Design of Superpave HMA for Low Volume Roads

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16. Abstract

The Superpave mix design system is being adopted by most of the states in the United 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 research was carried out to develop a proper mix design system for low volume roads from the standpoint of durability 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. Three 9.5 mm NMAS two 12.5 mm NMAS fine graded mixes were tested during this research. Based on the results from performance testing, film thickness of 11 microns in samples compacted to 7 percent voids were found to be desirable from a stability and durability standpoint. A design VMA of 16 percent was determined to be optimum value 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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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
		AREA		
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	mililitres	mL
gal	gallons	3.785	Litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
^oF	Fahrenheit temperature	5(F-32)/9	Celcius temperature	^oC

* SI is the symbol for the International System of Measurement

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
		AREA		
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2
		VOLUME		
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C+32	Fahrenheit temperature	°F

°F

°F 32 98.6 212

-40 0 40 80 120 180 200

-40 -20 0 20 40 60 80 100

°C 37 °C

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1.0 Introduction

The Departments of Transportation (DOT) offices of the six New England states are in the process of implementing the Superpave mix design system for 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 specimens and in-place cores from a limited number of pavements with different traffic levels in different climatic zones (1). These were 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 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.

1.1 Objectives of Research

The objective of this study was to develop a mix design system for Superpave HMA for low volume roads. More specifically the main objectives were to:

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

2.0 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.

2.1 Literature Review

A review of literature showed that a proper amount of asphalt binder is required for adequate durability. This proper amount of asphalt binder can be provided by allowing adequate space in the aggregate structure and by compacting the mix design specimens 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 specimens 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).

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. 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.

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? A review of existing literature does not provide any information to answer this question. Hence, any ram pressure other than 600 kPa will be an arbitrary choice.

The next option is to evaluate the effect of number of gyrations and determine a desirable number of gyration 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.

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, 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 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 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.

2.2 Scope

The is 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 re-compaction 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. 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

4. Analyzed the data and determined the effect of asphalt content and other volumetric properties on the properties determined in step 3.

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

6. 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 1 and Figure 2 respectively.

