2005

Development of new film thickness models for hot mix asphalt

Michael Alan Heitzman
Iowa State University

Development of new film thickness models for hot mix asphalt

by

Michael Alan Heitzman

A dissertation submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Civil Engineering (Civil Engineering Materials)

Program of Study Committee:
Charles Jahren, Co-major Professor
Halil Ceylan, Co-major Professor
James Cable
Vernon Schaefer
R. Bruce Thompson

Iowa State University

Ames, Iowa

2005

UMI Number: 3200424

Graduate College
Iowa State University

This is to certify that the doctoral dissertation of

Michael Alan Heitzman

has met the dissertation requirements of Iowa State University

Signature was redacted for privacy.

Committee Member

Signature was redacted for privacy.

Committee Member

Signature was redacted for privacy.

Committee Member

Signature was redacted for privacy.

Co-major Professor

Signature was redacted for privacy.

Co-major Professor

Signature was redacted for privacy.

For the Major Program

Table of Contents

List of Figures

List of Tables

List of Abbreviations

AAPT	Association of Asphalt Paving Technologists
AASHTO	American Association of State Highway and Transportation Organizations
BASE	hot mix asphalt for pavement base
CAA	coarse aggregate angularity
Cr LS	crushed limestone
Dia	diameter
DOT	Department of Transportation
ESAL	equivalent single axle load
FAA	fine aggregate angularity
FM	fineness modulus
FT	film thickness
Gb	specific gravity of the asphalt binder
Gsb	bulk specific gravity of the stone (aggregate)
Grad	gradation
HMA	hot mix asphalt
IDT	indirect tension
INTER	hot mix asphalt for pavement intermediate lifts
JMF	job mix formula
LTOA	long term oven aging
LS	limestone
M_R	Resilient Modulus
Max	maximum
Min	minimum
MF	mineral filler
MDL	maximum density line
NCAT	National Center for Asphalt Technology
NMAS	nominal maximum aggregate size
Pb	weight of asphalt binder by percent of mix
Pba	weight of absorbed asphalt binder by percent of aggregate
Pbe	weight of effective asphalt binder by percent of mix
R^2	regression coefficient of determination
SA	surface area
SHLD	hot mix asphalt for pavement shoulder
Std	standard
STOA	short term oven aging
SURF	hot mix asphalt for pavement surface
TRB	Transportation Research Board
Va	volume of air (air voids) by percent of mix
Vs	volume of solids (aggregate) by percent of mix
VFA	voids filled with asphalt binder
VMA	voids in the mineral aggregate
Wt	weight
2-D	two dimension
3-D	three dimension

Acknowledgements

This dissertation was only possible with the loving, patient, and generous support of my family. With the flexibility of the Iowa Department of Transportation Office of Materials to permit professionals to pursue educational development and work. With the advice and assistance of the major professors and graduate committee. And with the inspiration of Robert Nady's life-long dedication to the asphalt profession.

Abstract

The current standard model for calculating film thickness is not sufficiently detailed to adequately reflect differences in hot mix asphalt mixtures; and therefore, has limited value as a tool to evaluate research or mix designs. Modifications to the model (or replacement of the model) would give practitioners a better tool to assess the durability potential of a hot mix asphalt mixture.

Durability is an important characteristics of hot mix asphalt that must get adequate attention to insure long-term performance of hot mix asphalt. Film thickness is one mixture parameter used to characterize a mixture's potential durability. The standard film thickness model is only a nominal approximation that applies 1940's technology.

This study develops two film thickness models that more accurately reflect the relationship of the asphalt binder coating to other mixture parameters. The INDEX Model uses basic weight and volume relationships on each aggregate source in the mixture to improve the surface area value used in the standard model. The VIRTUAL Model uses three-dimensional concepts to redefine film thickness as the spatial relationship between aggregate particles and air voids. The VIRTUAL Model allows the practitioner to compute the film thickness at any level of field compacted density.

The study examines the historical development and application of the standard film thickness model. The proposed film thickness models account for the individual aggregate source gradations, specific gravities, and particle shape that comprise the hot mix asphalt blend. The study provides a practical approach to the significant contribution of the mineral filler as both an aggregate and asphalt binder extender. These parameters were not adequately accounted for prior to this study.

These new film thickness models provide the asphalt community with improved approaches to calculating film thickness that better reflect the unique properties of each hot mix asphalt mixture. Based on the analysis in this study, future studies of hot mix asphalt durability will have a more accurate perception of film thickness to compare differences in hot mix asphalt durability.

Chapter 1. Introduction

Film thickness is one of many volumetric characteristics of HMA that are generally accepted, but film thickness is not often seriously applied. Like VMA and other volumetric properties, film thickness is a computed value, not a physically measured property. In a very literal sense, the current definition of the film thickness value is the thickness of the effective asphalt binder coating on each particle in the mixture assuming all aggregate particles are uniformly and equally coated.

Most HMA practitioners will generally agree that film thickness is primarily a tool used to insure that the HMA has adequate asphalt binder to achieve a desired level of mix durability. This is easily supported by the type of research that applies film thickness as one of the analysis factors.

So why does film thickness get so little attention in the HMA community? The responses to this question are, in many ways, the basis for this research effort. Both the definition of film thickness and the method by which it is computed are likely reasons why it is not used. By its definition, the film thickness value is based on the assumption that all particles are coated uniformly and equally. The particles range from coarse aggregate (greater than 4.75 mm size), to the sand fractions (greater than 0.075 mm), down to very fine flakes of mineral filler (less than 0.020 mm). All of these particles play different roles in the HMA aggregate structure, yet the definition of film thickness treats them all equal.

The accepted method of computing film thickness dates back to the development of the Hveem mix design procedure and the use of paper, pencil and slide rule. The procedure for computing the surface area of all the aggregate particles only requires the weighted proportion of the combined aggregate on each sieve. Any differences in particle specific gravity, shape, and texture are ignored. Two mixtures with identical gradations (by weight) will have equal film thickness values (assuming equal binder volume) even if the specific gravities of the two mixes are significantly different. This problem is further complicated by the development of special mixes, like open graded friction course and stone mastic asphalt. The original film thickness procedure was based on relatively fine, dense graded mixes.

At best, the current film thickness value is an approximate index for evaluating the potential durability of the HMA. Similar to VMA (1,2), many HMA practitioners question the value of film thickness as an HMA volumetric characteristic if the procedure is too simple and does not properly account for easily recognized variables.

The current standard model for calculating film thickness is not sufficiently detailed to adequately reflect differences in hot mix asphalt mixtures; and therefore, has limited value as a tool to evaluate research or mix designs. Modifications to the model (or replacement of the model) would give practitioners a better tool to assess the durability potential of a hot mix asphalt mixture.

This research was undertaken to improve on the simple approach to a film thickness value using the knowledge and tools available today. The objectives of this study are to:

(1) develop a more accurate measure of film thickness,

(2) evaluate past HMA durability studies based on better film thickness models, and

(3) examine the impact of new models on hot mix asphalt job mix formulas used in Iowa.

This study does not attempt to validate the current procedure and criteria. Rather, it is structured to replace the current procedure and establish new film thickness criteria for good HMA durability performance.

So why examine the concept of film thickness if the current HMA practice does not endorse its use? In fact, much of the present HMA research is directed towards mixture performance under load. Currently developing HMA performance tests generally measure mixture properties related to rutting and fatigue and are not directly related to the durability of the mix.

Most public agencies and commercial property owners that design and award HMA projects use a single pay factor for placement of HMA. This single bid item typically requires the contractor to develop the blend of aggregates and asphalt binder (mix design), produce the HMA, and place/compact the HMA. A major portion of the cost is the asphalt binder, so the contractor is focused on keeping the asphalt binder content to a minimum. Yet it is in the agency/owner's interest to insure that the finished pavement is durable. Durability is generally acceptable if the mix has an adequate asphalt binder content. The mixture's volumetric property -film thickness- is the computed index that defines sufficient asphalt binder for durability.

Another reason to continue to examine HMA volumetric relationships is production quality control. While significant improvements in performance testing are emerging, a simple and rapid analysis of HMA mixture volumetrics will continue to be a predominant tool for monitoring and troubleshooting HMA production. Film thickness is one of only a few HMA volumetric properties that directly relate the aggregate characteristics (specifically gradation) to the volume of effective asphalt binder.

This research study is accomplished in three distinct phases that follow the objectives.

- Phase I of the study proposes two new methods for computing film thickness. One method is a better approximation of the surface area of the aggregate so that the film thickness value better represents the mixture in question. The other is a three-dimensional model.
- Phase II of the study uses the new computation procedures to examine databases from previous HMA durability studies to determine if better relationships are created.
- Phase III of the study draws from the population of hot mix asphalt job mix formulas applied in Iowa to observe how the practicing mixtures respond to the new concepts.

Chapter 2. Background

As asphalt paving technology evolved in the early 1900s, one of the predominant performance characteristics of the pavement was the hardening of the pavement material. It is very likely that these early pavements were built on poorly compacted, soft soil foundations and needed to be flexible. As the science and engineering of asphalt pavements developed into the 1930s, one of the recognized criteria for the paving material was asphalt binder hardening. Certainly a part of the focus was on the type or grade of asphalt binder, but practitioners also began to recognize the relationship between the aggregate gradation and amount of asphalt binder as a factor in hardening.

As mix design methods for dense graded HMA emerged, three concepts became dominant in technical circles. They are the Francis Hveem method (California), the Bruce Marshall method (Mississippi), and a little later, the Norm McLeod (VMA) method (Canada)(3). The Hveem method of mix design includes a confined stability component and a "target" asphalt content. The asphalt content is based on the aggregate surface area and aggregate surface characteristics. The Marshall method of mix design focused heavily on the density and stability of the mixture. McLeod promoted the importance of achieving a "minimum" binder content and introduced the VMA criteria.

Both Hveem and McLeod applied a concept of minimum asphalt binder content to address long-term durability of dense graded HMA mixtures, but the approaches are very different. McLeod's VMA approach has been examined through numerous studies because it does not account for variations in the aggregate gradation. And yet, it is the accepted criteria for establishing mixture durability for most asphalt practitioners. Hveem's surface area approach is used frequently in research studies, but is not a commonly accepted criteria for mix design. Studies report that neither approach to define mixture durability are founded on extensive research. In fact, both are criteria based on a fairly narrow and local basis of paving materials and pavement performance.

Both the Hveem and Marshall mix design procedures were developed in the 1940s and were outlined in the first edition of the Asphalt Institute Manual Series No. 2 in 1956 (4). The Hveem mix design procedure was developed for the California Highways and Public Works and documented in 1942. In the Hveem mix design procedure, the surface area calculation is part of the determination of the "estimated-optimum" asphalt binder content using the Centrifuge Kerosene Equivalent method. Hveem's surface area factors are still used today to determine the film thickness value.

The more intense interest and study of mixture durability followed in the 1950s. Both the VMA concept and the film thickness concept are products of this period of HMA development. The formal Hveem mix design procedure does not use film thickness, only the surface area calculation. The concept of film thickness was introduced by Campen and others during this period and applied Hveem's surface area value into the film thickness equation.

In 1955, McLaughlin and Goetz discussed the relationship between permeability, mixture air voids, and pavement durability (5). At the same time, McLeod proposed VMA as a volumetric parameter to insure that mixture gradation had sufficient space to hold both the air voids and a desired minimum asphalt content (6). By 1957, Campen and Lefebvre also reported on the importance of controlling the VMA, but Campen proposed that VMA should be a function of mixture air voids and a desired level of film thickness (7,8). In 1959, Campen reported on a study of mixture stability as it relates to air voids, aggregate surface area, and film thickness (9).

Campen, et al. (7) studied the impact of 20 variations in aggregate gradations on mixture volumetric properties. They found that the proportion of coarse aggregate and fine aggregate does influence the VMA. Further they conclude, ... ***"our conception of a satisfactory mixture is one in which the aggregate contains enough voids to permit the addition of sufficient asphalt to provide comparatively thick films without filling all voids in the aggregate."*** During the discussion of this paper at the AAPT meeting in 1957, Goetz and Campen discuss the differences in asphalt binder distribution between coarse aggregate and fine aggregate and the concept of using film thickness as a mix design parameter. This is the first documented statement to propose the use of a film thickness value in HMA mix design.

Two years later (1959) this same group of researchers expanded on their original concept (9). The focus of this second effort was to demonstrate that mixtures with equal VMA could have significantly different aggregate surface area (and durability). The 1959 report outlines the factors used to calculate film thickness, but does not express the equation. The surface area was derived from the Hveem formula and the computed film thickness ... ***"assumed that all the asphalt exists in the form of uniform films as long as appreciable air voids exist."*** The authors recognized that this assumption was not totally correct, but it was adequate for the purpose of their study. The report's summary notes that asphalt binder demand increases as surface area increases, but not at a proportional rate; and therefore, the desired film thickness decreases as the surface area increases. This concept of film thickness stirred a lively debate among numerous practitioners. Half of the comments favored a film thickness value (or an asphalt binder volume:aggregate surface area ratio) and the other half defended the VMA concept. Of particular note, H. G. Nevitt stated that he presented a paper on another approach to film thickness at the 1957 Seventh Pan American Highway Congress in Panama. Nevitt's paper was not pursued for this report.

McLeod's approach using VMA replaced the VFA parameter in the Marshall mix design procedure and the Marshall procedure became the dominant practice across the country. As the level of experience and expertise grew, some practitioners questioned the universal application of the VMA concept. Since VMA was intended to satisfy mixture durability, a few researchers began taking a closer look at HMA mixture durability. In 1965, Goode and Lufsey reported that HMA mixture durability is a function of a combination of factors (10). This United States Bureau of Public Roads study compared the measured Marshall stability and extracted asphalt binder properties of laboratory aged and un-aged specimens. They identified clear trends in the data to conclude that air voids, film thickness (expressed as bitumen index), and permeability all played a role in mixture hardening. The report proposed ***"that a combined factor consisting of a ratio of air voids to bitumen index provided a satisfactory means of comparing mixtures*** [with respect to resistance to asphalt hardening]***, regardless of aggregate gradation."***

In 1977, research by Kumar and Goetz concluded that mixture durability was primarily influenced by mixture permeability (11). ***"Logically speaking, only that asphalt in a compacted asphaltic mixture which is accessible to open air will be hardened by oxidation. If the thickness of the asphalt coating on the aggregate is greater, a longer time will be needed for the entire thickness of the asphalt film to become hardened and vice versa."*** The study was conducted at Purdue University and again, film thickness, air voids, and permeability were the target mixture parameters. The study included both open-graded and dense graded mixtures, but all mineral filler passing the 0.150-mm (No.100) sieve was removed from the mixes. A non-destructive compressive creep test measured the laboratory specimens as they aged. Three groups of mixtures were prepared, aged, tested, and statistically analyzed. The film thickness equation used the effective binder content. For open-graded mixtures, the study found that a ratio of film thickness to permeability had the best correlation to the creep test results. For dense-graded mixtures the analysis showed that the all three mixture parameters properly predicted mixture durability, but there was no significant difference between them.

By the early 1980's, pavements were struggling to achieve acceptable performance levels. The highway community embarked on a national research program, the Strategic Highway Research Program, in the mid 1980's to address the problem. The asphalt paving researchers and practitioners developed the Superpave mix design system. As part of Superpave development, hot mix asphalt experts listed and ranked the key mixture parameters. Film thickness appears on the short-list, but did not become a part of the mix design system.

Additional laboratory research in mixture durability started in the mid 1990s. Predominant reports by Kandahl and Chakraborty (12) in 1996, Nukunya, Roque, et al. (13) in 2001, and Ruth, et al. (14) in 2002 examined film thickness and/or VMA as a measure of mixture durability. Kandahl and Chakraborty focused on building supporting research for the minimum value of film thickness to ensure reasonable mixture durability. Both the mixture and asphalt binder were subjected to dynamic tests (resilient modulus and complex modulus) to measure the impact of laboratory short-term and long-term aging (STOA and LTOA). Beyond the studies in the 1960's and 1970's, this research recognized the critical difference between mix design and in-place mixture air voids. Previous research on HMA durability prepared specimens at 4 percent air voids, but the work by Kandahl and Chakraborty prepared specimens at the typical post-construction in-place air voids of 8 percent. The report concluded that ***"good correlation was obtained between the asphalt film thickness and***

the resilient modulus of the aged asphalt paving mixtures" and between the asphalt film thickness and the aged asphalt binder properties.

Nukunya, Roque, et al. examined the STOA and LTOA properties of six limestone mixes (13). The study concluded that current volumetric values did not distinguish between mixes with different levels of durability. ***"Results indicated that the rate of binder hardening in mixtures was not related to either the VMA or the film thickness of mixtures as currently determined."*** The study uses extracted binder tests and dynamic performance tests of the mixture to measure the effect of STOA and LTOA for comparison to the volumetric values. The study modified the volumetric equations to recognize the different contribution of coarse aggregate and fine aggregate. The study develops a new FT equation based on the surface area of the fine aggregate.

In 2002, Ruth et al. expanded on the 2001 durability study. The research studied ten mixtures to define gradation characteristics that influence mixture performance after STOA and LTOA (14). Mixture durability was not the focus, but the results of the laboratory testing demonstrated the impact of film thickness on the behavior of HMA as the mixture ages. The study recognized the strong dependency of fine aggregate gradation and mineral filler content on the surface area of the mixture. ***"Several fine graded mixtures*** (with low FT) ***were found to be more susceptible to long term oven aging (LTOA) when failure strains were compared to those for STOA."***

These reports from the mid 1990s and early 2000s examined film thickness as a durability parameter. The general consensus acknowledged that film thickness is a parameter, but lack of strong research measurement correlation usually eliminated film thickness as a strong parameter. Although some studies questioned the film thickness equation, they all used the 1942 Hveem table to determine aggregate surface area and applied Campen's 1959 approach for determining film thickness.

In 2003, Radowskiy stepped away from the standard concept and proposed a new approach for defining HMA mixture film thickness (15). The proposed procedure dropped the two-dimensional surface area concept and introduced a three-dimensional mixture model that better resembles HMA mixtures. This approach models the random geometric orientation of size-graded spheres and distributes the binder into the remaining available space. It takes into account that FT is not a uniform coating of each particle. This study analyzed the same six mixtures as Nukunya, Roque, et al.. The study develops a new FT equation based on particle size distribution, mixture volumetrics, and requires detailed knowledge of the mineral filler particle distribution.

