Development of a Rational Method of Designing Hot Mix Asphalt (HMA) for Low Volume Roads

by

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DEDICATION

This dissertation is dedicated to my parents

Mr. Dayakar Varma Nanagiri

and

Mrs. Uma Kumari Nanagiri

and
my loving husband
Mr. Vinay Kumar Narayana
for giving me invaluable opportunities in life and for their inspiration, constant encouragement and tremendous belief in me.

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ABSTRACT

The Superpave mix design system is being adopted by most of the states in the Unites States. Since the Superpave system was developed on the basis of data mostly obtained from medium to high traffic volume roads, there is a need to develop criteria for mix design for Hot Mix Asphalt (HMA) mixes for low traffic volume roads. In this study funded by the six New England states, research was carried out to develop a proper mix design system for low volume roads from the standpoint of durability properties and then, once a good mix design system was available, check it to determine if it meets required strength properties. For low volume roads the performance is primarily affected by the environment and not by traffic, the approach in this study has been to determine the optimum value of a key volumetric property and an optimum number of design gyrations for producing compacted HMA mixes with adequate resistance against aging/high stiffness related durability problems. Six mixes were obtained in which only one can be characterized as a fine mix, and the remaining five were all relatively close to the maximum density line - three of them were with 9.5 mm Nominal Maximum Aggregate Size (NMAS), and the other two were with 12.5 mm NMAS. Based on the results from performance testing, film thickness of 11 microns in samples compacted to 7 percent voids was found to be desirable from considerations of stability and durability and a design VMA of 16 percent was determined to be optimum for producing durable and stable mixes for low volume roads. Results from testing of in-place mixes from good performing 10 to 12 year old low volume roads indicated a design gyration of 50 for obtaining a void content of 4 percent for mixes with gradations close to the maximum density line.

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ACRONYMS AND NOTES

VTM – voids in total mix, the percentage of total volume of the HMA that are air voids, %

VMA – voids in mineral aggregate, the percentage of total volume of the HMA that are voids, %

Resilient Modulus - stress divided by strain, as measured by ASTM D 4123

Tensile strain at failure – strain (from horizontal deformation) at failure, as measured in indirect tensile strength test, ASTM D 4123

Binder stiffness – complex modulus, G*, divided by sine of phase angle, δ

Long term aging (AASHTO PP2) - American Association of State Highway and Transportation Officials (AASHTO) PP2 long term aging protocol, 120 hours in a forced draft oven at 85°C

CHAPTER 1

INTRODUCTION

1.1 Problem Statement

The six New England Departments of Transportation (DOT) are in the process of implementing the Superpave system in design of hot mix asphalt (HMA). In the Superpave mix design system, the most important step is to determine the proper asphalt content from volumetric properties of samples compacted with the Superpave gyratory compactor (SGC). For the SGC, Superpave specifies different gyration levels (N_{design}) for different traffic levels. The specific gyration numbers were derived by correlating air voids from laboratory compacted samples and in-place cores from a limited number of pavements with different traffic levels in different climatic zones (1), and later modified by correlating the change in voids in mineral aggregates (VMA) with change in the number of gyrations (2).

There is a general concern among state DOT personnel and contractors regarding the use of Superpave system in designing mixes for low volume roads. Several state DOTs and contractors have expressed concern about Superpave mixes being too dry (3). A study conducted with pavements with low, medium and high traffic roads has shown that the Superpave N_{design} values should be lowered, at least for projects with low traffic volume (4). Compaction of Superpave HMA over poor existing base materials poses a problem, often resulting in inadequate compaction, and lower than target densities. There is a need to develop a rational mix design system for low volume roads that would account for proper durability as well as stability of HMA, and, at the same time, produce mixes that can be compacted to proper densities using standard laydown and compaction equipment. In order to achieve such a rational mix design, apart from the compaction criteria, there is a need to choose the volumetric property which relates to both asphalt and aggregates.

1.2 Objectives of Research

The objective of this study is to develop a mix design system for Superpave HMA for low volume roads.

Specifically, the objectives are to:

1. Develop compaction and volumetric (mix design) criteria for designing asphalt mixes for low volume roads.
2. Evaluate the performance of mixes designed according to these criteria.
3. Provide recommendations for proper implementation of the new mix design system by the state DOTs.

1.3 Format of Report

The rest of the report is divided into six chapters.

Chapter 2 provides the background, scope and test plan of the study. Definitions of properties and explanations of acronyms are provided.

Chapter 3 presents details of experimental test results and analysis.

Chapter 4 presents details of finite element model and results.

Chapter 5 provides conclusions and recommendations.

Chapter 6 presents the list of references indicated in the different chapters.

Appendix A presents the formula for determination of air voids, voids in mineral aggregate and film thickness

Appendix B presents a detailed description of the program, “Asphalt Film Thickness Calculation Wizard”.

Appendix C presents an alternative method of mix design using film thickness as the starting point.

Appendix D presents the raw data obtained during tests conducted in this study.

CHAPTER 2

BACKGROUND, SCOPE, TEST PLAN AND MIX INFORMATION

2.1 Background

For any type of HMA pavement, mixes are primarily designed for two purposes – strength or stability and durability. The strength of a mix provides the resistance against rutting or permanent deformation under construction equipment and vehicular traffic. The durability of the mix provides resistance primarily against fatigue and thermal cracking and moisture damage. Any good mix design system strives to achieve a balance of strength and durability in a HMA mix.

In the case of low volume roads, which can be defined as roads with low number of vehicles per day and low cumulative equivalent single axle load (ESAL) in design period, durability problems seem to be more significant than stability related problems (5). This issue has become even more important in recent years since the introduction of Superpave system, with most of the experience pointing towards a reduction of asphalt content, compared with the asphalt content used before the introduction of Superpave (3). Hence, at present, the primary concern in the development of a good mix design system for low volume roads is that of durability of mixes. Adequate durability must be present to resist the effects of loads and environment and prevent excessive maintenance costs.

However, since in most cases, the low volume pavements are constructed with typical paving and rolling equipment, these mixes must also be stable enough to resist excessive deformation during construction. Also, mixes for low volume roads should be such that they can be compacted to proper density levels using standard construction equipment. Hence, the ideal mix for low volume pavement must be one that is easy to lay down and compact, has adequate durability, and enough strength to withstand construction and vehicular traffic.

2.2 Literature Review

A review of literature shows that a proper amount of asphalt binder is required for adequate durability and that the proper amount of asphalt binder can be provided by allowing adequate space in the aggregate structure and by compacting the mix design samples in such a way as to simulate construction and actual in-place traffic compaction (6, 7, 8, 9, 10). Therefore, volumetric and compaction criteria are the two key factors required for producing high performance mixes.

In the Superpave mix design system, volumetric properties - air voids, (voids in total mix, VTM), voids in mineral aggregate (VMA) and voids filled with asphalt (VFA) - are used as the key indicators of mix quality (11). Mix design is accomplished by compacting samples to N_{design} and determining the optimum asphalt content that produces a mix at 4 percent VTM or density of 96 percent (of theoretical maximum density, G_{mm}). The design VTM of 4 percent is considered to be an optimum void content for both stability and durability. The criteria for VMA (or VFA) are based on providing adequate amount of asphalt in the mix and on original recommendations from McLeod (10) and the Asphalt Institute (12).

A relatively new concept of average film thickness criteria has also been in application to achieve mixture durability. The generally recommended minimum asphalt film thickness ranges from 6 to 8 microns. Since there is no definite proof for this generally adopted range of minimum asphalt film thickness Kandhal et al (9) conducted a study to quantify the relationship between the various asphalt film thicknesses (4 microns to 13 microns were considered) and the aging characteristics of the asphalt paving mix to establish an optimum film thickness for mix durability. The mixes were subjected to both short term and long term aging. This study suggest that a minimum film thickness of 9 to 10 microns is required in order to prevent accelerated aging in an asphalt mix compacted to 8 percent voids. This range would decrease with a decrease in air voids since aging due to oxidation recedes with reduction in air voids. Film thickness was observed to have little effect on the aging of the mix beyond 11 microns film thickness. Film thickness was also observed to have the same effect on short term aging and long term aging of the mix implying that thick asphalt film reduces aging of the asphalt mixes during construction and service life.

It has been observed that in many cases especially coarse gradations (lower surface area), it is very difficult to achieve the minimum VMA requirement using the Superpave volumetric mix design in spite of thick asphalt films. Studies have shown that film thickness has a direct influence on the mixture stiffness. Moreover, the optimum asphalt content changes with the gradations. Hence it would be rational that the VMA requirement should be based on film thickness criteria instead of asphalt content since the latter would vary with gradations. A study by Kandhal et al (22) was performed on both, coarse and fine aggregates and recommends replacing the minimum VMA requirement with minimum average film thickness requirement of 8 microns at 4-5 percent air voids to qualify the mix design for durability. It also describes the calculation of average film thickness based on asphalt content and surface area of the aggregate. Surface area factors can be calculated in accordance with the Asphalt Institute Manual Series 2.

Superpave recommends the use of coarse graded mixes for high traffic volume roads to prevent rutting due to their stronger aggregate structures. In reality, however, these mixes performed otherwise due to the high minimum VMA requirement of Superpave which leads to higher asphalt contents leading to premature rutting. A study conducted by Nukunya et al (23) indicated that percentage of fines which is independent of theoretical film thickness and VMA appeared to control binder age hardening. It recommends the use of effective VMA and effective film thickness properties which are based on the percent passing 2.36 mm size sieve instead of the theoretical counterparts since they are capable of predicting binder age-hardening and mixture performance. It also recommends that different criteria of volumetric properties should be developed for coarse and fine graded mixes.

Superpave mix design was targeted to get performance enhanced mixes under extreme conditions of temperature and traffic load conditions. Hence, the specifications and guidelines are not explicit for low volume roads (16).

In order to develop a mix design system for low volume roads, the most important task is to determine desirable volumetric properties and compaction parameters such as the number of gyrations. The most direct approach of determining desirable volumetric properties is through evaluation of change in durability of mixes made with a range of these parameters. For example, if the durability seems to be affected significantly by VMA, then VMA should be considered the most important design parameter for durability, and the specific range of VMA, which corresponds to desirable durability properties, should be used.

Regarding compaction parameters, there are several things that can be evaluated in the SGC during compaction. These include the gyration angle, gyration pressure and gyration numbers. However, for practicality, gyration angle might not be a good option, since in most commercially available compactors (Pine and Troxler), changing the gyration angle would require a lengthy calibration procedure. A change in gyration pressure has been attempted in evaluating equivalent gyration numbers for mixes at different depths of the pavement (2). Since the pressure coming from a truck tire varies with the depth of the pavement, it seems logical to compact mixes to be placed at lower depths with a lower pressure compared to the pressure to be used for mixes that are to be used at the surface. This process has been utilized in developing recommendations for N_{design} or mixes at different depths by the researchers of NCHRP 9-9, Evaluation of the Superpave Gyratory Compaction Procedure. Obviously, mixes that are subjected to lower stress at deeper layers are recommended to be compacted at lower number of gyrations, if the same pressure is used.

However, in line with the findings of NCHRP 9-9, it must be mentioned that the compaction pressure in the field is not directly related to the compaction pressure in the laboratory (inside a SGC). Although in both cases, they help in compaction, in the field, the shear strain (which causes consolidation and permanent deformation) is dependent on the shear stress, which is dependent on the vertical stress. In the SGC though, the shear strain is provided by the fixed angle of gyration and is not dependent on the vertical pressure. Also, even though low volume roads might be experiencing low volumes of traffic, they might carry heavy loads (such as logging trucks) and also a mix of unconventional traffic such as farm machinery along with cars and buses and trucks.

The low volume pavements should also be able to withstand stresses generating from typical paving and rolling equipment during construction. Hence, even though the concept of using a reduced vertical pressure seems to by justified in compacting mixes for low volume roads, an important question remains – what is the correct or most desirable gyration pressure? In a study conducted by Cross et al (24) on the effect SGC pressure on low volume roads in Kansas, it was observed that reducing the ram pressure from 600 kPa to 400 kPa had the same effect on mixture volumetric properties as reducing the gyrations at 600 kPa from 75 to 50. Hence, it can be assumed that change in ram pressure can be compensated by the change in number of gyrations used in compaction.

The next option is to evaluate the effect of number of gyrations and determine a desirable number of gyrations that should be used for compacting mixes for low volume roads ($N_{designlv}$). The question that arises is – what is the correct N_{design}? Unlike the method of reducing ram pressure, some data is available in existing literature to provide guidance in selecting a trial number of gyrations (4). The conclusions and recommendations mentioned in Reference 4 were obtained from a study with pavements that performed well with low, medium and high volume traffic.

Low volume roads can be defined as roads with low number of vehicles per day and low cumulative equivalent single axle load (ESAL) in design period.

Though the low volume roads carry low traffic volume, they are often subjected to heavy and chanelized traffic such as heavy trucks. In such cases, conventional asphalt mixes with gradations less than one inch maximum size in base or binder course tend to develop premature rutting (20). Recent work has shown that at a given in-place air void content the permeability increased by one order of magnitude as the NMAS increased, and decreased with an increase in thickness (21). Permeability plays an important role in New England region especially during the spring thawing period. Therefore gradations with NMAS of 12.5 mm or less were considered for this study. Moreover such gradations are observed to be widely implemented on low volume roads by the State DOTs in New England region.

For any type of HMA pavement, mixes are primarily designed for two purposes – strength or stability and durability. The strength of a mix provides the resistance against rutting or permanent deformation under construction equipment and vehicular traffic. The durability of the mix provides resistance primarily against fatigue and thermal cracking and moisture damage. Any good mix design system strives to achieve a balance of strength and durability in a HMA mix.

Permanent deformation or rutting is directly affected by the increase in traffic load and tire pressure. Most of the permanent deformation occurs in the upper layers. Many studies have been conducted to evaluate Asphalt Pavement Analyzer (APA) as a tool for evaluating rutting potential of HMA. Even though the rut depths achieved in the APA do not provide a direct estimate of in place rutting, it has been observed to have the ability to predict the relative rutting potential of HMA (25).

For evaluation of durability, there are several possible options. One rational approach is through the evaluation of increase in stiffness of asphalt binder and mixes and, hence the cracking potential of mixes.

Thermal cracking results when the contraction strains exceed the maximum fracture strain of the HMA pavement layer. It is mostly affected by the asphalt in the mix. The main objective of the performance graded asphalt specification by SHRP Superpave project is its reliance on testing the asphalt binder in the three critical stages during its life. The first stage is transportation, storage and handling, second stage is mixing and construction, third stage is long term aging as a part of the pavement layer (26). Therefore, selection of the appropriate performance grade binder for a particular region is itself rather important in the prevention of thermal cracking.

Fatigue cracking is caused by the repeated stresses that are less than the tensile strength of the material. Fatigue cracking is complex to predict as it depends on several factors like repeated heavy loads, thin pavements or weak underlying layers, poor drainage, poor construction and/or under designed pavement. Fatigue cracking usually occurs when several of the above mentioned factors occur simultaneously. Several fatigue prediction models have been developed over the years. Since fatigue tests are expensive and require a large number of samples (27), the prediction models are more implemental. In recent years, there has been focus on fracture energy density, the area under the load-deformation curve as an indicator of fatigue life. Recent studies have shown that fracture energy density is also a good indicator of cracking performance (28). It was also observed that aggregate gradation has little effect on the cracking potential of HMA. However in another study by Nukunya et al (29), it was observed that the percent of fines passing 2.36 mm sieve did have an effect on the binder age hardening.

A review of literature indicates that various research studies have been carried out to determine the most rational way of determining the best aggregate gradation and optimum asphalt content. Research studies have focused on two primary areas:

- Determination of optimum levels of volumetric properties such as VMA [2-5].
- Determination of proper compactive effort, such as N_{design} [3-4].

While some researchers have argued for providing adequate asphalt film thickness others have supported the concept of using adequate VMA. In general, the approach has been to determine a rational way of designing mixes through the specification of optimum levels of volumetric properties, and using proper compactive effort.

In the quest for determination of a rational method of mix design most of the research has been focused on: using different gradations to achieve different VMA (or other volumetric properties), evaluating the effect of a change of VMA on performance related properties (fracture energy, for example), and attempts to specify desirable VMA. For example, a wealth of information exists on the effect of volumetric properties on aging of HMA mixes [5, 6, 7-13]. Obviously, the basic premise here is that adequate VMA ensures adequate asphalt binder, in the mix, and hence ensures adequate resistance against effect of the environment, namely, aging (loss of volatiles and oxidation).

However, determination of the design asphalt content is based on air voids of compacted samples – the basic premise being that the N_{design} produces 4 percent air voids with the "correct" or "optimum" asphalt content. Studies have shown that neither adequate VMA nor N_{design} values are unique for mixes with different gradations and designs for different traffic levels. This is because fine and coarse gradations (defined on the basis of position of gradation plots above and below the maximum density line) are affected differently by changes in volumetric properties and because mixes designed for different traffic levels are compacted differently (compacted more or compacted less) during their service life. These differences make the subject of specifying VMA or N_{design} numbers an extremely complex one.

In this study, which focuses on developing mix design criteria for low volume roads (and specifically in the New England region), the complex problem mentioned above can be reduced to a simpler one. If one considers some specific mixes with similar gradations (similar with respect to position of gradation plots with respect to the maximum density line) and one specific design traffic level ("low volume" – granted that "low" can be defined in different ways), the complex problem of developing criteria for the mix design is reduced to a much simpler one of finding out how much asphalt binder can be used in a mix without making it unstable.

Note that the concept of starting with an upper limit of asphalt content makes more sense in this case since, for low volume roads, the effect of environment is probably a more crucial factor than the effect of traffic. Therefore, one can argue that for low volume road mixes it would suffice to determine adequate asphalt content for developing a mix design. However, one also needs to determine a representative N_{design} that can be used to compact samples for testing. The question then is, what is the need for an N_{design} or compacted samples, since the asphalt content is already known? Perhaps a good answer is that, similar to approaches taken in the past, the best option is to achieve a balance by averaging the asphalt content determined on the basis of adequate durability <u>and</u> asphalt content based on compaction, using the proper N_{design}. And it is <u>this</u> approach that has been adopted in this study.

2.3 Scope

This study attempted to develop a proper mix design system for low volume roads from the standpoint of durability properties and then, once a good mix design system was available, check it to determine if it meets required strength properties. The scope of work consists of selection of mixes, compaction of samples of mixes with different asphalt contents, testing of samples, extraction of asphalt binder from conditioned samples, testing of asphalt binder, and analysis of data. Note that the originally proposed approach was changed slightly with the consent of the project advisory committee. The step of accelerated loading and testing in the laboratory was replaced with obtaining cores from two good performing low volume roads in New England, and using the materials for recompaction and development of density versus gyration data, as indicated in step 5 below.

The specific steps consisted of the following:

1. Selected typical gradations used for low volume road mixes in New England.

2. Prepared mixes with different asphalt contents and compacted mixes (with different number of gyrations) to produce samples with 6 to 8 percent air voids (construction air voids). Determined volumetric properties.

3. Developed "Asphalt Film Thickness Calculation Wizard", a JAVA application to simplify the process of calculation of volumetric properties by reducing the computational effort.

4. Tested unaged samples for rutting and resilient modulus, and aged (long term aging) samples for resilient modulus and tensile strain at failure. Extracted asphalt binder from the aged samples and tested for stiffness expressed as the complex modulus divided by the sine of phase angle δ ($G^*/\sin \delta$), using the dynamic shear rheometer (DSR) at a 64°C test temperature.

5. Analyzed the data and determined the effect of asphalt content and other volumetric properties on the properties determined in step 3 and came up with desirable volumetric properties based on the performance properties.

6. Studied the effect of film thickness on stability (resistance to rutting). Rutting is failure due to shearing. A 3D finite element model was developed using ABAQUS to calculate the shear strain developed in asphalt.

7. Obtained in-place cores from two ten to twelve year old, good performing, low volume roads in New England. Extracted aggregates and recompacted using virgin asphalt (of approximately same grade and content as original mix). Determined number of gyrations required to achieve 4 percent air voids.

8. Combined information from steps 4 and 5 to recommend appropriate volumetric properties and N_{design}.

The originally proposed steps and the actual approach are shown in Figure 2.1a and Figure 2.1b, respectively.

