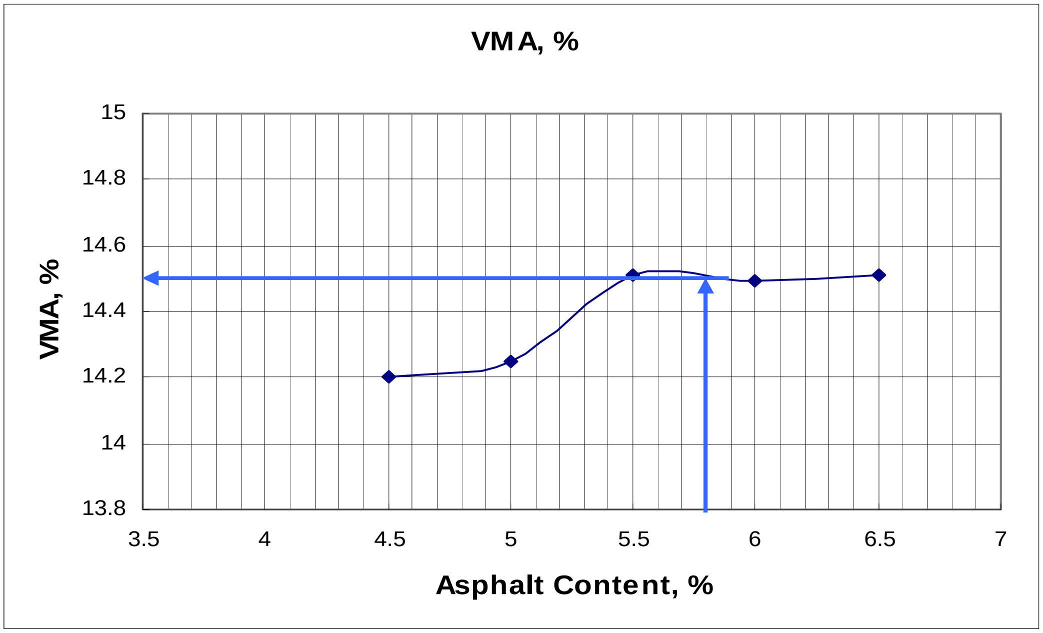
95
90
85
80
75
70
65
60
55
50
VFA, %
3.6
4.1
4.6
5.1
5.6
6.1
6.6
Asphalt Content, %

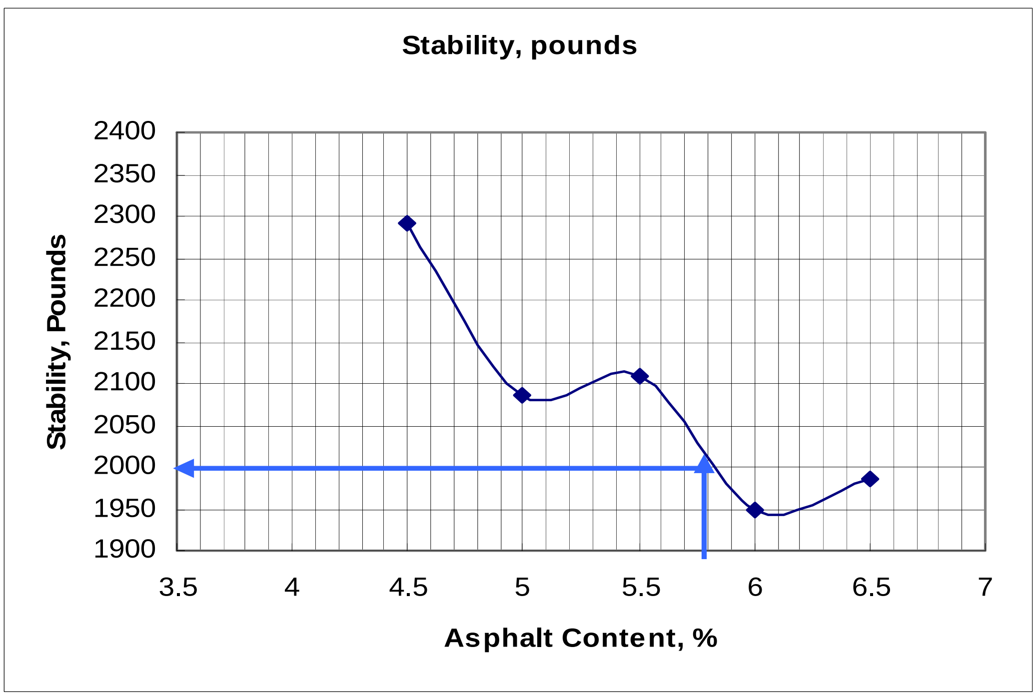
A.3 Ontario Trap Rock

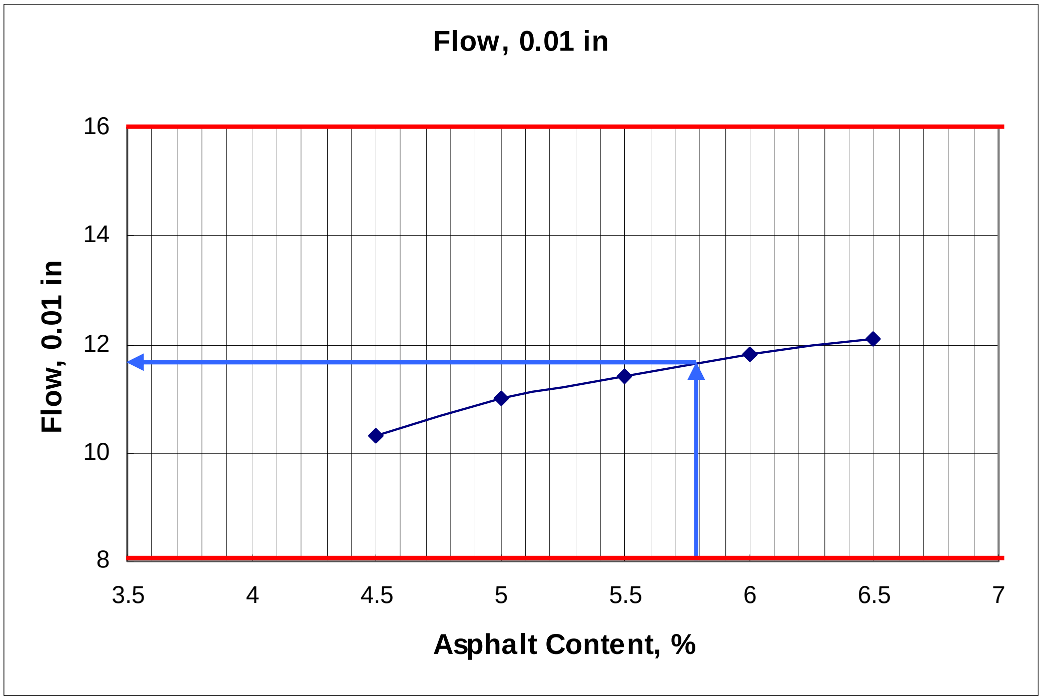
➢ Marshall mix design

Ontario Trap Rock						
% AC by wt. of mix.	Unit Weight, pcf (Mg/m3)	% Air Voids	% VMA	% VFA	Stability, lbs (N)	Flow 0.01 in. (0.25 mm)
4.5	153.75	9.38	14.20	40.11	2291	10.3
5	155.94	6.58	14.25	55.87	2087	11
5.5	157.50	4.54	14.51	68.72	2109	11.4
6	158.37	3.86	14.49	73.34	1948	11.8
6.5	159.18	2.41	14.51	83.39	1987	12.1