In general, HMA durability is a function of asphalt binder content, aggregate gradation, and mixture volumetrics. The history of HMA technology related to mixture durability shows that VMA is the accepted parameter, but film thickness is also recognized as a parameter. Studies in the last ten years routinely compared VMA and film thickness values to mixture durability.

Chapter 3. A Better Film Thickness Equation

Limitations of the Existing Equation

Film Thickness has been expressed in a number of ways over the years. The original equation was expressed in English variables and metric solution. It used the English values of total binder volume, weight of aggregate per cubic foot, the computed surface area. A constant converted the equation to film thickness in microns (0.001 mm). The equation was later improved to account for the absorbed asphalt binder. This equation (Equation 1) is used in the NCAT HMA manual (16).

$$FT = 304{,}800 \frac{Vbe}{SA * Ws}$$ (for English SA constants) eq-1

where: FT = mixture film thickness (microns, 0.001 mm)
Vbe = volume of effective asphalt binder (ft^3/ft^3 of mix)
SA = surface area of the gradation (ft^2/lb)
Ws = weight of aggregate (lb/ft^3 of mix)

This same equation can be converted to common mix design values and changed to metric units. Most mix design values are expressed as percent of total weight and accompanied by measured specific gravity values to apply to volumetric equations. To convert the NCAT film thickness equation, the volume of binder is expressed as the percent of effective binder (Pbe) by weight of total mix divided by the binder specific gravity. The weight of aggregate is expressed as the percent of aggregate (Ps) by weight of total mix. Since the binder and aggregate terms are expressed as percent of the total mix, the units of the surface area value will dictate the value of the constant so that the film thickness is expressed in microns (1 micron = 0.001 mm). The result using the metric value for surface area is given as Equation 2.

$$FT = 1000 \frac{Pbe}{SA * Ps * Gb}$$ (for metric SA constants) eq-2

where: FT = mixture film thickness (microns, 0.001 mm)
Pbe = percent (by mix weight) of effective asphalt binder
SA = surface area of the gradation (m^2/kg)
Ps = percent (by mix weight) of aggregate
Gb = specific gravity of the asphalt binder

This equation can be further refined to avoid an intermediate step of determining the percent aggregate by weight of total mix. The percent aggregate can be expressed in terms of the percent effective binder and percent absorbed binder. The percent absorbed binder is based on aggregate weight, not mix weight. Equation 3 shows the relationship for percent aggregate and Equation 4 shows the resulting film thickness equation.

$$Ps = 100\frac{(100 - Pbe)}{(100 + Pba)} \qquad \text{eq-3}$$

$$FT = 10\frac{Pbe(100 + Pba)}{SA(100 - Pbe)Gb} \quad \text{(for metric SA constants)} \qquad \text{eq-4}$$

where: Pba = percent (by aggregate weight) of absorbed asphalt binder

All three of the film thickness equations presented above will give you the same value expressed in microns, provided you are using the appropriate SA value. The film thickness value can be easily determined using any of today's HMA mix design software packages. There is, however, another film thickness equation that is commonly used, but further generalizes the value. Equation 5 shows a simplified version of Equation 2 where the percent aggregate is assumed to be 100 and the binder specific gravity is 1. This was a common version used before the laboratory technicians had calculators. The film thickness value resulting from Equation 5 will always be slightly smaller than the other computed values.

$$FT = 10\frac{Pbe}{SA} \quad \text{(for metric SA constants)} \qquad \text{eq-5}$$

In all of the film thickness equations identified above and nearly all the research that examines the film thickness value, one factor is used without any question about its origin or accuracy. That is the surface area of the gradation. All film thickness equations use the surface area factors developed in the mid-1900's. Where did these factors come from? And are they valid for all mixtures?

The current procedure for determining surface area was outlined in the Asphalt Institute Manual in 1956 as part of the Hveem mix design method. The procedure requires only one set of input values to determine the surface area of the total aggregate blend. The input is the gradation expressed as the total percent (by weight) passing on each sieve. Each percent passing, from the 4.75-mm sieve down, is multiplied by a surface-area factor. A constant for the coarse aggregate plus the sum of the products for the fine aggregate is the surface area of the total blend. The original procedure was developed in English units to compute a surface area in square feet per pound of aggregate blend. Later versions converted the procedure into metric units to compute a surface area in square meters per kilogram of aggregate and combined the 0.075-mm and 0.053-mm sieve factors. This study uses the metric version without the 0.053-mm sieve factors.

The surface-area factors are multiplied by the gradation expressed as total percent passing. Using the gradation in terms of the total percent passing means that each value represents all particles smaller than that sieve. Therefore, the surface area values are not a direct expression of total surface area for aggregate particles on a specific sieve. Further, the determination of surface area does not account for differences in the specific gravity of the aggregate. Simply stated, the volume of 100 kg of aggregate with a specific gravity of 2.5 is greater than the volume of 100 kg of aggregate with a specific gravity of 2.8. If we compare the two mixtures, the resulting film thickness values only express differences between the mixtures based on the gradation and all particles are treated as having the same specific gravity.

The current method for computing surface area does not adjust for the differences in the specific gravity of the aggregate. The literature does not address why the adjustment for aggregate specific gravity was omitted. The Hveem mix design nomographs for determining the asphalt binder content adjust the aggregate surface area value by the aggregate specific gravity. Campen's work on film thickness uses the same surface area tables, but does not make this adjustment.

This is a critical limitation of the current procedure for computing film thickness. Studies that examine differences in film thickness values in an attempt to identify trends in HMA mixture performance are not comparing equivalent film thickness values when the mixtures have aggregates with dissimilar specific gravities. If a research study uses a single aggregate source for the entire gradation and simply changes the gradation for the purposes of the study, then the film thickness comparisons are valid. But when the study examines multiple mixtures from multiple sources with different aggregate specific gravities, then the film thickness comparisons are not valid.

Even under the accepted norm that the film thickness value is an index and not a true measure of the asphalt binder film, the procedure for computing the film thickness value should account for known characteristics of the aggregate. This may lead to a better understanding of the impact of film thickness on mixture performance.

New Approach

Using Equation 2 as the current standard for computing film thickness with metric surface area factors, how do we build a better procedure to compute film thickness? The four variables in the equation are logically paired. The percent effective binder (Pbe) is paired with the specific gravity of the binder (Gb) to compute the volume of asphalt binder. The percent aggregate (Ps) is paired with the gradation's surface area (SA) to compute the total surface area of the particles in the mix. The volume of effective asphalt binder is well defined by the relationship of the weight and specific gravity. Provided the effective asphalt binder content is determined from an accurate measurement of the mixture's theoretical maximum specific gravity, the volume of the asphalt used to compute the film thickness is as accurate as possible. The percent aggregate in the mix is also easy to measure. It can be easily expressed as 100 minus the percent, by weight, total asphalt binder (100-Pb). What remains is the need to obtain a better value for the surface area of the aggregate.

Prior to the use of calculators and computers to develop HMA mix design and compute volumetric properties, engineers developed charts, tables and nomographs to simplify the calculations. The current surface area factors are a product of that philosophy. Now that spreadsheet programs are readily available, there is no reason to simplify the procedure for determining the HMA mixture's aggregate surface area. The proposed procedure uses the fundamental principles of weight, volume, specific gravity, and particle geometry to calculate a theoretical surface area of each aggregate particle. The surface area of the gradation is the summation of all the individual particle surface areas.

This approach can be further improved by using theoretical techniques to place the particles in a virtual three-dimensional model and examine the spatial relationship between particles. Boris Radovskiy introduced this technique as an alternative method to calculate the thickness of the asphalt mastic (binder and some mineral filler) between aggregate particle spheres and the air void space (15). In his procedure, the mineral filler (particles passing the 0.075-mm sieve) is further separated into a dense gradation using the 0.5-power function. This distributes the mineral filler from the 0.075-mm sieve down to the 0.005-mm sieve. The proposed approach in this study for calculating film thickness uses the theoretical model, but does not apply the 0.5-power function to distribute the mineral filler. The mineral filler gradation will be discussed in more detail later.

When we use this theoretical three-dimensional model, the need to compute the surface area of the particles is eliminated. The model applies geometric principles to determine the thickness of the asphalt mastic volume from the particle surface to air void space. The model recognizes and accounts for the different particle-to-particle dimensions such that the asphalt mastic fills the volume between closely spaced particles.

In theory, this three dimensional model achieves a film thickness value that approaches the true film thickness. If our primary interest in film thickness is to define the durability of the mixture, then the nominal thickness of the asphalt between the aggregate surface and the void space represents the minimal depth of exposed coating where binder aging occurs.

A new approach to measuring film thickness must account for today's common practices in proportioning HMA mixture components to satisfy the mix design criteria. The procedure should recognize that the aggregate gradation is a blend of multiple aggregates from different sources. Most of the aggregate sources will likely have a different specific gravity. Each aggregate source has a different gradation that typically plays a specific role in building the gradation and structure of the mixture. Each aggregate source has a unique set of particle shapes and surface textures.

The combined gradation plays a role. Mixtures that are coarse-graded rely on the fine aggregate and asphalt binder as a mastic to fill the space between the larger particles. Mixtures that are fine-graded are composed of a fine aggregate structure and the coarse particles simply float in the mixture. Studies have concluded that coarse-graded and fine-graded mixtures will have different durability characteristics.

Construction practice, particularly the as-constructed density, is a factor. Mixtures compacted to 8% air voids have more exposed asphalt binder film than mixtures compacted to 4% air voids. Typical dense-graded mixtures are compacted to 6% to 8% voids in normal paving operations. Open-graded surface mixtures are compacted to 12% to 15% voids to permit drainage. We know that these open-graded mixtures require thicker binder films to retard mixture aging.

The proposed procedures generate two different film thickness values as shown in Figure 1. The first is an extension of the past practice of a uniform coating "index" and the second is a new value based on a "virtual" three-dimensional model. Both procedures account for multiple aggregate sources, including differences in gradation and specific gravity. The INDEX Model can also account for particle shape, but cannot reflect the impact of as-constructed air voids. The VIRTUAL Model does account for as-constructed air voids, but does not adjust for different particle shapes. It is possible for the INDEX Model to account for differences in the film thickness of coarse and fine aggregate, but there are no studies to guide what those values would be. How the two proposed film thickness values reflect pavement performance is examined in the second phase of this study.

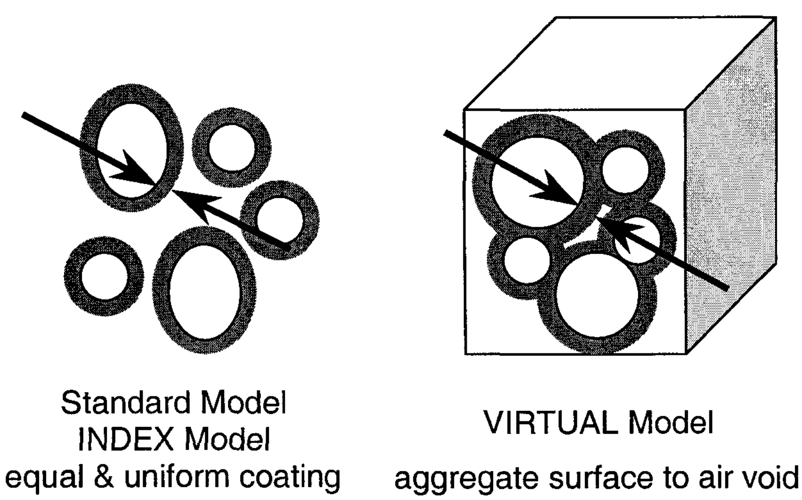


Figure 1 – Differences in Proposed Film Thickness Models

The INDEX Model

The film thickness INDEX model is a simple procedure to develop. After establishing a matrix of the gradations for each of the individual aggregate sources in an HMA mixture, the procedure determines the retained weight of particles from each source on each sieve based on a 1000 gr total aggregate batch weight. Each retained weight is converted to a total retained volume using the specific gravity for that source. The retained volume on each sieve in the matrix is then converted to the number of particles using an average particle volume. The average particle volume is based on the upper and lower sieve dimensions and the nominal particle shape. Once the number of particles is determined, the procedure multiplies that particle count by the surface area of each average particle to establish the total surface area of the particles retained on each sieve for each source. These values are all combined into the total surface area for the 1000 gr aggregate blend. A constant value is included to adjust the combined surface area value to square meters of surface area per one kilogram of aggregate. The computed surface area value is inserted into the standard metric film thickness equation.

The equations to step through the film thickness INDEX model are shown below. Equation 6 determines the volume retained on each sieve for each source of a 1000 gr batch. Equation 7 establishes the volume of each average particle. Equation 8 establishes the surface area of each average particle. Equation 9 combines Equations 6, 7, and 8 into the calculated surface area of the particles retained on a specific sieve for each source. Equation 10 inserts this new surface area equation into the film thickness INDEX equation.

$$Vs_{(i)(n)} = \frac{\frac{Pc_{(i)}}{100} * \frac{\left(Ps_{(i)(n-1)} - Ps_{(i)(n)}\right)}{100}}{Gsb_{(i)}} * 1000 \qquad (\text{cm}^3) \qquad \text{eq-6}$$

$$Vp_{(n)} = \frac{\frac{4}{3}\pi\left(\left(\frac{D_{(n-1)} + D_{(n)}}{2}\right)\Big/2\right)^3 * VF_{(i)(n)}}{1000} \qquad (\text{cm}^3) \qquad \text{eq-7}$$

$$SAp_{(n)} = 4\pi\left(\left(\frac{D_{(n-1)} + D_{(n)}}{2}\right)\Big/2\right)^2 * SAF_{(i)(n)} \qquad (\text{mm}^2) \qquad \text{eq-8}$$

$$SA_{(i)(n)} = \frac{0.0012 * Pc_{(i)} * \left(Ps_{(i)(n-1)} - Ps_{(i)(n)}\right) * SAF_{(i)(n)}}{Gsb_{(i)} * \left(D_{(n-1)} + D_{(n)}\right) * VF_{(i)(n)}} \qquad (\text{m}^2/\text{kg}) \qquad \text{eq-9}$$

$$FT_I = 1000 \frac{Pbe}{\sum SA_{(i)(n)} * Ps * Gb} \qquad (\text{microns}) \qquad \text{eq-10}$$

where: $Vs_{(i)(n)}$ = total volume of aggregate of the i^{th} source retained on the n^{th} sieve
$Pc_{(i)}$ = the percent (by aggregate weight) of the i^{th} source
$Ps_{(i)(n)}$ = the percent (by source wieght) of the i^{th} source passing the n^{th} sieve
$Gsb_{(i)}$ = the bulk specific gravity of the aggregate from the i^{th} source
$Vp_{(n)}$ = the volume of an average particle on the nth sieve
$D_{(n)}$ = nominal opening of the n^{th} sieve (mm)

$VF_{(i)(n)}$ = volume factor for the particles from the i^{th} source on the n^{th} sieve
$SAp_{(n)}$ = surface area of the average particle on the n^{th} sieve
$SAF_{(i)(n)}$ = surface area factor for the particles from the i^{th} source on the n^{th} sieve
$SA_{(i)(n)}$ = total surface area of the particles from the i^{th} source on the n^{th} sieve
FT_I = film thickness of the mixture, INDEX Model
Pbe = percent (by mix weight) of the effective asphalt binder
Ps = percent (by mix weight) of the aggregate
Gb = specific gravity of the asphalt binder

To determine the volume and surface area of each particle, the user must decide what the nominal particle shape is for that aggregate source. The shape factors (VF and SAF) convert the volume and surface area from a uniform sphere to the desired particle shape. The dimensions of the spheres are based on the sieve screen openings. As the particle changes to a cubical shape, the dimensions are changed to account for the ability of a square particle to randomly pass through a square opening. For this proposed procedure, the volume of spherical particles and cubical particles retained on the same sieve have approximately equal volume. The volume and surface area factors were derived from the geometric calculations in Table 1.

Table 1 – Particle Shape Factors

Particle Shape	Particle Volume (mm^3)	Volume Factor	Particle Surf. Area (mm^2)	Surface Area Factor
Sphere ● (22 mm dia) -base geometric value-	5,575	1.0	1521	1.0
Sphere 2:1 ◖■◗	13,938	2.5	3041	2.0
Sphere 3:1 ◖■■◗	22,301	4.0	4562	3.0
Cube ■ (17.67 mm edge)	5,525	1.0	1875	1.2
Cube 2:1 ■■	11,050	2.0	3125	2.1
Cube 3:1 ■■■	16,575	3.0	4375	2.9

The input for the proposed INDEX Model film thickness actually requires three pairs of volume and surface area factors for each aggregate source. In many cases all three values will be the same, but it may be appropriate for those values to change for an aggregate source as the particles decrease in size. The three pairs of volume and surface area factors allow the mix designer to distinguish between coarse-aggregate, coarser fine-aggregate, and finer fine-aggregate. There are no established test procedures to determine these values. The mix designer must examine the coarse and fine proportion of each source and judge its nominal particle shape.

Selection of the mineral filler gradation requires special attention. A large portion of the aggregate surface area is attributed to the mineral filler. Based on previous studies of baghouse fines, the designer has the choice of selecting a coarse, dense, or fine mineral filler gradation. For this study, the surface area of particles less than 10 micron size is not included in the film thickness determination. These very small particles are treated as a binder extender. Depending on the mineral filler gradation selected, the amount of mineral filler treated as binder extender ranges from 25 to 70 percent. The INDEX Model, however, does not add the mineral filler extender volume to the effective binder volume for computing the film thickness. The impact of the mineral filler on the film thickness value is very significant and is discussed in detail later in this chapter.

Equation 10 represents the proposed INDEX Model for determining the film thickness. The focus of the model is a logical sequence of calculations to determine the surface area of each aggregate particle. It requires the input of the gradation, specific gravity, and particle shape of each aggregate source. The resulting aggregate surface area is a better approximation of the true surface area because it accounts for these differences between aggregate sources. However, it is still an "index" of the mixture's film thickness. Equation 10 measures the thickness of the asphalt film with the simplification that the surface area coated by the asphalt binder is a flat surface, not three-dimensional particles; and, each particle is separately and uniformly coated.