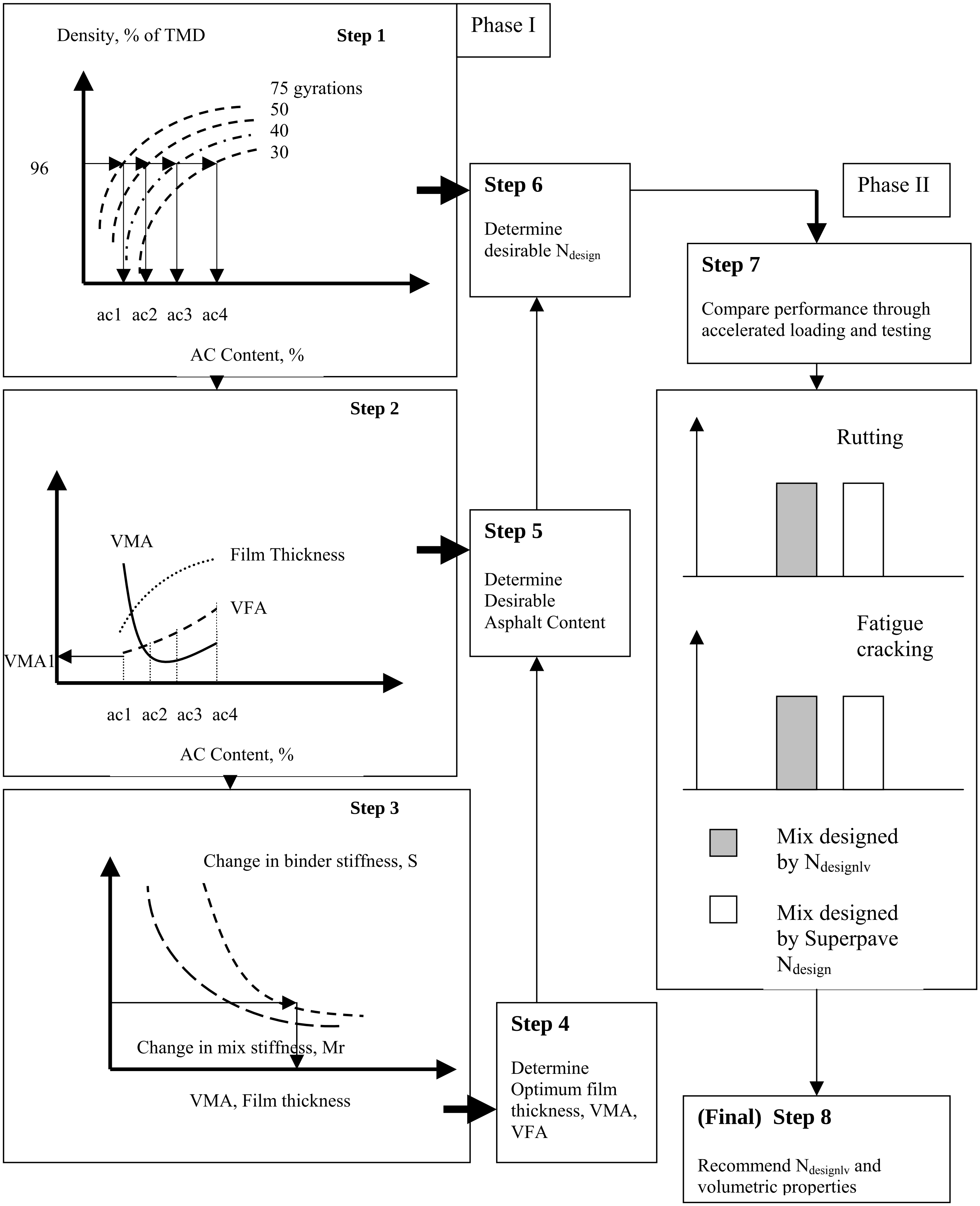

Figure 1: Proposed Study Approach

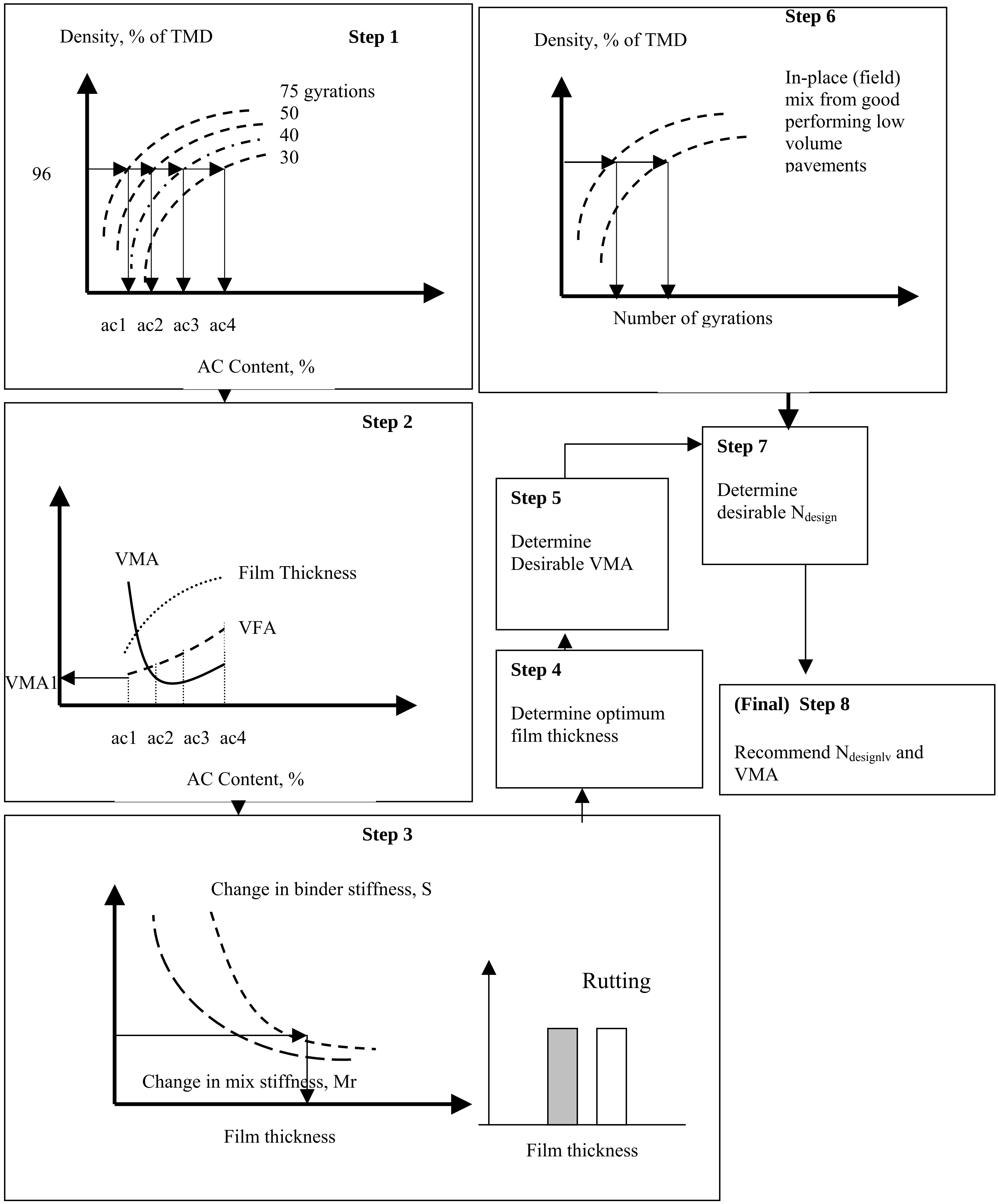

Figure 2: Actual Study Approach

2.3 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 draindown 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 3. The terms used in Figure 3, for labeling the different mixes have been used in subsequent chapters in this report.

Using PG 64-28 asphalt binder, mixes were prepared and compacted with the selected gyration numbers to produce specimens with 4 percent air voids, and the optimum asphalt contents were determined. Samples were then compacted to construction voids (approximately 7 to 8 percent Voids in Total Mix, VTM). Note that the target VTM was 7 ± 1 percent. The specimens were then tested for bulk specific gravity, and using the theoretical maximum gravity (tested in the laboratory for each mix) volumetric properties, namely, VTM, VMA and asphalt film thickness were determined.

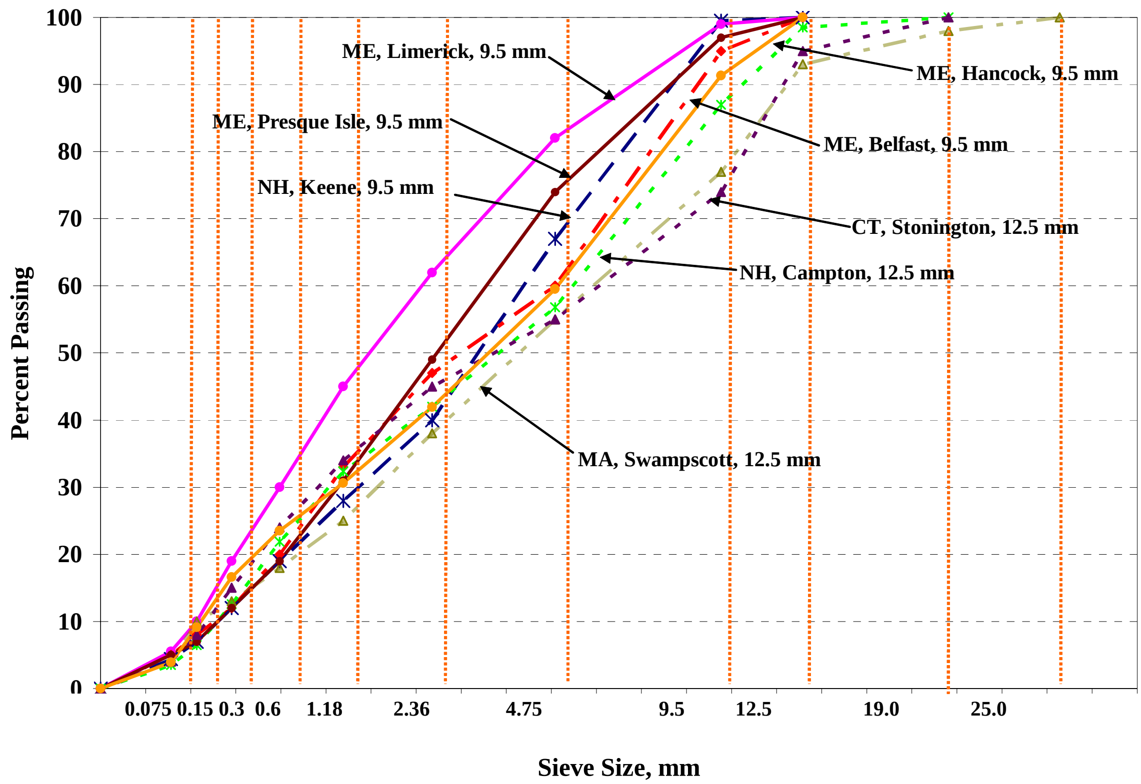

Figure 3: Gradations of Mixes

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

Samples were tested for resilient modulus and then conditioned for long term aging, using the AASHTO TP2 procedure. At the end of conditioning, the samples were tested for resilient modulus, and then tested for tensile strain at failure. The asphalt binder was extracted from the long-term aged samples and tested for stiffness (using dynamic shear rheometer) at 64^{o}C. Samples at selected asphalt contents were also tested with the Asphalt Pavement Analyzer (APA), for evaluation of rutting potential. 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.