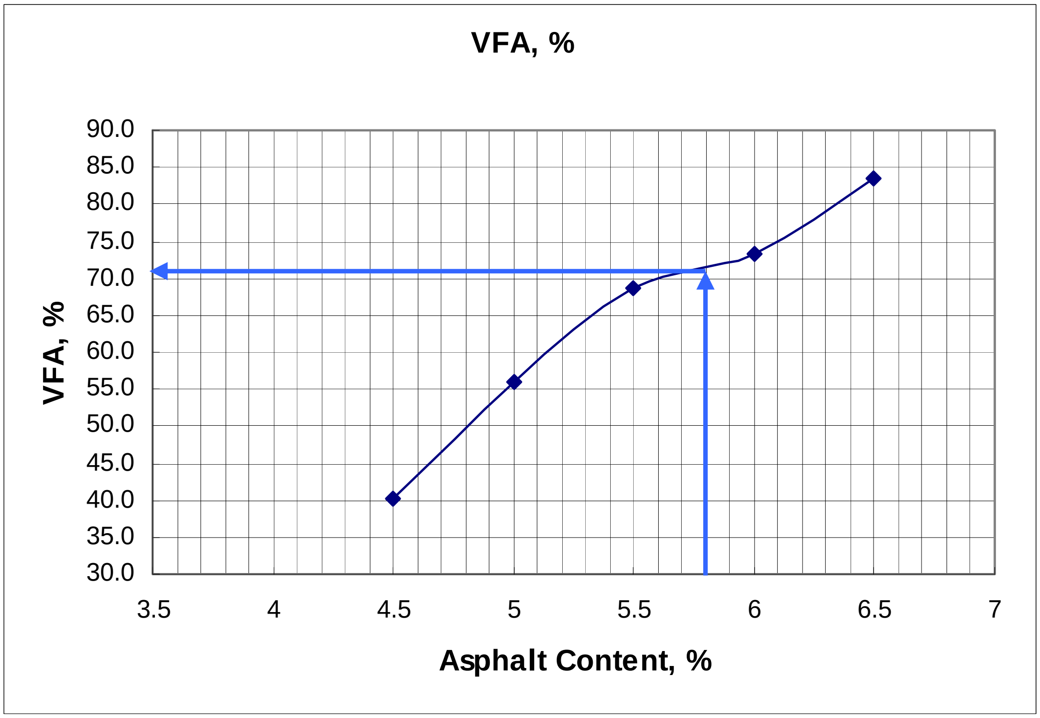



VMA, %
15
14.8
14.6
14.4
14.2
14
13.8
VMA, %
3.5
4
4.5
5
5.5
6
6.5
7
Asphalt Content, %

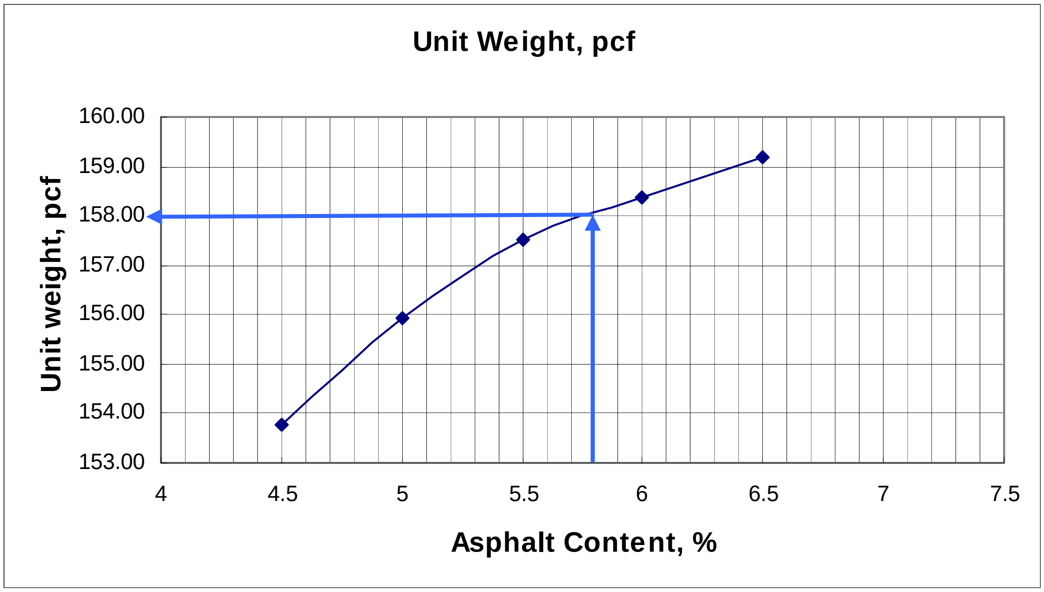

Stability, pounds
2400
2350
2300
2250
2200
2150
2100
2050
2000
1950
1900
Stability, Pounds
3.5
4
4.5
5
5.5
6
6.5
7
Asphalt Content, %



Flow, 0.01 in
16
14
12
10
8
Flow, 0.01 in
3.5
4
4.5
5
5.5
6
6.5
7
Asphalt Content, %