These two simplifications of the INDEX Model are very significant. Converting each particle's surface area to a flat plane greatly reduces the coated volume from a three-dimensional shell to a two-dimensional film. As the ratio of particle diameter to film thickness gets smaller, the impact of converting the surface area from a shell to a plane surface increases. For smaller particles, the computed two-dimensional film thickness is significantly larger than the actual three-dimensional binder shell thickness. This is easily demonstrated in Figure 2. A detailed discussion of this impact is given later in this section.

The simplification of separate and uniformly coated particles is also significant, but much more difficult (if not impossible) to quantify. We know that each particle is not uniformly coated. Further, the particles are compacted into a three-dimensional orientation and relationship by particle size. In coarser gradations, we expect the coarse particles to have direct contact with each other to build the aggregate skeleton. That same point-to-point relationship is less understood for the fine aggregate and mineral filler. In general terms, treating the film thickness as a separate and uniform coating gives a more conservative result (smaller film thickness).

The VIRTUAL Model

To achieve a better approximation of the asphalt film thickness, this study developed a derivation of Radovskiy's approach (15) to account for both the three-dimensional surface area of each particle and for the spatial relationship between particles in the mixture. In addition, the spatial relationship of the VIRTUAL Model can account for differences in compacted voids. The primary restriction of the VIRTUAL Model is that it cannot account for different particle shapes. This theoretical particle distribution model is based solely on spheres.

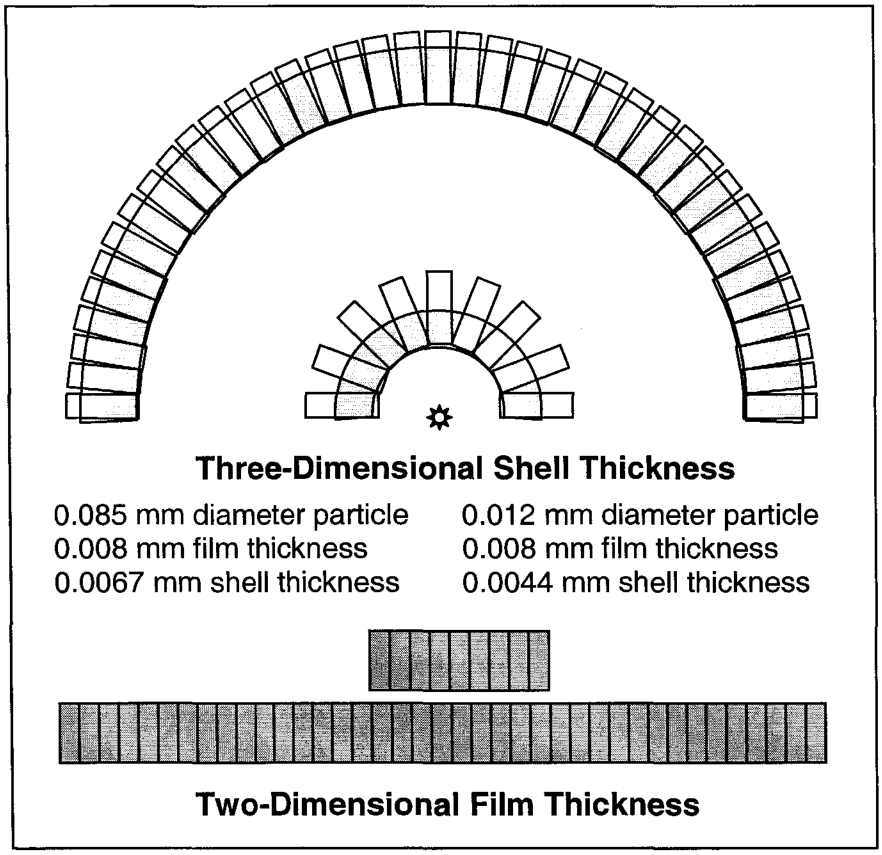


Figure 2 – Comparison of 3-D and 2-D Aggregate Coating

Similar to the proposed INDEX Model, this study treats all mineral filler smaller than 10 microns as a binder extender in the proposed VIRTUAL Model. This treatment of mineral filler does not conform to the approach taken by Radovskiy. His procedure requires analysis at individual 0.001 mm increments to determine the extender portion. Radovskiy's procedure treats all particles smaller than the calculated film thickness as part of the asphalt binder (as an asphalt extender) and includes that volume into the binder volume. In the proposed VIRTUAL Model, all particles smaller than 0.010 mm are treated as extender and the extender volume is added to the binder volume. Other modifications to Radovskiy's procedure account for specific gravity differences of the individual sources included in the aggregate blend and applies the same approach to mineral filler gradation used for the INDEX Model.

The VIRTUAL Model requires knowledge of the HMA mixture volumetrics, as well as knowledge of the aggregate and binder proportions. The central equation of the model is given as Equation 11. It combines the film thickness (t) and particle distribution relationships (a_1, a_2, a_3) and equates the sum of those values to a relationship of the adjusted VMA (1-Vs) to air void volume (Va). The particle distribution relationships (a_1, a_2, a_3) create the virtual three-dimensional aggregate model. Equations 12, 13, and 14 are used to determine the "a" values. In theory, these values would change as we adjust the amount of mineral filler that acts as an asphalt extender. In the proposed VIRTUAL Model these three values remain constant for a given gradation because the definition of asphalt extender is fixed. The other variable (q) in Equations 12, 13, and 14 is a ratio of the effective aggregate particle volume (Vs) to the adjusted VMA volume. The "effective" aggregate volume is determined by Equation 15 and accounts for the mixture's measured VMA and the volume portion of the gradation that is treated as asphalt extender ($V_{ext} = P_{0.010}/Gsb$). Equation 16 computes the volume of air (Va) using the volumetric relationships for VMA, the total and absorbed binder, and the specific gravities of the asphalt binder and aggregate.

$$a_1 t + a_2 t^2 + a_3 t^3 = \ln\left(\frac{1 - Vs}{Va}\right) \qquad \text{eq-11}$$

$$a_1 = 6q\frac{m_2}{m_3} \qquad \text{eq-12}$$

$$a_2 = 12q\frac{m_1}{m_3} + 18q^2\frac{m_2^{\,2}}{m_3^{\,2}} \qquad \text{eq-13}$$

$$a_3 = 8q\frac{1}{m_3} + 24q^2\frac{m_1 m_2}{m_3^{\,2}} + 16q^3\frac{m_2^{\,3}}{m_3^{\,3}} \qquad \text{eq-14}$$

$$Vs = (1 - VMA) * (1 - Vext) \qquad \text{eq-15}$$

$$Va = 1 - \left(\frac{1 - VMA}{100}\right) * \left[1 + \left(\frac{Pb/100}{1 - Pb/100} - \frac{Pba}{100}\right) * \frac{Gsb}{Gb}\right] \qquad \text{eq-16}$$

where: $t = FT_V$ = film thickness, VIRTUAL model (mm)
a_1 = first particle distribution (1/mm)
a_2 = second particle distribution ($1/mm^2$)
a_3 = third particle distribution ($1/mm^3$)
Vs = fraction (by mix volume) of the effective aggregate
Va = fraction (by mix volume) of the air voids
m_1, m_2, m_3 = particle moments, defined by Eqs 18, 19, & 20 (mm, mm^2, mm^3)
q = Vs/(1-Vs)
VMA = voids in the mineral aggregate
V_{ext} = percent (by aggregate volume) of particles passing 0.010-mm sieve
Pb = percent (by mix weight) of the total asphalt binder
Pba = percent (by aggregate weight) of the absorbed asphalt
Gsb = bulk specific gravity of the aggregate (weighted for proportion of sources)
Gb = specific gravity of the asphalt binder

Equation 6 and 7 used in the INDEX Model procedure also apply to the VIRTUAL Model. The input parameters related to the gradation and specific gravity for each aggregate source are used to determine the number of particles on each sieve. The same sequence is applied to convert retained weight to retained volume; and, divide the retained volume by the average particle volume. Equation 17 expresses the number of particles on a specific sieve for each source. Unlike the INDEX Model, we cannot apply shape factors to represent various particle shapes. In the VIRTUAL Model, all particles are treated as spheres. After the number of particles is computed on each sieve for each source, the total number of particles on each sieve is determined. The number of particles on each sieve is converted to a fraction of the total number of particles in the gradation, less the mineral filler acting as asphalt binder extender. The procedure uses Equations 18, 19, and 20 to compute the particle moments (m_1, m_2, m_3) based on the average particle diameter and fraction of particles retained. The summations of the particle moments on each sieve are the input values for the particle distribution relationships, a_1, a_2, and a_3 in Equations 12, 13, and 14.

$$Ns_{(i)(n)} = \frac{\frac{Pc_{(i)}}{100} * \left(\frac{\frac{Ps_{(i)(n-1)} - Ps_{(i)(n)}}{100}}{Gsb_{(i)}} \right)}{\frac{\pi * \left(\frac{D_{(n-1)} + D_{(n)}}{2} \right)^3}{6}} \qquad \text{eq-17}$$

$$m_1 = \sum \left(\frac{D_{(n-1)} + D_{(n)}}{2} * \frac{Ns_{(n)}}{\sum Ns_{(n)(i)}} \right) \qquad \text{Eq-18}$$

$$m_2 = \sum \left[\left(\frac{D_{(n-1)} + D_{(n)}}{2} \right)^2 * \frac{Ns_{(n)}}{\sum Ns_{(n)(i)}} \right] \qquad \text{Eq-19}$$

$$m_3 = \sum \left[\left(\frac{D_{(n-1)} + D_{(n)}}{2} \right)^3 * \frac{Ns_{(n)}}{\sum Ns_{(n)(i)}} \right] \qquad \text{Eq-20}$$

where: $Ns_{(i)(n)}$ = number of aggregate particles from the i^{th} source retained on the n^{th} sieve
$Pc_{(i)}$ = the percent (by aggregate weight) of the i^{th} source
$Ps_{(i)(n)}$ = the percent (by source wieght) of the i^{th} source passing the n^{th} sieve
$D_{(n)}$ = nominal opening of the n^{th} sieve (mm)
$Ns_{(n)}$ = particle count on the n^{th} sieve for all sources
$\Sigma Ns_{(n)(i)}$ = total particle count, all sieves and sources

Once the aggregate relationships are determined, the other input parameters related to the asphalt binder and mixture volumetrics are applied to solve Equation 11. Three input values (Pb, Pba, and Gsb) are used to define the volume of effective asphalt binder. The other input value is the mixture's measured VMA. Applying the binder input values is straight forward provided the correct base value is used. Total percent binder (Pb) is based on total mixture weight and percent binder absorbed (Pba) is based on total aggregate weight.

Selecting the proper measured VMA requires an understanding of the level of compaction when the VMA was measured. Most mix design summaries focus on the volumetric properties at 4% air voids. The VIRTUAL Model can determine the film thickness at any air void level, so the measured VMA must be adjusted to the desired air void level. Computing the correct VMA can be accomplished using Equation 21. Equation 21 starts from a known VMA and air void relationship for a mixture. The VMA value used for input in the VIRTUAL Model must coincide with the level of compaction that the film thickness represents.

$$VMA_1 = \frac{VMA_0 + (Va_1 - Va_0)}{1 + \frac{(Va_1 - Va_0)}{100}} \qquad \text{Eq-21}$$

where VMA_1 = computed (adjusted) VMA (percent)
VMA_0 = measured (initial) VMA (percent)
Va_1 = computed (target) air voids (percent)
Va_0 = measured (initial) air voids (percent)

When all the aggregate, asphalt binder, and mixture volumetric inputs are defined, we can solve Equation 11 for film thickness (t). The VIRTUAL Model uses a simple approach to determine the value "t" in Equation 11. The Solver Function in the Excel software generates an interactive process to find a value for "t" that gives a correct solution to the equation. Unfortunately, the Solver Function must be manually initiated, so the individual using the VIRTUAL Model must be familiar with this spreadsheet tool.

In summary, both the INDEX Model and VIRTUAL Model begin the procedure of computing the film thickness by determining the number of particles retained on each sieve. This step divides the gradation by each source to account for the differences in aggregate specific gravity. The INDEX Model converts the number of particles to particle surface area and applies the volume of effective asphalt to the total surface area as a thin sheet on a two-dimensional plane. The VIRTUAL Model places the aggregate particles in a three-dimensional matrix, fills the void space with effective asphalt, and measures the thickness of the asphalt from the particle surface to the air void space.

Comparison of Existing and New Equations

So what do we achieve with either the INDEX Model or VIRTUAL Model? And what input variables of each model have the greatest impact on the computed film thickness? To address these questions, this study ran a series of analyses on a family of generic mixes and examined the differences between the current film thickness "Standard Model" (Eq 2), the proposed INDEX Model (Eq 10), and the proposed VIRTUAL Model (Eq 11). The generic mixes represent a series of gradations, from fine to coarse graded. Figure 3 shows the combined gradation of each mixture and Table 2 gives the input data of each mixture. For simplicity, the sensitivity study uses a single source gradation.

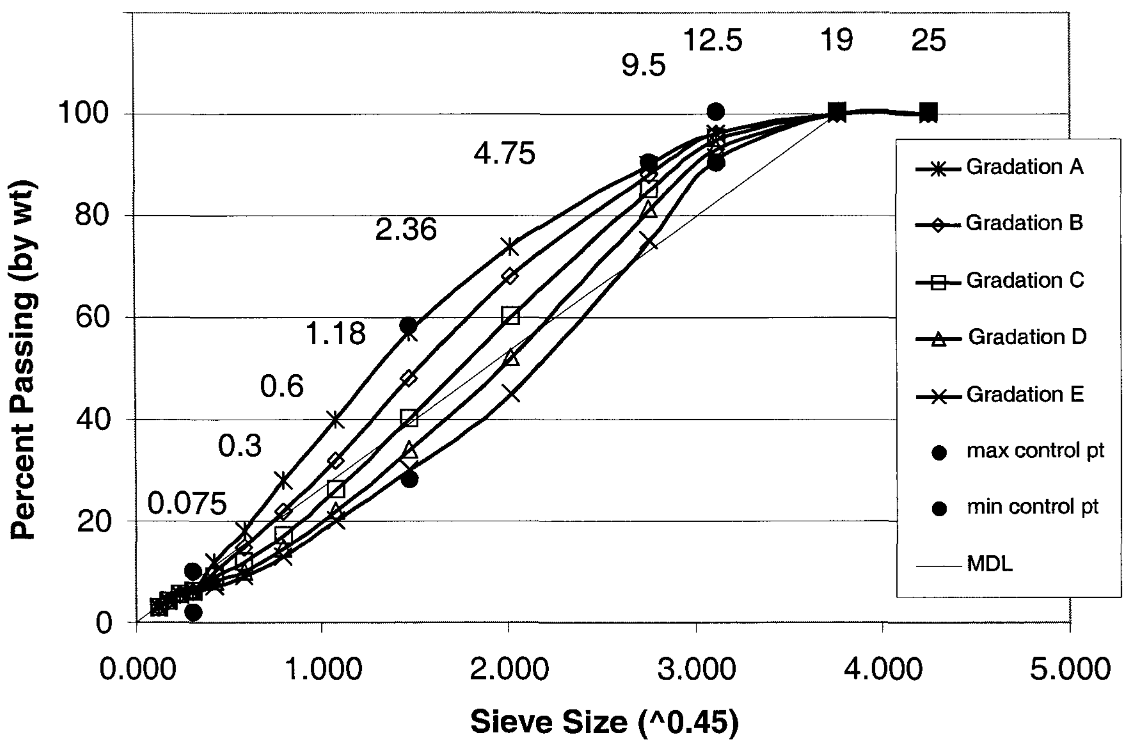


Figure 3 - Family of General Gradations

Table 2 - Mixture Properties for Gradations A - E

GRADATION	Va	VMA	Pb	Pbe	Gb	Gsb
A	4.0	14.5	5.6	4.5	1.035	2.550
B	4.0	14.0	5.6	4.5	1.035	2.550
C	4.0	13.5	5.6	4.5	1.035	2.550
D	4.0	14.0	5.6	4.5	1.035	2.550
E	4.0	14.5	5.6	4.5	1.035	2.550

The sensitivity study of the VIRTUAL Model is not precise due to the inclusion of the volumetric properties. For example, we would not expect the VMA of all five gradations to be the same. In reality, these values would need to be determined from the measurement of laboratory prepared mixes. For the sensitivity study, the volumetric properties for each gradation are based on reasonable judgment, not laboratory measurement.

Impact of Individual Variables

♦Gradation

The five gradations developed for this sensitivity study represent a typical range of gradations. The common elements of the gradations are the NMAS, the percent passing the 0.075-mm sieve, and the gradation of the MF. The differences between the gradations are the coarseness of the blend. Gradations A and B are generally defined as fine gradations and gradations D and E are defined as coarse gradations. Gradation C might be classified as a dense gradation following the 0.45 Maximum Density Line. A summary of the film thickness values for each of the gradations are shown in Figure 4.

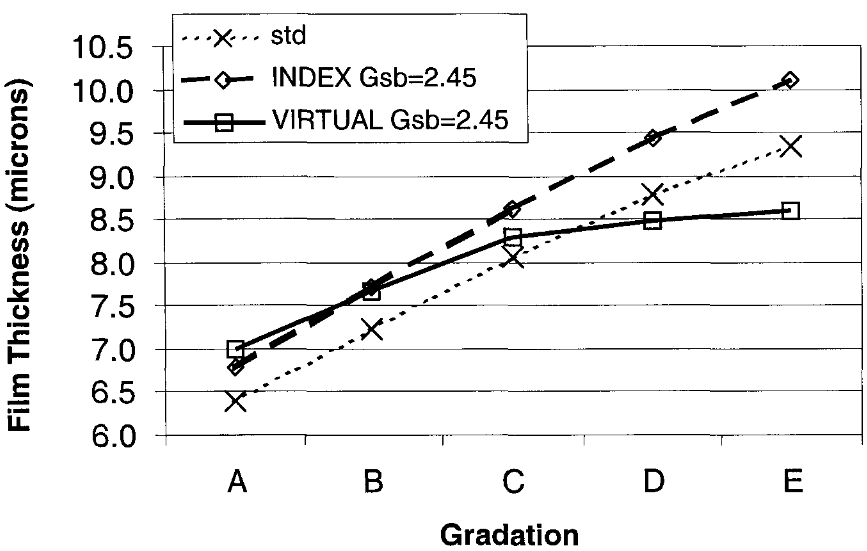


Figure 4 - Sensitivity of Film Thickness to Gradation

Starting with the Standard Model, the film thickness increases as the gradations change from fine blends to coarse blends. There is approximately a 3-micron change in the film thickness over the five gradations. This increase in film thickness coincides with the general expectation that the total surface area of the particles in each blend is decreasing as larger particles (less surface area) replace smaller particles (more surface area). The Standard Model is based on the aggregate specific gravity (Gsb) of about 2.44 (15).