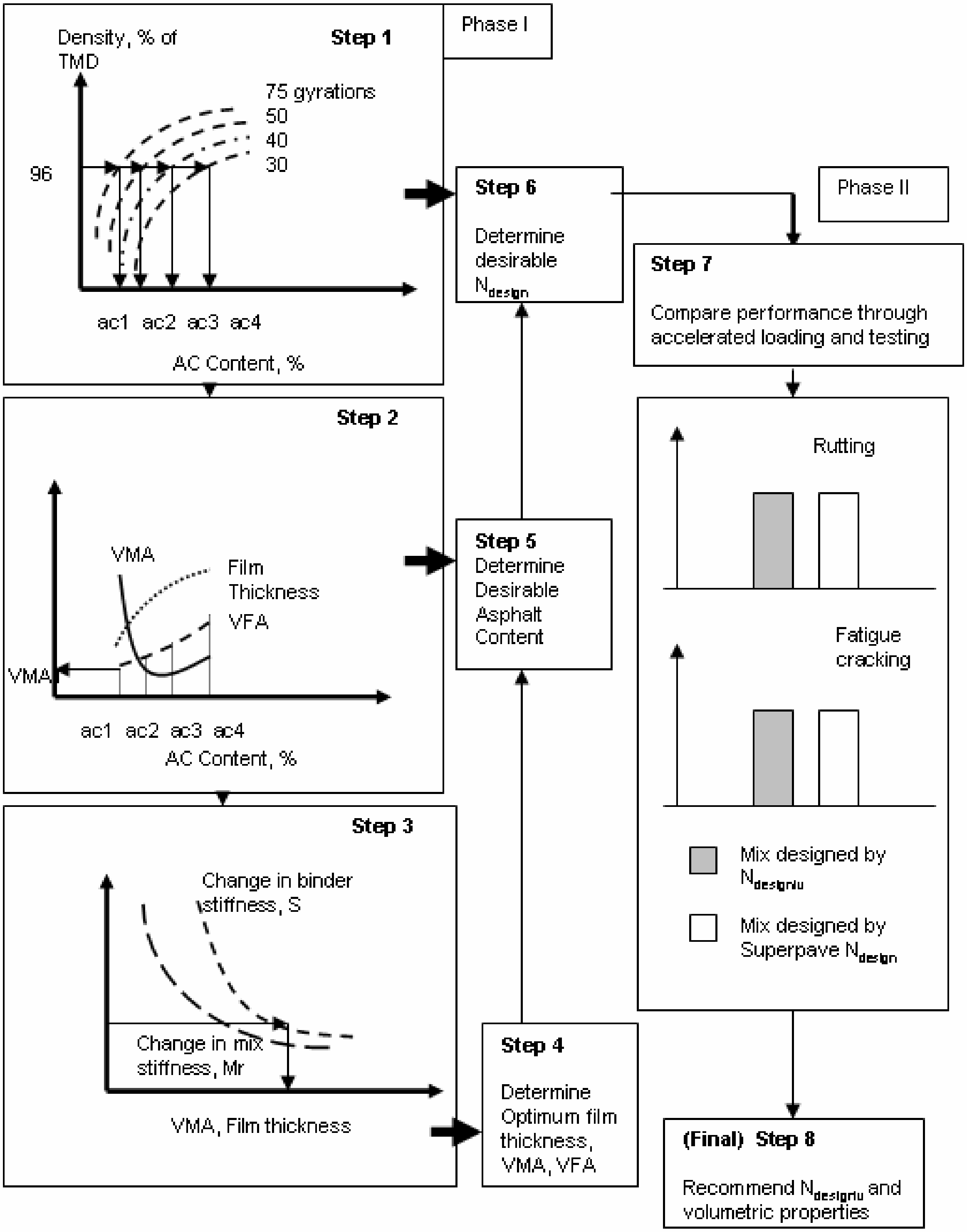

Figure 2.1a. Originally proposed study approach (Experimental Part)

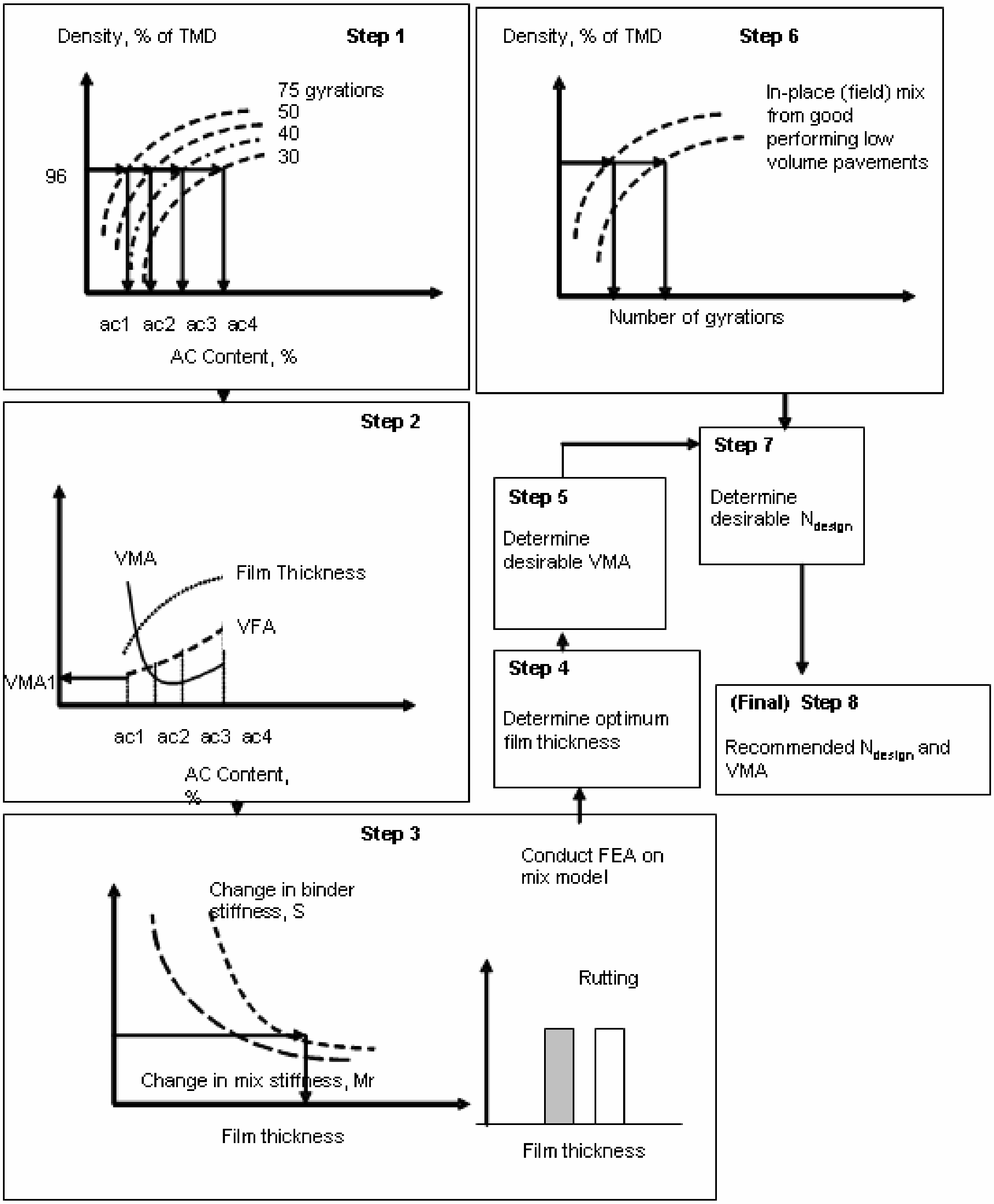

Figure 2.1b. Actual Study Approach (Experimental Part)

2.4 Test Plan

First, a set of gyration numbers – 30, 40, 50 and 75 was selected. This selection was based on levels suggested in the literature and levels that are currently being used by many state DOTs (14). The highest gyration level of 75 was suggested since it is being used by many state DOTs (for compacting HMA for low volume roads) at this time. The lowest number of 30 was suggested since lowering of gyration level below 30 would result in abnormally high asphalt content for most mixes (calculation based on increase of VMA due to lowering of gyration number from 75 to 50, as noted by researchers of NCHRP 9-9, *18*).

Next, six mixes (with different gradations) were obtained from the different state DOTs in New England. The selected gradations were suggested to fall in two broad categories – coarse (mix) and fine (mix). It seems that fine mixes are most likely to be used in designing mixes for low volume roads, since they are relatively easy to construct, compared to very coarse graded mixes. The fine graded mixes are easier to compact and also have a “tight” surface. Very coarse graded mixes can have higher permeability, compared to fine graded mixes at similar void level (15) and, hence, are prone to durability problems. In the case of very coarse graded mixes with sufficient asphalt there can be drain down problems. Note that of the six mixes actually obtained, only one can be characterized as a fine mix, and the remaining five were all relatively close to the maximum density line - three of them were with 9.5 mm Nominal Maximum Aggregate Size (NMAS), and the other two were with 12.5 mm NMAS. Aggregate gradations are shown in Figure 2.2. The terms used in Figure 2.2, for labeling the different mixes have been used in subsequent chapters in this report.

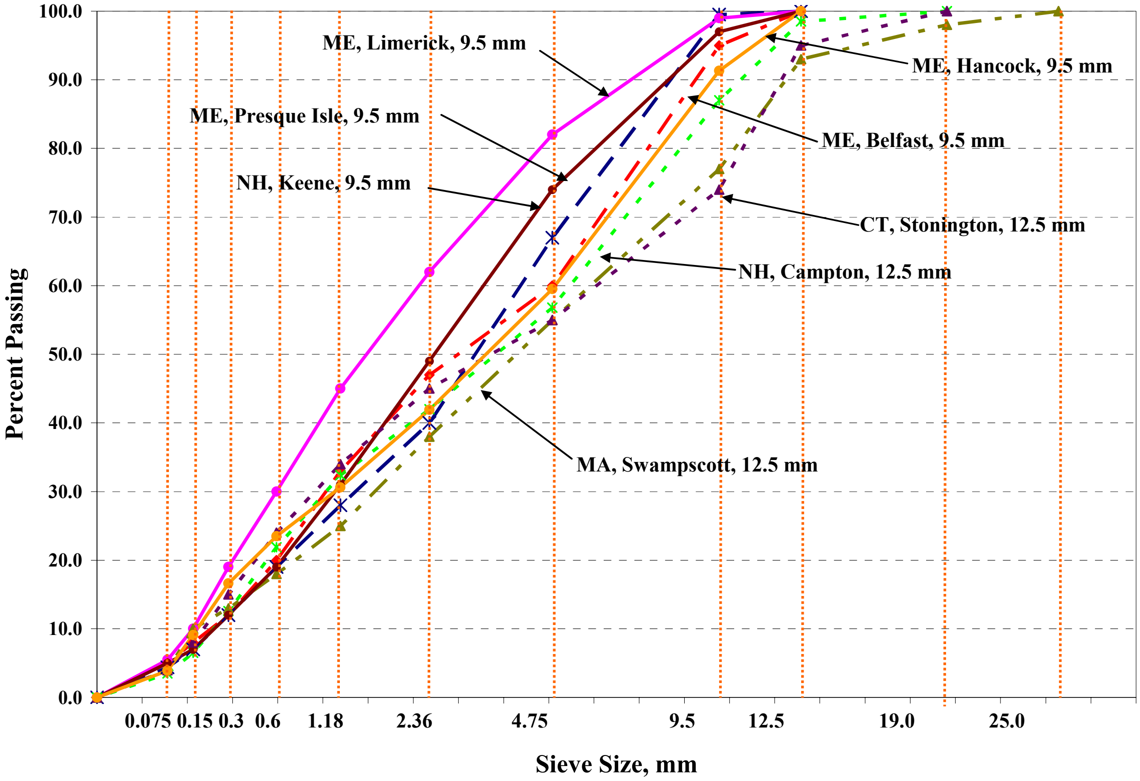

Figure 2.2. Gradations of Mixes Used

Note: ME, Hancock, 9.5 mm and CT, Stonington, 12.5 mm mixes are from in-place Cores

Using PG 64-28 asphalt binder, two mixes were prepared at particular asphalt content and aged for 1 to 2 hours (Short Term Oven Aging or STOA) at 135 ± 3^{o}C in a force draft oven according to Association of State Highway and Transportation Officials (AASHTO) PP2. The mixes were then tested for Theoretical Maximum Density (TMD) of the mix according to AASHTO TP209 described as follows.

The aged mixture particles were cooled down to room temperature making sure that they were segregated. The mixes were weighed and placed in a tared vacuum vessel. Sufficient water at 25^{o}C to completely immerse the sample was added. This vessel is subjected to a vacuum for 15 minutes to gradually reduce the residual pressure in the vessel to approximately 3.7 kPa. The vacuum was then released slowly and the vacuum container was immersed in a water bath and weighed.

Theoretical maximum density (TMD) is given by

$$G_{mm} = \frac{A}{A + (D - E)}$$

G_{mm} – TMD

A – Mass of dry sample (g)

D – Weight of tared vacuum vessel (g)

E – Weight of tared vacuum vessel and sample submerged in water (g)

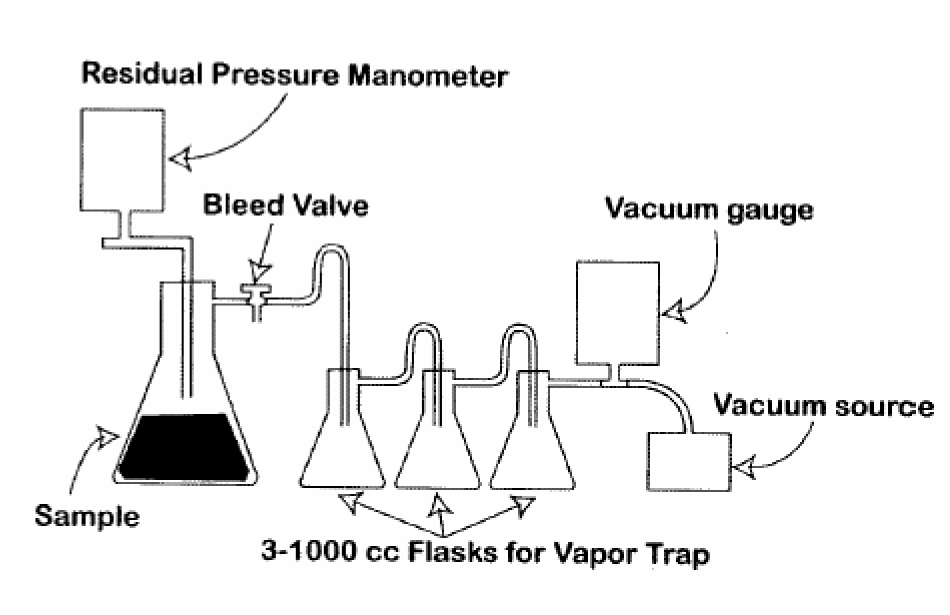

Figure 2.3. Test Equipment Set Up for Determination of Theoretical Maximum Density

A set of mixes were prepared and compacted using a Superpave Gyratory Compactor according to AASHTO TP4 after STOA as described earlier. The gyratory molds and base plates were preheated to 135°C for at least an hour before the compaction. A paper disk was placed at the bottom of the mold and the short term aged mixture was transferred into the mold with a chute. The mix was leveled and a paper disk was placed on top of it. The mold was placed in the compactor and locked in position. The ram was lowered until the pressure reached approximately 600 kPa. The compaction was performed at an angle of approximately 1.25°.

Figure 2.4. Superpave Gyratory Compactor

Samples were compacted with the selected gyration numbers to produce samples with 4 percent air voids, and the optimum number of gyrations to produce construction voids (6-8% VTM) were determined. Samples were then compacted to the construction voids (approximately 7 to 8 percent Voids in Total Mix, VTM). Note that the target VTM was 7 ± 1 percent. The samples were then tested for bulk specific gravity in saturated surface dry (SSD) condition according to AASHTO TP166. The weight of the dry samples was recorded. Each sample was immersed in a water bath at 25°C for 4 minutes and the immersed mass was recorded. The sample was then taken out of the water and quickly surface dried with a damp cloth and mass of the sample inclusive any seeping water was recorded again.

The bulk specific gravity (BSG) is given by

$$G_{mb} = \frac{A}{C - B}$$

G_{mb} – bulk specific gravity

A – Mass of sample in air (g)

B – Mass of surface dry sample in air (g)

C – Mass of submerged sample in water (g)

Using the BSG values and the TMD values (tested in the laboratory for each mix), volumetric properties, namely, VTM, VMA and asphalt film thickness were determined.

Samples were tested for resilient modulus by indirect tension according to AASHTO TP31. Resilient modulus measured in indirect tensile mode is the most popular form of stress-strain measurement used to evaluate elastic properties (30). An IPC Universal Testing Machine pneumatic system was used to load the samples. The load was measured through the load cell, whereas, the deformations were measured through the two spring-loaded horizontal LVDTs. All tests were conducted at room temperature within an environmentally controlled chamber throughout the testing sequence. The test was conducted through repetitive application of compressive loads in a haversine waveform with load duration of 0.1 sec followed by a rest period of 0.9 sec. The compressive load was applied along the vertical diametric plane of the cylindrical samples. The Poisson's ratio was assumed to be 0.35 for all test temperatures. The recoverable horizontal deformations were recorded by the LVDTs and the resilient modulus was displayed in the output. The samples were tested for resilient modulus by loading on two perpendicular axes. Average values were used for characterization.

Figure 2.5. Universal Testing Machine

The samples were then conditioned for long term aging, using the AASHTO PP2 procedure – long term oven aging (LTOA) procedure. A force draft oven was used for this purpose. The samples were placed on a rack in the oven for 120 ± 0.5 hours at a temperature of 85 ± 3°C. After the aging, the samples were allowed to cool to room temperature before further testing.

The long term aged samples were again tested for resilient modulus, and then tested for indirect tensile strength according to AASHTO TP9 T 25°C. A mechanical testing machine manufactured by Sintech was used for testing. Only long term aged samples were tested for tensile strength. The indirect tensile strength is used to characterize bituminous mixtures for thermal and fatigue cracking analysis. The samples were loaded in compression along the diametric axis at a rate of 2 inches per minute. The test terminates when the load no longer increases. Load and vertical deformation were both monitored during the entire loading time. The maximum load sustained was used for the calculation of indirect tensile strength. The tensile strain and indirect tensile strength were calculated. The area under the load and vertical deformation curves were used to calculate fracture energy.

Figure 2.6. Mechanical Testing Machine by Sintech

Asphalt binder from the aged samples was extracted at different asphalt contents according to AASHTO TP2. This procedure can be used when physical and chemical properties of extracted binder are to be determined. A HMA sample in loose form that will approximately yield 50 to 60 grams of asphalt was used for extraction. The sample was placed in an extraction vessel which was sealed securely. The HMA sample in the extraction chamber was washed and filtered with toluene. The filtrate was extracted into a flask which is then transferred to the recovery flask. When the recovery flask was about 2/3 full, primary distillation was performed. The extraction process was repeated till the filtrate extracted is light brown in color. Toluene was used for the first three washes and toluene with 15 percent ethanol for subsequent washes. The primary distillation of solvent was performed at 100 ± 25°C and 93.3 ± 0.7 kPa vacuum. In the final extraction and recovery stage, glass beads were added to the recovery flask and distilled at 174 ± 2.5°C. When the recovery flask was void of residual solvent concentration, the asphalt was poured into sample tins for binder testing.

Figure 2.7. Asphalt Extraction Equipment Setup

The extracted asphalt binders were tested for stiffness (using dynamic shear rheometer) at 64°C according to AASHTO TP5. This testing was performed by external sources.

Samples at selected asphalt contents were also tested for evaluation of rutting potential. Rutting of asphalt mixes was assessed by placing rectangular or cylindrical samples under repetitive wheel loads and measuring the amount of permanent deformation under the wheel path. Asphalt Pavement Analyzer (APA) was used for the evaluation of the rutting potential of the mixes. In the APA, the load is applied by a wheel (going back and forth) to a pneumatic hose which rests on top of the test sample. The rut depth is measured after the desired number of cycles (usually 8000) of load applications. The APA features an automated data acquisition system that obtains the rutting measurements and produces the results in graphical and numerical formats. In the present study, cylindrical samples of 100 mm diameter were used in this testing. The machine has a capability to test 6 samples of 100 mm diameter simultaneously. Tests were conducted using 4,000 cycles with 690 kPa pressure and temperature of 60^{o}C. The lower number of cycles (4,000) compared to the usual 8,000 cycles was selected to simulate low traffic volume. The results were used to correlate stiffness (of asphalt binder and mix) with film thickness. This correlation provided the basis for selecting the desirable volumetric properties.

Figure 2.8. Asphalt Pavement Analyzer

Ten cores were obtained from two good performing, twelve year old, low volume roads from Connecticut and Maine. These cores were tested for bulk specific gravity and theoretical maximum density and the air voids were subsequently calculated. Aggregates were recovered from these cores after burning off the asphalt binder with an ignition oven. The recovered aggregates were then mixed with virgin PG 64-28 grade asphalt binder. The mixes were subjected to short term aging and then compacted to 125 gyrations. The compacted samples were then tested for bulk specific gravity and the air voids and VMA, at different gyrations, were back calculated. The number of gyrations corresponding to 4 percent air voids provided the basis for selecting the desirable N_{design}.

CHAPTER 3

EXPERIMENTAL RESULTS AND ANALYSIS

3.1 Definition of Low Volume Roads

The importance of low volume roadways has drastically increased over the last decade due to the realization that these roadways not only serve the transportation needs of a certain area, but they also improve the economic and social status of that area. In 1975, the first International Conference on Low Volume Roads was held in Boise, Idaho, and the committee on low volume roads (16) defined low volume roads as those that have less than 500 vehicles per day. However, the definition of low volume road varies from state to state. An informal survey of state DOTs in New England revealed that definitions can be either in terms of vehicles per day or equivalent single axle loads (ESAL) in the design period (shown below).

State	Definition
Connecticut	< 300,000 ESAL in design period
Maine	< 1,000 AADT
Massachusetts	<2,000 AADT, <70 km per hour speed
New Hampshire	≤ 10,000 vehicles per day
Rhode Island	≤ 1000 vehicles per day for two lane and ≤ 15,000 vehicles per day for four lanes
Vermont	≤ 100,000 ESAL in design period

Based on the wide range of definitions of low volume roads, it is suggested that the definition be consistent with Superpave and AASHTO, which is less than 0.3 million design ESALs.

3.2 Practical Considerations

Before discussing the results and analyses it is perhaps proper to consider some practical aspects of designing HMA for low volume roads. First, note that N_{design} values are used by state DOTs to compact HMA during mix design, for specific traffic levels and temperatures – no separate considerations are made for coarse and fine graded mixes or for different nominal maximum aggregate size (NMAS). The N_{design} is required to produce 4 % target air voids in mixes – irrespective of coarse or fine graded mixes. Based on experience, it can be said that the same N_{design} would produce different optimum asphalt contents for coarse and fine graded mixes. However, the properties for both coarse and fine graded mixes will be optimized for these asphalt contents. Hence, although one can research on difference in optimum air voids for coarse and fine graded mixes, and difference in optimum compaction effort for coarse and fine graded mixes, at this time, within the scope of Superpave philosophy, that research is not relevant.

Second, note that the concept of film thickness (used in this study) is controversial – there are arguments for and against it. The arguments against film thickness are many – for example, it is a theoretical concept, there is no actual "film" in the HMA, should the filler/dust be included in calculation of surface area? However, we do use the concept of VMA and it is interesting to remember that the original concept of VMA was derived from the theoretical concept of film thickness. In spite of being a theoretical concept, film thickness does help us in explaining performance related properties, particularly those related to durability. The film thickness concept has been used in this study because it is the most practical available tool, even if it is not the best one. Most essentially it relates to both aggregates and asphalt simultaneously.

Lastly, it is important to remember that aggregates and asphalt in HMA work together – it is impossible to separate the action of one from the other. For many polymer modified mixes, a low optimum air voids is selected. Properly modified mixes can be designed with relatively low design air voids and hence low potential of long term aging. These mixes, in spite of having relatively high asphalt contents, are generally very resistant to rutting. The scope of work in this study does not consider these mixes, with modified binders.