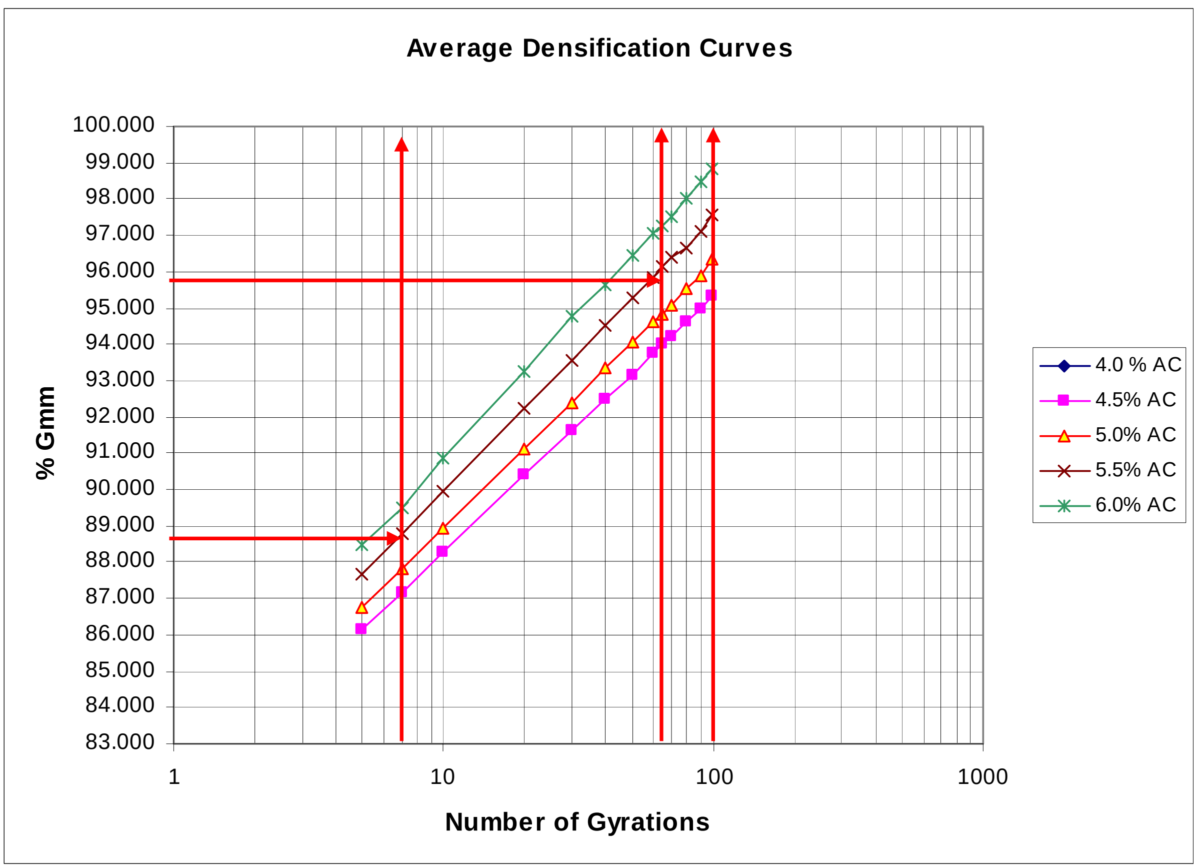


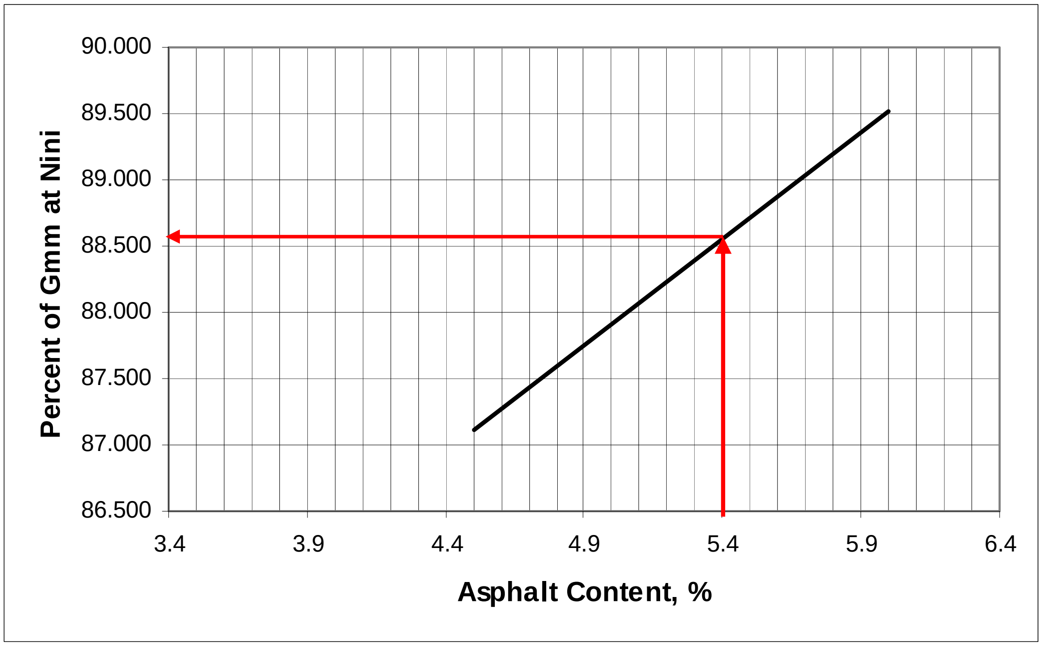
VFA, %
90.0
85.0
80.0
75.0
70.0
65.0
60.0
55.0
50.0
45.0
40.0
35.0
30.0
VFA, %
3.5
4
4.5
5
5.5
6
6.5
7
Asphalt Content, %

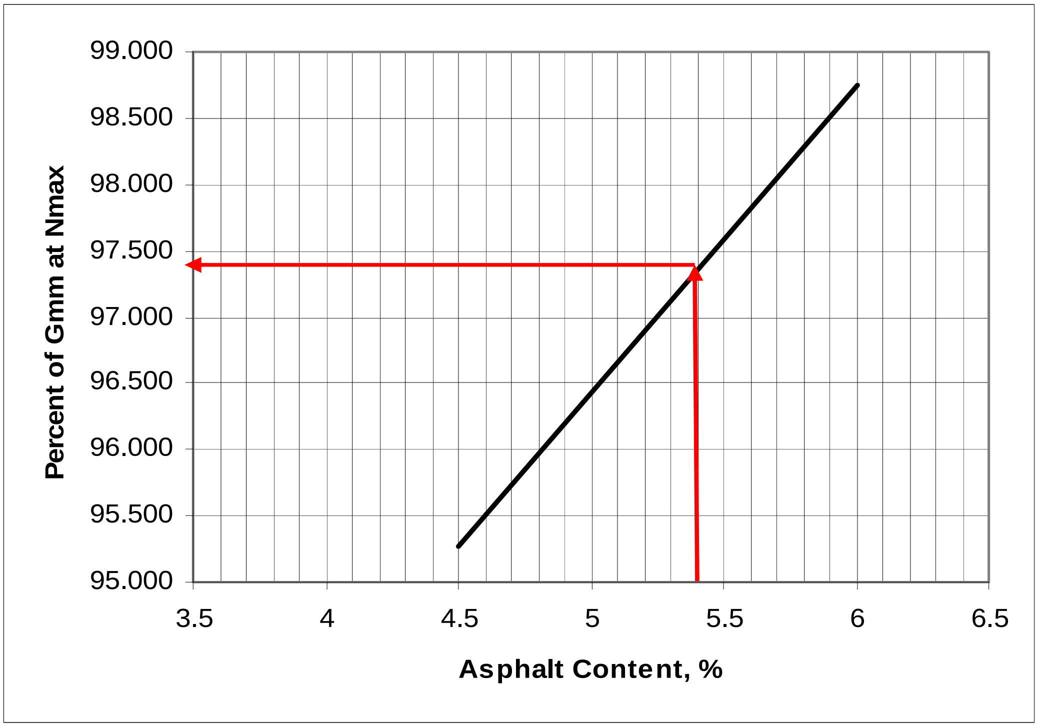

Unit Weight, pcf
Unit weight, pcf
160.00
159.00
158.00
157.00
156.00
155.00
154.00
153.00
4
4.5
5
5.5
6
6.5
7
7.5
Asphalt Content, %