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 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}.

2.4 Acronyms and Definitions

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 Sin of phase angle, δ

Long term aging (AASHTO TP2) - American Association of State Highway and Transportation Officials (AASHTO) TP2 long term aging protocol, 120 hours in a forced draft oven at 85°C

3.0 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.

3.1 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. Despite 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.

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 potentials for 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 a 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 following 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.

3.2 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. Thus, 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 4, 5 and 6 show plots of asphalt content versus film thickness, asphalt content versus VMA and film thickness versus VMA, respectively.

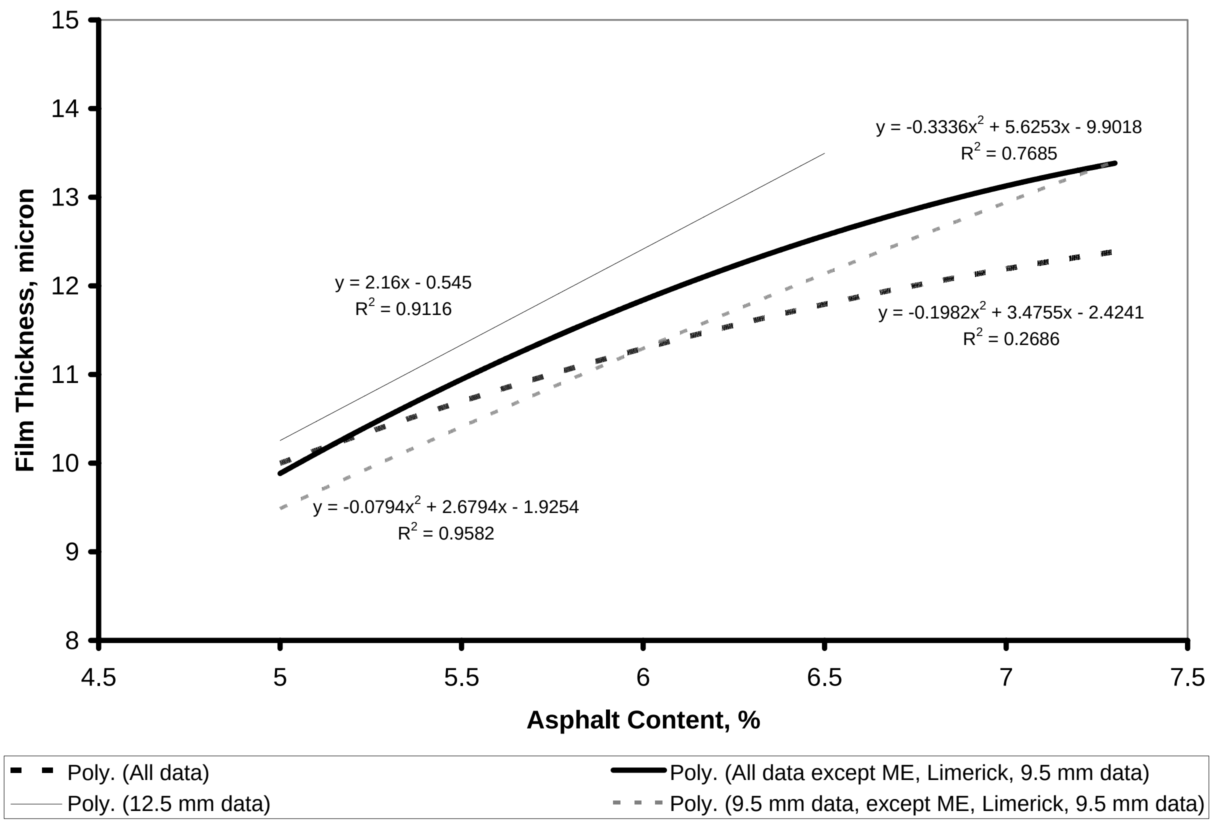

Figure 4: Asphalt Content vs. Film Thickness

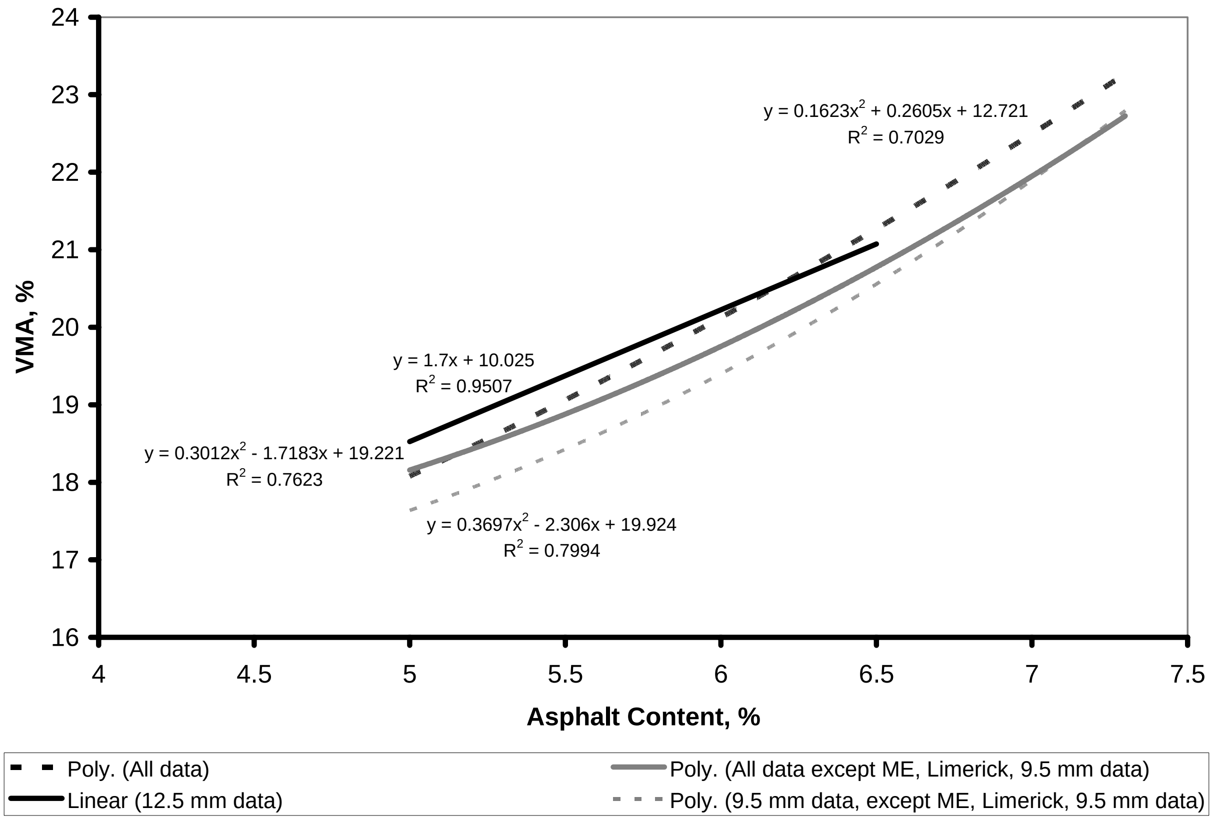

Figure 5: Asphalt Content vs. Voids in Mineral Aggregate (VMA)