The INDEX Model at the aggregate specific gravity of 2.45 shows a similar increasing trend, but the film thickness is about 0.4 microns to 0.75 microns greater then the Standard Model depending on the gradation selected. There is one major factor contributing to the increased film thickness value. The INDEX Model treats all mineral filler less than 0.010 mm as asphalt binder extender, so there are fewer mineral filler particles with a high surface area to include in the total aggregate surface area. Using the dense mineral filler gradation constants, only half (50%) of the mineral filler is included in the surface area of the gradation blend in the INDEX Model.

The VIRTUAL Model shows a similar increasing trend for the fine graded blends, but the trend becomes relatively flat as the gradation becomes coarser. At a Gsb of 2.45, which is similar to the Gsb used for the Standard Model, the VIRTUAL Model is 0.6 microns higher for Gradation A, narrows to 0.2 microns for Gradation C, and is 0.8 microns lower for Gradation E. It appears that the visual break in the trend at Gradation C reflects the difference in the shape of the gradation curves (the general distribution of the particles). The finer gradations are generally concave and the coarse gradations are more convex relative to the maximum density line.

Another way to associate this trend change in VIRTUAL film thickness to the gradation is to look at the change in the ratio of the fine aggregate portion of the gradation blend. The ratio of the total percent passing the 4.75-mm sieve to the total percent passing the 0.600-mm sieve expresses the slope of the fine aggregate. Just as the film thickness increased for the fine gradations and remained level for the coarse gradations, Figure 5 shows the ratio (slope) of the fine aggregate increased for fine gradations and remained level for coarse gradations. This association between the gradation and film thickness may reflect the transition from a fine aggregate structure (with floating coarse aggregate) to a coarse aggregate structure (skeleton) with a fine aggregate/asphalt binder mastic. All particles in the fine gradation blend are "equally" involved in the binder thickness; where as, the binder volume for the coarse gradations is a function of the mastic volume in the coarse aggregate skeleton.

In general terms, the INDEX Model reflected a similar pattern of film thickness change as the Standard Model. The VIRTUAL Model gives a similar pattern for fine aggregate gradations, but gives a dramatically different film thickness result for coarse gradations.

♦Specific Gravity

As discussed earlier in the study, the Standard Model does not directly account for differing aggregate specific gravities. The INDEX Model and VIRTUAL Model require aggregate specific gravity input values to determine the film thickness. The five generic gradations were analyzed at four aggregate specific gravities ranging from 2.45 to 2.75. To simplify the analysis, the asphalt binder content, by weight, (Pb and Pbe) was held constant. Figure 6 graphically displays the impact of varying aggregate specific gravity. As expected, film thickness increases as aggregate specific

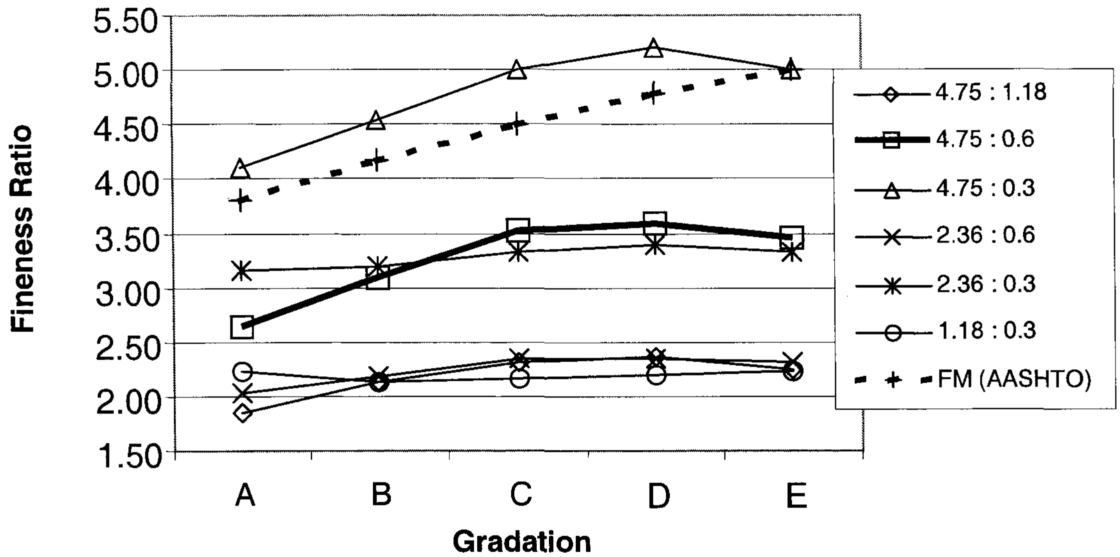


Figure 5 - Relationship of Gradation to Fineness Ratio

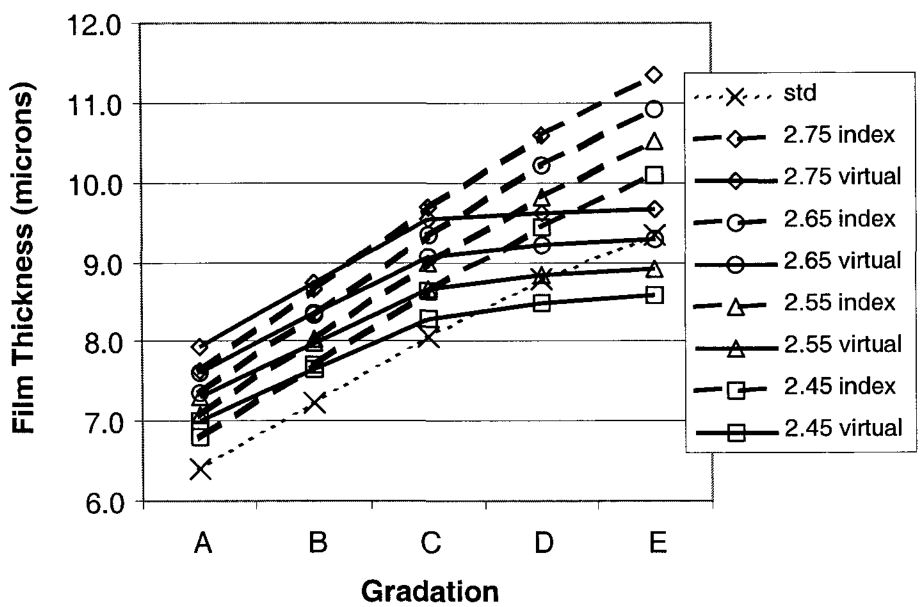


Figure 6 – Sensitivity of Film Thickness to Aggregate Specific Gravity

gravity increases. Since the weight (and volume) of asphalt binder remains constant, the number of particles retained on each sieve decreases since each particle weighs more. With fewer particles retained on each sieve, the surface area of the gradation is smaller. The reduction in surface area coupled with a constant binder volume increases the film thickness.

Because the sensitivity analysis holds the weight (and volume) of the asphalt binder constant, the impact of Gsb is not entirely accurate for the Standard Model and INDEX Model. While the Standard Model does not directly account for Gsb, it does reflect the impact of varying Gsb through the Pbe and Pb terms in the equation. A true analysis of the impact of Gsb would need to be based on equal mixture volumetrics with varying Gsb. To achieve equal mixtures, the binder and aggregate volumes of each mixture would need to be equal, not the weight proportions. The analysis of the impact of Gsb in Figure 6, above, is based on equal binder volume only. The analysis holds the Pb and Pbe constant, so the aggregate weight proportion to binder weight proportion is held constant. But in fact, if the weight of aggregate is held constant as the Gsb changes, then the volume of aggregate in the analysis is changing. If the volume of aggregate is changing, then the mixtures are not truly equal.

To look at the impact of Gsb on an equal volume (mix proportion) basis, an analysis was performed to see how the Standard Model would react to varying Gsb. To achieve an equal aggregate volume for each mixture, the aggregate volume at the baseline Gsb is converted to an aggregate weight using the new Gsb. A new Pbe is calculated from the revised mixture weight values (Equation 22). A new Pb value is then determined from the new Pbe value (Equation 23). Since the revised Pbe and Pb values are intended to reflect mixtures with equal binder and aggregate volume, we should expect the computed film thickness values to be equal. However, as shown in Figure 7, the computed film thickness using the Standard Model shows a decreasing film thickness as the Gsb increases. In general terms, the values in Figure 7 show that the Standard Model will calculate a smaller film thickness as the aggregate specific gravity increases.

$$Pbe_{(i)} = \frac{Pbe_{(0)}}{\left(\frac{\left(1 - Pbe_{(0)}\right)}{Gsb_{(0)}} \times Gsb_{(i)}\right) + Pbe_{(0)}} \qquad \text{Eq-22}$$

$$Pb_{(i)} = Pbe_{(i)} \times \frac{Pb_{(0)}}{Pbe_{(0)}} \qquad \text{Eq-23}$$

where: Pbe = percent effective asphalt binder
Gsb = bulk specific gravity of the aggregate
Pb = percent total asphalt binder

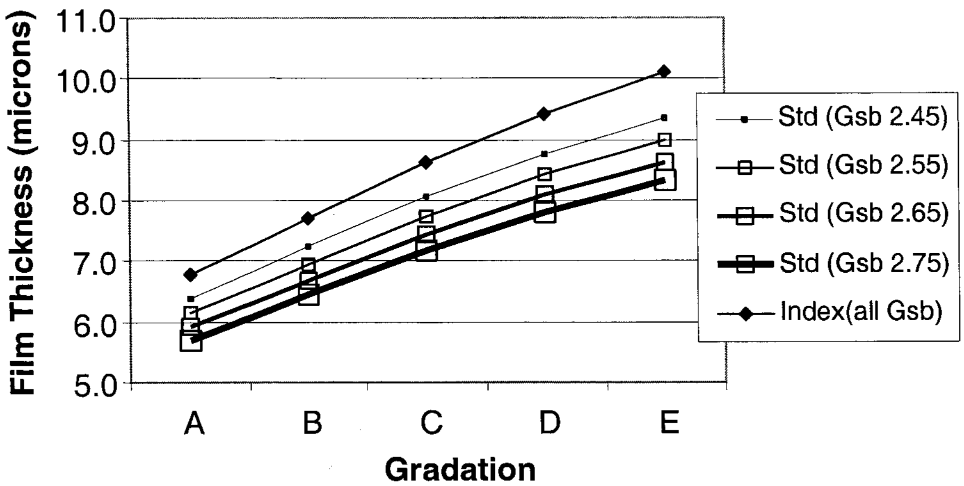


Figure 7 – Sensitivity of Film Thickness to Aggregate Specific Gravity on an Equal Material Volume Basis

The proposed INDEX Model applies the same basic film thickness equation as the Standard Model. The equation uses Pbe and Gb to determine the asphalt binder volume. For mixtures compared on an equal volume basis, the Pbe value will decrease as the mixture Gsb increases. However, the surface area factors computed as part of the INDEX Model change as the aggregate specific gravity changes. Using the same adjustments to the Pbe and Pb as the Gsb changes, the INDEX Model correctly computes the same film thickness for two mixtures with equal binder and aggregate volumes, but different aggregate specific gravities. This demonstrates the value of the basic revisions in the INDEX Model over the Standard Model.

Figures 6 and 7 are mirror images of the same analysis. Both look at the impact of the change of aggregate specific gravity on the computed film thickness. While Figure 6 would imply that the INDEX Model and VIRTUAL Model would increase the film thickness, the more realistic scenario is Figure 7 which indicates that the Standard Model underestimates the film thickness as the aggregate specific increases.

♦Mineral Filler Content and Gradation

The Standard Model and INDEX Model for film thickness are based on determining the surface area of the aggregate particles. As the particle size gets smaller, the impact of the particle surface area increases dramatically. Conventional aggregate gradation testing for HMA mixtures typically stops at the 75-micron sieve. For purposes of this study, the material passing the 75-micron sieve is called mineral filler. Most HMA mix designers have no detailed information on the composition of the mineral filler. And yet, it is the gradation of the mineral filler that has a significant impact on the surface area calculated by the Standard Model and INDEX Model. The study examined a spectrum of mineral filler gradations and established a fine, dense and coarse mineral filler gradation for purposes of this study.

The Standard Model bases its film thickness determination on the surface area factors developed by Hveem. The surface area factors are fixed constants and the entire mineral filler proportion is included in the film thickness calculation. The INDEX Model and VIRTUAL Model limit the amount of mineral filler acting as aggregate particles. The analysis used by Radovskiy defined the mineral filler that acts as binder extender as those particles with diameters less than the computed film thickness. This requires an interactive process to compute the film thickness and establish the mineral filler acting as binder extender. Since we know very little about the actual gradation of the mineral filler, the INDEX Model and VIRTUAL Model define the mineral filler extender as all particles less than 10 microns (0.010 mm). Fixing the definition of the binder extender simplifies the model. A film thickness of 10 microns is commonly observed for mixes in Iowa and is supported by the analysis in Chapter 5.

There are two questions relative to the impact of the mineral filler on film thickness. How does the amount of mineral filler change the film thickness and how does the gradation of the mineral filler impact the film thickness? To examine the question of mineral filler quantity, the gradation of the aggregate and mineral filler were held constant and the amount of mineral filler was increased from 4.5 percent to 7.5 percent. Figure 8 shows the computed film thickness values for all three film thickness calculation models. The graph shows that all three models react similarly to the quantity of mineral filler. A one percent change in the amount of mineral filler changed the film thickness by approximately 0.5 micron.

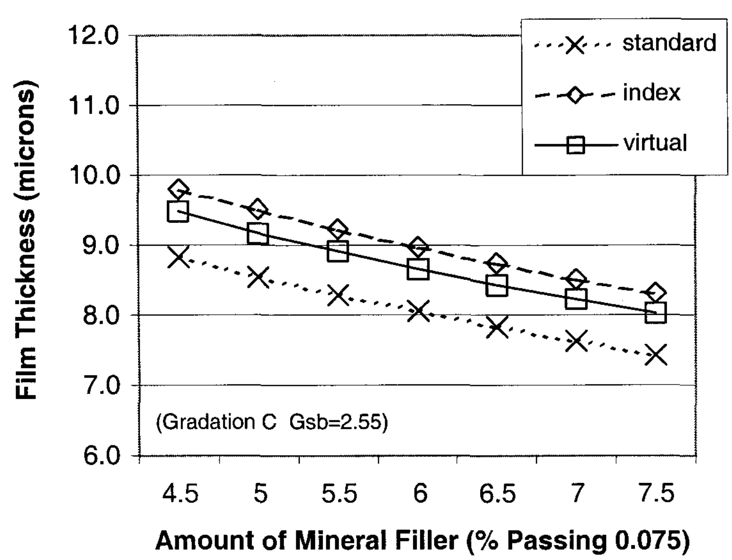


Figure 8 – Sensitivity of Film Thickness to Mineral Filler Quantity

To examine the impact of the mineral filler gradation, the fine, dense and coarse mineral filler gradations were developed from mineral filler particle distributions studied by Anderson and Tarris (17). These gradations were applied to aggregate gradation C and 6 percent mineral filler quantity. Figure 9 shows the significant impact of changes to the mineral filler gradation. As expected, the Standard Model does not show any change in film thickness because the surface area factors do not extend below the 0.075-mm sieve. Both the INDEX Model and VIRTUAL Model reflect the impact of mineral filler gradation. There is a 4 micron film thickness difference between the fine and coarse mineral filler gradations. Because the INDEX Model and VIRTUAL Model treat a portion of the mineral filler as asphalt binder extender, the change in film thickness values reflect the amount of mineral filler that is considered aggregate particles. For the coarse mineral filler gradation, 75 percent of the mineral filler is considered aggregate particles. For the fine mineral filler gradation, only 30 percent of the mineral filler is part of the aggregate. We could conclude from these differences that the mineral filler gradation should be measured. However, is it practical to specify this level of gradation analysis?

Another aspect of the mineral filler sensitivity study is the difference between the INDEX Model and VIRTUAL Model regarding the treatment of the mineral filler that is defined as binder extender. Since the VIRTUAL Model adds the volume of mineral filler extender to the asphalt binder volume, we might expect a noticeable increase in film thickness as the amount of mineral filler extender increases. At the coarse mineral filler gradation (with only 25% extender), the difference between the INDEX Model and VIRTUAL Model film thickness is approximately 0.2 microns. At the fine mineral filler gradation (70% extender), the difference is approximately 0.6 microns. These results show a change of about 0.4 microns that is attributed to how the mineral filler extender is addressed in the models. The study defines mineral filler acting as asphalt binder extender as any particle smaller than the film thickness. It is not the focus of this study to examine the details of the characteristics of binder extender. The film thickness models could be further refined by a better understanding of how mineral filler acts as an asphalt binder extender.

In general, all three models show that a change in mineral filler content of one percent will change the film thickness approximately 0.5 micron. The gradation of the mineral filler has a significant impact on film thickness when either the INDEX Model or VIRTUAL Model are used, but the practicality of measuring mineral filler gradation may limit the use of this feature.