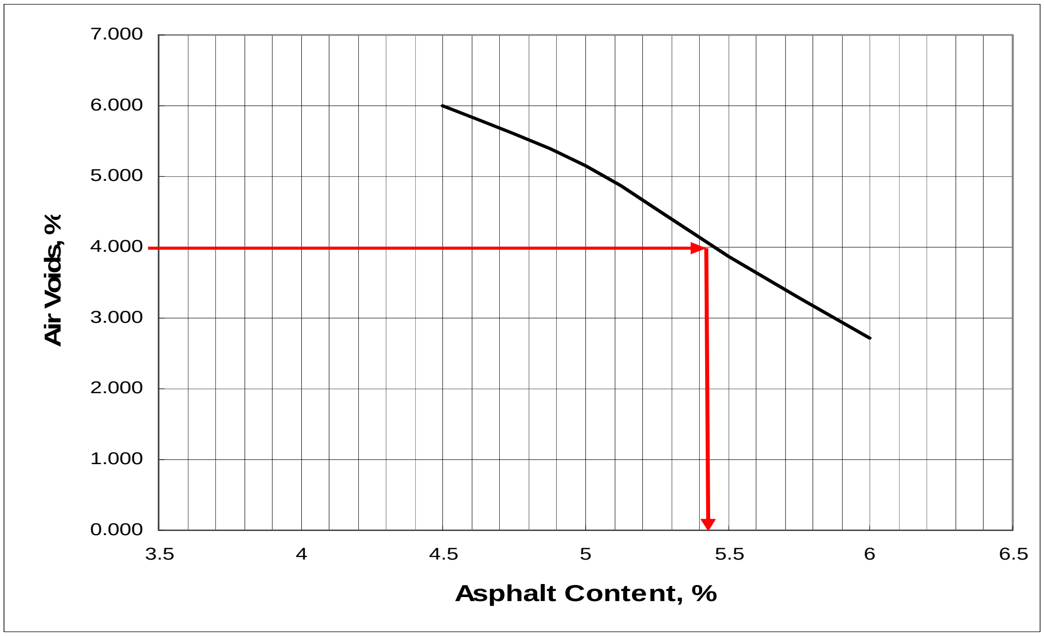
➢ Gyratory 6 inch mix design

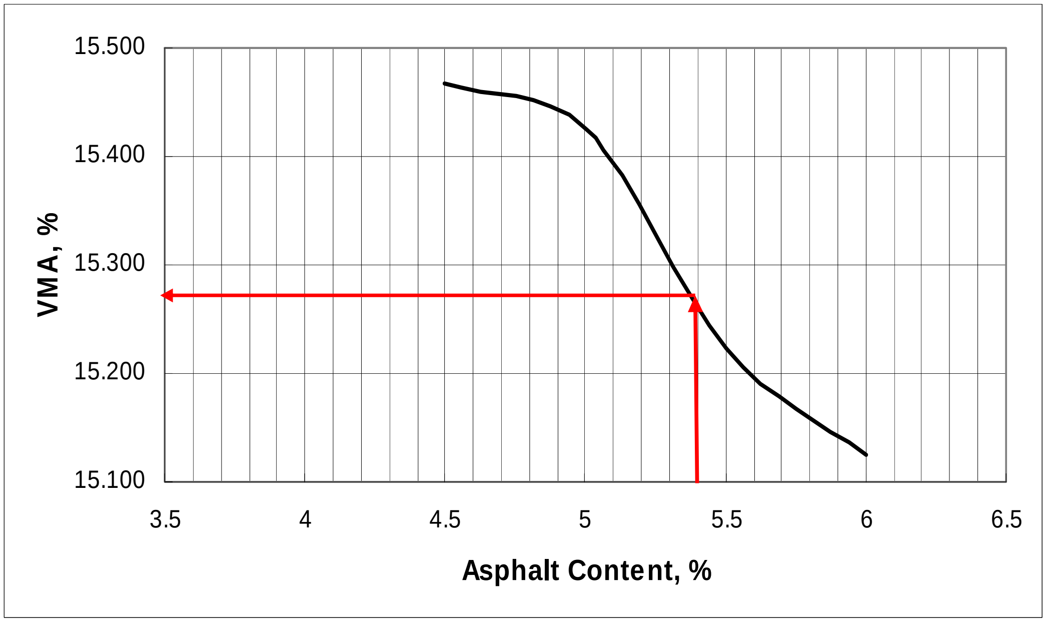
AC %	%Gmm @N=7	%Gmm @N=65	%Gmm @N=99	Air Void, %,@Ndes	Gsb	Ps	Gmm	%VMA	%VFA
4.5	87.163	93.990	95.322	6.010	2.576	0.955	2.426	15.466	61.140
5	87.815	94.843	96.361	5.157	2.576	0.95	2.418	15.426	66.567
5.5	88.779	96.130	97.546	3.870	2.576	0.945	2.404	15.223	74.577
6	89.506	97.278	98.808	2.722	2.576	0.94	2.391	15.126	82.004

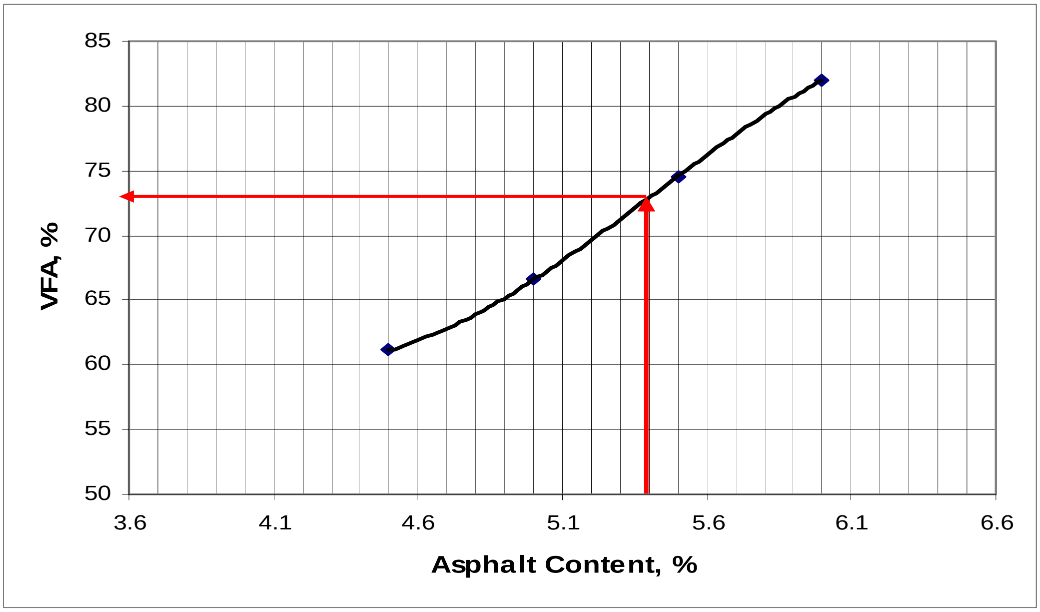



90.000
89.500
89.000
88.500
88.000
87.500
87.000
86.500
3.4
3.9
4.4
4.9
5.4
5.9
6.4
Percent of Gmm at Nini
Asphalt Content, %


99.000
98.500
98.000
97.500
97.000
96.500
96.000
95.500
95.000
3.5
4
4.5
5
5.5
6
6.5
Percent of Gmm at Nmax
Asphalt Content, %


7.000
6.000
5.000
4.000
3.000
2.000
1.000
0.000
3.5
4
4.5
5
5.5
6
6.5
Air Voids, %
Asphalt Content, %

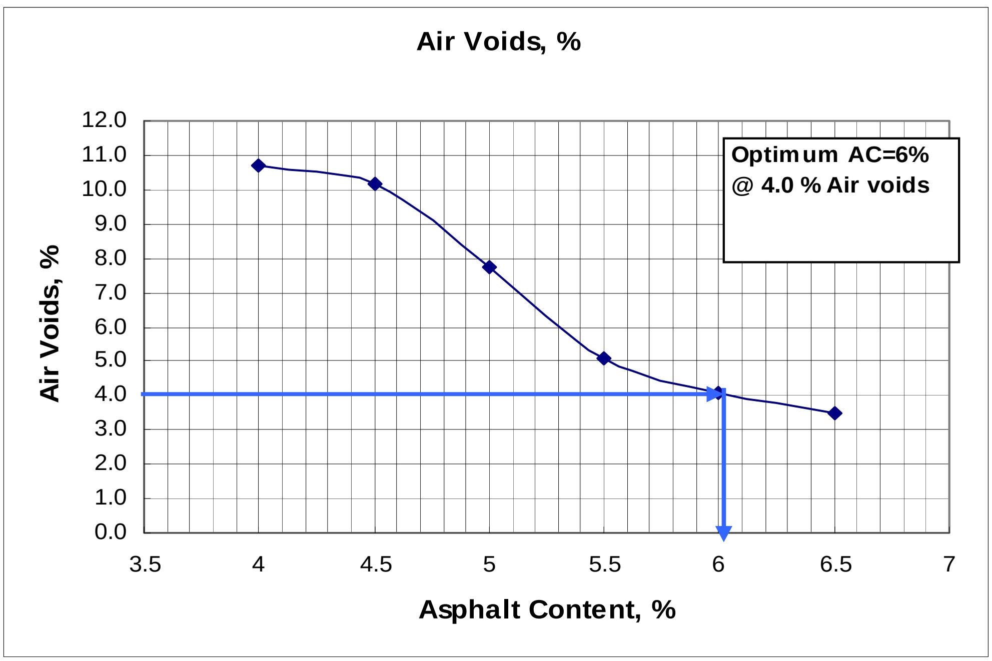

15.500
15.400
15.300
15.200
15.100
3.5
4
4.5
5
5.5
6
6.5
VMA, %
Asphalt Content, %