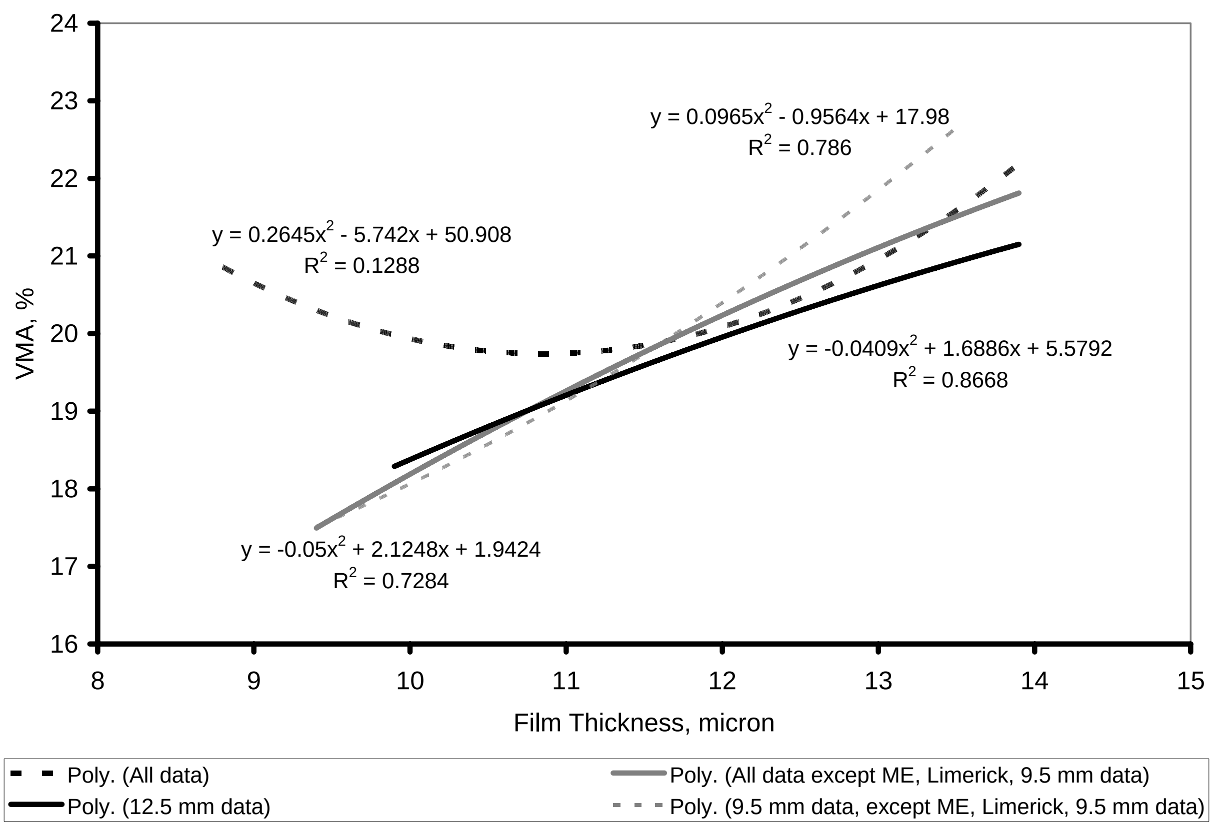

Figure 6: Film Thickness vs. Voids in Mineral Aggregate (VMA)

It is evident from Figure 4, 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 4 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.

Note in Figure 4, 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, specific changes in asphalt content causes different changes in film thickness for the different mixes. Similar conclusions can be drawn from Figures 5 and 6, 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.

3.3 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.

3.3.1 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 7 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.

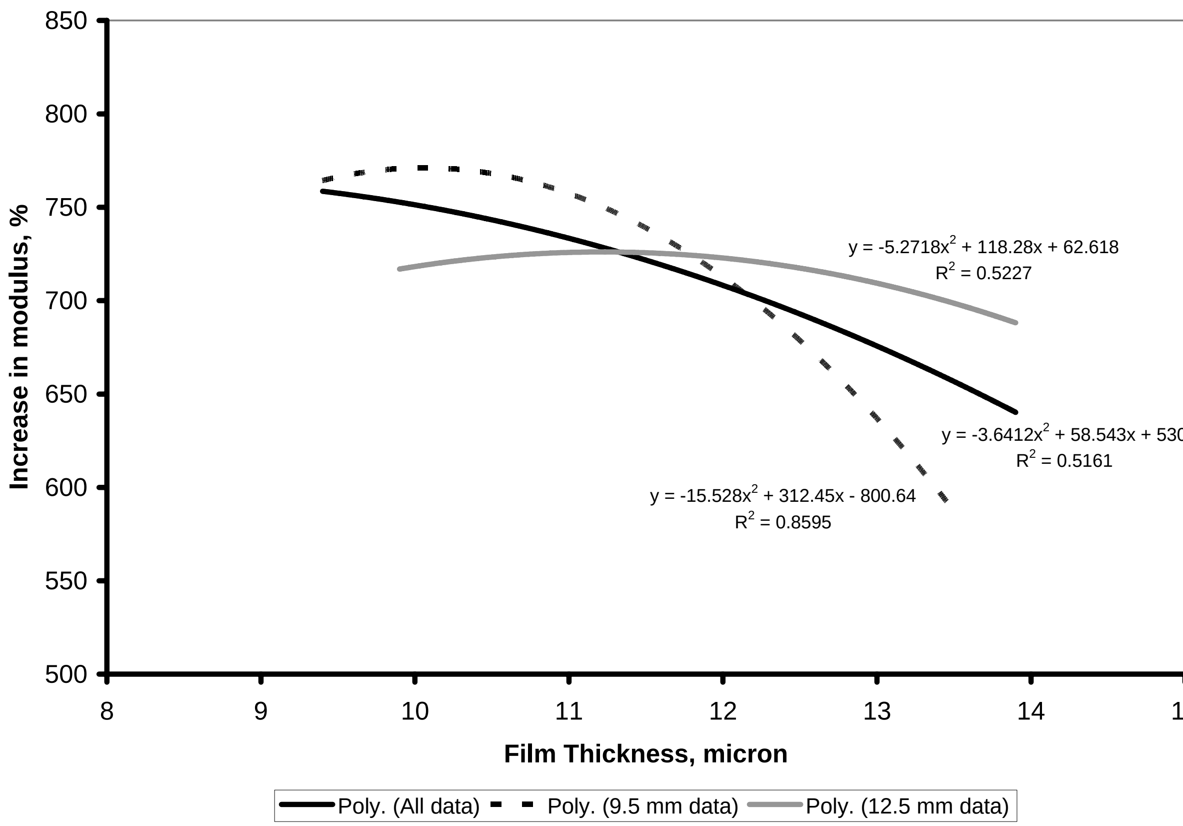

Figure 7: Film Thickness vs. Increase in Modulus

Figure 8 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 9 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.