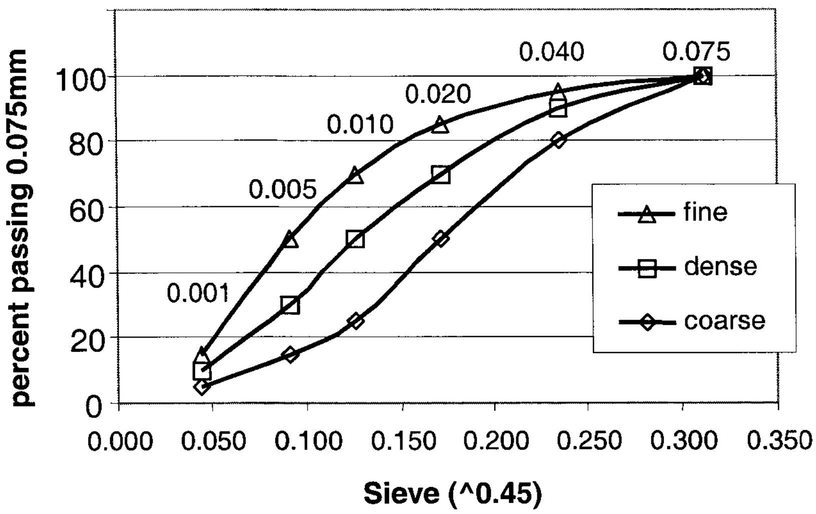


Figure 9a – Mineral Filler Gradation

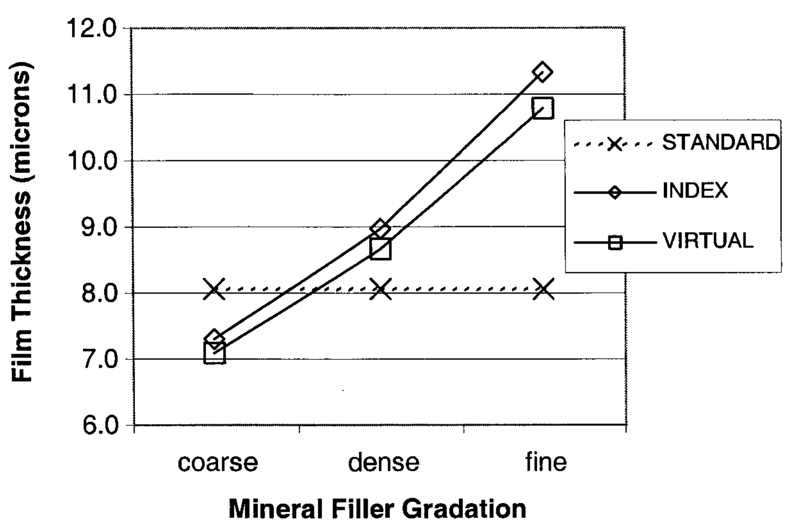


Figure 9b – Sensitivity of Film Thickness to Mineral Filler Gradation

♦Particle Shape

The VIRTUAL Model is based solely on the geometric configuration of spherical particles and the Standard Model is believed to originate from gravel (spherical) shapes. The INDEX Model is the only model that has the ability to account for differences in particle shape. These differences include spherical to cubical shape and elongation. The INDEX Model makes some assumptions to relate particle shapes to the probable size of particles on a specific sieve. The two principle assumptions are the volume of a cubical particle is approximately equal to the volume of the spherical particle on the same sieve and that elongation is not a factor in determining the retained sieve. For example: a spherical particle retained on the 12.5-mm sieve would have a volume of 2046 mm^3. The equivalent cubical particle has a volume of 2027 mm^3. If these particles have an elongation factor of 2:1, the longest dimension would be greater than the next larger sieve (19.0-mm), but the particles would still be analyzed as part of the 12.5-mm retained proportion.

To examine the question of particle shape, the gradation C proportions with 6 percent mineral filler was examined for both spherical and cubical shape and for up to 3:1 elongation. Figure 10 shows the results of the analysis. As expected, there is no change in the Standard Model or VIRTUAL Model values when either shape or elongation are changed. The results of the INDEX Model show that the film thickness of spherical shape particles is higher than cubical shaped particles. This follows the basic geometric principle that the sphere is the most efficient volumetric shape. To achieve the same particle volume, a cubical shape generates more surface area and will result in a lower film thickness. At a 1:1 elongation factor, the spherical gradation created 0.6 micron more film thickness than the same gradation with cubical shaped particles.

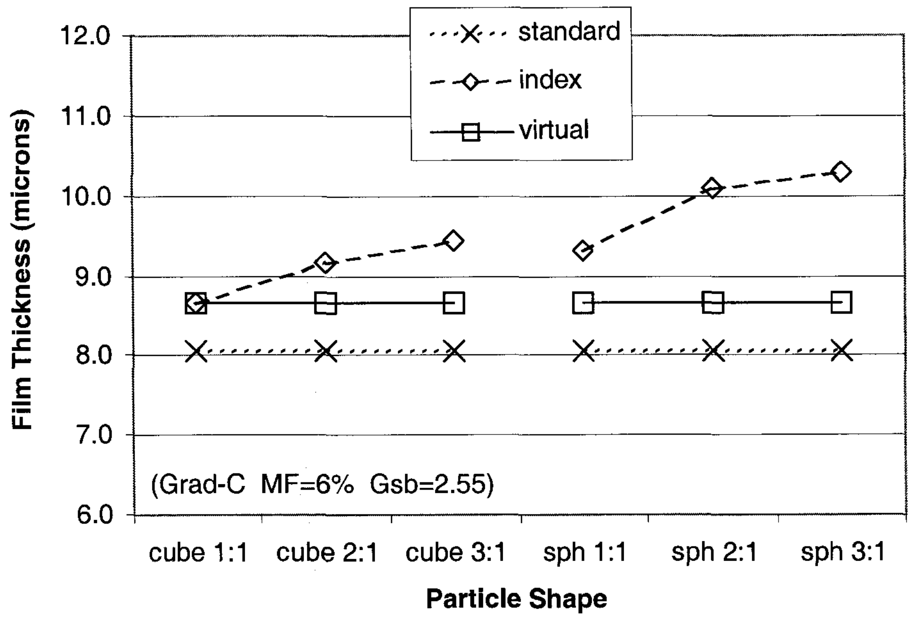


Figure 10 – Sensitivity of Film Thickness to Aggregate Shape and Elongation

The INDEX Model shows a general increasing trend in the film thickness value as the elongation increases. The increase is greater between 1:1 and 2:1 elongation, than between 2:1 and 3:1 elongation. This trend supports the impact of elongation. As particles become elongated, the amount of surface area for a unit of particle volume decreases. As the surface area decreases, the film thickness increases. If an aggregate source has a degree of elongation and the source is a large fraction of the mixture, the film thickness will likely increase.

In general, particle shape and elongation will impact the film thickness of the mixture. Mixtures with higher amounts of crushed (cubical) particles have a lower film thickness than mixtures composed of round gravel (spherical) particles. On the other hand, mixtures with substantial amounts of elongated particles will have a higher film thickness. It should be added here that these observed conclusion do not imply any recommendation to make mixtures more spherical and elongated to achieve film thickness.

♦Air Voids – VMA – Degree of Compaction

The input values for the equations of the Standard Model and INDEX Model are generally weight proportion relationships, percent binder by weight and surface area by weight. These models compute a theoretical film thickness without regard to the orientation of the particles. The VIRTUAL Model does account for the spatial relationship between particles and the input includes the VMA of the mixture. How does a change in the VMA impact the computed film thickness? To examine this question, a model mixture was established using Gradation C and general volumetric relationships from a comparable real mixture. To develop a set of similar mixtures for this impact analysis, the VMA was adjusted to reflect changes in the air voids. The aggregate and binder volume are held constant, but the increase in air voids creates a similar increase in VMA. For this study, the standard air voids of 4 percent was reduced to 2 percent and increased to 10 percent. Figure 11 shows the impact of changes to the air voids on the computed value of film thickness.

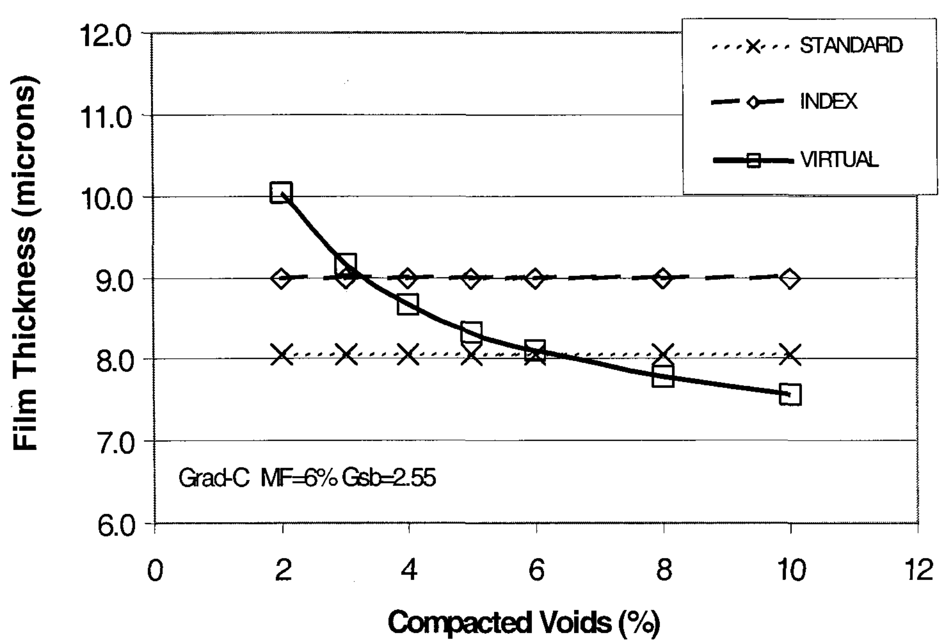


Figure 11 – Sensitivity of Film Thickness to Degree of Compaction

The graph clearly shows that the Standard Model and INDEX Model are not affected by the change in air voids. The VIRTUAL Model is impacted by changes to the air voids. Decreasing the air voids to 2 percent creates a 1.4 micron increase in film thickness. This is in line with the expectation that a reduction of the mixture volume from 4 percent to 2 percent air voids brings the aggregate particles closer together, displaces more binder from between particles to fill in the void space, and therefore increases the thickness of the binder between the aggregate particles and the remaining voids. In theory, if the air voids could be reduced to 0 percent, the film thickness would be infinite.

As the air voids increased from 4 percent to 10 percent, the calculated film thickness decreased by almost 1.0 micron and the rate of change diminished as the air voids moved closer to 10 percent. This trend is also expected from the VIRTUAL Model. As the mixture is expanded to higher air voids, the aggregate particles move further apart. The space between particles requires more asphalt binder.

Both the rapid increase in film thickness as the voids decreased to 2 percent and the slowing trend of film thickness decrease as the air voids increased to 10 percent are reasonable changes to the film thickness of an HMA mixture relative to the level of density. Through the use of the VIRTUAL Model, it would be possible to define the minimum required film thickness on the basis of the level of compaction when the mixture is placed, instead of defining film thickness at the conventional 4.0 percent air voids. While some additional compaction is achieved in the wheel paths, the majority of the HMA mixture remains at the initial post-construction level of compaction (air voids). If mixture durability is the primary intent of calculating film thickness, then it is appropriate to determine the film thickness at the in-place air voids, not 4.0 percent air voids.

Only the analysis procedure of the VIRTUAL Model is capable of determining the film thickness at varying levels of air voids (mixture compaction). As expected, reducing the air voids creates a higher film thickness and increasing the air voids lowers the film thickness. The level of compaction (air voids) may be an appropriate input for film thickness and would allow the mix design to compute the film thickness of the "as-placed" mixture.

Impact of Blended Aggregates

Each of the previous sensitivity analyses isolated a specific mixture parameter to see how the INDEX Model and VIRTUAL Model would respond to a range of values. This allows the study to check the reasonableness of the proposed models. Taking the sensitivity analysis to the next level, three parameters were combined to examine the response of the models to a partial "real world" scenario. For this analysis, a fine and coarse gradation were developed from four individual sources. The sources represented a crushed limestone, clean limestone chip, manufactured sand and natural sand. A mineral filler was added as a fifth source for the coarse gradation to bring the mineral filler proportion up to approximately 6 percent. The individual sources were proportioned to approximately mirror Gradation A (fine) and Gradation D (coarse). A summary of the fine and coarse gradations is given in Table 3 and Figure 12.

Table 3a – Individual Aggregate Source Gradations

INDIVIDUAL SOURCES	Total percent passing, by weight										
	25	19	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Crush Limestone	100	100	90	65	49	36	27	21	17	13	7
Limestone chip	100	100	100	97	63	19	0	0	0	0	0
Manufactured sand	100	100	100	100	89	70	32	4	0	0	0
Natural sand	100	100	100	100	100	91	75	47	25	14	8

Table 3b – Fine Aggregate Blend Gradation

Combined Gradation		Total percent passing, by weight											
		25	19	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075	
		100	100	96.7	87.8	74.3	55.6	39.1	24.3	14.6	9.3	5.2	
Source proportion		Individual sieve percent retained, by weight of total blend											
		25	19	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	75μ	MF
Cr. LS	33%	0	0	3.3	8.3	5.28	4.29	2.97	1.98	1.32	1.32	1.98	2.31
LS chip	21%	0	0	0	0.6	7.14	9.24	3.99	0	0	0	0	0
Man Sand	10%	0	0	0	0	1.10	1.90	3.80	2.80	0.40	0	0	0
Nat Sand	36%	0	0	0	0	0	3.24	5.76	10.08	7.92	3.96	2.16	2.88

Table 3c – Coarse Aggregate Blend Gradation

Combined Gradation		Total percent passing, by weight											
		25	19	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075	
		100	100	95.7	83.6	60.9	34.2	19.2	14.1	11.3	9.2	6.2	
Source proportion		Individual sieve percent retained, by weight of total blend											
		25	19	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	75μ	MF
Cr. LS	43%	0	0	4.3	10.7	6.88	5.59	3.87	2.58	1.72	1.72	2.58	3.01
LS chip	45%	0	0	0	1.3	15.3	19.8	8.55	0	0	0	0	0
Man Sand	5%	0	0	0	0	0.55	0.95	1.90	1.40	0.20	0	0	0
Nat Sand	4%	0	0	0	0	0	0.36	0.64	1.12	0.88	0.44	0.24	0.32
MF	3%	0	0	0	0	0	0	0	0	0	0	0.15	2.85

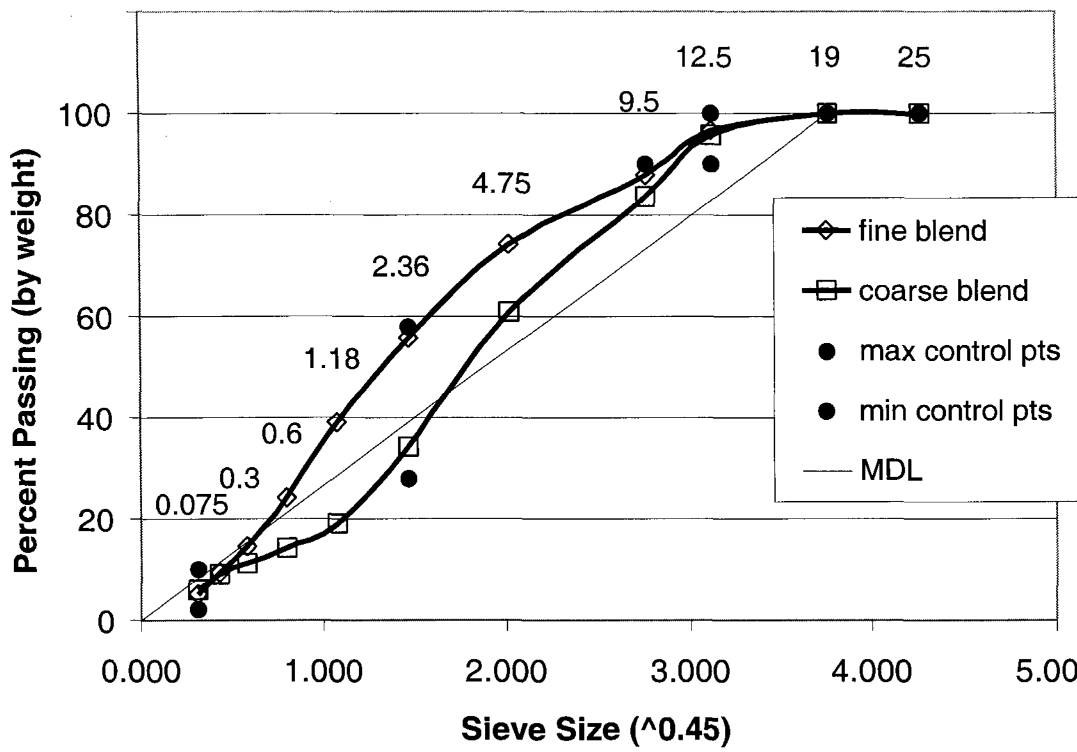


Figure 12 – Multi-Source Aggregate Blends

With these two established gradation blends, the analysis expanded to 16 tests for each gradation. Each test represents a unique set of the four sources with either a low aggregate specific gravity (Gsb = 2.550) or high aggregate specific gravity (Gsb = 2.750). The analysis held the other factors constant (binder content, mineral filler gradation, particles shape, & air voids).

To obtain the volumetric properties for the VIRTUAL Model, the analysis used the Iowa DOT HMA Mix Design Software package (SHADES). The SHADES software includes a "virtual" design feature to estimate the mixture's volumetric properties based on the aggregate gradation/specific gravity and asphalt binder specific gravity. For each of the 16 specific gravity combinations for each gradation, SHADES provided an estimate for asphalt binder content and VMA based on a 3M ESAL (N-design = 86 design gyrations) mixture at 4 percent design air voids. A complete set of the volumetric properties used for the analysis are included in Table 4a & 4b.