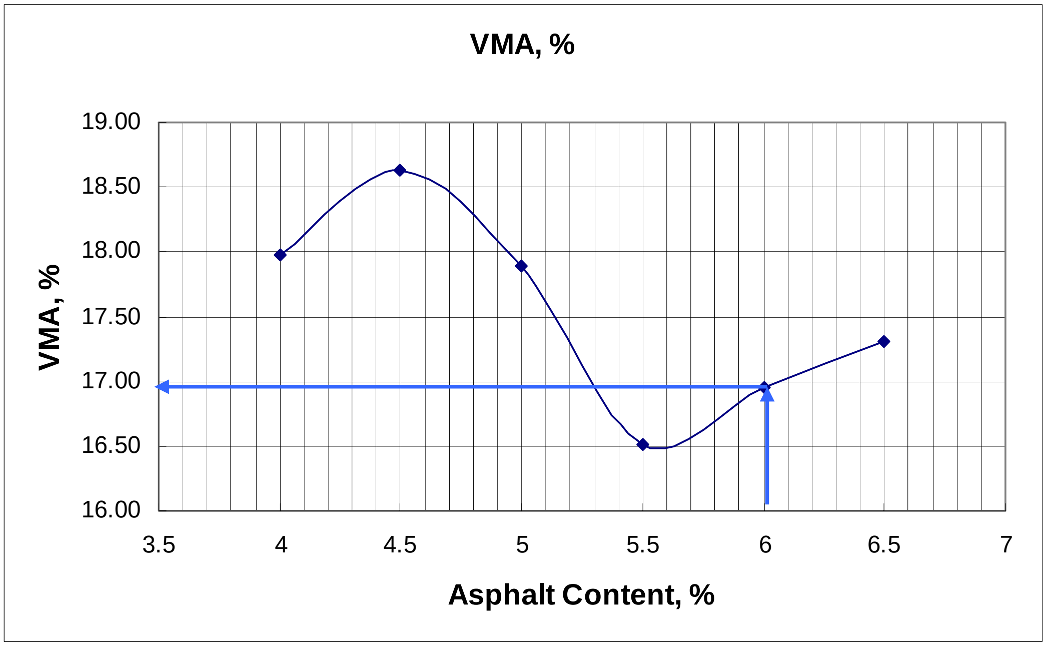

85
80
75
70
65
60
55
50
VFA, %
3.6
4.1
4.6
5.1
5.6
6.1
6.6
Asphalt Content, %

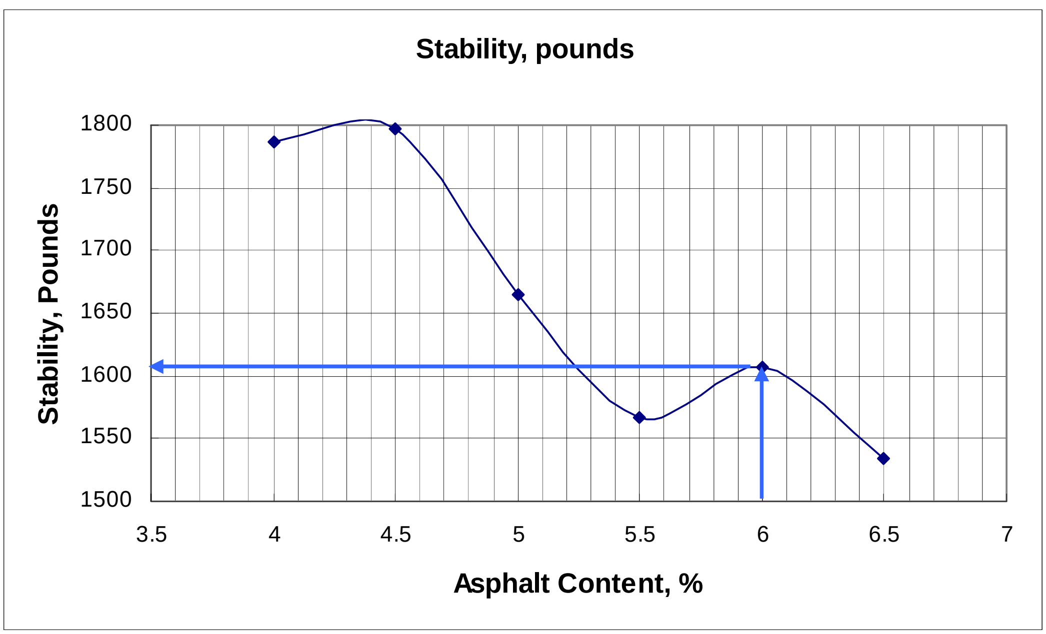
A.4 Stocker Sand Gravel

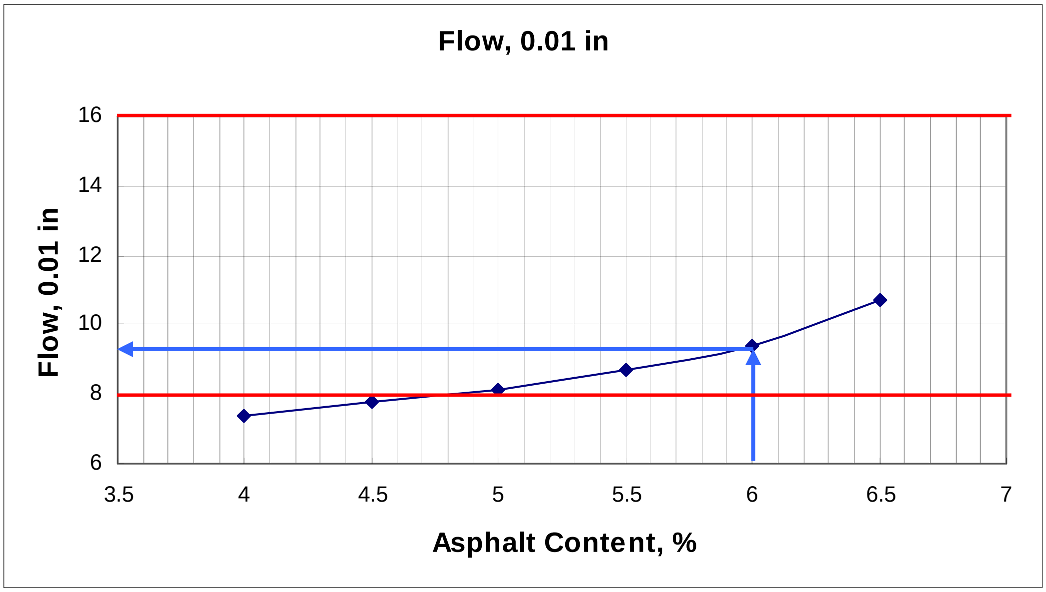
➢ Marshall mix design

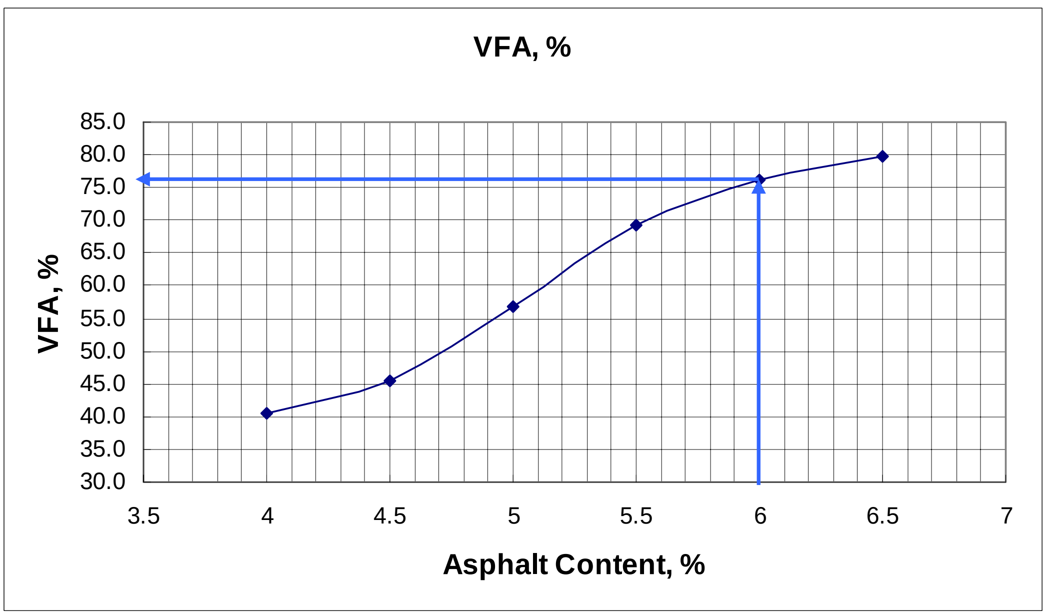
Stocker Gravel						
% AC by wt. of mix.	Unit Weight, pcf (Mg/m3)	% Air Voids	%VMA	%VFA	Stability, lbs(N)	Flow 0.01 in.
4	140.75	10.70	17.98	40.46	1786	7.4