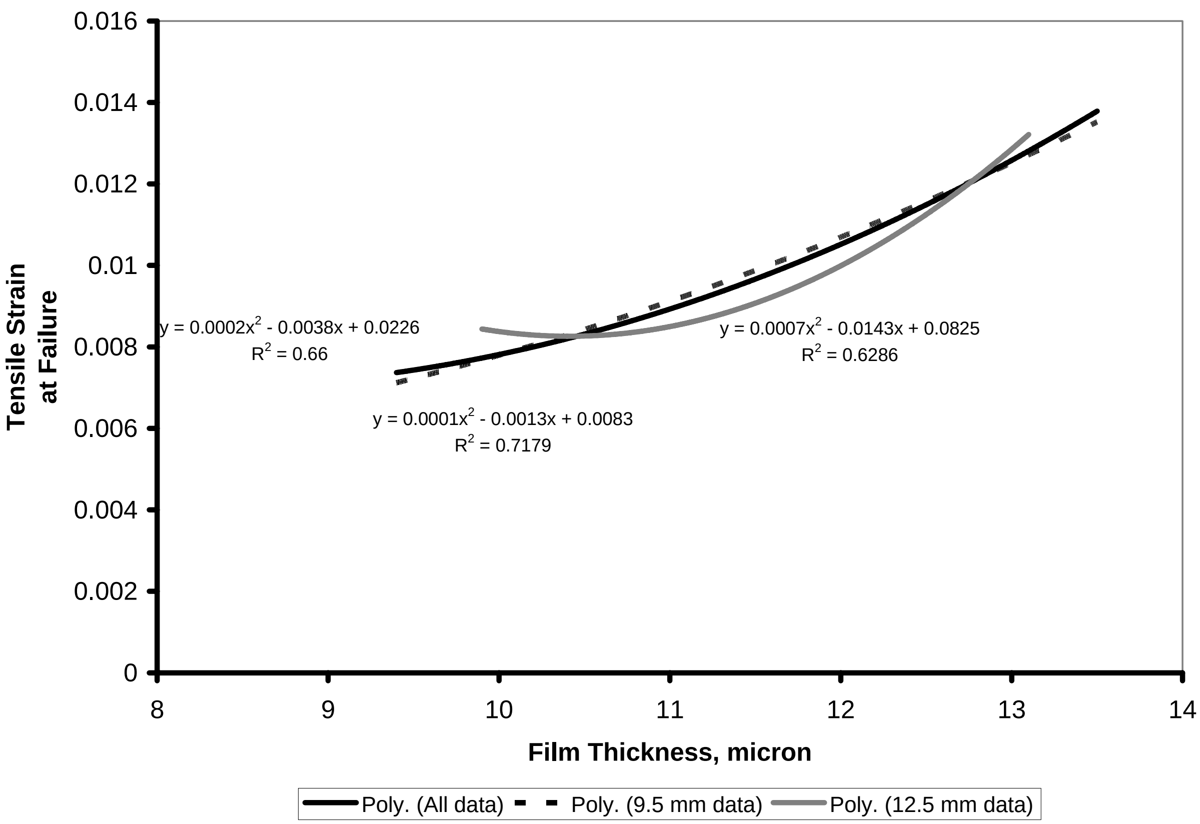

Figure 8: Film Thickness vs. Tensile Strain at Failure

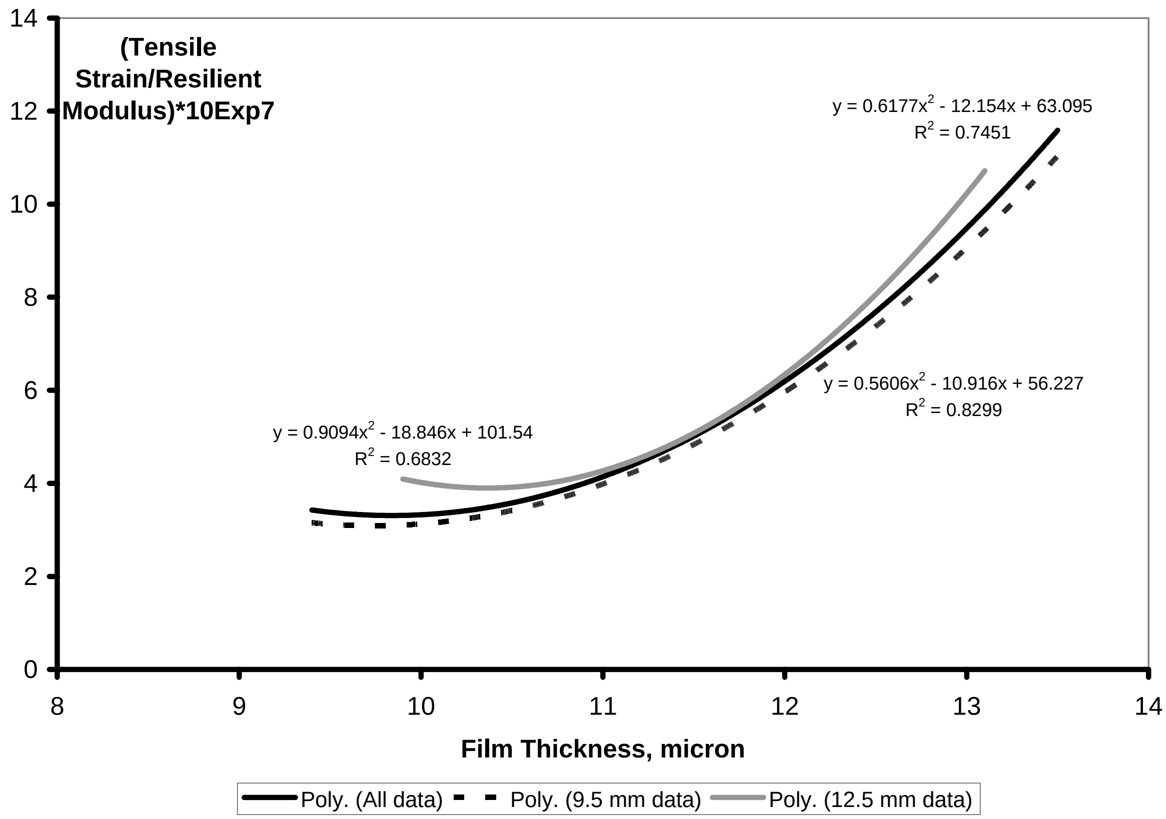

Figure 9: Film Thickness vs. Tensile Strain/Resilient Modulus

3.3.2 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 10, 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.