The concept on which this study rests is that high asphalt content is needed to achieve sufficient durability, but it should not be as high as to cause rutting. To achieve this high asphalt content one should use relatively low number of gyrations. To check rutting, one should use "proof" testing, such as loaded wheel testers.

The results and analyses provided in the followings sections provide data and justification for the above concepts. It shows that increasing the asphalt content improves the durability of mix (which is already known). What is attempted in this study is to determine a way of finding out just how much asphalt should be used. Since asphalt contents can be different for different mixes, film thickness is used to illustrate the effect of adding more asphalt binder on specific mechanical properties.

3.3 Asphalt Content, Film Thickness and VMA

The amount of air voids in an aggregate structure is expressed as VMA. Part of this air voids is filled with asphalt and the remaining part remains as air voids (VTM). The asphalt which fills up part of these air voids produces a "film" which is simply the volume of asphalt spread over the entire surface area of the aggregates. Hence, asphalt content, VMA and film thickness are related parameters, and it is possible to determine one from the remaining two. In this section, however, plots of VMA and film thickness versus asphalt contents are provided to show the film thickness and VMA ***corresponding*** to specific asphalt contents, so that later on, when an optimum film thickness is determined, we can refer back to this plot and pick our asphalt contents and VMA. Since VMA has originally been derived from film thickness requirements, henceforth, film thickness only will be discussed in the later chapters.

Figures 3.1, 3.2 and 3.3 show plots of asphalt content versus film thickness, asphalt content versus VMA and film thickness versus VMA, respectively**.**

It is evident from Figure 3.1, that to obtain a higher film thickness one needs higher asphalt content; however, the sensitivity of film thickness to a change in asphalt content is different for different mixes, obviously because of difference in gradation. This sensitivity indirectly supports the use of the concept of film thickness. It is interesting to note from Figure 3.1 that for typical asphalt contents for dense graded mixes, the value of film thickness ranges from 9 to 14. It will be seen that in subsequent sections, this range will be mostly discussed and related to mechanical properties of HMA.

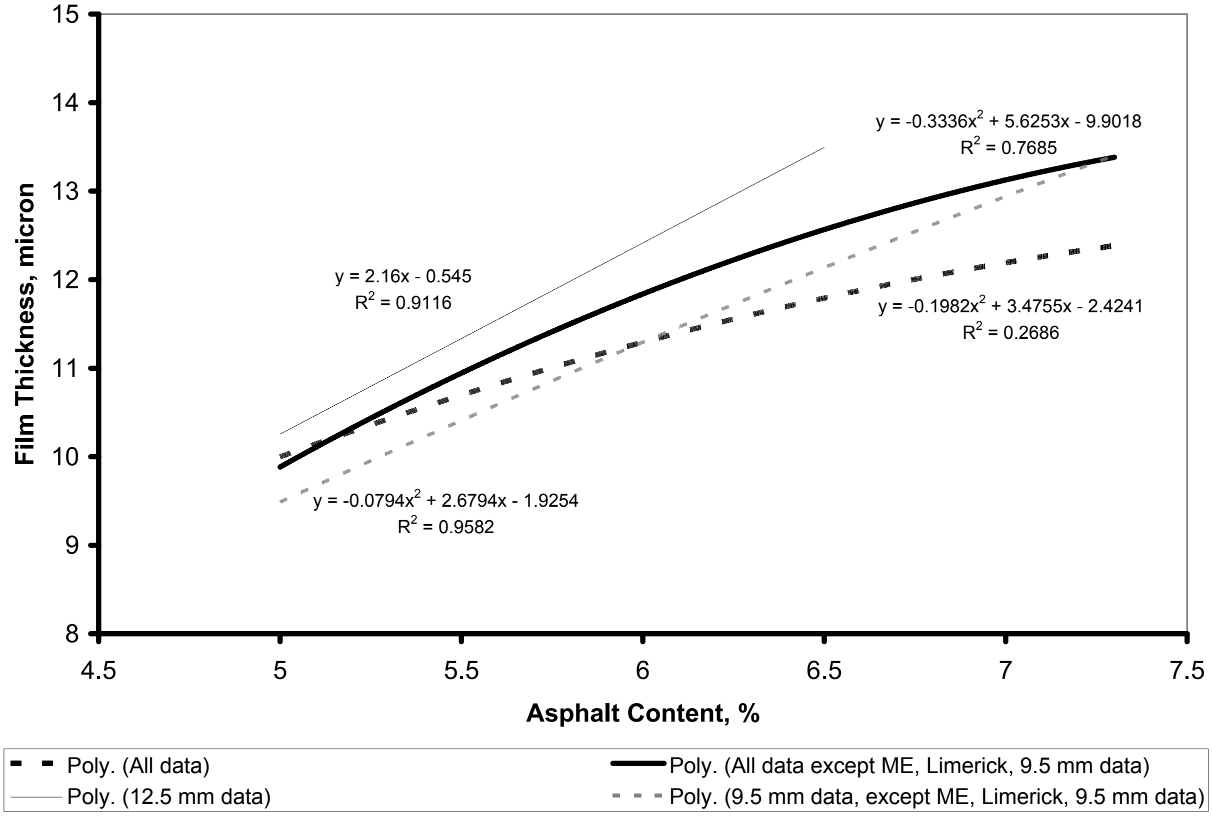

Figure 3.1. Plot of Asphalt Content versus Film Thickness

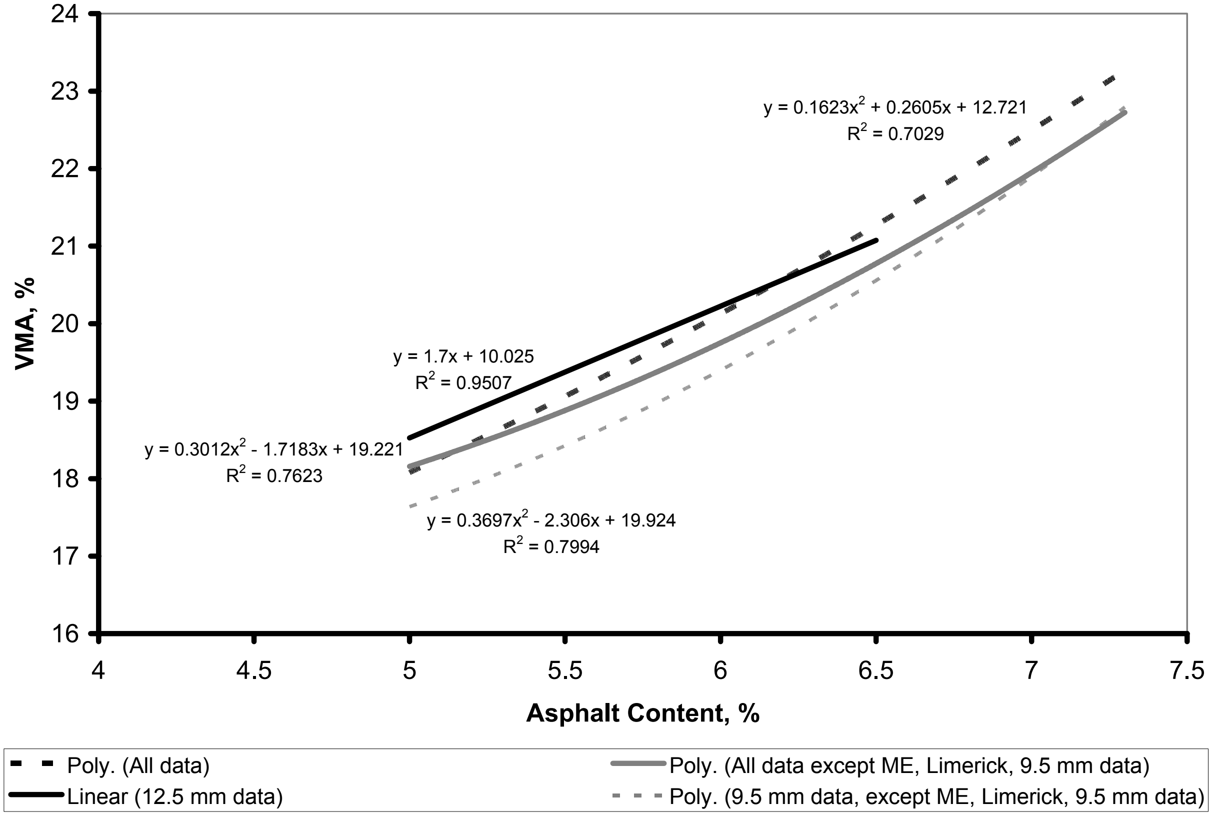

Figure 3.2. Plot of Asphalt Content versus Voids in Mineral Aggregate

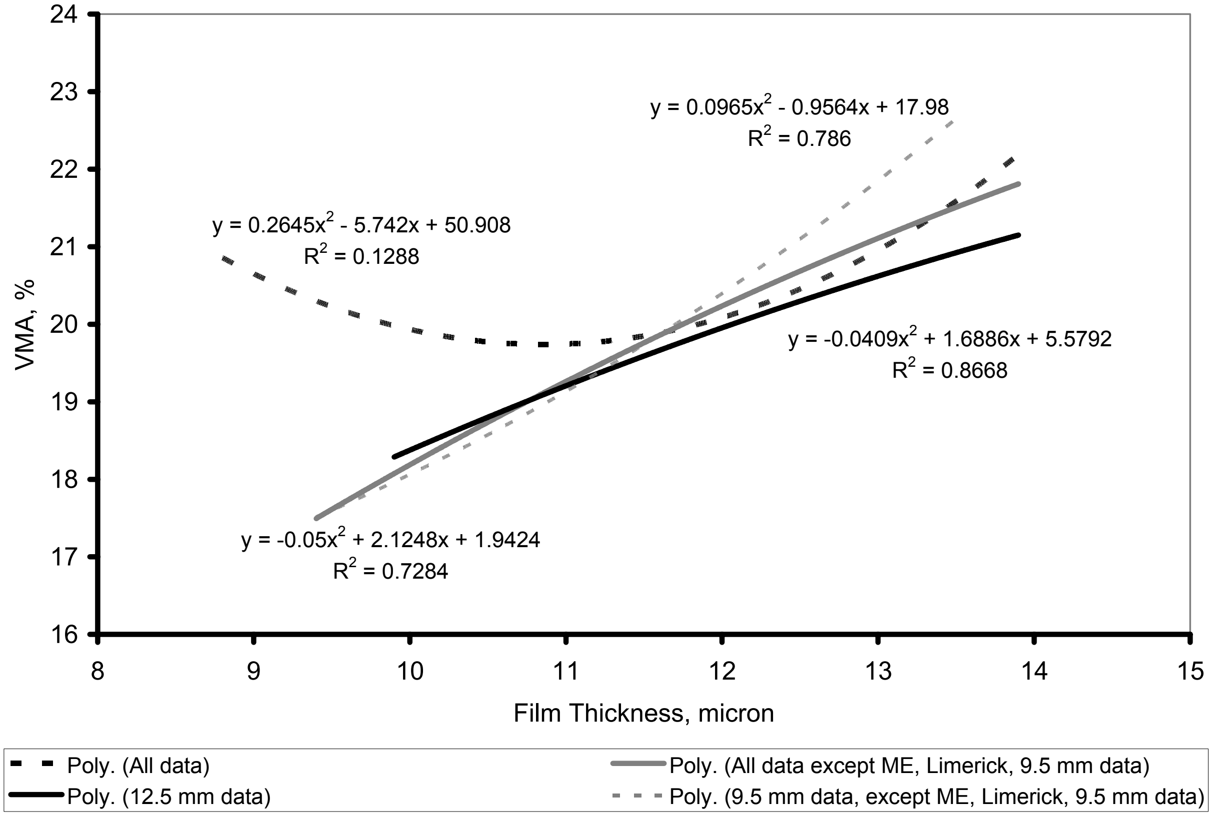

Figure 3.3. Plot of Film Thickness versus Voids in Mineral Aggregate

Note in Figure 3.1, that a very poor regression fit (R^2=0.3) is obtained when all the data is pooled. When the ME, Limerick, 9.5 mm data is taken out, the regression is improved considerably (R^2=0.8). Further, when the 12.5 mm data are separated from the 9.5 mm data, significantly improved regression models (R^2= 0.9) are obtained for both cases. Since film thickness values are ***calculated*** for specific asphalt contents, one would expect a perfect fit between asphalt content and film thickness values, if the two are related in the same way for all of the mixes. Obviously, because of differences in gradation, a specific change in asphalt content causes different changes in film thickness for the different mixes. Similar conclusions can be drawn from Figures 3.2 and 3.3, where the models improve significantly when the ME, Limerick, 9.5 mm data is taken out.

It seems that the ME, Limerick, 9.5 mix is significantly different in gradation (significantly more "fine graded") compared to the other mixes. Also, it is evident that the 12.5 mm and 9.5 mm mixes show differences in effect of asphalt content on film thickness. Hence, from this point onwards, the ME, Limerick, 9.5 mm data has not been used in analysis, and wherever found to be appropriate, the data from the 9.5 mm and 12.5 mm mixes have been separately presented and analyzed. Note that in the plots in the following discussions, the legend "All Data" refers to all pooled (9.5 mm and 12.5 mm mix) data ***except*** the ME, Limerick, 9.5 mm data.

3.4 Film Thickness and Performance Properties

Four specific performance properties and their sensitivity to film thickness are discussed in this section. Of these four, three are mix properties - modulus, tensile strain at failure and rutting, and the fourth one is asphalt binder stiffness. Since the stiffness and hence the potential of durability problems increase with aging, all of the properties (except rutting and unaged resilient modulus) were measured on long term aged mixes.

3.4.1 ***Resilient Modulus and Tensile Strain at Failure***

The effect of film thickness on increase in stiffness (modulus) due to aging was investigated. Note that mixes with higher age related increase in moduli are more susceptible to cracking, and in general, all fatigue failure models use an inverse proportionality between number of repetitions to failure and modulus ($N_f \infty 1/E$). Hence, it is desirable to have a mix with low increase in modulus (due to aging). The modulus parameter is discussed here as indicator of aging – and is not the design modulus (for structural design of flexible pavements).

Figure 3.4 shows plots of film thickness versus increase in modulus (expressed as a percentage of modulus of unaged samples). Note that improved models are obtained when the data is split between 9.5 mm and 12.5 mm mixes. Within the range of data available, it is interesting to note that beyond a certain film thickness, the increase in modulus actually drops. The point at which the increase is maximum, or the "slope" of change in increase with an increase in film thickness becomes "zero" deserves attention. Obviously, this is the point, beyond which, an increase in film thickness is effective in reducing the effect of aging on stiffness. Note that these points are 10.6 micron and 11.2 micron for the 9.5 mm and 12.5 mm mixes, respectively. These points can be considered as the minimum values of film thickness required for effective retarding of age-related stiffness increase.

Next, the effect of film thickness on tensile strain at failure was investigated. The tensile strain at failure is directly related to the potential of thermal cracking in HMA mixes – the lower the strain, higher is the potential of cracking. Note that tensile strain at failure is a direct indication of bonding of the material. This bonding is critical in resisting "disintegration" or raveling under traffic. It should be remembered that in many cases low volume roads do carry high traffic loads (such as log trucks) and a low adhesion between aggregates can lead to rapid deteriorating of the mix by raveling. Tensile strain at failure is a direct indicator of the adhesion in the mix.

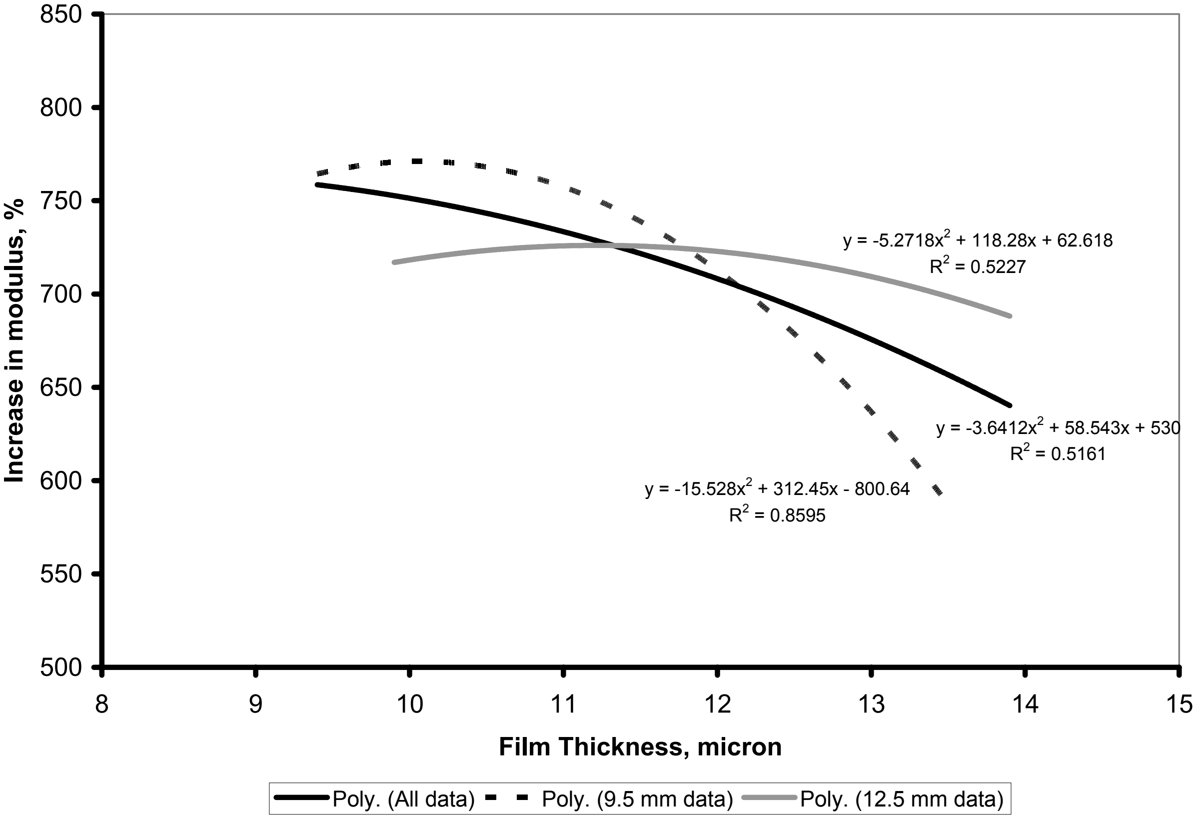

Figure 3.4. Plot of Film Thickness versus Increase in Modulus

Figure 3.5 shows plots of tensile strain at failure (tensile strain) versus film thickness. In general, there is an increase in tensile strain with an increase in film thickness. Good models are obtained for pooled as well as split up data (9.5 mm and 12.5 mm mix) – although not a significant amount of improvement was made by splitting up the data between 9.5 mm and 12.5 mm. In view of the good regression fit ($R^2 = 0.7$), the “all data” model was used to determine the “zero slope” point, and it was determined to be 9.5 microns. This film thickness can be considered to be the minimum limit for causing a significant effect on the tensile strain at failure.

Note that instead of determining an optimum film thickness for tensile strain at failure, it makes more sense to investigate the effect of film thickness on the (tensile strain at failure)/(the resilient modulus) parameter. This parameter has been related to cracking potential in the AAMAS study (17), which is the precursor of SHRP (and the last study that had successfully related volumetric properties to performance). The concept is that there must be a minimum tensile strain at failure corresponding to certain modulus – that is the ratio of tensile strain to modulus must be above a certain limit. This concept can be used in the present study to determine a film thickness that causes a significant effect on increase of the ratio of strain to (aged) modulus.

Figure 3.6 shows plots of ratios of strain to modulus versus film thickness. Note that the ratio has been multiplied by a factor to make them whole numbers. The “zero” slope point for the plots were determined to be 9.7 micron and 10.4 micron for the 9.5 mm and 12.5 mm mixes, respectively. This indicates that beyond 9.7 micron and 10.4 microns, an increase in film thickness becomes more effective in increasing the tensile strain at failure by modulus ratio.