4.5	140.37	10.16	18.63	45.43	1797	7.8
5	142.38	7.72	17.89	56.86	1665	8.1
5.5	145.53	5.08	16.52	69.26	1567	8.7
6	145.55	4.05	16.95	76.10	1607	9.4
6.5	145.70	3.51	17.30	79.70	1534	10.7

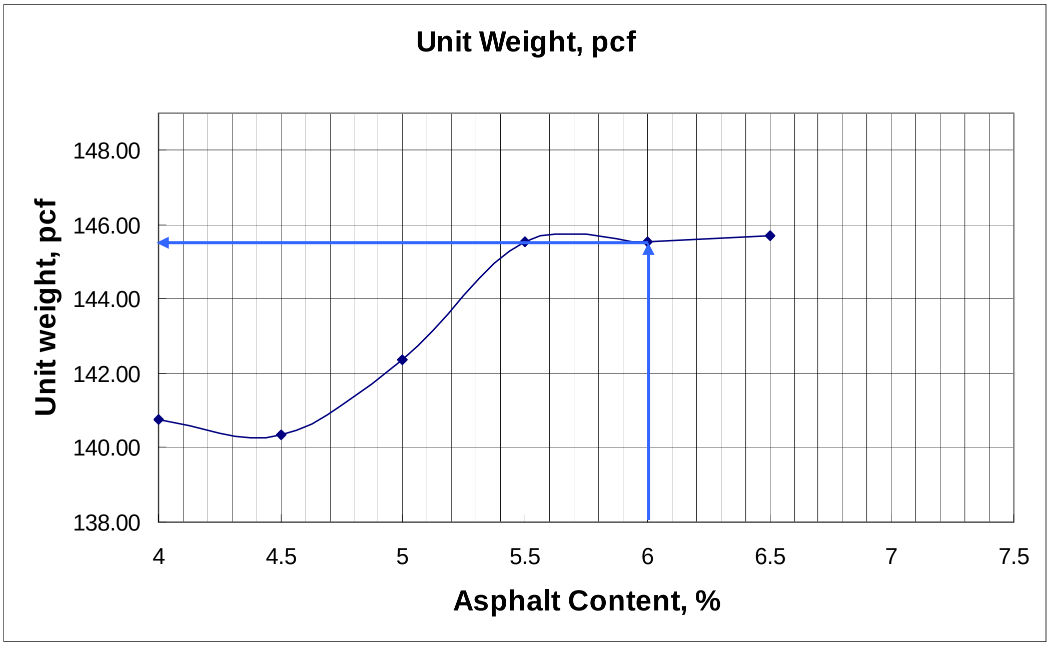



VMA, %
VMA, %
19.00
18.50
18.00
17.50
17.00
16.50
16.00
3.5
4
4.5
5
5.5
6
6.5
7
Asphalt Content, %


Stability, pounds
Stability, Pounds
1800
1750
1700
1650
1600
1550
1500
3.5
4
4.5
5
5.5
6
6.5
7
Asphalt Content, %