3.3.3 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 11 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).

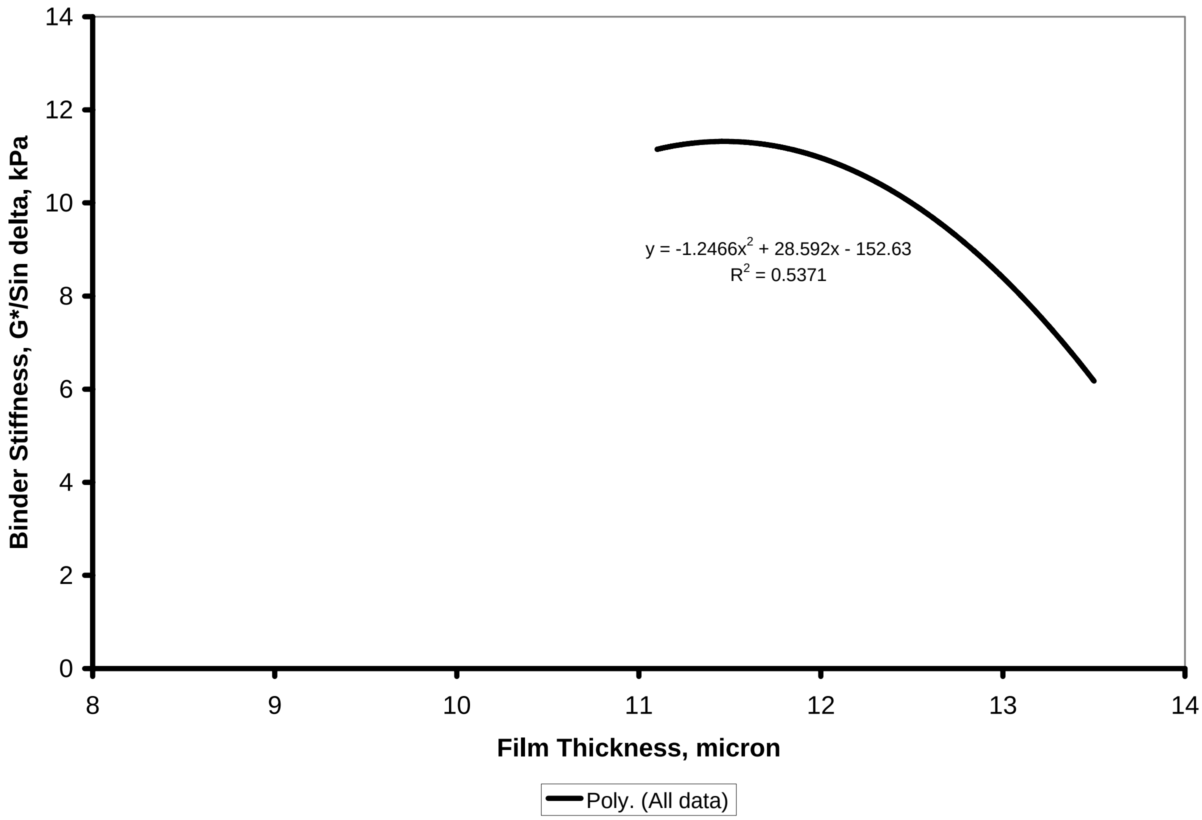

Figure 10: Film Thickness vs. Binder Stiffness

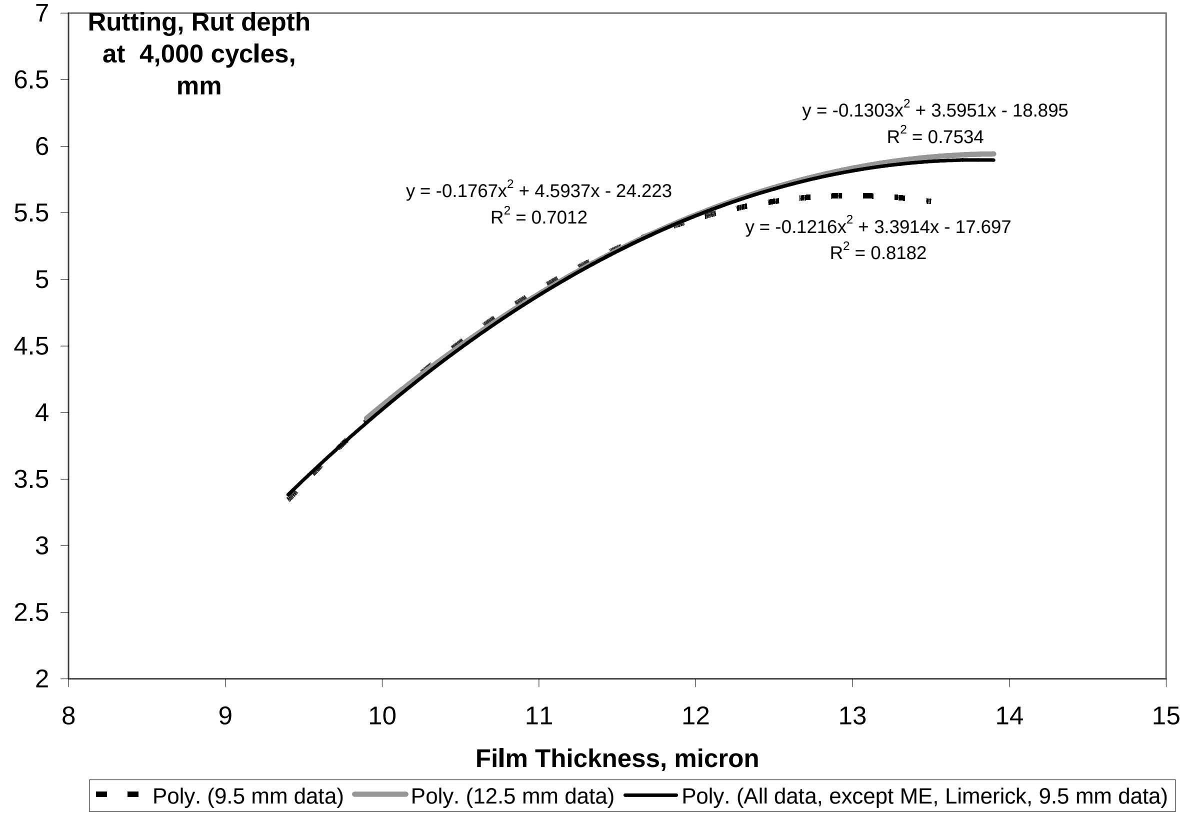

Figure 11: Film Thickness vs. Rutting

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 up to 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 up to 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 12 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.