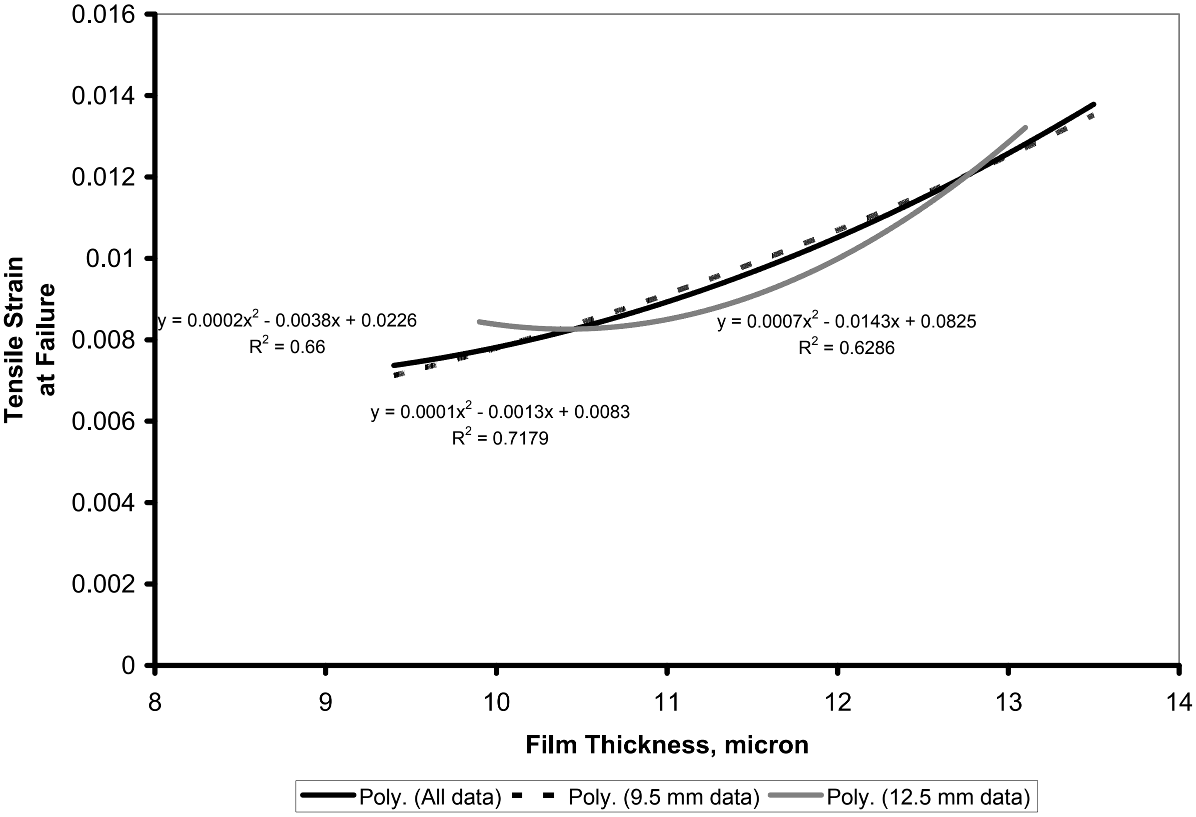

Figure 3.5. Plot of Film Thickness versus Tensile Strain at Failure

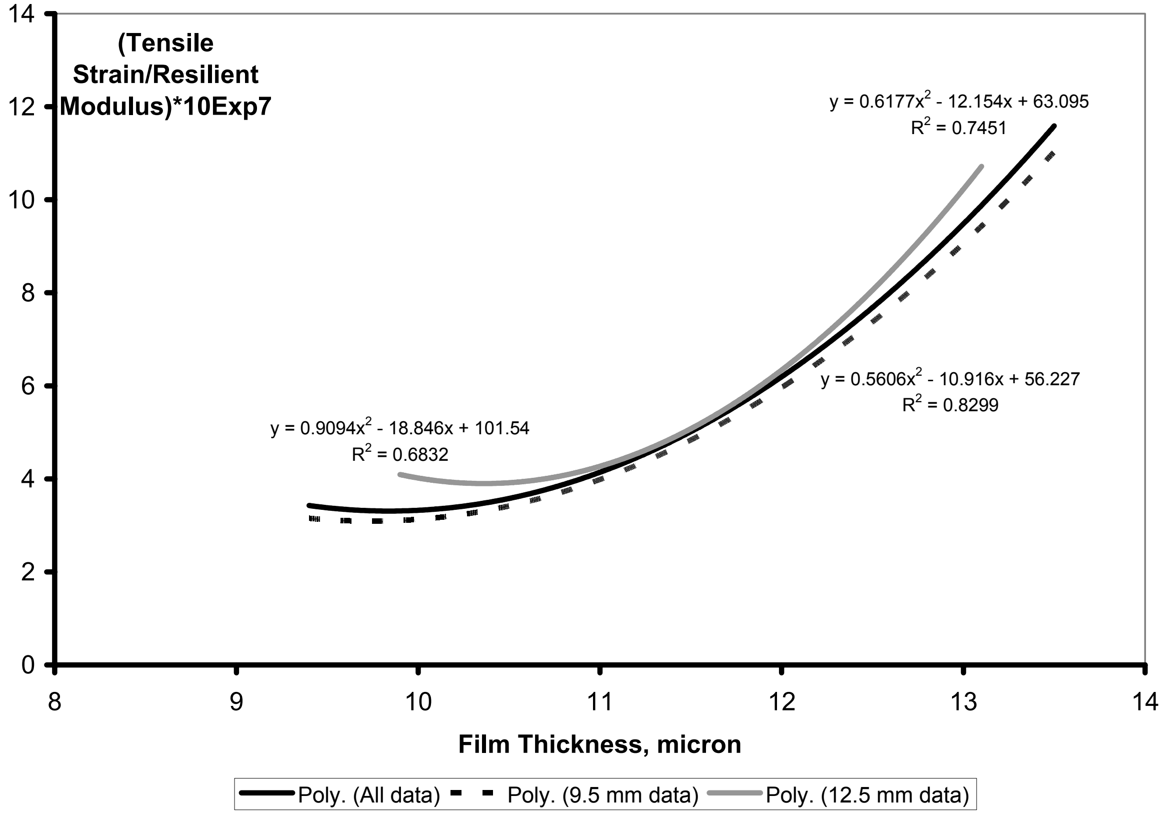

Figure 3.6. Plot of Film Thickness versus (Tensile Strain/Resilient Modulus)

3.4.2 ***Binder Stiffness***

Asphalt binder was extracted from long-term aged samples of NH, 9.5 mm, Keene and ME, 9.5 mm, Belfast mixes, and tested with the Dynamic Shear Rheometer for stiffness (G* and δ). The results (in terms of G*/sinδ) are shown in Figure 3.7, in Y axis, with film thickness in X axis. The sharp drop in stiffness values above a film thickness of 11.5 microns indicates a reduced effect of aging. Therefore, it can be concluded that for the range of data available in this study, a film thickness of 11.5 microns and higher is effective in preventing excessive increase in stiffness due to aging.

3.4.3 ***Rutting***

While strain and moduli values indicate resistance against durability problems, rutting or rut depth under loaded wheel testing can be used as indicator of stability. It is expected that as film thickness increases (with increase in asphalt content) the potential of rutting would increase. Note that these samples were tested at 7±1 % air voids, and that all of the recommendations from NCHRP Report 508 ((18), latest available NCHRP report on APA) are based on samples compacted to 4 or 5 percent air voids. The reader should use the rut depths reported here as parameters for evaluation of effect of film thickness on stability and should use caution in considering these as critical values.

Figure 3.8 shows the plot of rutting versus film thickness. As expected rutting increases with an increase in film thickness. The effect of film thickness on rutting is almost identical for the 9.5 mm and 12.5 mm mixes. Using the pooled data model, it seems that the maximum value of rutting, approximately, 6 mm is obtained corresponding to a film thickness of 13.8 micron. Whether a value of 6 mm means anything in terms of in-place rutting or not is debatable. However, it should be mentioned that this value is very close to the critical value of 7 mm (at 8,000 cycles for traffic volume greater than that in low volume roads) in the only available literature that used samples with 7 % air voids and an asphalt with high grade (PG) of 64 (19).

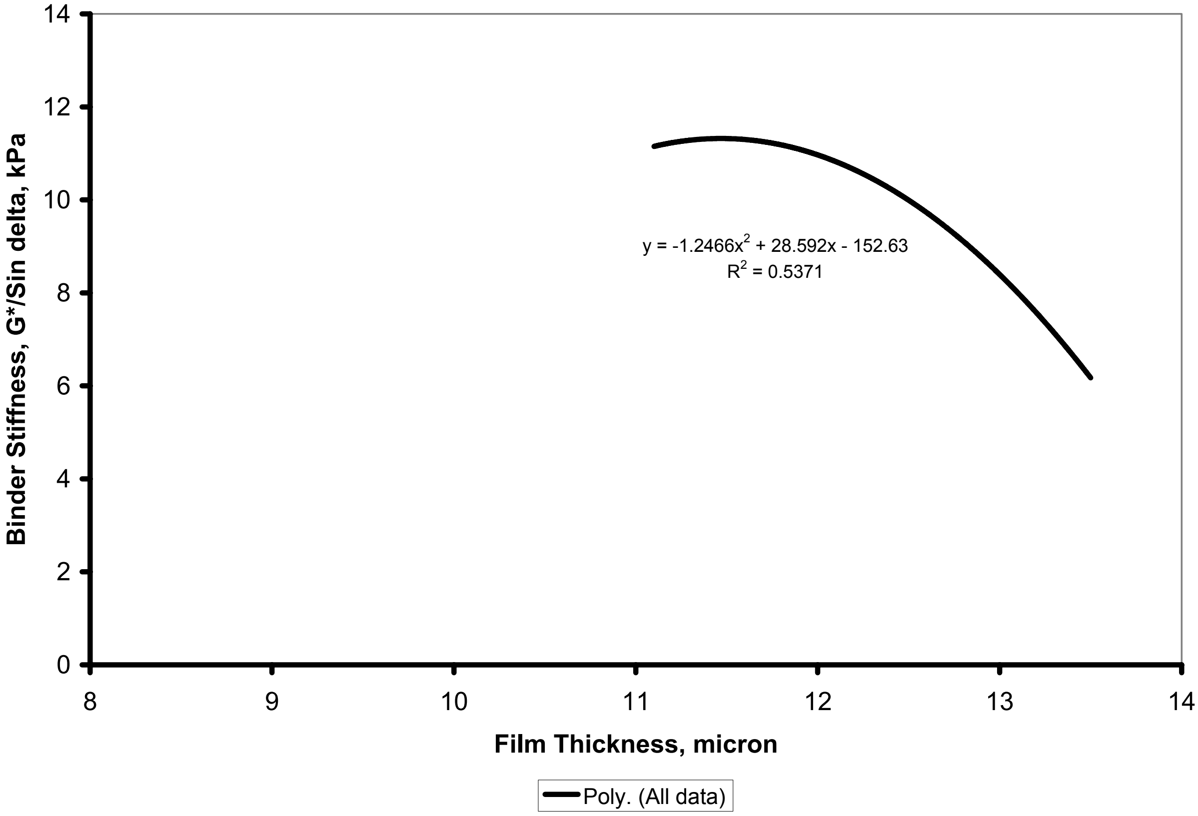

Figure 3.7. Plot of Film Thickness versus Binder Stiffness

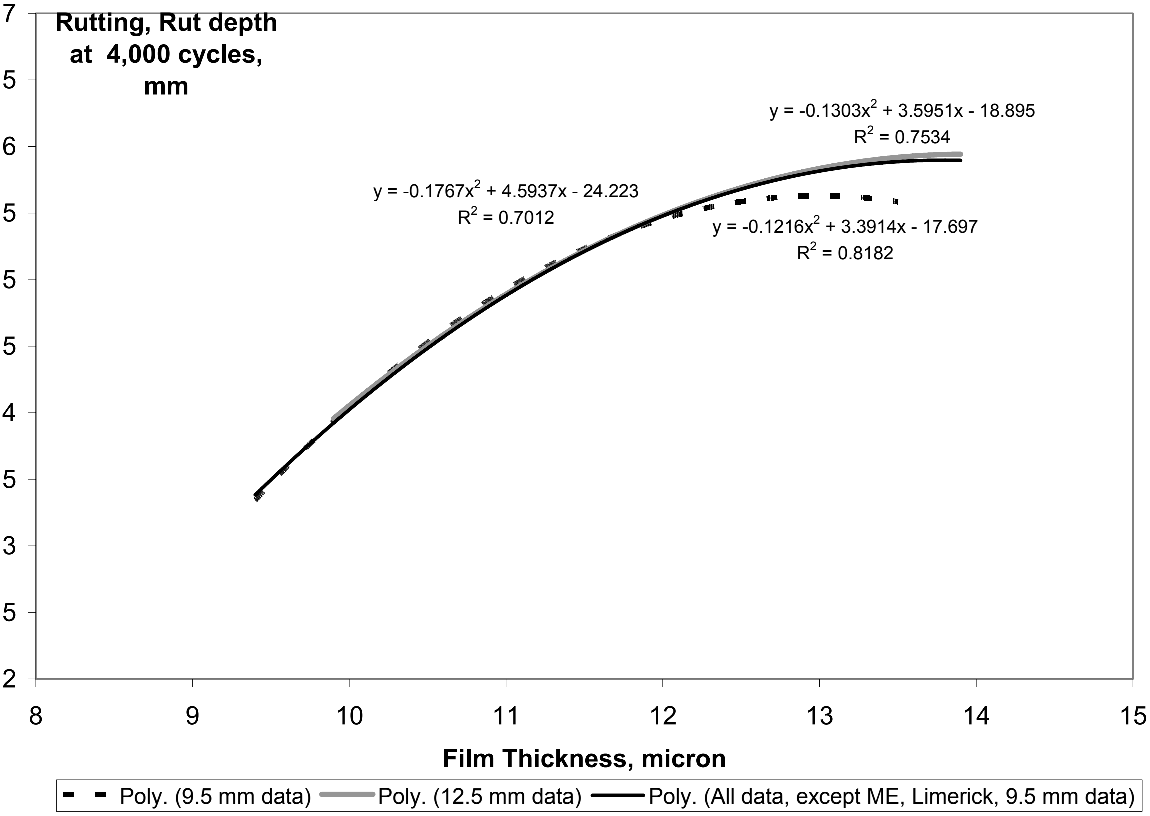

Figure 3.8. Plot of Film Thickness versus Rutting

Note that although most of the data points lie below 6 mm rutting (in this study), a relatively thick film, corresponding to a relatively high asphalt content can lead to bleeding and/or shoving problems. Hence, a different criterion should probably be used.

A look at the plots shows that the effect of film thickness on rutting is identical for the 9.5 mm and 12.5 mm mixes upto a film thickness of 11.2 micron, beyond which the 12.5 mm mixes show a less effect compared to the 9.5 mm mixes. This means that upto 11.2 microns, the effect of film thickness dominates over the difference in NMAS and gradation. In the absence of any other guideline, it is perhaps sensible to say that the maximum allowable film thickness, for both 9.5 and 12.5 mm mixes, from the point of view of rutting, is 11.2 microns, since beyond that film thickness rutting is affected significantly by other factors such as gradation and nominal maximum size also.

Figure 3.9 shows the optimum film thickness ranges obtained from the analysis of different durability and stability related properties for the mixes tested in this study. From considerations of change in modulus, tensile strain, tensile strain/modulus ratio, binder stiffness and rutting, the desirable film thickness seems to be 11.2, approximately 11 microns, for both 9.5 mm and 12 mm NMAS mixes.

Hence, for the mixes studied, it seems that a 11 micron film thickness, and a corresponding 19 percent VMA (at construction voids) is a good choice for ensuring both durability and stability. Since these mixes were compacted to 7 percent air voids (on an average), this means that corresponding to 4 percent air voids the desirable ***design*** VMA should be approximately 16 percent.

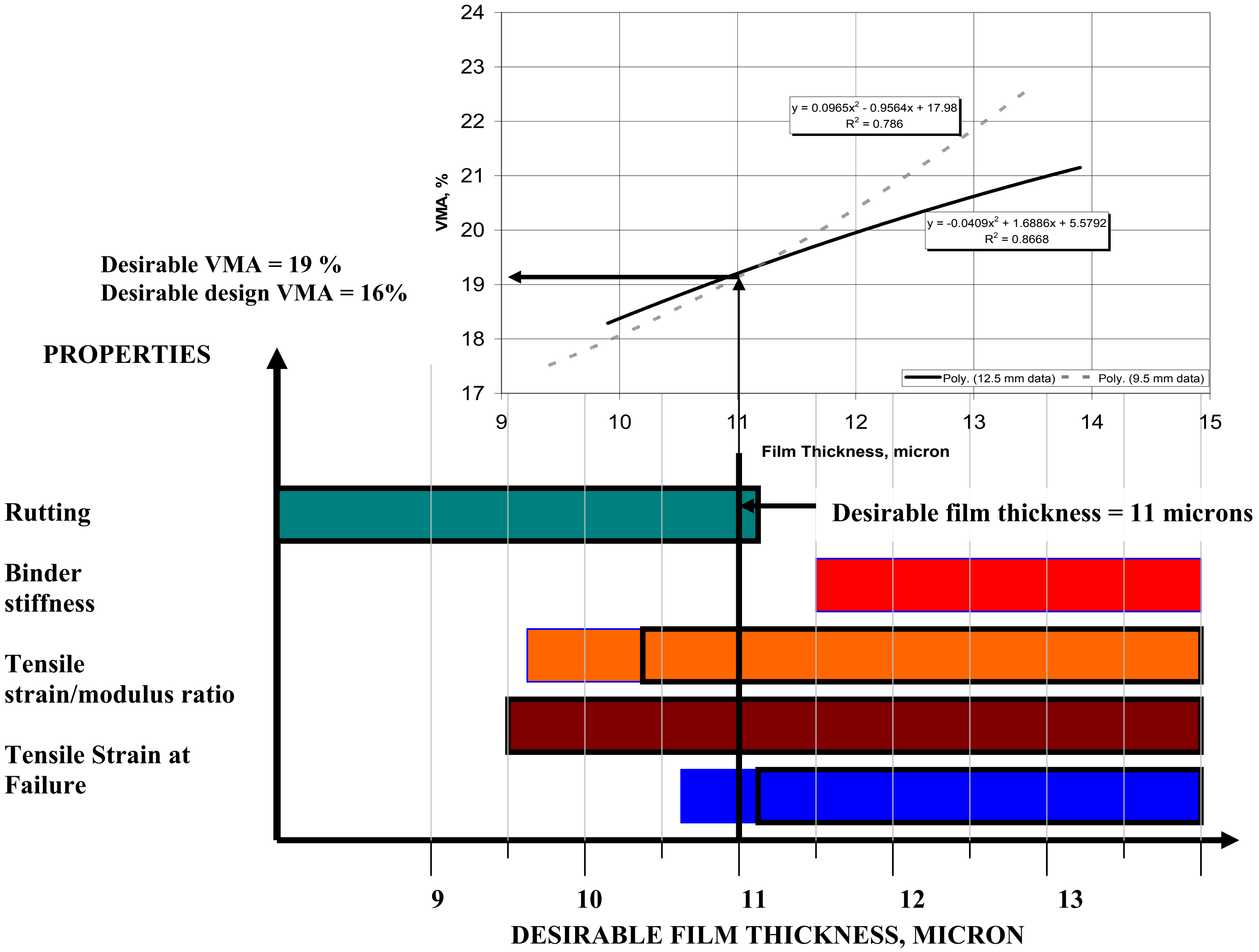

Figure 3.9. Optimum Film Thickness and VMA from Different Considerations. Note: Boxes with black lines indicate results for 12.5 mm NMAS, boxes without lines indicate results for 9.5 mm NMAS mixes; One single box indicates overlap of results for two NMAS mixes.

3.5 Design Number of Gyrations from In-Place Mixes

One very important basis of HMA mix design is that the selected mix gets compacted to its design voids, generally accepted as 4%, within three or four summers of traffic, and performs well thereafter, throughout its design life, without undergoing any significant further compaction. Based on this concept, state DOTs use different N_{design}, or gyration numbers, when compacting HMA samples with the Superpave gyratory compactor (SGC). N_{design} refers to the "compactive effort" that is used in the Superpave mix design system. Those number of gyrations, which provides the same density as the in-place density after sufficient traffic compaction (close to 4%) is selected as the N_{design} for projects with similar mixes, similar traffic levels and similar or same climatic region.

For determination of proper N_{design}, cores were obtained from two good performing, 10-12 twelve year old, low volume roads from Connecticut and Maine. Aggregates were recovered from these cores after burning off the asphalt binder with an ignition oven. The recovered aggregates were then mixed with virgin PG 64-28 grade asphalt binder, using the same asphalt content as used in the original mix. The mixes were subjected to short term aging and then compacted to 125 gyrations. The compacted samples were then tested for bulk specific gravity and the air voids at different gyrations, were back calculated as shown in Figure 3.10.

Observations from change in density with number of gyrations for the two in-place mixes indicate N_{design} values of 32 and 65 for the ME, Hancock, 9.5 mix (asphalt content of 6.3 percent) and the CT Stonington, (asphalt content of 5.2 percent), 12.5 mm mix respectively. Note that at the average gyration of 48, the voids range from approximately 3 (for the 9.5 mm mix) to 5 (for the 12.5 mm mix). Hence, a $N_{designlv}$ of 50 seems to reasonable for designing HMA for low volume roads.

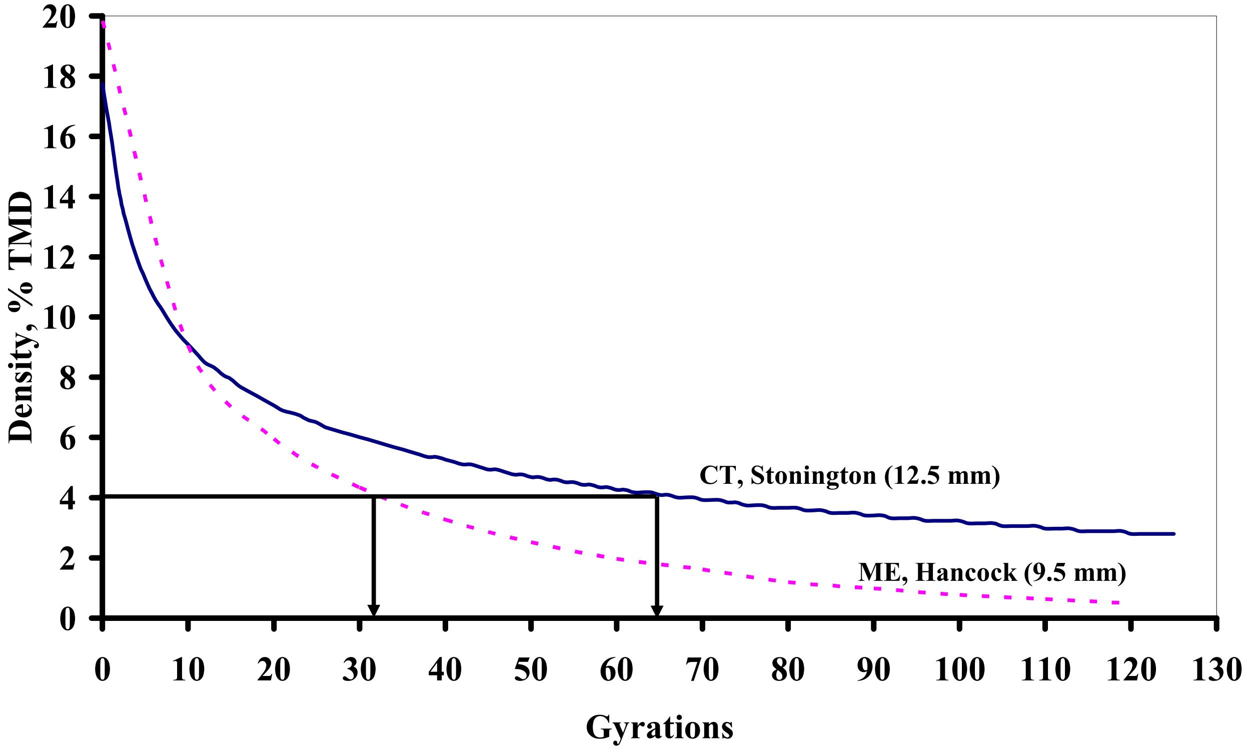

Figure 3.10. Plot of Number of Gyrations versus Voids in Total Mix

CHAPTER 4

FINITE ELEMENT ANALYSIS AND RESULTS

4.1 Layered Elastic Analysis

Mechanics is the science of motion and the action of forces on bodies. Thus, a mechanistic approach seeks to explain phenomena only by reference to physical causes. In pavement design, the phenomena are the stresses, strains and deflections within a pavement structure, and the physical causes are the loads and material properties of the pavement structure. The relationship between these phenomena and their physical causes is typically described using a mathematical model. Various mathematical models are available; the most common is a layered elastic model.