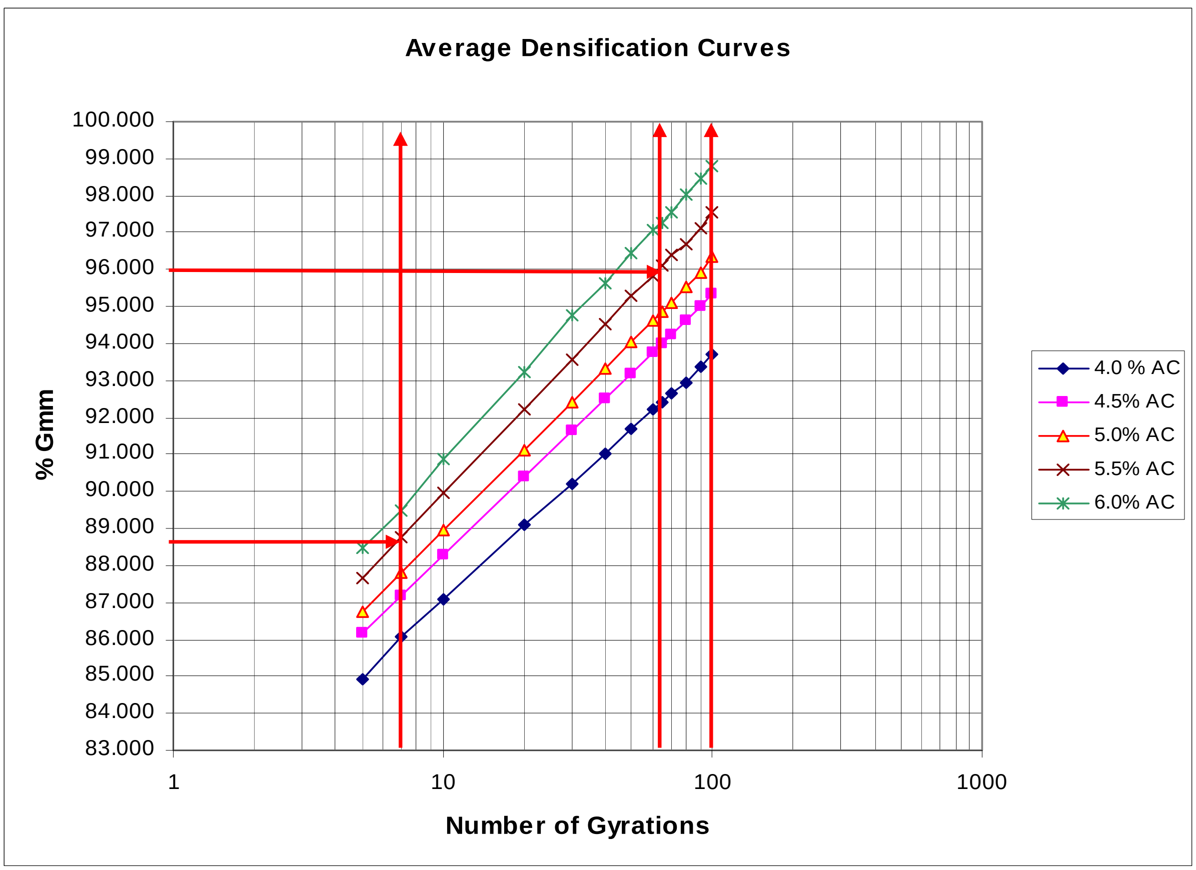

Flow, 0.01 in
16
14
12
10
8
6
Flow, 0.01 in
3.5
4
4.5
5
5.5
6
6.5
7
Asphalt Content, %

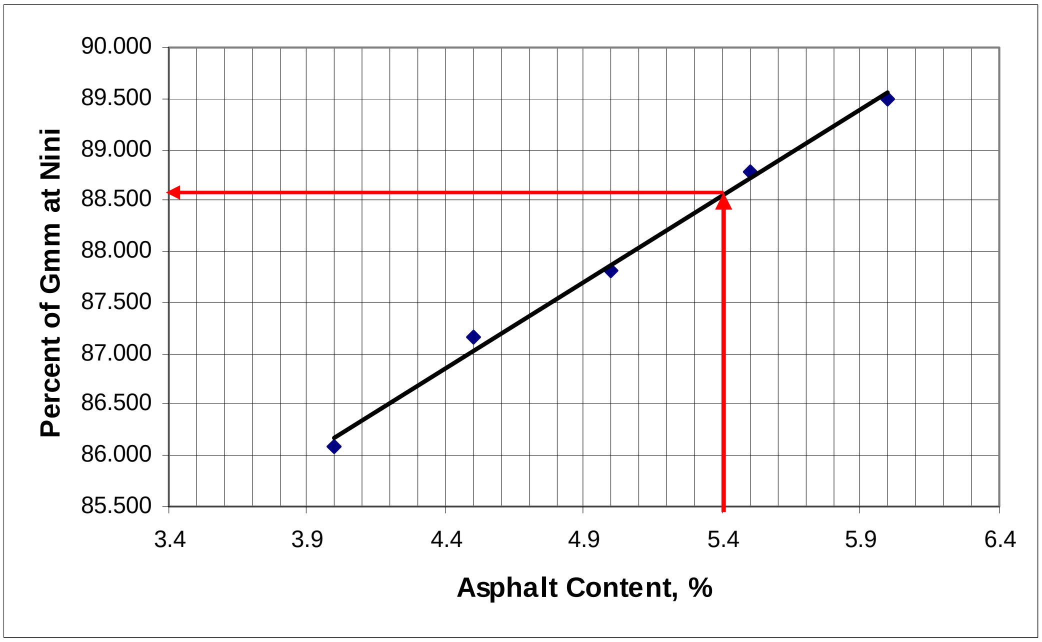

VFA, %
85.0
80.0
75.0
70.0
65.0
60.0
55.0
50.0
45.0
40.0
35.0
30.0
VFA, %
3.5
4
4.5
5
5.5
6
6.5
7
Asphalt Content, %


Unit Weight, pcf
Unit weight, pcf
148.00
146.00
144.00
142.00
140.00
138.00
4
4.5
5
5.5
6
6.5
7
7.5
Asphalt Content, %

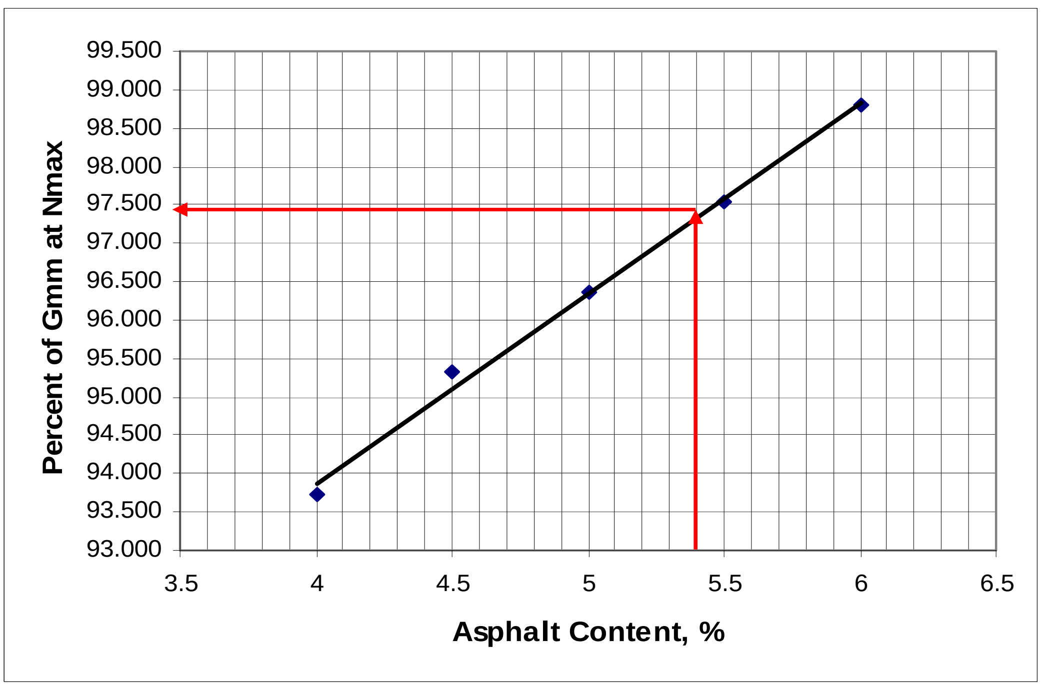
- Gyratory 6 inch specimen mix design

AC %	% Gmm @N=7	% Gmm @N=65	% Gmm @N=99	Air Void, %, @ Ndes	Gsb	Ps	Gmm	%VMA	%VFA
4	86.085	92.413	93.719	7.587	2.576	0.96	2.452	15.554	51.220
4.5	87.163	93.990	95.322	6.010	2.576	0.955	2.426	15.466	61.140
5	87.815	94.843	96.361	5.157	2.576	0.95	2.418	15.426	66.567
5.5	88.779	96.130	97.546	3.870	2.576	0.945	2.404	15.223	74.577
6	89.506	97.278	98.808	2.722	2.576	0.94	2.391	15.126	82.004