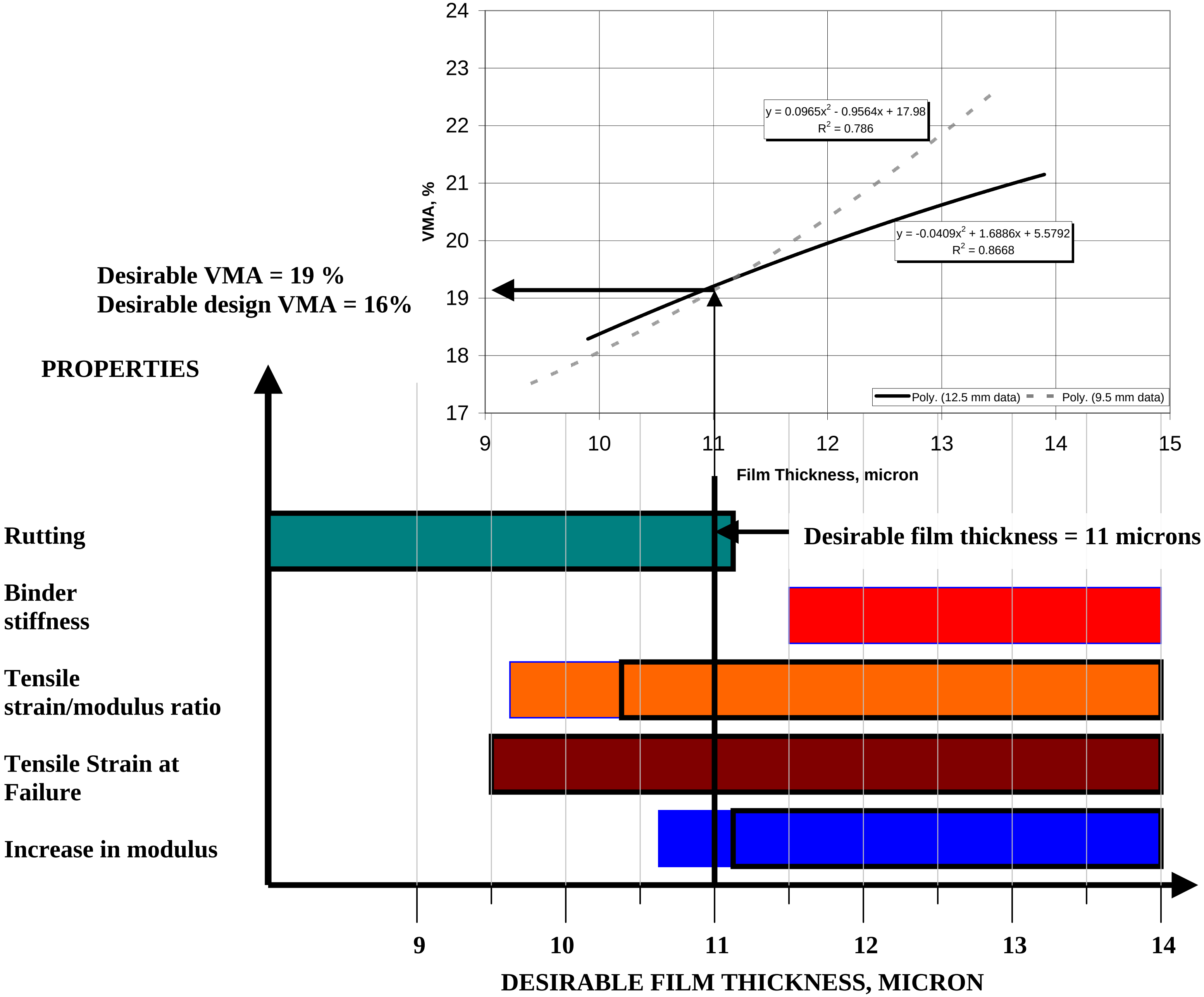

Figure12: Optimum Film Thickness and VMA from Different Considerations.

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.

3.4 N_{design} 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 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 13.

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 too reasonable for designing HMA for low volume roads.