Since flexible pavements consist of several layers of different materials, they cannot be considered as a homogenous mass. Hence Burmister's layered theory is implemented instead of the homogenous half space.

The basic assumptions of an n-layered system are as follows (27):

1. Each layer is homogenous, isotropic, and linearly elastic with an elastic modulus E, and a Poisson's ratio ν.
2. The material is weightless and infinite in aerial extent.
3. Each layer has a finite thickness h, except that the lowest layer is infinite in thickness.
4. A uniform pressure q is applied on the surface over a circular area of radius a.
5. Continuity conditions are satisfied at the layer interfaces, as indicated by the same vertical stress, shear stress, vertical displacement, and radial displacement. For frictionless interface, the continuity of the shear stress and radial displacement is replaced by zero shear stress at each side of the interface.

There are several readily available computer programs based on layered elastic analysis theory. These programs allow the user to calculate the theoretical stresses, strains, and deflections anywhere in a pavement structure. However, there are a few critical locations that are often used in pavement analysis as shown in Table 4.1.

Table 4.1. Critical Analysis Locations in a Pavement Structure

Location	Response	Use
Pavement Surface	Deflection	Impose load restrictions during spring thaw and overlay design (for example)
Bottom of HMA layer	Horizontal Tensile Strain	Predict fatigue failure in the HMA
Top of Intermediate Layer (Base or Subbase)	Vertical Compressive Strain	Predict rutting failure in the base or subbase
Top of Subgrade	Vertical Compressive Strain	Predict rutting failure in the subgrade

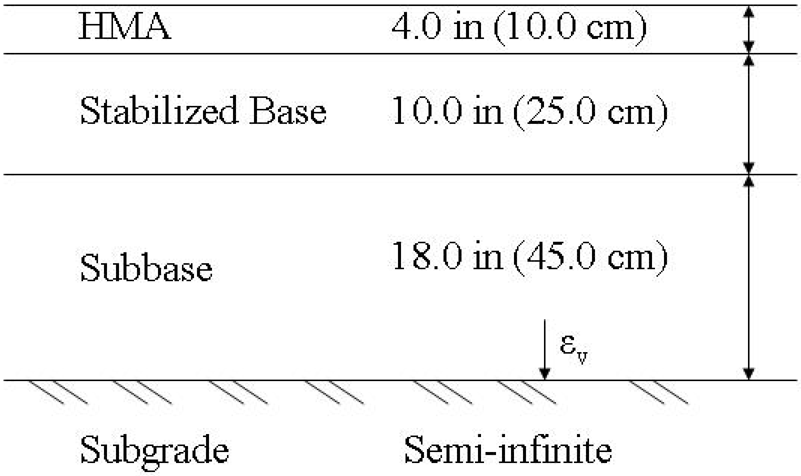

Figure 4.1. Cross-Section of a Typical Low Volume Road

In the relevant study, Weslea, a mechanistic pavement analysis program has been used to calculate pavement response to applied tire loads for a typical low volume pavement structure as shown in Figure 4.1.

A layered elastic model requires a minimum number of inputs to adequately characterize a pavement structure and its response to loading. The inputs corresponding to the analyzed structure are as shown in Table 4.2.

Table 4.2. Input Data for Weslea Analysis

Layer	**HMA**	**Stabilized Base**	**Subbase**	**Subgrade**
Modulus of elasticity (MPa)	3122.0	1500.0	206.8	24.8
Poisson's ratio	0.35	0.35	0.40	0.45
Pavement layer thickness (cm)	10.0	25.0	45.0	Semi-infinite

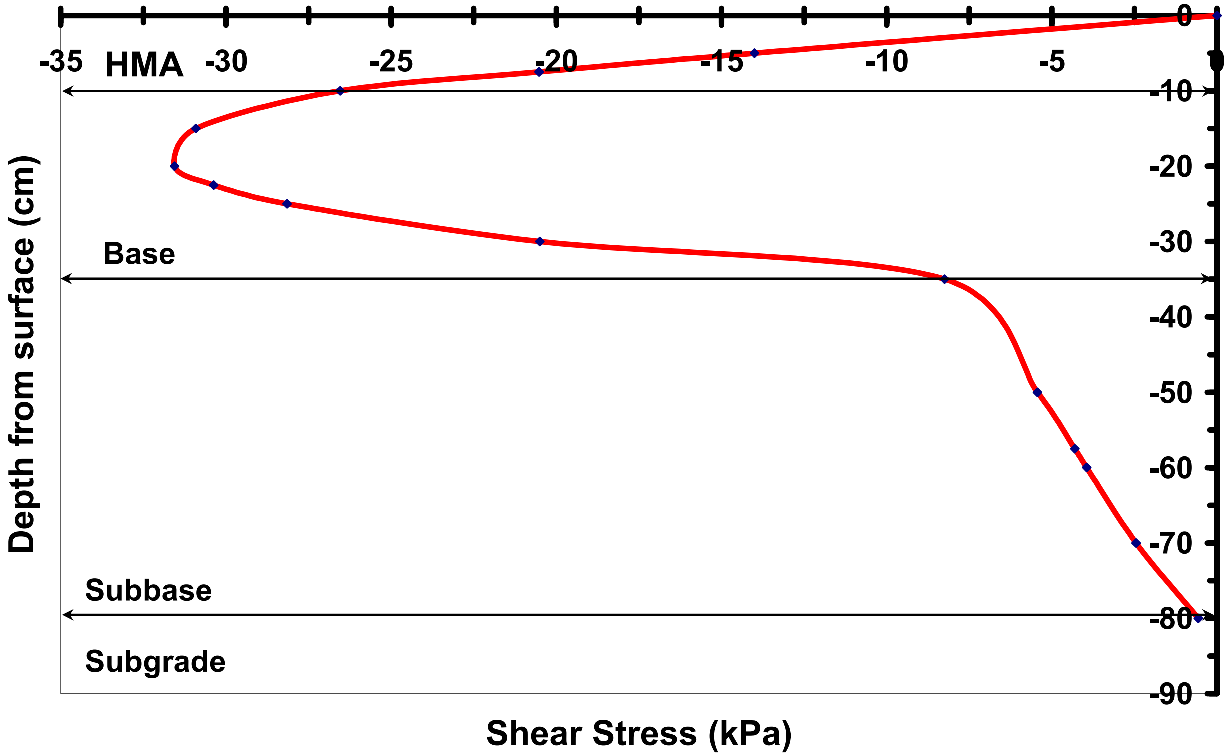

Figure 4.2. Shear Stress Profile for a Typical Low Volume Road

A single axle wheel load of magnitude 22.24 kN and a tire pressure of 690 kPa were applied. The shear stress computed by the program at various depths from surface of pavement is shown in Figure 4.2. The maximum shear stress in the HMA layer occurs at the bottom of the layer with a magnitude of 26.54 kPa.

The shear stress in the HMA layer is an important parameter to be considered.
Rutting (or permanent deformation) results from the accumulation of small amounts of unrecoverable strain as a result of repeated loads applied to the pavement. Rutting can occur as a result of problems with the subgrade, unbound base course, or HMA. However, the rutting which is the primary focus of HMA mix design is the one that occurs in the HMA layer. This type of rutting results when the shear strength of an asphalt mixture is insufficient to withstand repeated heavy loads. This leads to the accumulation of small, permanent deformation eventually leading to the formation of a rut due to the downward and lateral movement of the asphalt mixture. Rutting typically occurs during the summer which suggests that it is caused due to asphalt binder in the mix. Hence, there is a need to look at the behavior of asphalt itself under shear stress.

4.2 Finite Element Method

The finite element method (FEM) is a numerical analysis technique for obtaining the approximate solutions to a wide variety of engineering problems. In finite element analysis, the structure to be analyzed is discretized into small elements, each having an associated stiffness matrix. Several finite elements have been developed to represent common structures, including quadrilateral plates, triangular plates, solid brick elements, and beam elements. For each such element, the stiffness matrix is stored mathematically in the form of fundamental equations. When problem-specific parameters such as dimensional coordinates, the material elastic modulus, Poisson’s ratio and density are put in these equations, the local stiffness, as represented by one element, is uniquely known. When a structure is fully discretized, or meshed, into many such elements, its global stiffness can be assembled, again in the form of a matrix, from the combined stiffness of all the interacting elements. If a force or set of forces is subsequently applied to the structure, the static displacement response can be calculated from the global stiffness matrix (31). This basic concept is used in the solution of many problems involving a variety of applied loading conditions, including externally applied forces, pressures and temperatures.

The 3D-FE codes (for example, ABAQUS, DYNA3D, LSDYNA) are available for comprehensive pavement structural response analysis that considers static, harmonic, transient dynamic loads, and thermal gradient conditions (impulse, steady-state vibratory force, and moving wheel load). Pavement layer material can be modeled as linear, nonlinear elastic, viscoelastic, and modified elastic (allowing no tension layers).
Finite element modeling involves three stages:

1. Pre-processing: the finite element mesh is generated, loads and boundary conditions are assigned, and material properties are defined using pre processor.
2. Analysis: displacements, stresses, and strains are computed using 3D-FE code.
3. Post-processing: the results are graphically presented using post processor.

4.3 ABAQUS

ABAQUS (35) is a suite of general purpose nonlinear finite element analysis (FEA) tools which provides solutions for linear, non-linear, explicit and multi-body dynamics problems. It was initially developed to help nuclear power and off shore engineering communities to solve complex, nonlinear engineering problems.

The advanced technology of ABAQUS allows the user to model complex elaborate structures and at the same time take into consideration even the most subtle effects. Since the current general trend is the real-world, real-time simulation and testing of digital prototypes instead of physical prototypes, there is a lot of demand for such advanced software.

ABAQUS provides the user with a wide range of element types, loading situations, and type of analysis which can be used to simulate specific situations and hence provides the user with a considerable control on the various aspects of the design and analysis of models.

A data pool for ABAQUS contains model data and history data. The model data defines the finite element model in terms of its geometry, materials definition, element properties, etc. The history data defines the sequence of events or loadings. History data is divided into steps, each step being a period of response of a specific type.

Currently, tailored solutions are being developed for the production environment by combing the utility of ABAQUS with the focus of a customized user interface. Such systems provide the end user with the ABAQUS numerical solutions while requiring little or no knowledge of FE analysis.

4.4 3D-FE Model, Analysis and Results

A 3D-FE model of asphalt film sandwiched between two aggregate particles was analyzed using ABAQUS. The purpose of this modeling was to observe the effect of change in thickness and stiffness of asphalt film on the shear strain. The 3D-FE was subjected to the maximum shear stress computed in the HMA layer from layered elastic analysis as discussed in the previous section. A static analysis was performed on the model.

The following are the various steps followed to accomplish the model (32).

1. The model was created using the ABAQUS/CAE, the ABAQUS pre-processor which generates the input file. There are various modules which allow for the construction of model. Using the Part module, the various parts of the model were created. The model consisted of 3 parts – 2 aggregates and 1 film layer in between them. They were modeled as 3 layers of three dimensional solids.
2. After the physical model was created the material properties for each layer are specified: Poisson's ratio, Young's modulus. The layers were specified as elastic, isotropic materials in Property module. A Poisson's ratio of 0.35 was used for all layers. The modulus values used were 138,000 MPa and 10,000 MPa for aggregate and asphalt film respectively.
3. Each part created is oriented in its own coordinate system and is independent of the other parts. All these part geometries are defined with respect to a global coordinate system in Assembly module.

4. The analysis is defined in the Step module. The initial step is always used to define the boundary conditions. The third layer which is aggregate is constrained at the bottom. Another step was created in which the shear stress was applied as pressure on one side of the top layer and the type of analysis was chosen as static, general. General procedures are used to analyze linear and nonlinear response.
5. The required outputs are also selected in the Step module. Default values were selected for the model.
6. The prescribed conditions such as loads, boundary conditions are step-dependent. The steps at which they become active are to be defined by the user. The Load module is used for this purpose. The magnitude of 0.02654 MPa for the load was also specified in this module. The load was applied as a pressure on the entire surface for the model.
7. A very crucial part of finite-element modeling is the mesh size and configuration, precise mesh refinement being necessary in regions of high intensity of stress (33). The mesh configuration is defined in the Mesh module. This module is used to create the mesh, the element shape, and the element type. Solid 'hex' element with 8 nodes linear brick, reduced integration, of type 'C3D8R' were used to create the model. A finer mesh of the film was defined for the asphalt film layer since the strains generated in this layer are of interest.
8. Having configured the analysis, the Job module is used to create and submit a job associated with the model for analysis.
9. The ABAQUS/CAE post processor also known as the Visualization module is used to view the results in graphical form.

Figure 4.3 shows the three-dimensional view of the entire model. The dimensions of the model, the boundary conditions applied and the load area are also indicated.

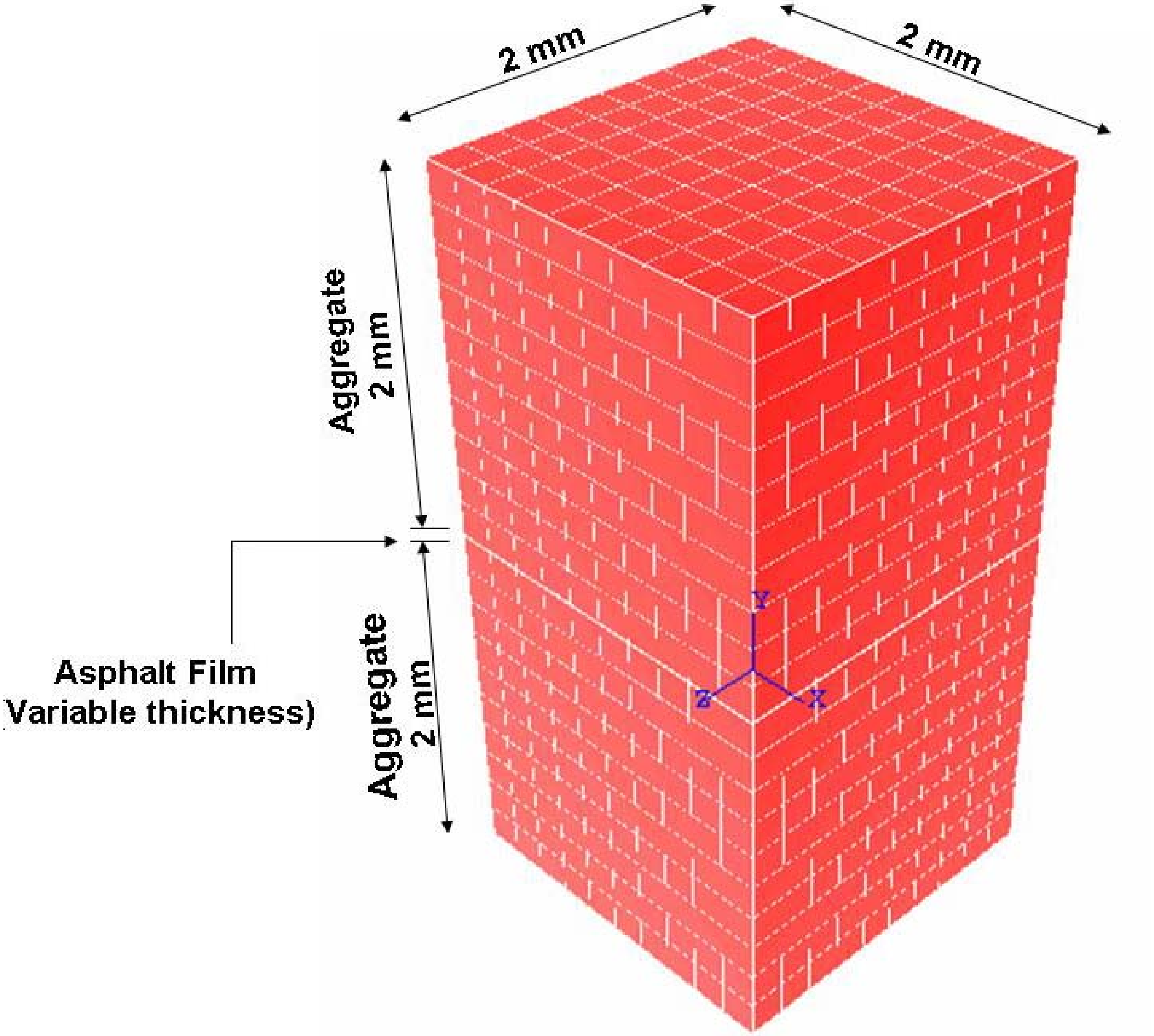

Figure 4.3a. Three Dimensional Full View of the Model

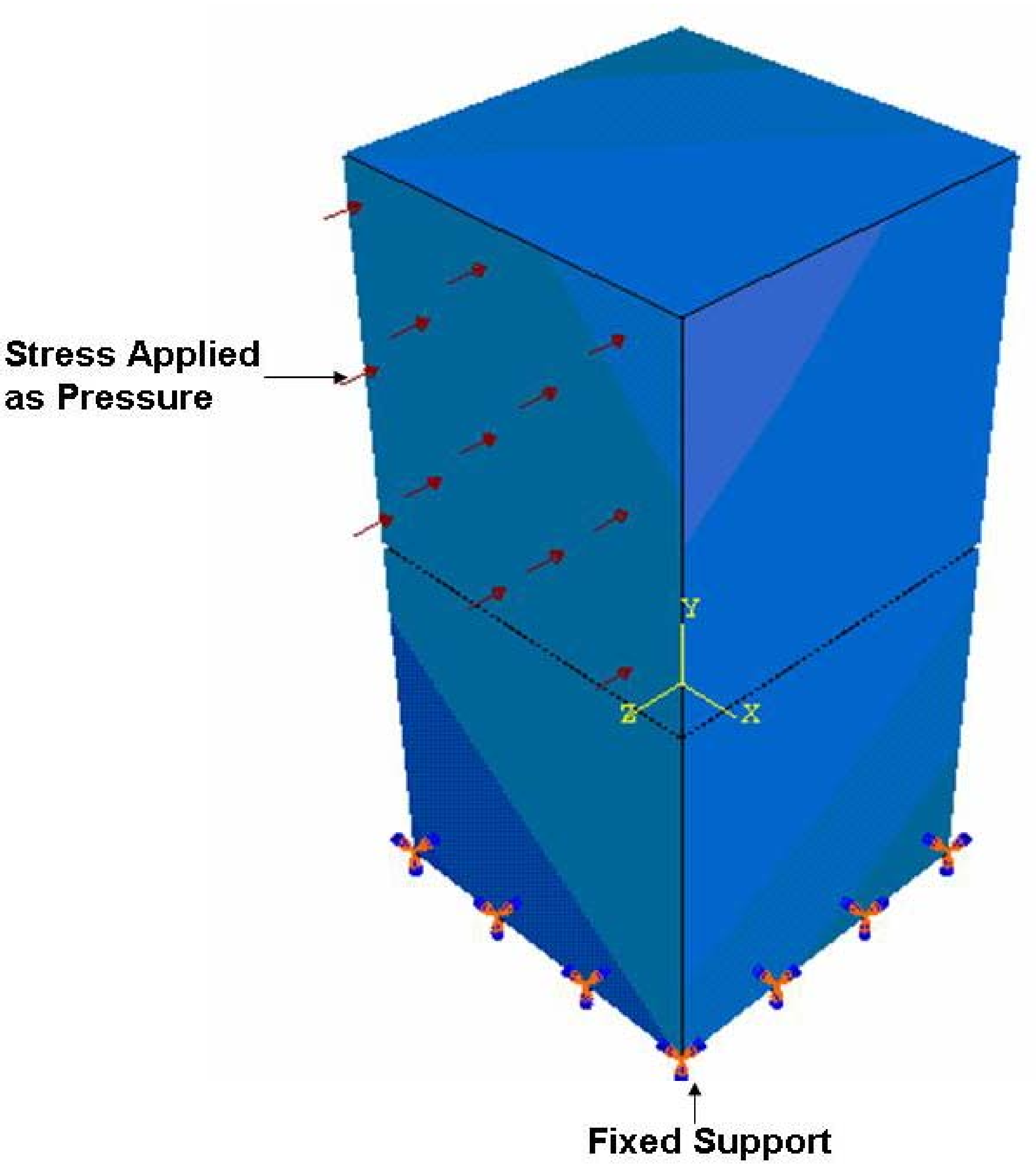

Figure 4.3b. Three Dimensional Full View of the Model

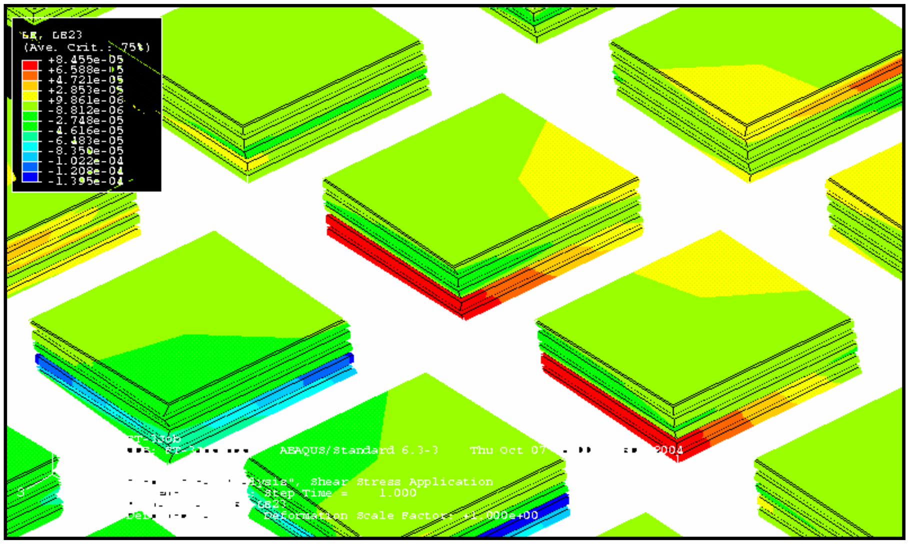

Figure 4.4. Deformation in Asphalt Film Layer (Elements Shrunk for a Better View)