The 32 test mixtures were run through the Standard Model, INDEX Model, and VIRTUAL Model to examine the response of computed film thickness values for the various combinations. Figures 13, 14, 15, and 16 summarize the results of the three film thickness models. As expected,

Table 4a – Test Mixture Parameters – Fine Gradation Blend

	Aggregate Specific Gravity (Gsb)					Mixture Volumetrics					
MIX	Crush LS	LS chip	Man Sand	Nat Sand	blend	VMA	Va	Pb	Pbe	Pba	Gb
1	2.550	2.550	2.550	2.550	2.550	15.2	4	5	5	0	1.02
2	2.550	2.550	2.550	2.750	2.619	15.4	4	5	5	0	1.02
3	2.550	2.550	2.750	2.550	2.569	15.2	4	5	5	0	1.02
4	2.550	2.550	2.750	2.750	2.638	15.5	4	5	5	0	1.02
5	2.550	2.750	2.550	2.550	2.590	15.3	4	5	5	0	1.02
6	2.550	2.750	2.550	2.750	2.660	15.6	4	5	5	0	1.02
7	2.550	2.750	2.750	2.550	2.609	15.4	4	5	5	0	1.02
8	2.550	2.750	2.750	2.750	2.681	15.7	4	5	5	0	1.02
9	2.750	2.550	2.550	2.550	2.613	15.4	4	5	5	0	1.02
10	2.750	2.550	2.550	2.750	2.685	15.7	4	5	5	0	1.02
11	2.750	2.550	2.750	2.550	2.632	15.5	4	5	5	0	1.02
12	2.750	2.550	2.750	2.750	2.705	15.8	4	5	5	0	1.02
13	2.750	2.750	2.550	2.550	2.654	15.6	4	5	5	0	1.02
14	2.750	2.750	2.550	2.750	2.729	15.8	4	5	5	0	1.02
15	2.750	2.750	2.750	2.550	2.674	15.6	4	5	5	0	1.02
16	2.750	2.750	2.750	2.750	2.750	15.9	4	5	5	0	1.02

Table 4b – Test Mixture Parameters - Coarse Gradation Blend

	Aggregate Specific Gravity (Gsb)					Mixture Volumetrics					
MIX	Crush LS	LS chip	Man Sand	Nat Sand	blend	VMA	Va	Pb	Pbe	Pba	Gb
1	2.550	2.550	2.550	2.550	2.553	15	4	4.9	4.9	0	1.02
2	2.550	2.550	2.550	2.750	2.560	15	4	4.9	4.9	0	1.02
3	2.550	2.550	2.750	2.550	2.562	15	4	4.9	4.9	0	1.02
4	2.550	2.550	2.750	2.750	2.570	15	4	4.9	4.9	0	1.02
5	2.550	2.750	2.550	2.550	2.639	15.3	4	4.9	4.9	0	1.02
6	2.550	2.750	2.550	2.750	2.647	15.3	4	4.9	4.9	0	1.02
7	2.550	2.750	2.750	2.550	2.649	15.3	4	4.9	4.9	0	1.02
8	2.550	2.750	2.750	2.750	2.657	15.4	4	4.9	4.9	0	1.02
9	2.750	2.550	2.550	2.550	2.635	15.3	4	4.9	4.9	0	1.02
10	2.750	2.550	2.550	2.750	2.643	15.3	4	4.9	4.9	0	1.02
11	2.750	2.550	2.750	2.550	2.645	15.3	4	4.9	4.9	0	1.02
12	2.750	2.550	2.750	2.750	2.653	15.3	4	4.9	4.9	0	1.02
13	2.750	2.750	2.550	2.550	2.728	15.6	4	4.9	4.9	0	1.02
14	2.750	2.750	2.550	2.750	2.736	15.7	4	4.9	4.9	0	1.02
15	2.750	2.750	2.750	2.550	2.738	15.7	4	4.9	4.9	0	1.02
16	2.750	2.750	2.750	2.750	2.747	15.7	4	4.9	4.9	0	1.02

the Standard Model film thickness does not change over the series of 16 test mixtures. Looking at Figures 13 and 14, there are visually apparent differences between the INDEX Model and VIRTUAL Model film thickness response to the fine gradation model and response to the coarse gradation model. From the fine gradation tests, the INDEX Model and VIRTUAL Model film thickness values parallel the changes to the combined aggregate specific gravity. These values are higher than the Standard Model film thickness values similar to the analysis that isolated gradation (Figure 4). Also, the film thickness values trend higher as the aggregate specific gravity transitions from 2.55 to 2.75. Overall, the changes in the fine gradation tests reflect similar observations to the individual parameters of gradation and specific gravity.

The coarse gradation test sequence generated different results. The coarse gradation specific gravity sequence shows four distinct primary changes, unlike the zigzag pattern of the fine gradation. This difference reflects the fact that the coarse gradation is dominated by only two of the four aggregate sources. The crushed limestone and limestone chip sources account for 88 percent of the aggregate. The manufactured sand and natural sand only contribute 5 and 4 percent, respectively. In addition, the coarse aggregate gradation includes 3 percent mineral filler which makes up about 50 percent of the total mineral filler and does not change specific gravity in this analysis. Each of the four combined aggregate specific gravity sequences represents a change of one of the primary aggregate sources. The minor changes in each set of four tests reflect the changes of the secondary aggregates.

With this explanation of the coarse gradation specific gravity results, Figure 14 shows that the INDEX Model and VIRTUAL Model film thickness values do not mirror the same changes as the combined specific gravity. In fact, the film thickness values primarily reflect the change in the crushed limestone specific gravity. All other specific gravity changes had little impact on the film thickness. The other factor that relates the crushed limestone source to the change in the INDEX Model and VIRTUAL Model film thickness vales is the amount of mineral filler. The impact of the specific gravity change on approximately 50 percent of the mineral filler is the predominant reason for the film thickness difference. None of the changes to the other sources had a significant impact on the calculated film thickness.

The other difference between the fine and coarse gradation test results is the relationship of the INDEX Model and VIRTUAL Model film thickness values to the Standard Model value. The sensitivity study of the gradation (Figure 4) showed that the INDEX Model film thickness values continued to increase as the gradation became coarser, but the VIRTUAL Model film thickness values trended towards a constant value for coarse gradations. The multi-source analysis shows that the VIRTUAL Model film thickness values are similar to the Standard Model values and the INDEX Model film thickness values are higher for the coarse gradation.

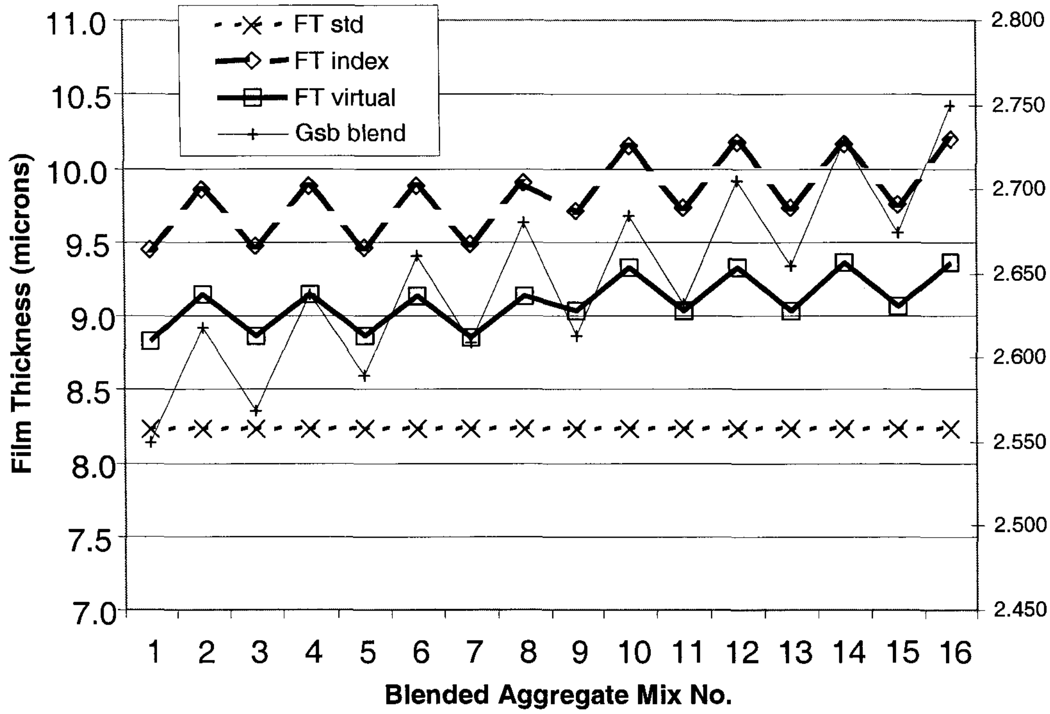


Figure 13 – Sensitivity of Film Thickness to Aggregate Source Combinations (Fine Blend Gradation)

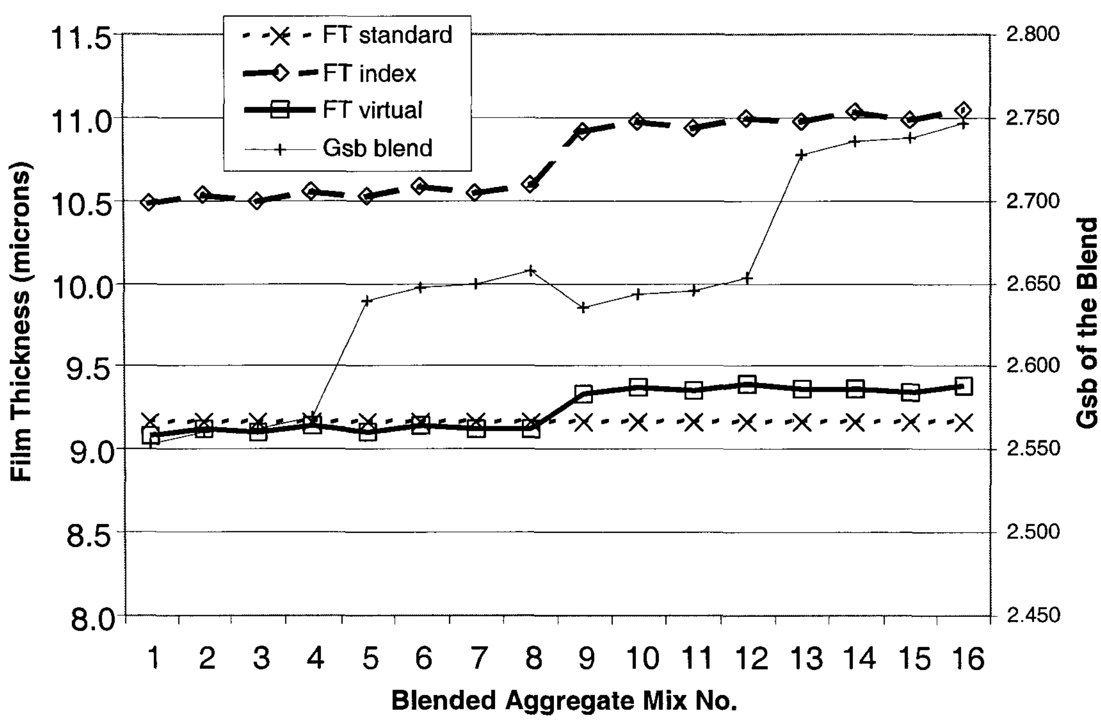


Figure 14 – Sensitivity of Film Thickness to Aggregate Source Combinations

(Coarse Blend Gradation)

In Figures 15 and 16 we resorted the results and graphed the computed film thickness values against the combined aggregate bulk specific gravities. For the fine aggregate gradation tests, the film thickness results tend to divide into three distinct groups. For the coarse gradation tests, the film thickness results divided into four groups. The explanations discussed above could be used again to distinguish between groups. For simplicity, this analysis clearly concludes that computing the film thickness without the input of the source specific gravities will lead to incorrect film thickness values.

2-D Versus 3-D Particle Surface Area

Both the Standard Model and INDEX Model compute film thickness as the depth of asphalt binder over a two-dimensional (2-D) sheet representing the surface area of the particles. Converting the three-dimensional (3-D) particle surface area to a 2-D surface generates errors in the actual film thickness of the asphalt binder shell over each particle. This error increases as the particles get smaller. The 2-D approximation is reasonably accurate for most particles down to the 1.18-mm sieve. Below the 1.18-mm sieve, the difference between the 2-D film thickness and 3-D shell thickness increase dramatically. Figure 17 gives the reduction factors to convert a 2-D film thickness to a 3-D shell thickness. From the figure, if the 2-D film thickness is 10 microns, then the 3-D shell thickness is less than 9.5 microns for particles retained on the 0.150-mm sieve, slightly more than 7.5 microns for 0.038-mm particles, and less than 5.5 microns for 0.010-mm particles.

This study did not perform a detailed examination of the difference between 2-D and 3-D film thickness. In general, if a film thickness model bases the film thickness on uniform 3-D shell thickness, the film thickness values would be lower than the current 2-D model. For a film thickness model that determines an equal film thickness on all particles, a 3-D analysis would require an iterative process to match asphalt binder volume to accumulated film thickness shell volume. If a film thickness model used the 3-D shell volumes to compute a uniform shell film thickness, the impact of the mineral filler particles would be even greater.

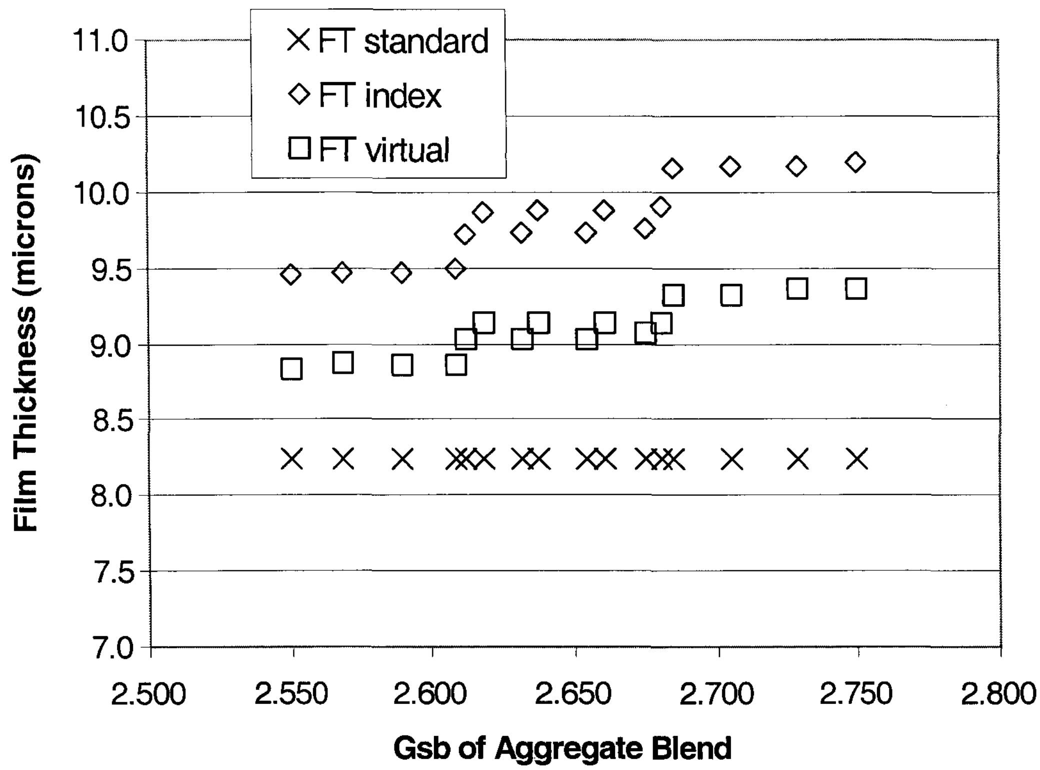


Figure 15 – Sensitivity of Film Thickness to Aggregate Combinations (Gsb) (Fine Blend Gradation)

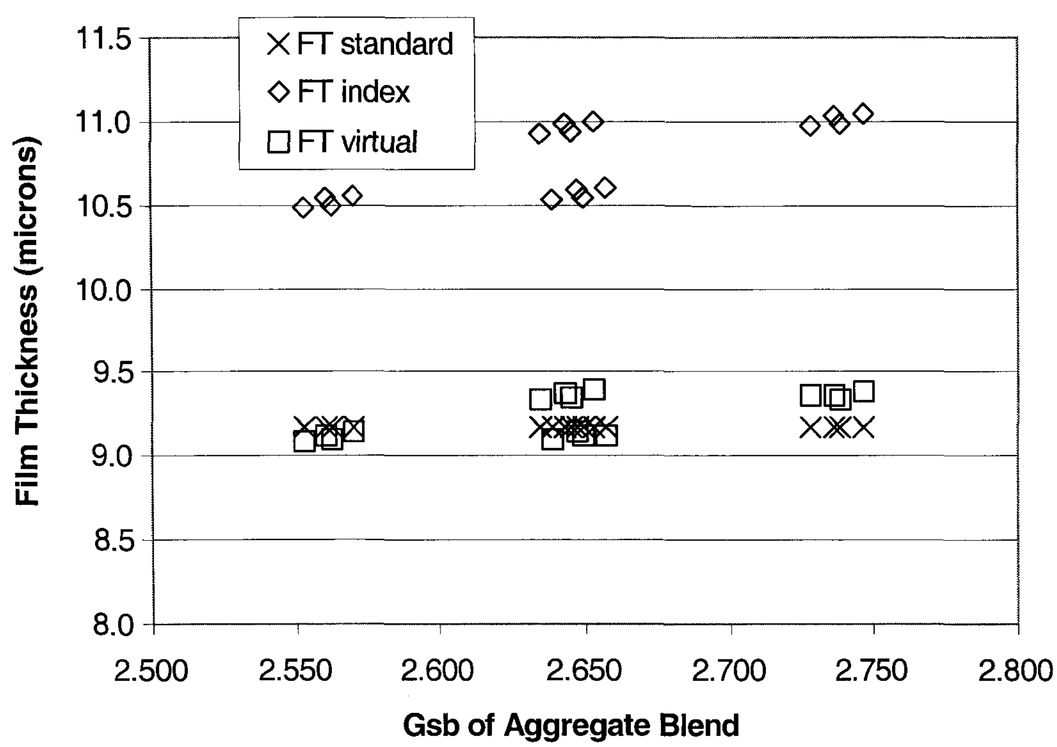


Figure 16 – Sensitivity of Film Thickness to Aggregate Combinations (Gsb) (Coarse Blend Gradation)