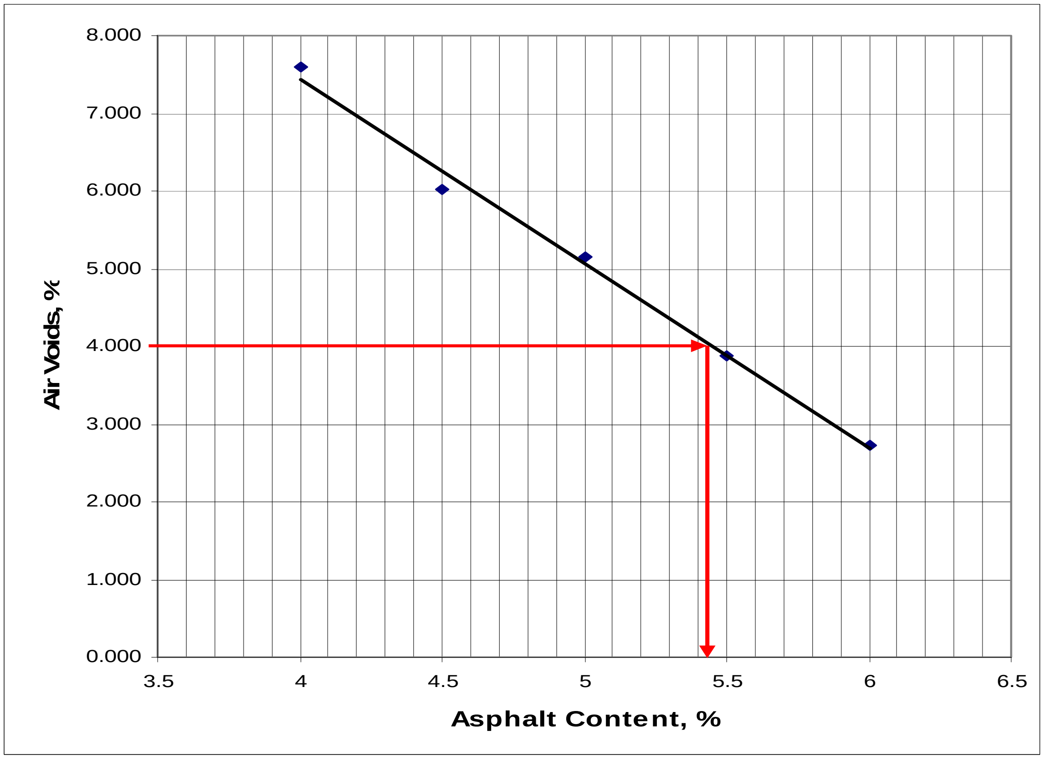


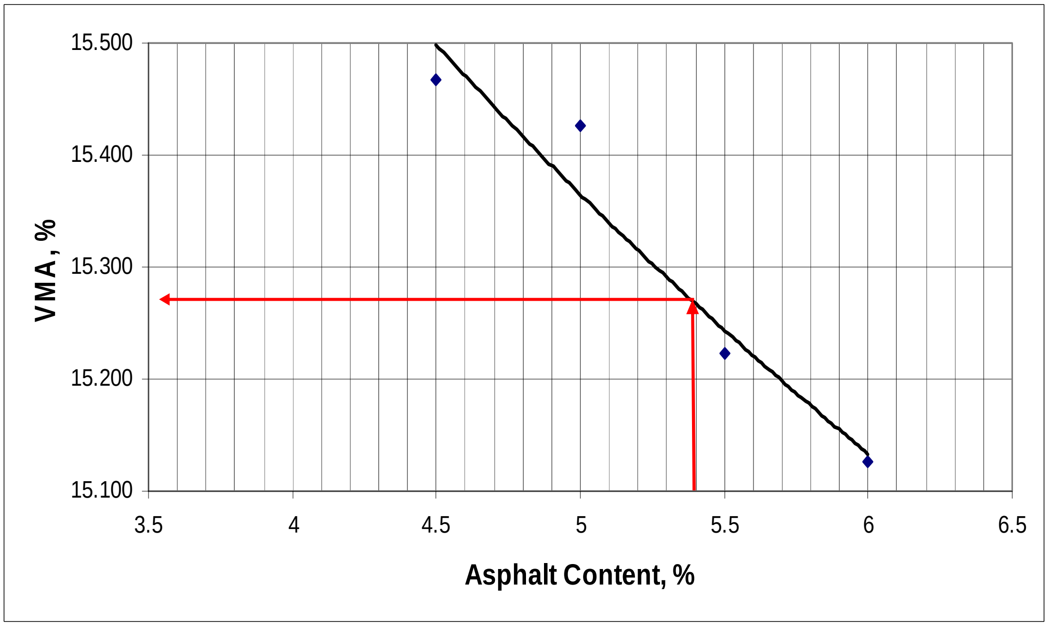


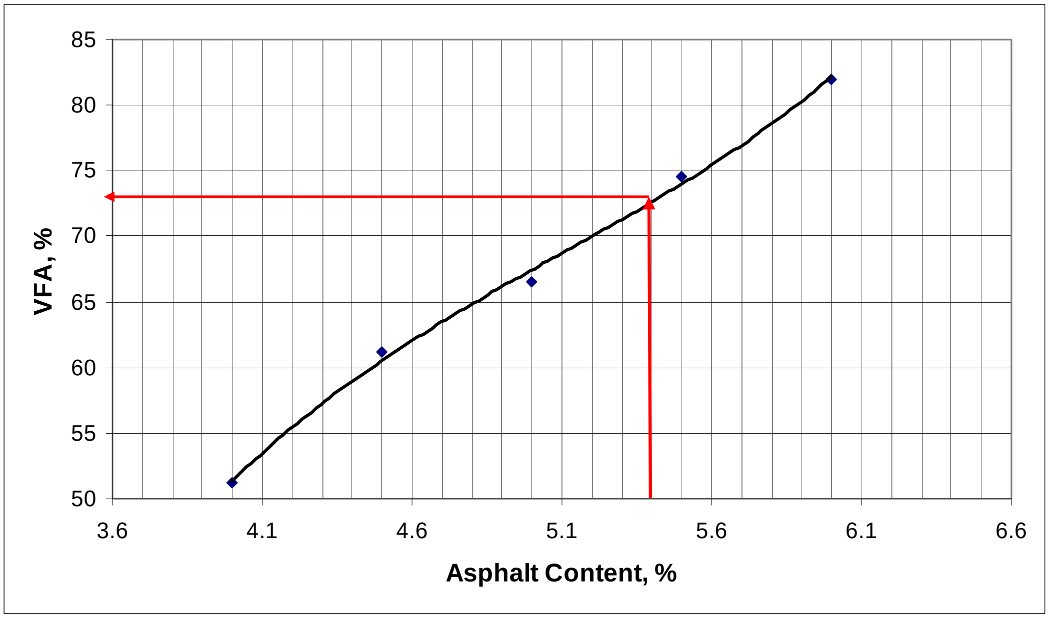
90.000
89.500
89.000
88.500
88.000
87.500
87.000
86.500
86.000
85.500
Percent of Gmm at Nini
3.4
3.9
4.4
4.9
5.4
5.9
6.4
Asphalt Content, %



99.500
99.000
98.500
98.000
97.500
97.000
96.500
96.000
95.500
95.000
94.500
94.000
93.500
93.000
Percent of Gmm at Nmax
3.5
4
4.5
5
5.5
6
6.5
Asphalt Content, %


8.000
7.000
6.000
5.000
4.000
3.000
2.000
1.000
0.000
Air Voids, %
3.5
4
4.5
5
5.5
6
6.5
Asphalt Content, %


15.500
15.400
15.300
15.200
15.100
VMA, %
3.5
4
4.5
5
5.5
6
6.5
Asphalt Content, %


85
80
75
70
65
60
55
50
VFA, %
3.6
4.1
4.6
5.1
5.6
6.1
6.6
Asphalt Content, %