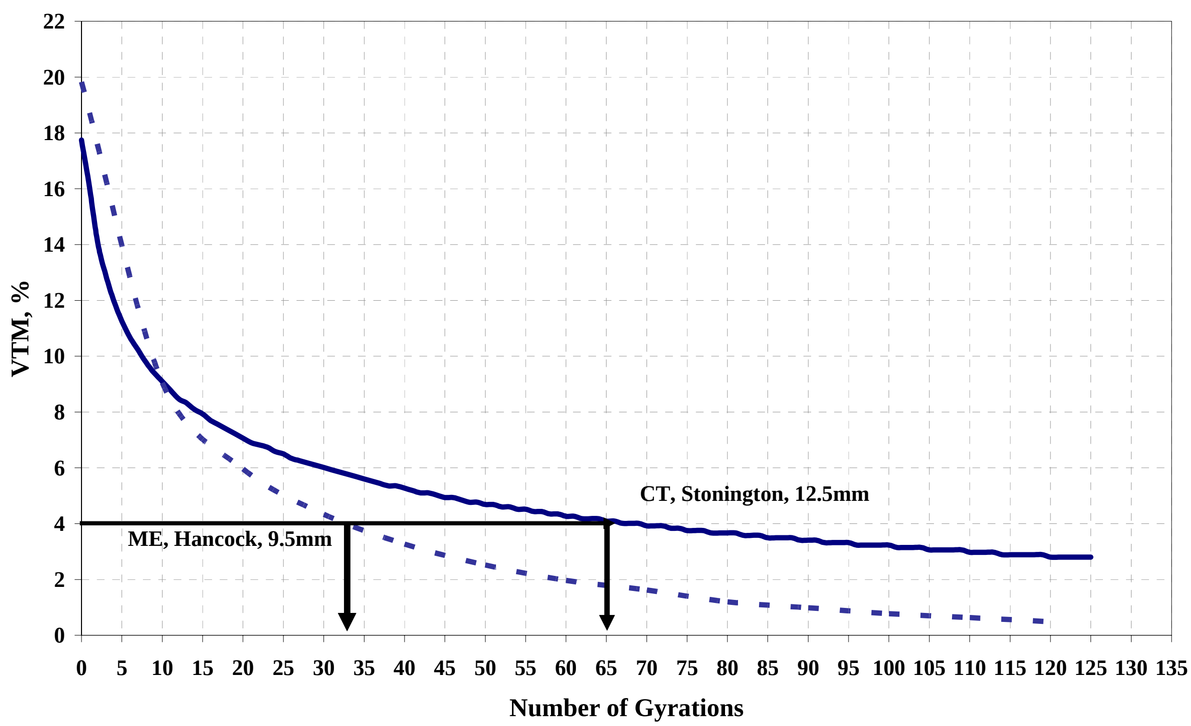

Figure 13: Number of Gyrations vs.Voids in Total Mix

4.0 Conclusions and Recommendations

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

- A film thickness of 11 microns in samples compacted to 7 percent voids was found to be desirable from considerations of stability and durability.
- A design VMA of 16 percent was determined to be optimum for producing durable and stable mixes for low volume roads.
- An $N_{designlv}$ of 50 is recommended for compacting HMA for low volume roads in New England.
- There needs to be developed 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.
- An alternative mix design approach, as outlined in Appendix B, be evaluated.
- 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, this balancing can be made less critical by using polymer modified HMA. 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.

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APPENDIX A
Formulas for Calculation of Volumetric Properties

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

VMA = voids in mineral aggregate, %
G_{mb} = mix density (bulk specific gravity), g/cc
G_{sb} = bulk specific gravity of the total aggregate
P_s = aggregate content by total mass of mixture, cm^3/cm^3

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

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

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

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

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

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

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

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
Alternate Approach

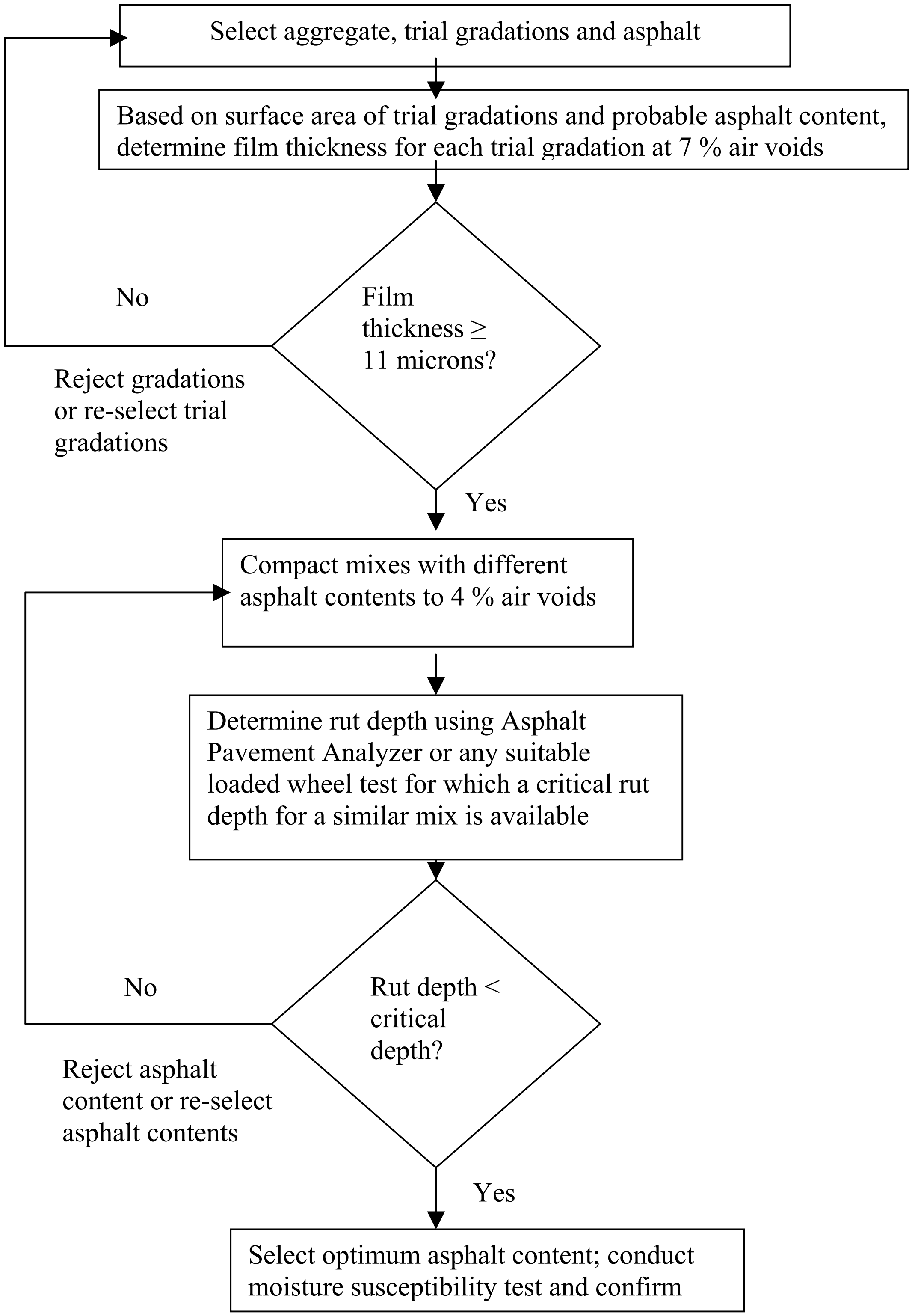

Figure B1: Suggested Alternate Approach for Designing Hot Mix Asphalt (HMA) for Low Volume Roads

APPENDIX C
Raw Data

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 C1: Aggregate Material Properties

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 C2: Aggregate Material Gradation Details

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 C3: Aggregate Material Gradation Details – Field Cores

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**
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 C4: 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)
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**
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 C5: 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)
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**
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 C6: 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)
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**
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 C7: 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)
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**
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 C8: 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)
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**
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 C9: Volumetric and Mechanical Properties of Mixtures – Presque Isle, ME

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 Specimens				
CT-S1	5.2	9.82		
CT-S12	5.2	9.82		

Table C10: Volumetric and Mechanical Properties of Mixtures – Stonington, CT (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 Specimens				
Agg-1	5.50	10.17		
Agg-2	5.50	10.17		

Table C11: Volumetric and Mechanical Properties of Mixtures – Hancock, ME (Field Cores)

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**	
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 C12: 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)
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**
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 C13: 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)
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**	
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 C14: 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)
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**	
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 C15: 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)
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**	
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 C16: 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)
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**	
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 C17: Volumetric and Mechanical Properties of Mixtures – Presque Isle, ME

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 Specimens					
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 C18: Volumetric and Mechanical Properties of Mixtures – Stonington, CT (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 Specimens					
Agg-1	5.50	0.2	14.6	98.3	13.35
Agg-2	5.50	0.7	15.0	95.1	13.35

Table C19: Volumetric and Mechanical Properties of Mixtures – Hancock, ME (Field Cores)