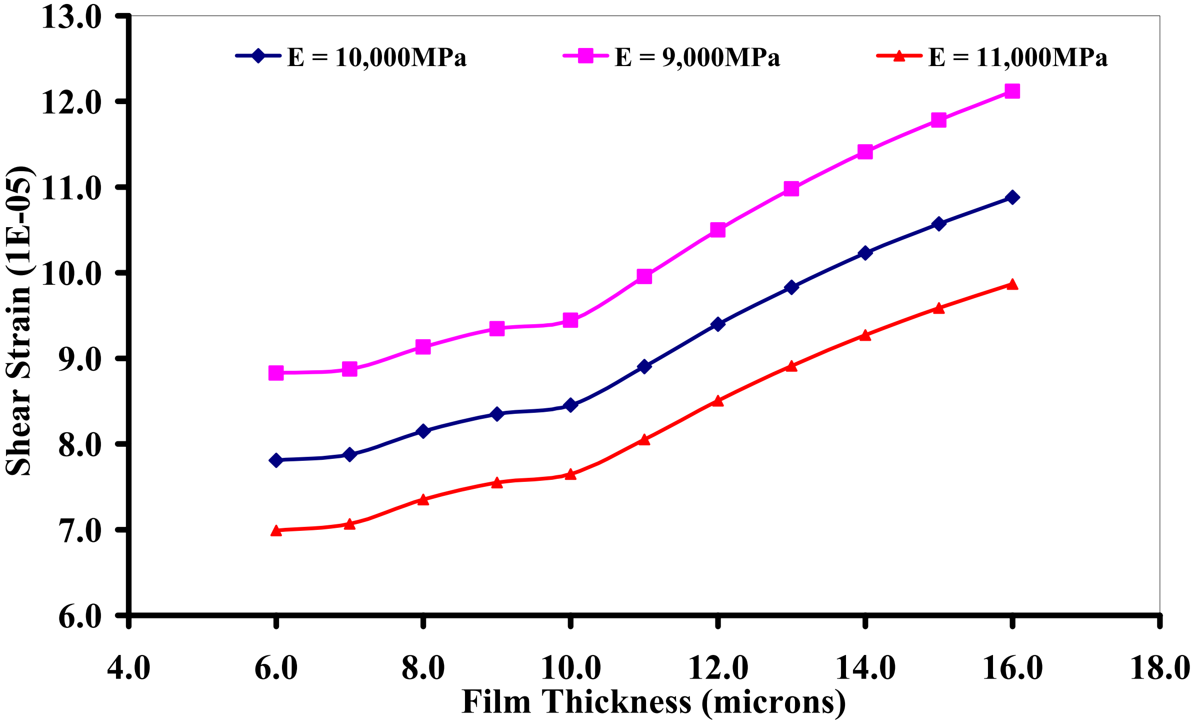

Figure 4.5. Shear Strain Profile

The film thickness was varied by 1 micron and analyzed ranging from 6 microns to 16 microns. Figure 4.4 shows the deformed shape of the asphalt film at 10 microns thickness. The maximum shear strain of 8.445e-05 was calculated at time step 11.

The variation of the shear strain with change in film thickness and elastic modulus of asphalt are shown in Figure 4.5. It can be observed that there is no effect of change in asphalt stiffness on the profile of the strain. However, the effect of increase in asphalt thickness beyond 10 microns is very high. Hence, any film thickness value below 10 microns can be considered for resistance against shear failure. This confirms with the results of the APA. It should be noted that this is only a preliminary investigation. Hence, the magnitude of strain may not be useful for real time comparison but the shear strain profile can be useful in studying the effect of film thickness on shear strain.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Based on the results of this study, the following conclusions and recommendations are made:

1. A film thickness of 11 microns in samples compacted to 7 percent voids was found to be desirable from considerations of stability and durability.

2. A design VMA of 16 percent was determined to be optimum for producing durable and stable mixes for low volume roads.

3. An $N_{designlv}$ of 50 is recommended for compacting HMA for low volume roads in New England.

4. There is a need to develop a criterion for identifying good and poor mixes, based on the results of "proof testing" for rutting. At this time, in the absence of any other practical method, the Asphalt Pavement Analyzer (APA) is suggested as the proof testing equipment. It is suggested that cores from good, medium and poor performing low volume roads be tested with the APA, and corresponding rut depths, at 4,000 cycles be obtained. These rut depths can be used as baselines for identifying good, medium and poor performing mixes.

5. An alternative approach for designing Hot Mix Asphalt (HMA) for Low Volume Roads is outlined in Appendix C. This method is based on the desirable film thickness recommended in this study. Implementation of this new procedure will greatly reduce the number of trial samples compacted as a part of mix design. Hence this alternative approach is recommended.

6. "Asphalt Film Thickness Calculation Wizard" application described in Appendix B be used for calculation of volumetric properties of mixes. It is a JAVA application

developed to simplify the process of calculation of volumetric properties by reducing the computational effort.

7. The FE model developed in this study is only a preliminary investigation. The results from the model confirm with the rut depth results using APA. However, this is only a preliminary investigation. Further study using a more realistic model of HMA pavement layer structure is recommended.

8. The balancing of asphalt content to suit demands for durability and stability can be done best by engineers experienced with local materials, climate and traffic. However, using polymer modified HMA can make this balancing less critical. Properly designed and constructed polymer modified mixes allow users to provide a relatively high asphalt content, that is a thicker asphalt film, without increasing the potential of rutting. The higher cost of polymer modified mixes can prohibit their use, but their applicability must be judged in consideration of their lower life cycle cost and their higher stiffness, and hence, probably, the ability of reducing pavement layer thickness.

CHAPTER 6

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APPENDIX A

Formulae for Calculation of Volumetric Properties

$$VMA = 100 - \left(\frac{G_{mb} * P_s}{G_{sb}} \right)$$

V_b = volume of asphalt, cc

G_b = asphalt density, g/cc

VMA = voids in mineral aggregate, %

VTM = voids in total mix, %

G_{mb} = mix density (bulk specific gravity), g/cc

G_{mm} = maximum theoretical density, g/cc

SA = surface area, sq.m/kg

PP = percent passing a sieve, %

SAF = surface area factor

$$FilmThickness(microrns) = \left\{ \frac{\left({ACwt/kgAgg}\big/{1000 * G_b} \right)}{(SA)} \right\} * 10^6$$

$$ACwt/kgAgg(kg) = \frac{ACwt(kg)}{Aggwt(kg)}$$

$$ACwt(kg) = \frac{V_b * 1000 * G_b}{100}$$

$$Aggwt(kg) = \frac{ACwt(kg)}{AC\%} * (100 - AC\%)$$

$$V_b(\%) = VMA - VTM$$

$$SA = \sum(PP * SAF)$$

$$VTM = \left(1 - \frac{G_{mb}}{G_{mm}} \right) * 100$$

V_b = volume of asphalt, cc

G_b = asphalt density, g/cc

VMA = voids in mineral aggregate, %

VTM = voids in total mix, %

G_{mb} = mix density (bulk specific gravity), g/cc

G_{mm} = maximum theoretical density, g/cc

SA = surface area, sq.m/kg

PP = percent passing a sieve, %

SAF = surface area factor

APPENDIX B

Asphalt Film Thickness Calculation Wizard

This application is available on a CD and can be run directly through the CD. It can also be copied onto a hard drive and run.

Steps for using the "Asphalt Film Thickness Calculation Wizard":

1. To launch the wizard double-click on the MS-DOS batch file named FM.bat.
2. Enter a "Description" for the mix which is not mandatory.
3. The first screen of the wizard requires you to input the aggregate gradation.
4. Click on 'Next'. This takes you to the second screen which requires you to input mixture and its component properties.
5. Once the values are input, the program automatically deletes the previous existing data and saves the new data for the screen.
6. Click on 'Next'. This takes you to the third screen which displays the results.
7. The wizard can be closed by using the window or by pressing on the Cancel button

Other Features of the Wizard:

1. You can go to the previous screen at any time to re-enter or change any of the input data. The output is automatically recalculated with the new values.
2. The clear button on the wizard can be used to clear all the values on the corresponding screen (1st or 2nd only).
3. When you close the wizard, your custom description (if any) along with the input data will be saved, so when you relaunch the wizard next time you will be able to see all your previous entered data. This will be particularly useful when one or more of your input data remains the same as the previous calculations.

Input:

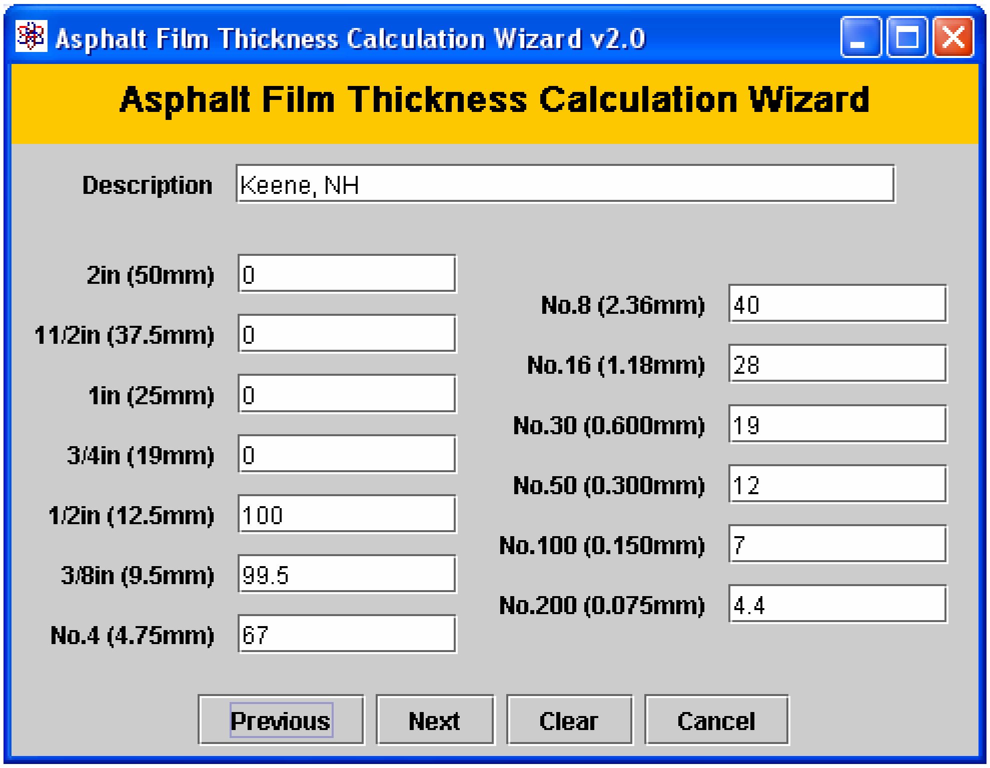
Screen 1: gradation

Screen 2: asphalt content (%), theoretical maximum mix density (g/cc), bulk specific gravity (g/cc), bulk density of aggregates (g/cc), and specific gravity of asphalt (g/cc)

Output:

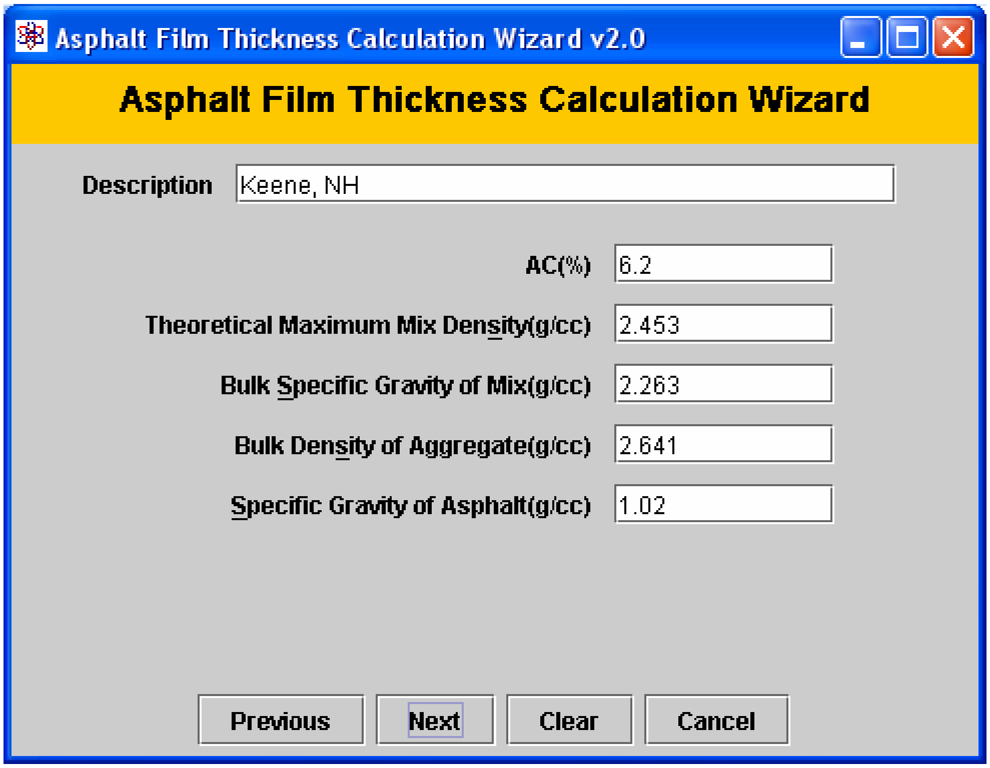
Screen 3: surface area (sq.m/kg), VTM (%), VMA (%), and film thickness (micron)

Screen 1 - Input



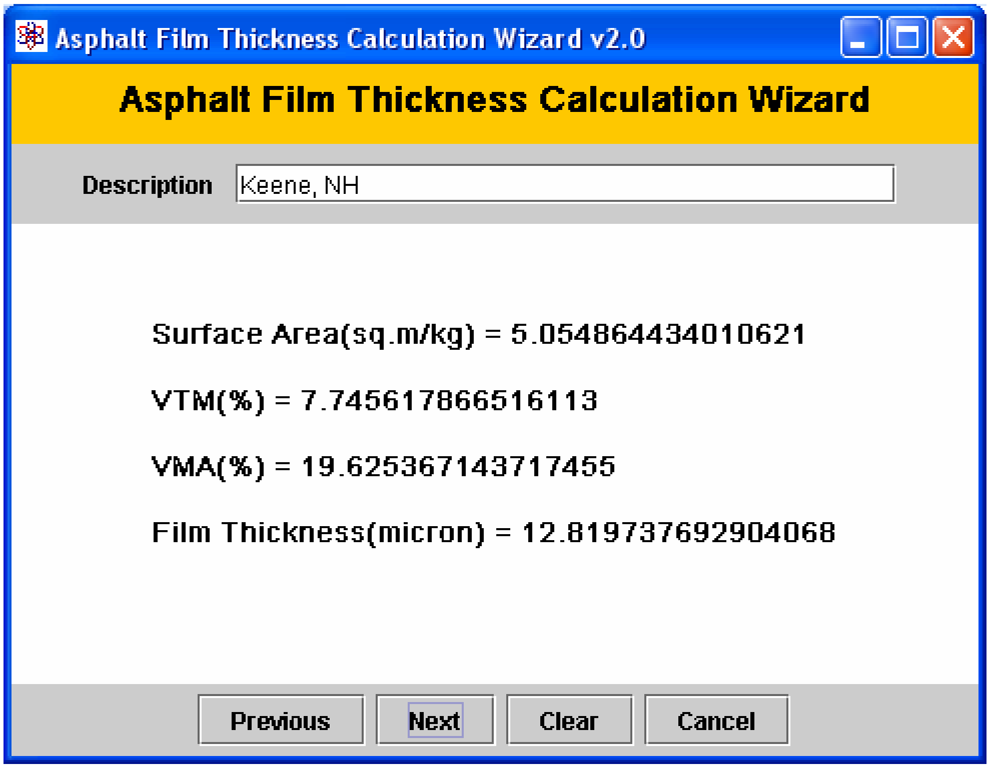
Description	Keene, NH
2in (50mm)	0
11/2in (37.5mm)	0
1in (25mm)	0
3/4in (19mm)	0
1/2in (12.5mm)	100
3/8in (9.5mm)	99.5
No.4 (4.75mm)	67
No.8 (2.36mm)	40
No.16 (1.18mm)	28
No.30 (0.600mm)	19
No.50 (0.300mm)	12
No.100 (0.150mm)	7
No.200 (0.075mm)	4.4

Screen 2 - Input



Description	Keene, NH
AC(%)	6.2
Theoretical Maximum Mix Density(g/cc)	2.453
Bulk Specific Gravity of Mix(g/cc)	2.263
Bulk Density of Aggregate(g/cc)	2.641
Specific Gravity of Asphalt(g/cc)	1.02

Screen 3 - Output



Description: Keene, NH

Surface Area(sq.m/kg) = 5.054864434010621

VTM(%) = 7.745617866516113

VMA(%) = 19.625367143717455

Film Thickness(micron) = 12.819737692904068

APPENDIX C

Alternative Approach

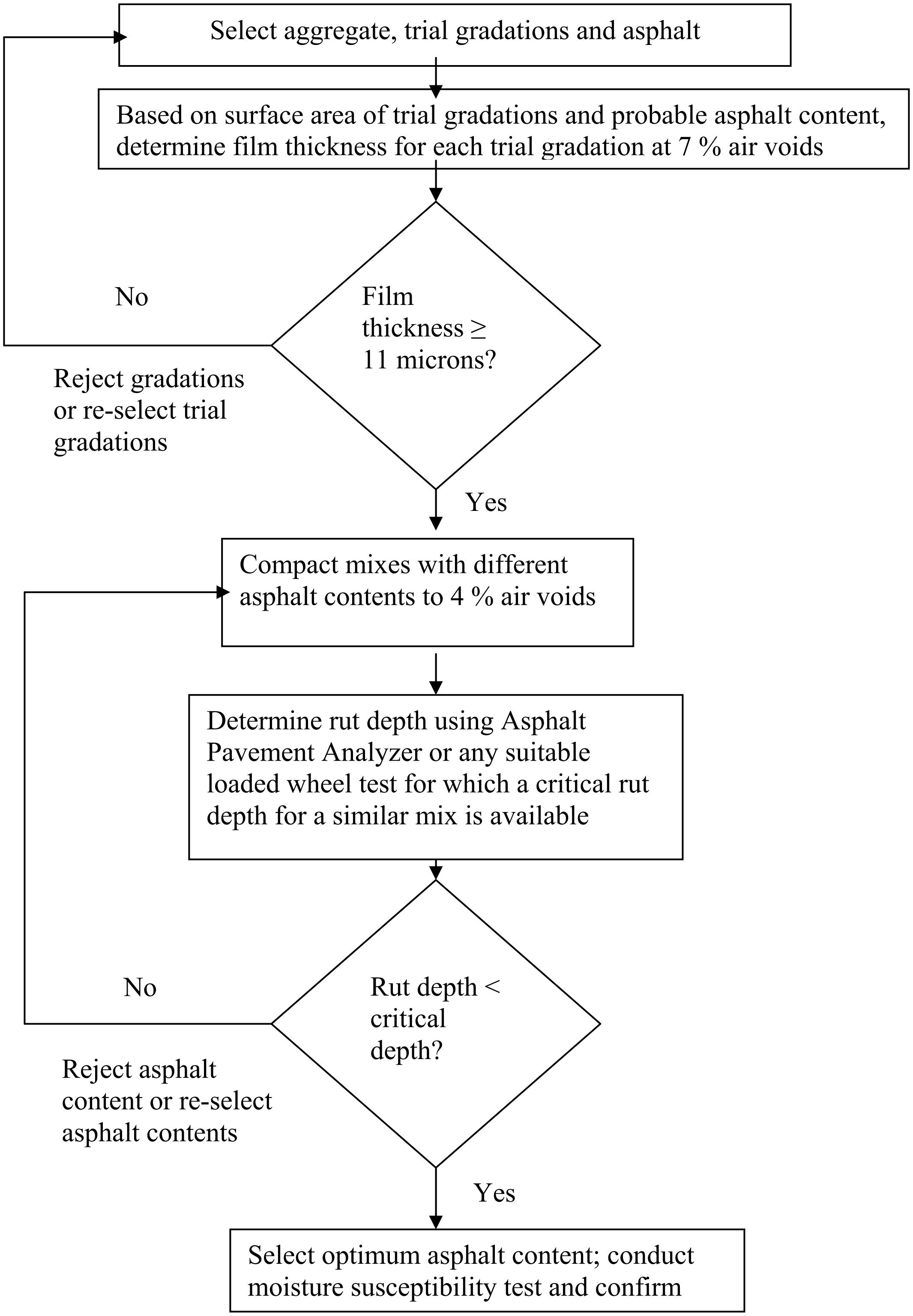


Figure C1. Suggested alternative approach for designing Hot Mix Asphalt (HMA) for Low Volume Roads

APPENDIX D

Raw Data

Table 1. Aggregate Material Properties

Aggregate Properties	**Measure**							
Location	Keene, NH	Limerick, ME	Belfast, ME	Campton, NH	Swampscott, MA	PresqueIsle, ME	Stonington, CT	Hancock, ME
NMAS (Nominal Maximum Aggregate Size)	9.5 mm	9.5 mm	9.5mm	12.5 mm	12.5 mm	9.5 mm	12.5 mm	9.5 mm
Gradation	Coarse	Very Fine	Fine	Fine	Fine	Fine	Fine	Coarse
Combined Specific Gravity of Aggregate	2.641	2.658	2.687	2.661	2.756	2.660		
Water Absorption	0.9	0.81						
Crushed Face (coarse aggregate angularity)	100	99.8/99.6	98.6/98.2					
FAA (fine aggregate angularity)	47.1	48	47					
Flat and Elongated Particles	3%	-	-					