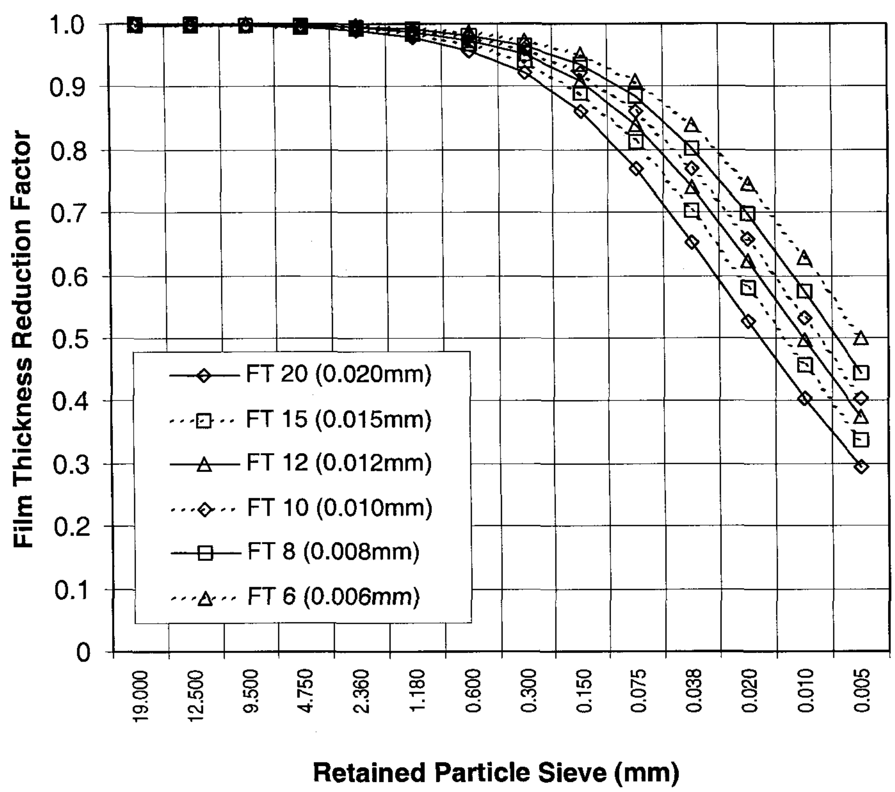


Figure 17 – 2-D to 3-D Film Thickness Reduction Factors

Phase I Summary

At best, the current Standard Model for calculating film thickness is a poor approximation of the concept of an asphalt binder film. The Standard Model only uses the combined gradation and asphalt binder content on a weight basis. It cannot account for specific gravity and shape differences in multiple aggregate sources combined to develop the HMA mixture. Both the INDEX Model and VIRTUAL Model account for multiple aggregate sources with different specific gravities. The INDEX Model includes shape factors for each aggregate source. The VIRTUAL Model accounts for the spatial relationship between particles. But how do these new variables impact the film thickness when they are all combined into the INDEX Model or VIRTUAL Model? Is the minimum film thickness criteria of 8.0 microns still valid for assuring the durability of a HMA mixture? The Phase II effort of this study is intended to examine these questions.

Chapter 4. Film Thickness Related to Hot Mix Asphalt Research

The INDEX Model and VIRTUAL Model bring new variables into determining film thickness. Both the models are improvements over the existing film thickness equation, but do they improve our ability to rate the durability of the HMA mixture? Is the minimum film thickness criteria of 8.0 microns still valid for assuring the durability of a HMA mixture? The Phase II effort of this study is intended to examine this question.

The study looks at previous HMA durability studies and places the new models along side the existing film thickness equation. Simply generating a new film thickness value is not sufficient. If the new models better represent the aggregate/binder relationship of the HMA, then we should see improvements in the correlation of film thickness to test results measuring the durability of mixtures.

This phase of the study will first examine previous studies that specifically looked at HMA durability and film thickness. Only studies that measured the impact of aging on the HMA are used. These studies subjected the HMA to both short-term aging and long-term aging. Further, these studies measured both the properties of the aged mixes and aged binders. Two studies were selected. Kandahl and Chakraborty's 1996 report (noted as the Auburn Study in this section) highlights the study of a single aggregate gradation with multiple binder contents. Nukunya and Roque's (et al.) 2001 report (noted as the Florida Study in this section) looked at six different aggregate gradations from a single limestone aggregate source with a unique optimum binder content for each gradation.

Comparison with Durability Studies

Auburn 1996

Auburn's 1996 study (12) is limited to one dependent variable, binder content. The research involved six mixtures using a single gradation and six binder contents. Five replicates of each mix were prepared, measured and tested. The gradation was a fine-graded 12.5-mm NMAS limestone with relatively low absorption (0.3 percent binder). The gradation is shown in Figure 18. The AC-20 binder contents ranged from 2.2 percent to 7.1 percent. The loose mixtures were short-term oven aged at 135°C for 4 hours, then compacted to 8 percent air voids. The compacted mixtures were measured for density and tested for resilient modulus at 25°C. Following the testing, the compacted specimens were long-term oven aged at 85°C for 120 hours and then tested again at 25°C for resilient modulus. The specimens were finally subjected to standard IDT loading to failure. Some mixture was set-aside after short-term aging for recovery of the asphalt binder. Additional mixture was taken after the completed IDT test for recovery of the long-term aged binder. All of the binder testing for penetration was done at 25°C and the viscosity testing was done at 60°C. Complex modulus testing was not done at the same temperature. The recovered short-term aged binder was tested at 64°C and the long-term aged binder was tested at 19°C. The report justifies the use of 19°C, but makes the comparison of short-term and long-term aging difficult.

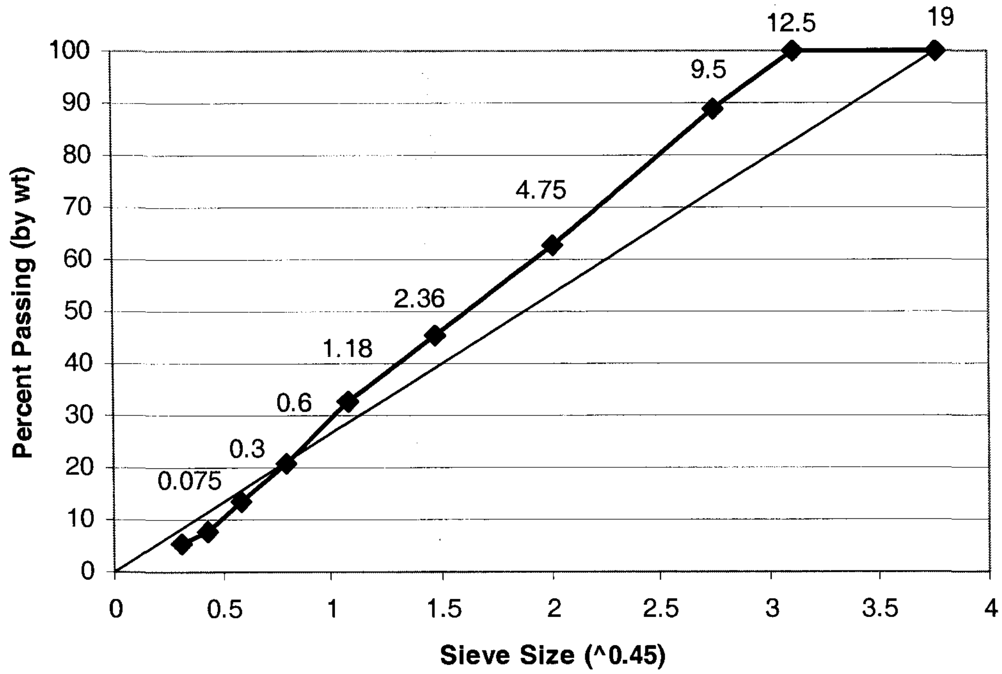


Figure 18 – Gradation for Auburn Study

The first step in examining this data was a review of the computed mixture parameters used in the original study. Sufficient detail was not provided in the TRB report, so the detailed 1994 NCAT/Auburn study (18) was obtained to get the mixture details. From the measured mixture volumetric properties, an adjustment of the percent asphalt absorbed was required. The Auburn study used a 0.2% asphalt absorption for the aggregate based on a previous report, but measured mixture densities in the Auburn research showed that the asphalt absorption was between 0.29 and 0.3 percent. This correction reduced the standard film thickness value by 0.2 microns.

The study is easy to analyze because there is only one dependent variable, binder content. Most of the correlations of film thickness to mixture properties (like resilient modulus) and film thickness to recovered binder properties (like penetration) are very sound and agree with general engineering expectation. The report notes two deviations in the analysis. The data for film thickness versus long-term aged asphalt binder viscosity did not lend itself to a "best fit" curve and the measured long-term aged asphalt binder complex modulus for the 13.0 micron film thickness appears to be an outlier.

Injecting the new film thickness values into the study's data created similar well correlated parameters. The film thickness values are given in Table 5 and displayed in Figure 19. Similar to the results of the generic gradations used to demonstrate the equations, the INDEX Model film thickness tends be provide higher values than the standard equation. The value is approximately 0.5 micron greater at the lowest binder content and almost 2.0 microns greater at the highest binder content. Accounting for aggregate specific gravity is probably the largest contributing factor. Because the VIRTUAL Model requires knowledge of the mixture volumetrics, the film thickness values from the VIRTUAL Model are based on the average of the computed values for each of the five replicates. The VIRTUAL Model cuts across the other two film thickness values. It shows the highest film thickness value at the lowest asphalt binder content (lowest reported film thickness) and is approximately 1.5 microns lower than the standard value at the highest binder content (highest reported film thickness). The reduction in film thickness at high binder contents reflects the ability of the VIRTUAL Model to account for three-dimensional distribution of the binder and aggregate. In three dimensions, it takes more binder to get an incremental change in film thickness and, at equal mixture air voids, the aggregate particles are further apart as the binder content increases.

To measure the impact of the new film thickness values, a correlation table was built using the correlation data analysis feature in Microsoft Excel. The correlation function displays the result of the covariance of the X,Y pairs divided by the product of the standard deviation of the values in each set. The correlation values do not distinguish between types of regression curves that best fit the data. They merely provide a first-step examination of the differences (or lack of differences) between each pair. Values approaching 1.00 or –1.00 are considered strongly correlated and values closer to 0.00 show little or no correlation.

A more detailed look at specific pairs of data followed the correlation analysis. Most of the regression curves are third order polynomials. These regressions express the expected trend in the data. The trend includes a probable plateau at either or both ends of the data. Mixtures with low film thickness would be expected to behave similarly and mixtures with high film thickness would be expected to behave similarly.

Table 5 – Film Thickness Values for Auburn Study

Computed Film Thickness Values (microns)			
Reported	Standard	INDEX Model	VIRTUAL Model
3.71	3.52	3.98	4.26
5.57	5.38	6.08	5.90
7.42	7.24	8.18	7.43
9.28	9.08	10.25	8.78
11.15	10.95	12.36	10.13
13.01	12.80	14.46	11.44

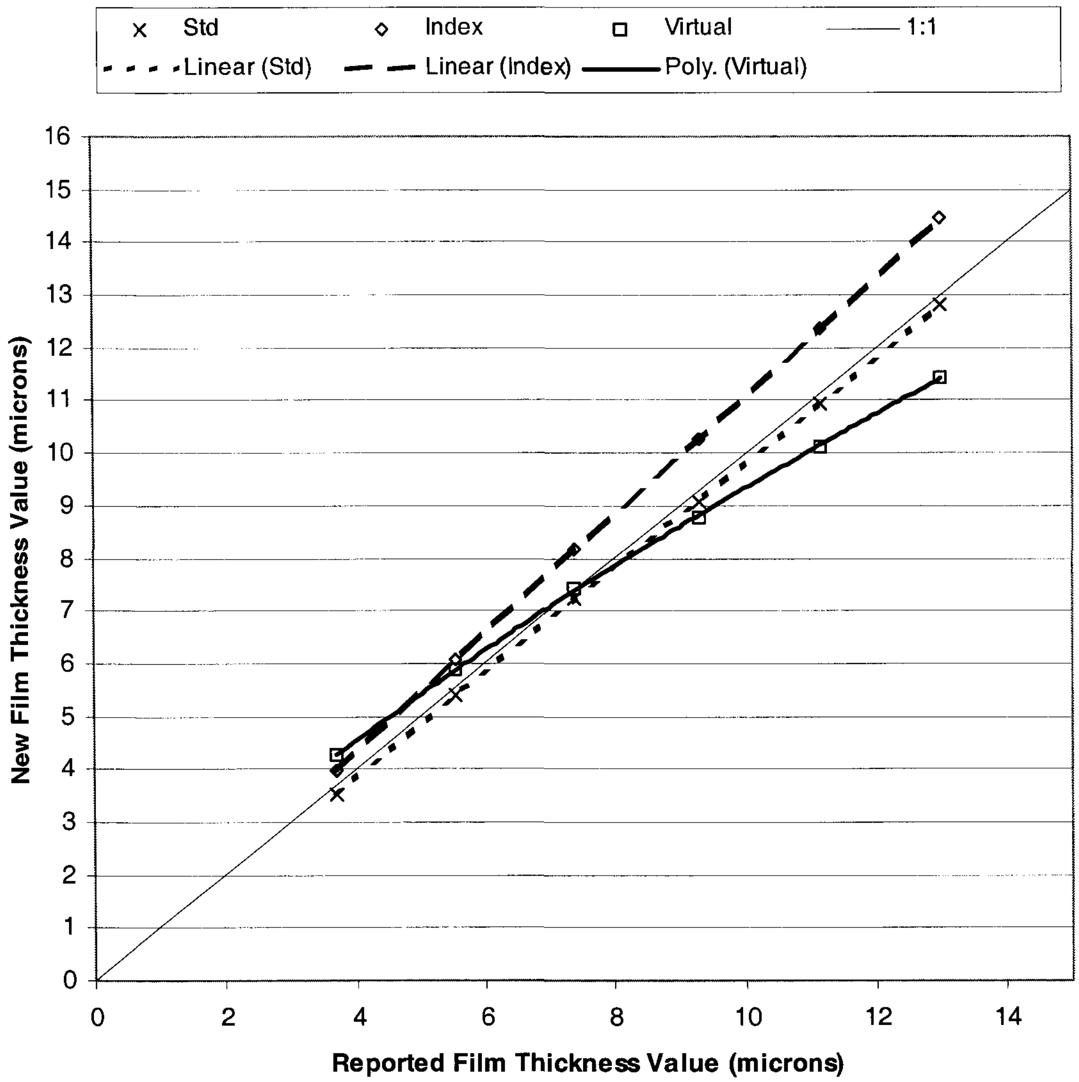


Figure 19 – Film Thickness Comparison for Auburn Study

The correlation summary for comparing the film thickness values to the measured material properties in the Auburn study is given in Table 6. Changes in the penetration and viscosity measurements of the recovered binder for both short-term and long-term aging trended as expected and have very high correlations. Although there is no change in the level of correlation, the regression curves given in Appendix B show the impact of the film thickness values from the VIRTUAL Model. All of the penetration curves in Figure B1 flatten at very low film thickness values, then begin to improve as the value reaches 8 microns. Under both aging conditions, the curve for the VIRTUAL Model increases steeper.

Table 6 – Correlation Summary for Auburn Study

Binder / Mixture Property	FT(std)	FT(index)	FT(virtual)
Penetration STOA	0.98	0.98	0.98
Viscosity STOA	-0.94	-0.94	-0.95
Complex Modulus, G* STOA	-0.68	-0.68	-0.66
Phase Angle STOA	0.70	0.70	0.67
Penetration LTOA	0.97	0.97	0.97
Viscosity LTOA	-0.97	-0.97	-0.96
Complex Modulus, G* LTOA	-0.82	-0.82	-0.84
Phase Angle LTOA	0.85	0.85	0.85
Tensile Strength LTOA	-0.99	-0.99	-0.99
Tensile Strain LTOA	0.97	0.97	0.96
Tensile Modulus LTOA	-0.98	-0.98	-0.98
Resilient Modulus STOA	-0.95	-0.95	-0.97
Resilient Modulus LTOA	-0.95	-0.95	-0.97
Resilient Modulus Index	-0.97	-0.97	-0.97
STOA – Short Term Oven Aging (4 hours at 135°C) LTOA – Long Term Oven Aging (120 hours at 85°C)			

In Figure B2, the viscosity curves for short-term aging increase dramatically as the film thickness falls below 8 microns. This trend shows the increased aging of the binder during the production of the mixture. The viscosity curves for the recovered binder after long-term aging reinforce the observation that low film thickness values can be associated with severe aging of the binder. Again, the viscosity measurements for film thickness values below 8 microns become flat. An indication that the binder has lost most of its lighter fractions. Similar to the penetration curves, the long-term aged viscosity curve for the VIRTUAL Model improves quicker as the film thickness increases.

The correlation values for the Complex Modulus measurements and phase angle measurements are low due to a probable outlier value in each dataset. The measured complex modulus for the lowest film thickness in the short-term aged dataset and the measured value for the highest film thickness in the long-term aged dataset do not follow the expected trend, as shown in Figure B3, and could be removed as outliers. The Auburn research report also noted these outliers. With the outliers omitted, the R^2 values for the regression curves improve to 0.90 and 0.99 respectively for the Complex Modulus. The regression curves for the Complex Modulus also show that the trend of the film thickness values from the VIRTUAL Model change at a steeper rate than the standard and INDEX Model values.

The regression curves in Figure B4 for the phase angle of the short-term aged binder exaggerate the influence of the third-order polynomial equation. The low film thickness phase angle does not follow the expected trend and was removed from the regression curve. The remaining data points show a clear plateau at both ends of the film thickness range. All six data points of the long-term aged binder phase angle measurements are included in the regression curve. Unlike the

Complex Modulus value, the phase angle at the highest film thickness does not appear to deviate from the expected trend.

Collectively, the measured response of the recovered binder follows the expected trend. The penetration and viscosity measurements appear to be more uniform than the Complex Modulus and phase angle. In most cases, the trends for the VIRTUAL Model film thickness curves show an increased rate of binder change over the standard and INDEX Model curves. The comparison of the correlation and regression values for the three film thickness datasets showed no practical change or improvement.