Note: Flat and Elongated Particles testing is not conducted when there is less than 10 percent retained on the 9.5 mm sieve

Table 2a. Aggregate Material Gradation Details

Location		**Keene, NH**	**Limerick, ME**	**Belfast, ME**	**Campton, NH**	**Swampscott, MA**	**PresqueIsle, ME**
Sieve Size		**Percent Passing**					
(inch)	**(mm)**						
1	25					100.0	
3/4	19				100	98.0	
1/2	12.5	100.0	100.0	100.0	98.5	93.0	100
3/8	9.5	99.5	99.0	95.0	87	77.0	97
4	4.75	67.0	82.0	60.0	56.8	55.0	74
8	2.36	40.0	62.0	47.0	42	38.0	49
16	1.18	28.0	45.0	33.0	32.4	25.0	31
30	0.6	19.0	30.0	20.0	21.9	18.0	19
50	0.3	12.0	19.0	12.0	12.6	13.0	12
100	0.15	7.0	10.0	8.0	6.5	10.0	7
200	0.075	4.4	5.5	5.0	3.5	4.0	5
Surface Area, sq.m/kg		5.1	7.1	5.5	4.9	5.2	5.4
Coefficient of curvature, Cc		2.0	1.7	1.0	0.9	2.2	1.7
Coefficient of uniformity, Cu		17.0	15.9	22.2	26.5	29.0	13.6

Table 2b. Aggregate Material Gradation Details – Field Cores

Location		**Stonington, CT**	**Hancock, ME**
Sieve Size		**Percent Passing**	
(inch)	**(mm)**		
1	25		
3/4	19	100.0	
1/2	12.5	95.0	100.0
3/8	9.5	74.0	91.3
4	4.75	55.0	59.5
8	2.36	45.0	41.9
16	1.18	34.0	30.6
30	0.6	24.0	23.5
50	0.3	15.0	16.6
100	0.15	8.0	9.1
200	0.075	4.0	3.9
Surface Area, sq.m/kg		5.4	5.6
Coefficient of curvature, Cc		0.9	1.42
Coefficient of uniformity, Cu		24.6	33.9

Table 3a. Volumetric and Mechanical Properties of Mixtures – Keene, NH

Sample#	Asphalt Content (%)	Film Thickness (microns)	Aged Mr (MPa)	Aged Mr (ksi)	Tensile Strain @Failure	Fracture Energy (N-mm)
31	7.3	13.53	1471.5	213.6		
32	7.3	13.53	1864.5	270.6		
33	7.3	13.53	1909.5	277.1		
34	7.3	13.53	1545.5	224.3		
35	7.3	13.53	1826.0	265.0	0.0136	16864.97
36	7.3	13.53	1854.0	269.1	0.0135	15781.27
Average	**7.3**	**13.53**	**1745.2**	**253.3**	**0.0135**	**16323.1**
Std Dev	**0.00**	**0.00**	**186.8**	**27.1**	**0.0001**	**766.29**
CV (%)	**0.00**	**0.00**	**10.7**	**10.7**	**0.3781**	**4.69**
25	6.8	12.41	2083.5	302.4	0.0138	15021.04
26	6.8	12.41	2142.5	311.0		
27	6.8	12.41	1946.0	282.4	0.0138	14910.09
28	6.8	12.41	2394.0	347.5		
29	6.8	12.41	2359.0	342.4		
30	6.8	12.41	2280.5	331.0		
Average	**6.8**	**12.41**	**2200.9**	**319.4**	**0.0138**	**14965.6**
Std Dev	**0.00**	**0.00**	**173.7**	**25.2**	**0.0000**	**78.45**
CV (%)	**0.00**	**0.00**	**7.9**	**7.9**	**0.2315**	**0.52**

(Table Continued)

Sample#	Asphalt Content (%)	Film Thickness (microns)	Aged Mr (MPa)	Aged Mr (ksi)	Tensile Strain @Failure	Fracture Energy (N-mm)
19	6.6	12.08	2479.5	359.9	0.0121	14054.50
20	6.6	12.08	2181.0	316.5		
21	6.6	12.08	2296.0	333.2		
22	6.6	12.08	2461.0	357.2	0.0111	14975.17
23	6.6	12.08	2840.0	412.2		
24	6.6	12.08	2842.5	412.6		
Average	**6.6**	**12.08**	**2516.7**	**365.3**	**0.0116**	**14514.8**
Std Dev	**0.00**	**0.00**	**274.4**	**39.8**	**0.0007**	**651.01**
CV (%)	**0.00**	**0.00**	**10.9**	**10.9**	**5.7937**	**4.49**
13	6.2	11.07	4206.5	610.5		
14	6.2	11.07	3170.0	460.1		
15	6.2	11.07	3031.0	439.9	0.0104	13788.51
16	6.2	11.07	3102.0	450.2	0.0109	14510.26
17	6.2	11.07	3356.5	487.2		
18	6.2	11.07	2692.0	390.7		
Average	**6.2**	**11.07**	**3259.7**	**473.1**	**0.0107**	**14149.4**
Std Dev	**0.00**	**0.00**	**512.5**	**74.4**	**0.0004**	**510.35**
CV (%)	**0.00**	**0.00**	**15.7**	**15.7**	**3.4697**	**3.61**

Table 3b. Volumetric and Mechanical Properties of Mixtures – Limerick, ME

Sample#	Asphalt Content (%)	Film Thickness (microns)	Aged Mr (MPa)	Aged Mr (ksi)	Tensile Strain @Failure	Fracture Energy (N-mm)
41	7.0	10.36	1520.0	220.6	0.0110	15507.86
42	7.0	10.36	1410.0	204.6		
43	7.0	10.36	1615.0	234.4		
44	7.0	10.36	1564.5	227.1	0.0108	14546.54
45	7.0	10.36	1395.0	202.5		
46	7.0	10.36	1614.0	234.3		
Average	**7.0**	**10.36**	**1519.8**	**220.6**	**0.0109**	**15027.2**
Std Dev	**0.0**	**0.00**	**97.5**	**14.2**	**0.0002**	**679.76**
CV (%)	**0.0**	**0.00**	**6.4**	**6.4**	**1.3816**	**4.52**
35	6.6	9.73	1690.5	245.4	0.0089	12096.57
36	6.6	9.73	1825.5	264.9	0.0103	14941.73
37	6.6	9.73	1678.0	243.5		
38	6.6	9.73	1955.5	283.8		
39	6.6	9.73	1667.0	241.9		
40	6.6	9.73	1861.0	270.1		
Average	**6.6**	**9.73**	**1779.6**	**258.3**	**0.0096**	**13519.1**
Std Dev	**0.0**	**0.00**	**118.8**	**17.2**	**0.0010**	**2011.83**
CV (%)	**0.0**	**0.00**	**6.7**	**6.7**	**10.0230**	**14.88**

(Table Continued)

Sample#	Asphalt Content (%)	Film Thickness (microns)	Aged Mr (MPa)	Aged Mr (ksi)	Tensile Strain @Failure	Fracture Energy (N-mm)
29	6.4	9.41	2064.0	299.6		
30	6.4	9.41	2271.0	329.6	0.0102	15144.75
31	6.4	9.41	2385.5	346.2		
32	6.4	9.41	2107.0	305.8		
33	6.4	9.41	2255.0	327.3	0.0082	missing
34	6.4	9.41	2303.5	334.3		
Average	**6.4**	**9.41**	**2231.0**	**323.8**	**0.0092**	**15144.7**
Std Dev	**0.0**	**0.00**	**122.1**	**17.7**	**0.0015**	
CV (%)	**0.0**	**0.00**	**5.5**	**5.5**	**15.7858**	
23	6.0	8.79	2714.5	394.0		
24	6.0	8.79	2400.5	348.4		
25	6.0	8.79	2481.5	360.2	0.0091	13938.21
26	6.0	8.79	2645.5	384.0	0.0090	15441.09
27	6.0	8.79	2695.0	391.1		
28	6.0	8.79	2347.5	340.7		
Average	**6.0**	**8.79**	**2547.4**	**369.7**	**0.0090**	**14689.7**
Std Dev	**0.0**	**0.00**	**158.2**	**23.0**	**0.0001**	**1062.70**
CV (%)	**0.0**	**0.00**	**6.2**	**6.2**	**0.7982**	**7.23**

Table 3c. Volumetric and Mechanical Properties of Mixtures – Belfast, ME

Sample#	Asphalt Content (%)	Film Thickness (microns)	Aged Mr (MPa)	Aged Mr (ksi)	Tensile Strain @Failure	Fracture Energy (N-mm)
11	6.3	11.95	3799.5	551.5	0.0087	19356.08
12	6.3	11.95	3027.5	439.4	0.0089	18254.28
13	6.3	11.95	2381.0	345.6	0.0093	17750.09
14	6.3	11.95	3096.5	449.4	0.0096	18511.30
15	6.3	11.95	2764.0	401.2	0.0094	17086.08
16	6.3	11.95	3033.5	440.3	0.0094	20360.56
Average	**6.3**	**11.95**	**3017.0**	**437.9**	**0.0092**	**18553.1**
Std Dev	**0.0**	**0.00**	**466.4**	**67.7**	**0.0004**	**1166.16**
CV (%)	**0.0**	**0.00**	**15.5**	**15.5**	**3.8299**	**6.29**
5	5.9	11.15	3027.5	439.4	0.0082	17828.80
6	5.9	11.15	3918.0	568.7	0.0083	21350.06
7	5.9	11.15	3086.0	447.9	0.0081	18134.44
8	5.9	11.15	3805.5	552.3	0.0093	20009.76
9	5.9	11.15	3282.0	476.3	0.0079	17769.66
10	5.9	11.15	2954.5	428.8	0.0081	16359.55
Average	**5.9**	**11.15**	**3345.6**	**485.6**	**0.0083**	**18575.4**
Std Dev	**0.0**	**0.00**	**415.9**	**60.4**	**0.0005**	**1792.61**
CV (%)	**0.0**	**0.00**	**12.4**	**12.4**	**5.8899**	**9.65**

(Table Continued)

Sample#	Asphalt Content (%)	Film Thickness (microns)	Aged Mr (MPa)	Aged Mr (ksi)	Tensile Strain @Failure	Fracture Energy (N-mm)
17	5.0	9.36	3492.0	506.8	0.0062	8274.16
18	5.0	9.36	3067.0	445.1	0.0072	10074.68
19	5.0	9.36	3021.0	438.5	0.0070	8721.03
20	5.0	9.36	3697.0	536.6	0.0065	10894.47
21	5.0	9.36	2603.5	377.9	0.0068	9240.96
22	5.0	9.36	2426.0	352.1	0.0078	8413.74
Average	**5.0**	**9.36**	**3051.1**	**442.8**	**0.0069**	**9269.8**
Std Dev	**0.0**	**0.00**	**490.7**	**71.2**	**0.0006**	**1030.87**
CV (%)	**0.0**	**0.00**	**16.1**	**16.1**	**8.1189**	**11.12**

Table 3d. Volumetric and Mechanical Properties of Mixtures – Campton, NH

Sample#	Asphalt Content (%)	Film Thickness (microns)	Aged Mr (MPa)	Aged Mr (ksi)	Tensile Strain @Failure	Fracture Energy (N-mm)
1	6.5	13.94	1919.5	278.6	0.0116	11748.39
2	6.5	13.94				
3	6.5	13.94				
4	6.5	13.94	2228.0	323.4	0.0095	13941.32
5	6.5	13.94	1886.0	273.7	0.0095	14585.30
Average	**6.5**	**13.94**	**2011.17**	**291.90**	**0.0102**	**13425.00**
Std Dev	**0.0**	**0.00**	**188.53**	**27.36**	**0.0013**	**1487.26**
CV (%)	**0.0**	**0.00**	**9.37**	**9.37**	**12.3609**	**11.08**
1	6.0	12.80	2052.0	297.8	0.0104	15535.28
2	6.0	12.80				
3	6.0	12.80				
4	6.0	12.80	2156.0	312.9	0.0103	14011.99
5	6.0	12.80	2374.5	344.6	0.0096	16240.62
Average	**6.0**	**12.80**	**2194.17**	**318.46**	**0.0101**	**15262.63**
Std Dev	**0.0**	**0.00**	**164.60**	**23.89**	**0.0004**	**1139.06**
CV (%)	**0.0**	**0.00**	**7.50**	**7.50**	**4.2513**	**7.46**
1	5.5	11.67	2769.5	402.0	0.0084	14455.13
2	5.5	11.67	3330.0	483.3	0.0078	14728.01
3	5.5	11.67				
4	5.5	11.67	3412.5	495.3	0.0074	15607.36
5	5.5	11.67				
Average	**5.5**	**11.67**	**3170.67**	**460.18**	**0.0079**	**14930.17**
Std Dev	**0.0**	**0.00**	**349.86**	**50.78**	**0.0005**	**602.13**
CV (%)	**0.0**	**0.00**	**11.03**	**11.03**	**6.3914**	**4.03**

(Table Continued)

Sample#	Asphalt Content (%)	Film Thickness (microns)	Aged Mr (MPa)	Aged Mr (ksi)	Tensile Strain @Failure	Fracture Energy (N-mm)
1	5.0	10.55	3169.0	459.9	0.0071	17186.61
2	5.0	10.55				
3	5.0	10.55	3067.0	445.1	0.0078	17338.43
4	5.0	10.55				
5	5.0	10.55	3331.5	22954.0	0.0075	13885.50
Average	**5.0**	**10.55**	**3189.17**	**7953.04**	**0.0075**	**16136.85**
Std Dev	**0.0**	**0.00**	**133.40**	**12991.25**	**0.0004**	**1951.20**
CV (%)	**0.0**	**0.00**	**4.18**	**163.35**	**4.9132**	**12.09**

Table 3e. Volumetric and Mechanical Properties of Mixtures – Swampscott, MA

Sample#	Asphalt Content (%)	Film Thickness (microns)	Aged Mr (MPa)	Aged Mr (ksi)	Tensile Strain @Failure	Fracture Energy (N-mm)
3	6.5	13.09	1520.0	Sample crumbled during LTOA		
4	6.5	13.09				
5	6.5	13.09	1805.0	262.0	0.0129	17921.4
6	6.5	13.09	1576.5	228.8	0.0162	15060.2
Average	**6.5**	**13.09**	**1690.75**	**245.39**	**0.0146**	**16490.81**
Std Dev	**0.0**	**0.00**	**161.57**	**23.45**	**0.0023**	**2023.15**
CV (%)	**0.0**	**0.00**	**9.56**	**9.56**	**15.7623**	**12.27**
3	6.0	12.01	2024.0	293.8	0.0126	16030.0
4	6.0	12.01				
5	6.0	12.01	2152.5	312.4	0.0107	16027.0
6	6.0	12.01				
7	6.0	12.01	1988.0	288.5	0.0113	17497.8
Average	**6.0**	**12.01**	**2054.83**	**298.23**	**0.0115**	**16518.27**
Std Dev	**0.0**	**0.00**	**86.48**	**12.55**	**0.0010**	**848.29**
CV (%)	**0.0**	**0.00**	**4.21**	**4.21**	**8.2984**	**5.14**
3	5.5	10.96				
4	5.5	10.96	2443.0	354.6	0.0098	14568.3
5	5.5	10.96	2389.5	346.8	0.0097	15284.3
6	5.5	10.96	2465.0	357.8	0.0104	13247.3
Average	**5.5**	**10.96**	**2432.50**	**353.05**	**0.0100**	**14366.62**
Std Dev	**0.0**	**0.00**	**38.83**	**5.64**	**0.0004**	**1033.40**
CV (%)	**0.0**	**0.00**	**1.60**	**1.60**	**3.8113**	**7.19**

(Table Continued)

Sample#	Asphalt Content (%)	Film Thickness (microns)	Aged Mr (MPa)	Aged Mr (ksi)	Tensile Strain @Failure	Fracture Energy (N-mm)
3	5.0	9.91				
4	5.0	9.91				
5	5.0	9.91	3356.0	487.1	0.0090	15997.7
6	5.0	9.91	2963.5	430.1	0.0081	15839.3
7	5.0	9.91	3133.5	454.8	0.0081	15252.8
Average	**5.0**	**9.91**	**3151.00**	**457.33**	**0.0084**	**15696.60**
Std Dev	**0.0**	**0.00**	**196.83**	**28.57**	**0.0005**	**392.46**
CV (%)	**0.0**	**0.00**	**6.25**	**6.25**	**6.5290**	**2.50**

Table 3f. Volumetric and Mechanical Properties of Mixtures – Presque Isle, ME

Sample#	Asphalt Content (%)	Film Thickness (microns)	Aged Mr (MPa)	Aged Mr (ksi)	Tensile Strain @Failure	Fracture Energy (N-mm)
1	6.5	12.55	2365.5	343.3	0.0112	22456.7
2	6.5	12.55				
3	6.5	12.55				
4	6.5	12.55	2863.0	415.5	0.0082	14602.5
5	6.5	12.55	2382.0	345.7	0.0106	15944.2
Average	**6.5**	**12.55**	**2536.83**	**368.19**	**0.0100**	**17667.80**
Std Dev	**0.0**	**0.00**	**282.59**	**41.01**	**0.0015**	**4201.24**
CV (%)	**0.0**	**0.00**	**11.14**	**11.14**	**15.4986**	**23.78**
1	6.0	11.52	2215.0	321.5	0.0097	15696.5
2	6.0	11.52	2577.5	374.1	0.0106	17974.5
3	6.0	11.52	2607.5	378.4	0.0093	16580.3
4	6.0	11.52				
5	6.0	11.52				
Average	**6.0**	**11.52**	**2466.67**	**358.01**	**0.0098**	**16750.42**
Std Dev	**0.0**	**0.00**	**218.47**	**31.71**	**0.0006**	**1148.50**
CV (%)	**0.0**	**0.00**	**8.86**	**8.86**	**6.5591**	**6.86**
1	5.5	10.51	3387.0	491.6	0.0083	14554.3
2	5.5	10.51				
3	5.5	10.51	3427.5	497.5	0.0083	15463.0
4	5.5	10.51	4648.5	674.7	0.0075	15068.7
5	5.5	10.51				
Average	**5.5**	**10.51**	**3821.00**	**554.57**	**0.0080**	**15028.66**
Std Dev	**0.0**	**0.00**	**716.92**	**104.05**	**0.0004**	**455.65**
CV (%)	**0.0**	**0.00**	**18.76**	**18.76**	**5.4129**	**3.03**

(Table Continued)

Sample#	Asphalt Content (%)	Film Thickness (microns)	Aged Mr (MPa)	Aged Mr (ksi)	Tensile Strain @Failure	Fracture Energy (N-mm)
1	5.0	9.50	3307.0	480.0	0.0076	15350.7
2	5.0	9.50				
3	5.0	9.50	3587.5	520.7	0.0077	15082.6
4	5.0	9.50	3911.0	567.6	0.0076	16200.5
5	5.0	9.50				
Average	**5.0**	**9.50**	**3601.83**	**522.76**	**0.0076**	**15544.60**
Std Dev	**0.0**	**0.00**	**302.25**	**43.87**	**0.0000**	**583.62**
CV (%)	**0.0**	**0.00**	**8.39**	**8.39**	**0.2974**	**3.75**

Table 3g. Volumetric and Mechanical Properties of Mixtures – Stonington, CT (Field Cores)

Sample#	**Asphalt Content (%)**	**Film Thickness (microns)**	**Aged Mr (MPa)**	**Aged Mr (ksi)**
Field Cores				
CT-1	5.2	9.84	3402.0	493.8
CT-2	5.1	9.66	5031.0	730.2
CT-3	5.2	9.82	3886.5	564.1
CT-4	5.2	9.82	3752.5	544.6
CT-5	Sample Uneven			
CT-6	5.1	9.64	4203.0	610.0
CT-7	5.4	10.22	3557.5	516.3
CT-8	Sample Uneven			
CT-9	5.2	9.88	4202.0	609.9
CT-10	5.4	10.30	4470.0	648.8
CT-11	5.3	10.04	5680.0	824.4
CT-12	5.6	10.54	4309.0	625.4
Laboratory Samples				
CT-S1	5.2	9.82		
CT-S12	5.2	9.82		

Table 3h. Volumetric and Mechanical Properties of Mixtures – Hancock, ME (Field Cores)

Sample#	**Asphalt Content (%)**	**Film Thickness (microns)**	**Aged Mr (MPa)**	**Aged Mr (ksi)**
Field Cores				
HCK1	6.30	11.74	2141.0	310.7
HCK2	6.30	11.74	1788.5	259.6
HCK3	6.30	11.74	1990.5	288.9
HCK4	6.30	11.74	1749.0	253.8
HCK5	6.30	11.74	2049.0	297.4
HCK6	6.30	11.74	1853.5	269.0
HCK7	6.30	11.74	1750.5	254.1
HCK8	6.30	11.74	1873.5	271.9
HCK9	6.30	11.74	1917.5	278.3
HCK10	6.30	11.74	1623.0	235.6
Laboratory Samples				
Agg-1	5.50	10.17		
Agg-2	5.50	10.17		

Table 4a. Volumetric and Mechanical Properties of Mixtures – Keene, NH

Sample#	**Asphalt Content (%)**	**VTM (%)**	**VMA (%)**	**Eff. VMA (%)**	**VFA (%)**	**Film Thickness (microns)**	**Eff. Film Thickness (microns)**	**Rutting at 4,000 cycles (mm)**
31	7.3	8.2	22.3	41.7	63.1	13.53	31.36	
32	7.3	8.3	22.3	41.8	62.9	13.53	31.36	
33	7.3	8.5	22.5	42.0	62.3	13.53	31.36	
34	7.3	6.7	21.0	39.9	68.0	13.53	31.36	
35	7.3	8.4	22.5	42.0	62.4	13.53	31.36	
36	7.3	9.9	23.7	43.7	58.2	13.53	31.36	
Average	**7.3**	**8.3**	**22.4**	**41.9**	**62.8**	**13.53**	**31.36**	
Std Dev	**0.0**	**1.01**	**0.85**	**1.20**	**3.10**	**0.00**	**0.00**	
CV (%)	**0.0**	**12.08**	**3.81**	**2.86**	**4.94**	**0.00**	**0.00**	
25	6.8	11.8	24.3	44.5	51.6	12.41	28.90	
26	6.8	9.1	22.0	41.4	58.7	12.41	28.90	
27	6.8	10.0	22.8	42.5	56.0	12.41	28.90	
28	6.8	8.6	21.6	40.7	60.3	12.41	28.90	
29	6.8	10.0	22.8	42.5	56.0	12.41	28.90	
30	6.8	7.1	20.3	38.9	65.0	12.41	28.90	
Average	**6.8**	**9.4**	**22.3**	**41.8**	**57.9**	**12.41**	**28.90**	
Std Dev	**0.0**	**1.58**	**1.35**	**1.90**	**4.55**	**0.00**	**0.00**	
CV (%)	**0.0**	**16.72**	**6.07**	**4.55**	**7.86**	**0.00**	**0.00**	

(Table Continued)

Sample#	**Asphalt Content (%)**	**VTM (%)**	**VMA (%)**	**Eff. VMA (%)**	**VFA (%)**	**Film Thickness (microns)**	**Eff. Film Thickness (microns)**	**Rutting at 4,000 cycles (mm)**
19	6.6	8.5	21.2	40.2	59.9	12.08	28.20	
20	6.6	8.3	21.0	40.0	60.6	12.08	28.20	
21	6.6	9.0	21.7	40.9	58.3	12.08	28.20	
22	6.6	7.6	20.4	39.0	62.9	12.08	28.20	
23	6.6	8.1	20.9	39.7	61.1	12.08	28.20	
24	6.6	7.7	20.5	39.2	62.6	12.08	28.20	
Average	**6.6**	**8.2**	**20.9**	**39.8**	**60.9**	**12.08**	**28.20**	**5.56**
Std Dev	**0.0**	**0.55**	**0.47**	**0.68**	**1.72**	**0.00**	**0.00**	
CV (%)	**0.0**	**6.68**	**2.25**	**1.71**	**2.83**	**0.00**	**0.00**	
13	6.2	7.7	19.6	37.9	60.6	11.07	25.96	
14	6.2	7.4	19.4	37.5	61.6	11.07	25.96	
15	6.2	6.2	18.3	35.9	65.9	11.07	25.96	
16	6.2	7.2	19.2	37.2	62.4	11.07	25.96	
17	6.2	8.1	19.9	38.3	59.5	11.07	25.96	
18	6.2	7.7	19.6	37.8	60.8	11.07	25.96	
Average	**6.2**	**7.4**	**19.3**	**37.4**	**61.8**	**11.07**	**25.96**	**4.39**
Std Dev	**0.0**	**0.63**	**0.55**	**0.83**	**2.24**	**0.00**	**0.00**	
CV (%)	**0.0**	**8.53**	**2.84**	**2.22**	**3.62**	**0.00**	**0.00**	

Table 4b. Volumetric and Mechanical Properties of Mixtures – Limerick, ME

Sample#	Asphalt Content (%)	VTM (%)	VMA (%)	Eff. VMA (%)	VFA (%)	Film Thickness (microns)	Eff. Film Thickness (microns)	Rutting at 4,000 cycles (mm)
41	7.0	7.6	23.5	33.1	67.8	10.36	16.64	8.93
42	7.0	7.3	23.3	32.9	68.6	10.36	16.64	7.84
43	7.0	7.5	23.4	33.0	68.0	10.36	16.64	9.85
44	7.0	7.5	23.4	33.0	68.0	10.36	16.64	7.13
45	7.0	7.4	23.3	32.9	68.4	10.36	16.64	
46	7.0	7.6	23.5	33.2	67.6	10.36	16.64	
Average	**7.0**	**7.5**	**23.4**	**33.0**	**68.1**	**10.36**	**16.64**	**8.44**
Std Dev	**0.0**	**0.12**	**0.10**	**0.12**	**0.37**	**0.00**	**0.00**	**1.20**
CV (%)	**0.0**	**1.57**	**0.41**	**0.36**	**0.54**	**0.00**	**0.00**	**14.19**
35	6.6	8.5	23.5	33.1	63.9	9.73	15.77	8.17
36	6.6	8.1	23.2	32.7	65.1	9.73	15.77	5.38
37	6.6	8.3	23.3	32.9	64.6	9.73	15.77	6.85
38	6.6	7.8	22.9	32.4	66.1	9.73	15.77	4.16
39	6.6	7.1	22.4	31.7	68.1	9.73	15.77	
40	6.6	8.0	23.1	32.6	65.4	9.73	15.77	
Average	**6.6**	**8.0**	**23.1**	**32.6**	**65.5**	**9.73**	**15.77**	**6.14**
Std Dev	**0.0**	**0.47**	**0.39**	**0.49**	**1.47**	**0.00**	**0.00**	**1.74**
CV (%)	**0.0**	**5.90**	**1.70**	**1.49**	**2.24**	**0.00**	**0.00**	**28.41**

(Table Continued)

Sample#	Asphalt Content (%)	VTM (%)	VMA (%)	Eff. VMA (%)	VFA (%)	Film Thickness (microns)	Eff. Film Thickness (microns)	Rutting at 4,000 cycles (mm)
29	6.4	7.6	22.4	31.8	65.9	9.41	15.32	
30	6.4	8.1	22.8	32.2	64.6	9.41	15.32	
31	6.4	7.4	22.2	31.5	66.8	9.41	15.32	
32	6.4	7.4	22.2	31.5	66.8	9.41	15.32	
33	6.4	7.5	22.3	31.6	66.3	9.41	15.32	
34	6.4	7.6	22.4	31.7	66.0	9.41	15.32	
Average	**6.4**	**7.6**	**22.4**	**31.7**	**66.1**	**9.41**	**15.32**	
Std Dev	**0.0**	**0.26**	**0.22**	**0.27**	**0.83**	**0.00**	**0.00**	
CV (%)	**0.0**	**3.44**	**0.98**	**0.86**	**1.25**	**0.00**	**0.00**	
23	6.0	7.2	21.3	30.3	66.2	8.79	14.45	
24	6.0	8.3	22.2	31.5	62.7	8.79	14.45	
25	6.0	8.2	22.1	31.4	62.8	8.79	14.45	
26	6.0	8.2	22.1	31.4	62.9	8.79	14.45	
27	6.0	7.8	21.8	31.0	64.2	8.79	14.45	
28	6.0	8.2	22.1	31.4	62.8	8.79	14.45	
Average	**6.0**	**8.0**	**21.9**	**31.2**	**63.6**	**8.79**	**14.45**	
Std Dev	**0.0**	**0.43**	**0.36**	**0.46**	**1.37**	**0.00**	**0.00**	
CV (%)	**0.0**	**5.36**	**1.65**	**1.46**	**2.16**	**0.00**	**0.00**	

Table 4c. Volumetric and Mechanical Properties of Mixtures – Belfast, ME

Sample#	**Asphalt Content (%)**	**VTM (%)**	**VMA (%)**	**Eff. VMA (%)**	**VFA (%)**	**Film Thickness (microns)**	**Eff. Film Thickness (microns)**	**Rutting at 4,000 cycles (mm)**
11	6.3	6.8	18.9	33.1	63.9	11.95	20.04	
12	6.3	7.2	19.2	33.6	62.6	11.95	20.04	
13	6.3	7.6	19.5	34.1	61.3	11.95	20.04	
14	6.3	6.2	18.4	32.4	66.2	11.95	20.04	
15	6.3	6.9	18.9	33.2	63.8	11.95	20.04	
16	6.3	6.4	18.5	32.6	65.4	11.95	20.04	
Average	**6.3**	**6.8**	**18.9**	**33.2**	**63.9**	**11.95**	**20.04**	**6.03**
Std Dev	**0.0**	**0.49**	**0.43**	**0.62**	**1.78**	**0.00**	**0.00**	
CV (%)	**0.0**	**7.22**	**2.27**	**1.87**	**2.79**	**0.00**	**0.00**	
5	5.9	7.1	18.3	32.3	61.1	11.15	18.53	
6	5.9	6.3	17.6	31.3	64.1	11.15	18.53	
7	5.9	6.5	17.8	31.5	63.4	11.15	18.53	
8	5.9	6.7	18.0	31.8	62.5	11.15	18.53	
9	5.9	7.6	18.7	32.9	59.4	11.15	18.53	
10	5.9	8.1	19.2	33.6	57.7	11.15	18.53	
Average	**5.9**	**7.1**	**18.3**	**32.2**	**61.4**	**11.15**	**18.53**	**4.82**
Std Dev	**0.0**	**0.69**	**0.61**	**0.88**	**2.46**	**0.00**	**0.00**	
CV (%)	**0.0**	**9.75**	**3.32**	**2.74**	**4.01**	**0.00**	**0.00**	

(Table Continued)

Sample#	**Asphalt Content (%)**	**VTM (%)**	**VMA (%)**	**Eff. VMA (%)**	**VFA (%)**	**Film Thickness (microns)**	**Eff. Film Thickness (microns)**	**Rutting at 4,000 cycles (mm)**
17	5.0	8.4	17.6	31.2	52.0	9.36	15.12	
18	5.0	8.2	17.4	30.4	52.8	9.36	14.80	
19	5.0	6.1	15.5	27.2	60.5	9.36	14.50	
20	5.0	7.4	16.7	28.6	55.4	9.36	14.21	
21	5.0	8.0	17.2	28.9	53.5	9.36	13.93	
22	5.0	7.3	16.6	27.7	55.7	9.36	13.67	
Average	**5.0**	**7.6**	**16.8**	**29.0**	**55.0**	**9.36**	**14.37**	**3.52**
Std Dev	**0.0**	**0.84**	**0.75**	**1.56**	**3.08**	**0.00**	**0.54**	
CV (%)	**0.0**	**11.03**	**4.49**	**5.37**	**5.60**	**0.00**	**3.78**	

Table 4d. Volumetric and Mechanical Properties of Mixtures – Campton, NH

Sample#	**Asphalt Content (%)**	**VTM (%)**	**VMA (%)**	**Eff. VMA (%)**	**VFA (%)**	**Film Thickness (microns)**	**Eff. Film Thickness (microns)**	**Rutting at 4,000 cycles (mm)**
1	6.5	8.0	21.4	39.3	62.5	13.94	29.17	
2	6.5	7.5	20.9	38.6	64.3	13.94	29.17	
3	6.5	7.6	21.0	38.7	63.9	13.94	29.17	
4	6.5	6.8	20.3	37.7	66.7	13.94	29.17	
5	6.5	8.2	21.5	39.5	61.8	13.94	29.17	
Average	**6.5**	**7.6**	**21.0**	**38.8**	**63.8**	**13.94**	**29.17**	**5.86**
Std Dev	**0.0**	**0.54**	**0.48**	**0.70**	**1.89**	**0.00**	**0.00**	
CV (%)	**0.0**	**7.09**	**2.27**	**1.80**	**2.97**	**0.00**	**0.00**	
1	6.0	8.1	20.4	37.9	60.4	12.80	26.78	
2	6.0	7.8	20.1	37.5	61.5	12.80	26.78	
3	6.0	7.5	19.9	37.2	62.3	12.80	26.78	
4	6.0	7.3	19.8	37.0	62.9	12.80	26.78	
5	6.0	7.1	19.5	36.6	63.9	12.80	26.78	
Average	**5.0**	**7.6**	**19.9**	**37.2**	**62.2**	**12.80**	**26.78**	**5.80**
Std Dev	**0.0**	**0.40**	**0.34**	**0.50**	**1.33**	**0.00**	**0.00**	
CV (%)	**0.0**	**5.26**	**1.69**	**1.34**	**2.14**	**0.00**	**0.00**	
1	5.5	8.4	19.7	36.9	57.2	11.67	24.38	
2	5.5	8.1	19.4	36.4	58.3	11.67	24.38	
3	5.5	8.1	19.4	36.5	58.2	11.67	24.38	
4	5.5	8.3	19.6	36.7	57.5	11.67	24.38	
5	5.5	8.0	19.3	36.4	58.5	11.67	24.38	
Average	**5.5**	**8.2**	**19.5**	**36.6**	**57.9**	**11.67**	**24.38**	**4.79**
Std Dev	**0.0**	**0.16**	**0.16**	**0.22**	**0.56**	**0.00**	**0.00**	
CV (%)	**0.0**	**2.01**	**0.84**	**0.60**	**0.97**	**0.00**	**0.00**	

(Table Continued)

Sample#	Asphalt Content (%)	VTM (%)	VMA (%)	Eff. VMA (%)	VFA (%)	Film Thickness (microns)	Eff. Film Thickness (microns)	Rutting at 4,000 cycles (mm)
1	5.0	8.8	19.0	35.8	53.6	10.55	21.98	
2	5.0	8.4	18.7	35.3	54.8	10.55	21.98	
3	5.0	8.6	18.8	35.5	54.4	10.55	21.98	
4	5.0	8.5	18.7	35.4	54.6	10.55	21.98	
5	5.0	8.6	18.8	35.6	54.3	10.55	21.98	
Average	**5.0**	**8.6**	**18.8**	**35.5**	**54.3**	**10.55**	**21.98**	**5.87**
Std Dev	**0.0**	**0.15**	**0.12**	**0.19**	**0.46**	**0.00**	**0.00**	
CV (%)	**0.0**	**1.73**	**0.65**	**0.54**	**0.84**	**0.00**	**0.00**	

Table 4e. Volumetric and Mechanical Properties of Mixtures – Swampscott, MA

Sample#	**Asphalt Content (%)**	**VTM (%)**	**VMA (%)**	**Eff. VMA (%)**	**VFA (%)**	**Film Thickness (microns)**	**Eff. Film Thickness (microns)**	**Rutting at 4,000 cycles (mm)**
3	6.5	8.4	21.3	36.6	60.6	13.09	22.92	
4	6.5	9.3	22.1	37.7	58.0	13.09	22.92	
5	6.5	7.8	20.9	35.9	62.4	13.09	22.92	
6	6.5	8.2	21.2	36.4	61.2	13.09	22.92	
Average	**6.5**	**8.4**	**21.4**	**36.6**	**60.6**	**13.09**	**22.92**	**5.90**
Std Dev	**0.0**	**0.63**	**0.51**	**0.73**	**1.86**	**0.00**	**0.00**	
CV (%)	**0.0**	**7.53**	**2.40**	**1.99**	**3.07**	**0.00**	**0.00**	
3	6.0	8.1	20.0	34.7	59.7	12.01	20.90	
4	6.0	7.9	19.9	34.5	60.2	12.01	20.90	
5	6.0	8.1	20.1	34.8	59.5	12.01	20.90	
6	6.0	8.3	20.2	35.0	59.0	12.01	20.90	
7	6.0	8.5	20.4	35.3	58.4	12.01	20.90	
Average	**6.0**	**8.2**	**20.1**	**34.9**	**59.4**	**12.01**	**20.90**	**5.99**
Std Dev	**0.0**	**0.23**	**0.19**	**0.28**	**0.69**	**0.00**	**0.00**	
CV (%)	**0.0**	**2.79**	**0.96**	**0.79**	**1.16**	**0.00**	**0.00**	
3	5.5	9.1	19.9	34.6	54.0	10.96	18.88	
4	5.5	8.8	19.6	33.6	55.1	10.96	18.49	
5	5.5	8.1	19.0	32.4	57.2	10.96	18.11	
6	5.5	8.4	19.2	32.2	56.5	10.96	17.75	
Average	**5.5**	**8.6**	**19.4**	**33.2**	**55.7**	**10.96**	**18.31**	**6.03**
Std Dev	**0.0**	**0.44**	**0.40**	**1.12**	**1.43**	**0.00**	**0.49**	
CV (%)	**0.0**	**5.11**	**2.08**	**3.36**	**2.57**	**0.00**	**2.66**	

(Table Continued)

Sample#	**Asphalt Content (%)**	**VTM (%)**	**VMA (%)**	**Eff. VMA (%)**	**VFA (%)**	**Film Thickness (microns)**	**Eff. Film Thickness (microns)**	**Rutting at 4,000 cycles (mm)**
3	5.0	9.2	18.9	33.1	51.2	9.91	16.86	
4	5.0	8.3	18.1	31.9	54.0	9.91	16.86	
5	5.0	9.0	18.6	32.8	52.0	9.91	16.86	
6	5.0	7.7	17.6	31.2	56.0	9.91	16.86	
7	5.0	8.5	18.2	32.1	53.5	9.91	16.86	
Average	**5.0**	**8.5**	**18.3**	**32.2**	**53.3**	**9.91**	**16.86**	**3.99**
Std Dev	**0.0**	**0.59**	**0.50**	**0.77**	**1.86**	**0.00**	**0.00**	
CV (%)	**0.0**	**6.96**	**2.72**	**2.38**	**3.50**	**0.00**	**0.00**	

Table 4f. Volumetric and Mechanical Properties of Mixtures – Presque Isle, ME

Sample#	**Asphalt Content (%)**	**VTM (%)**	**VMA (%)**	**Eff. VMA (%)**	**VFA (%)**	**Film Thickness (microns)**	**Eff. Film Thickness (microns)**	**Rutting at 4,000 cycles (mm)**
1	6.5	8.3	21.1	35.3	60.8	12.55	21.59	
2	6.5	8.1	21.0	35.1	61.4	12.55	21.59	
3	6.5	8.2	21.1	35.3	61.0	12.55	21.59	
4	6.5	8.2	21.1	35.2	61.0	12.55	21.59	
5	6.5	8.3	21.1	35.3	60.9	12.55	21.59	
Average	**6.5**	**8.2**	**21.1**	**35.3**	**61.0**	**12.55**	**21.59**	**4.96**
Std Dev	**0.0**	**0.08**	**0.04**	**0.09**	**0.23**	**0.00**	**0.00**	
CV (%)	**0.0**	**1.02**	**0.21**	**0.25**	**0.37**	**0.00**	**0.00**	
1	6.0	8.7	20.5	34.5	57.4	11.52	19.74	
2	6.0	8.8	20.5	34.5	57.3	11.52	19.74	
3	6.0	8.3	20.1	34.0	58.6	11.52	19.74	
4	6.0	8.2	20.0	33.8	59.1	11.52	19.74	
5	6.0	8.2	20.0	33.8	59.1	11.52	19.74	
Average	**6.0**	**8.4**	**20.2**	**34.1**	**58.3**	**11.52**	**19.74**	**4.36**
Std Dev	**0.0**	**0.29**	**0.26**	**0.35**	**0.89**	**0.00**	**0.00**	
CV (%)	**0.0**	**3.41**	**1.28**	**1.01**	**1.53**	**0.00**	**0.00**	
1	5.5	8.0	18.8	32.1	57.6	10.51	17.88	
2	5.5	8.3	19.1	32.6	56.4	10.51	17.88	
3	5.5	8.7	19.4	33.0	55.3	10.51	17.88	
4	5.5	8.7	19.4	33.0	55.3	10.51	17.88	
5	5.5	8.3	19.1	32.6	56.4	10.51	17.88	
Average	**5.5**	**8.4**	**19.2**	**32.6**	**56.2**	**10.51**	**17.88**	**4.42**
Std Dev	**0.0**	**0.30**	**0.25**	**0.38**	**0.96**	**0.00**	**0.00**	
CV (%)	**0.0**	**3.57**	**1.31**	**1.15**	**1.70**	**0.00**	**0.00**	

(Table Continued)

Sample#	**Asphalt Content (%)**	**VTM (%)**	**VMA (%)**	**Eff. VMA (%)**	**VFA (%)**	**Film Thickness (microns)**	**Eff. Film Thickness (microns)**	**Rutting at 4,000 cycles (mm)**
1	5.0	8.7	18.4	31.6	52.6	9.50	16.03	
2	5.0	8.5	18.2	31.2	53.4	9.50	16.03	
3	5.0	8.7	18.4	31.5	52.7	9.50	16.03	
4	5.0	8.6	18.3	31.3	53.1	9.50	16.03	
5	5.0	8.5	18.3	31.3	53.2	9.50	16.03	
Average	**5.0**	**8.6**	**18.3**	**31.4**	**53.0**	**9.50**	**16.03**	**4.10**
Std Dev	**0.0**	**0.10**	**0.08**	**0.14**	**0.34**	**0.00**	**0.00**	
CV (%)	**0.0**	**1.16**	**0.46**	**0.45**	**0.64**	**0.00**	**0.00**	

Table 4g. Volumetric and Mechanical Properties of Mixtures – Stonington, CT (Field Cores)

Sample#	Asphalt Content (%)	VTM (%)	VMA (%)	VFA (%)	Film Thickness (microns)
Field Cores					
CT-1	5.2	7.0	18.6	62.6	9.84
CT-2	5.1	4.8	16.6	71.1	9.66
CT-3	5.2	4.8	16.5	70.7	9.82
CT-4	5.2	4.4	16.3	73.2	9.82
CT-5	Sample Uneven				
CT-6	5.1	7.2	18.7	61.7	9.64
CT-7	5.4	6.1	18.3	66.7	10.22
CT-8	Sample Uneven				
CT-9	5.2	7.1	18.8	62.3	9.88
CT-10	5.4	5.8	18.1	68.0	10.30
CT-11	5.3	6.5	18.3	64.5	10.04
CT-12	5.6	7.7	20.0	61.6	10.54
Laboratory Samples					
CT-S1	5.2	7.2	18.8	61.7	9.82
CT-S12	5.2	6.6	18.3	63.8	9.82

Table 4h. Volumetric and Mechanical Properties of Mixtures – Hancock, ME (Field Cores)

Sample#	**Asphalt Content (%)**	**VTM (%)**	**VMA (%)**	**VFA (%)**	**Film Thickness (microns)**
Field Cores					
HCK1	6.30	1.2	16.0	92.5	11.74
HCK2	6.30	1.3	16.1	92.0	11.74
HCK3	6.30	1.6	16.4	90.2	11.74
HCK4	6.30	1.8	16.5	89.2	11.74
HCK5	6.30	1.4	16.2	91.2	11.74
HCK6	6.30	1.5	16.3	90.7	11.74
HCK7	6.30	1.6	16.4	90.4	11.74
HCK8	6.30	1.6	16.4	90.4	11.74
HCK9	6.30	1.4	16.2	91.2	11.74
HCK10	6.30	1.7	16.5	89.6	11.74
Laboratory Samples					
Agg-1	5.50	0.2	14.6	98.3	13.35
Agg-2	5.50	0.7	15.0	95.1	13.35