The examination of the changes in binder properties are a direct measure of the rate of aging (or durability). However, the process for acquiring binder samples to test requires extraction and recovery of the binder from the mixture. In addition to testing error, the extraction/recovery process introduces another level of variability in the measured data. The other approach to identify changes in durability is to measure the change in the mixture response to physical testing. In the Auburn study, Resilient Modulus was used as a non-destructive test to measure the response of the same set of mixture specimens after both short-term aging and long-term aging. This physical testing was followed by IDT loading to failure (destructive testing) of the long-term aged specimens. The intent of this testing is not to define the acceptable level of mixture stiffness or tensile strength. Rather, the results can be used to see how trends in the mixture response changed as the film thickness changed.

In general, Resilient Modulus testing is inherently more variable than other methods of testing due to the added components of aggregate, mixture interaction, and the very small (non-destructive) levels of strain applied. However, with attention to testing protocol and a greater number of repetitions, consistent modulus values can be achieved. The trend of the Resilient Modulus values in the Auburn study is very good and the variation is relatively small. The initial correlation analysis showed film thickness to Resilient Modulus data set pairs at 0.95 values. Applying the third-order polynomial best fit, the R^2 values are 0.99 for all regression curves. Both the short-term aged and long-term aged regression curves in Figure B5 agreed with the expected trend. As film thickness (binder content) decreased, the mixture stiffness increased, so the modulus values increased. This trend would occur without regard to the amount of aging. But with closer examination, the Resilient Modulus values at the higher film thickness values for both short-term and long-term aged conditions tend to flatten off at 2000 MPa. We can conclude from this observation that the mixture experienced very little additional aging during the long-term aging process at higher levels of film thickness. The affect of film thickness on mixture aging is easier to see through the use of a modulus ratio graph. Using the ratio of long-term aged mixture modulus divided by short-term aged mixture modulus, we create a value that expresses the increased rate of mixture stiffness and neutralize the general affect of variation in binder content. The regression curves generated on this graph in Figure B5 clearly show how the difference in film thickness impacts the change in mixture stiffness. At very low film thickness levels, the stiffness of the mixture increases by 50 percent (M_R ratio ~ 1.5). At very high film thickness values, the mixture stiffness only changes slightly (M_R ratio ~ 1.05). The curves for the mixture Resilient Modulus agree with the curves for the recovered asphalt binder. Like the trends in the binder tests, the curves for VIRTUAL Model film thickness are steeper.

The last measured property of each mixture was the IDT loading at constant deformation rate to failure. The results are expressed as strength (stress), strain, and modulus (stress/strain). All the correlation values are 0.96 and above. The third-order polynomial regression curves shown in Figure B6 have R^2 values of 0.99 or 1.00. The results of the IDT testing are only provided for the long-term aged condition. The results are very similar to the Resilient Modulus testing, but we cannot examine the rate of IDT change since there are no short-term test results to compare to. As shown in the other tests, the curves for the VIRTUAL Model film thickness change quicker than the standard and INDEX Model curves.

Overall, the Auburn study was well thought out and accurately executed. There are very few questions about errant data and the only measured properties that exhibited significant variation were the recovered asphalt binder Complex Modulus from both the short-term aged loose mixture and the long-term aged compacted specimens. With relatively high correlation values and strong regression curve R^2 values, there is no improvement in the film thickness relationships from using the INDEX Model or VIRTUAL Model. The only consistent observation was the increased rate of aging change when applying the VIRTUAL Model.

Florida 2001

The second durability study selected for the film thickness comparison was performed by Nukunya, Roque, et al. (13) at the University of Florida and reported at AAPT in 2001. Florida's research examined the affect of gradation on mixture durability. Six 12.5 NMAS gradations were developed using a single limestone aggregate source with a nominal 1-percent asphalt absorption. The gradations ranged from fine to coarse with approximately 30 to 50 percent passing the 2.36-mm sieve. The gradations are shown in Figure 20. The binder content varied by mix from 5.3 to 6.5 percent to achieve 4 percent air voids at N=109 using a gyratory compactor. By fixing the air voids at 4 percent, the film thickness for each mix reflected the differences in the gradation and binder content. The loose mixture was short-term oven aged at 135°C for two hours, compacted to 7 percent air voids, and measured for volumetric properties. Half of the compacted specimens were then long-term oven aged at 85°C for 120 hours. All specimens were prepared for IDT testing to measure Resilient Modulus, Creep Compliance, and strength at 10°C. Following the mixture testing, the asphalt binder from each combination of gradation and aging condition was extracted and recovered for binder testing. Details of the mixture tests are referenced in the AAPT report.

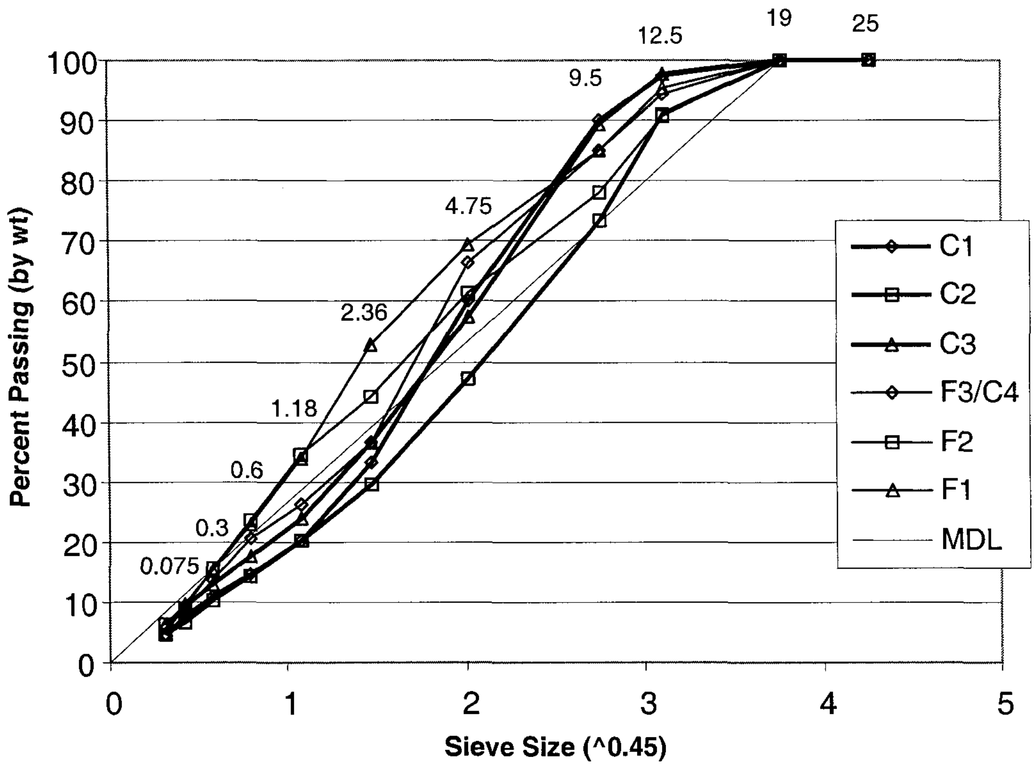


Figure 20 – Gradations for Florida Study

The initial review of the Florida study identified several computed volumetric values that were slightly different and probably associated with rounding answers during the intermediate steps of calculations. These rounding differences were also found in the aggregate surface area and film thickness calculated values. The new values are used in this film thickness study. The only significant difference is in the values related to the computed filler:bitumen ratio. The study applies the total binder weight, but should apply the effective binder weight.

This study was selected for application of the new film thickness values because it shows a high amount of variation in the test results. The use of gradation and constant air voids as the control variables do not establish any relationship between the six sets of data. There is no evidence that the mixtures represent optimal properties and some mixture volumetric values do not satisfy standard mixture criteria. The key to examining this data is to make comparisons to the rate of mixture property change from short-term aging to long-term aging. We can also examine the recovered binder properties because they are isolated from the influence of the aggregate in binder testing.

The primary approach to examining data from multiple mixtures is to compare the relative change in properties, not the actual measured properties. Since each mixture (gradation, binder, and air voids) responds differently to the tests, the relationship between the mixtures at any given point during the aging process has no meaning when we are trying to examine durability. The correct analysis looks at the relative change in a mixture's measured response from one level of age conditioning to another. By computing the relative change, the analysis brings all the mixtures to an equal basis for further study. As an example, if two mixtures have different Resilient Modulus values after short-term aging, we cannot conclude that the difference in values is related to the age conditioning. The mixture could simply represent two uniquely different mixture compositions. However, if one mixture becomes dramatically stiffer than the other after long-term aging, then we can confidently conclude that the greater change in mixture stiffness was likely a result of increased aging.

A comparison of INDEX Model and VIRTUAL Model film thickness values to the Florida's report film thickness values is displayed in Table 7 and Figure 21. The graph also marks which film thickness value is associated with which gradation. As expected, the film thickness values computed by the INDEX Model are 0.3 to 0.4 microns higher than the standard values. The values computed by the VIRTUAL Model create the same deviation from the trend for the mixtures with coarse gradations (C1 and C2). The VIRTUAL Model is 0.5 microns higher for the smallest film thickness (fine mix, F2) and 0.9 microns lower for the highest film thickness (coarse mix, C1). The spread in mixture characteristics can be seen in Figure 21 by looking at the association of surface area to film thickness for the six gradations. The data points correctly trend from high surface/low film thickness to low surface area/high film thickness, but the individual mixtures with comparable surface area have more than a 1.0 micron difference range. Figure 21 compares the film thickness values to effective binder content (the other primary input into film thickness), the trend is reasonable, but mixtures F1 and C2 invert their relationship to the group.

Table 7 – Film Thickness Values for Florida Study

Computed Film Thickness Values (microns)				
Mix No.	Reported	Standard	INDEX Model	VIRTUAL Model
C1	11.2	11.2	11.6	10.3
C2	10.1	10.1	10.5	9.5
C3	8.0	7.8	8.1	7.9
F1	9.0	9.0	9.3	9.4
F2	6.9	6.7	7.0	7.3
F3C4	8.1	8.0	8.3	8.2

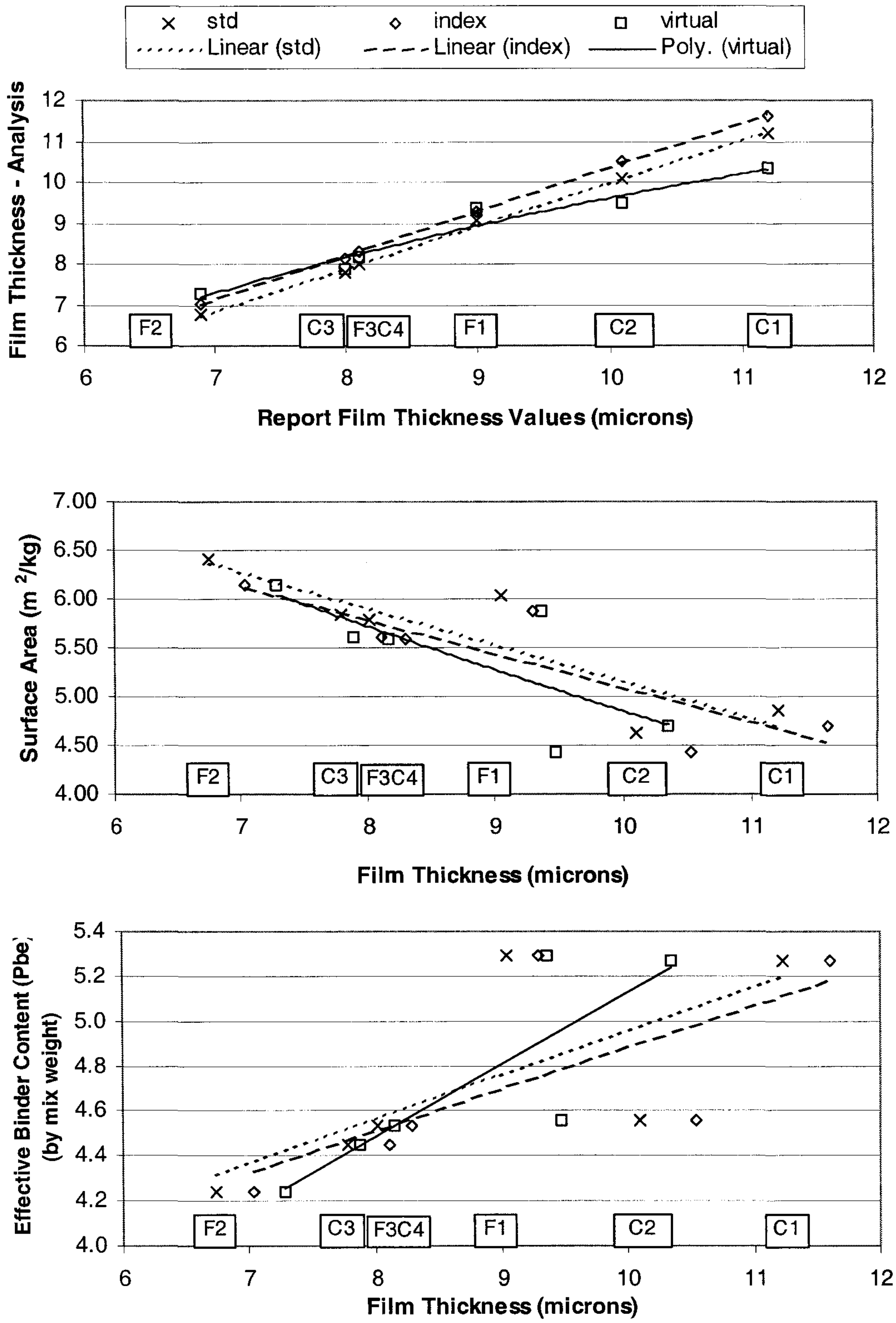


Figure 21 – Film Thickness Comparisons for Florida Study

The correlation analysis for the recovered asphalt binder properties is provided in Table 8. In every analysis group, the standard and INDEX Model correlation values are better than the VIRTUAL Model correlation values. It identified a moderately strong relationship (0.82-0.85) for penetration in both short-term aged and long-term aged conditions. The correlation values for the phase angle are a degree lower (0.77-0.72) and the viscosity and Complex Modulus relationships are only fair.

Table 8 – Correlation Summary of Binder Properties for Florida Study

Binder / Mixture Property	FT(std)	FT(index)	FT(virtual)
Penetration STOA	0.83	0.84	0.70
Viscosity STOA	-0.55	-0.55	-0.48
Complex Modulus, G* STOA	-0.53	-0.54	-0.38
Phase Angle STOA	0.73	0.74	0.64
Penetration LTOA	0.84	0.85	0.73
Viscosity LTOA	-0.54	-0.55	-0.40
Complex Modulus, G* LTOA	-0.66	-0.68	-0.51
Phase Angle LTOA	0.76	0.78	0.67
STOA – Short Term Oven Aging (2 hours at 135°C) LTOA – Long Term Oven Aging (120 hours at 85°C)			

Film thickness versus penetration graphs for short-term aged and long-term aged are given in Appendix C, Figure C1. The data sets were fitted with third-order polynomial regression curves. Both the short-term and long-term aged regressions show a similar trend. The penetration of the binder drops at low film thickness and increases at high film thickness. This trend follows the general expectation, but the spread of the data can generate other interpretations. The relative order of the results for each mixture indicate that the binder recovery process was successful and there appears to be little or no influence from the extraction solvents. The standard and INDEX Model curves are very similar, as expected. The VIRTUAL Model curve has a lower R^2 value and displays are more aggressive change in penetration as it relates to film thickness.

The data from the viscosity testing shown in Figure C2 displays the comparable trend to the penetration data. Higher viscosity (stiffer binder) at low film thickness and lower viscosity at high film thickness. The R^2 values are misleading, because the regression function attempts to fit all the data. The normal expectation for the viscosity values would not find a decreasing-increasing-decreasing pattern. A manually fitted curve would likely display a flat transition between the low and high ends. Contrary to the penetration results, the relative change in the viscosity measurements for mixture C2 between the short-term aged and long-term aged binder does not fit the balance of the binder tests. Again, the standard and INDEX Model results are similar and the VIRTUAL Model creates a tighter curve.

The results of the Complex Modulus testing in Figure C3 reflect the same pattern as the penetration and viscosity results. The diversity of the data is displayed in the R^2 values, 0.52 and lower.

In Figure C4, the phase angle measurements for the coarse mixtures (C1 and C2) change the best fit third-order polynomial curves. It is difficult to conclude which set of test results are more likely to mis-represented the binder. The overall trend is reasonable, but the regression on the high film thickness end should not peak and drop. Manual curve fitting would improve the expected trend.

The consistency of the penetration, viscosity, and Complex Modulus data trends, even at relatively nominal levels of correlation, could conclude that film thickness is a factor in determining the durability of different mixtures. This is a weak conclusion in light of the very small database in this study.

The analysis of the impact of the INDEX Model and VIRTUAL Model using the Florida study uses the relative change in material properties as the primary method of comparisons. The relative change value represents a percent increase (or decrease) in a measured response computed as the difference between the short-term aged value and long-term aged value divided by the short-term aged value, expressed as (LTOA-STOA)/STOA. The results of the initial correlation analysis are summarized in Table 9. Three groups of the four recovered binder correlation groups show good correlation. Only one of the six mixture property groups have relatively good correlation. The other five mixture groups have no correlation with values less than 0.23 and most are below 0.10.

Table 9 - Correlation Summary of Relative Change for the Florida Study

Binder / Mixture Property	FT(std)	FT(index)	FT(virtual)
Penetration	-0.82	-0.83	-0.72
Viscosity	0.23	0.26	0.09
Complex Modulus (G*)	0.85	0.87	0.77
Phase Angle	-0.82	-0.84	-0.70
Resilient Modulus (M_R)	-0.11	-0.08	-0.23
Creep Compliance	-0.05	-0.08	0.14
M-value	-0.73	-0.74	-0.61
Fracture Energy	-0.02	-0.02	-0.01
Failure Strain	0.002	-0.01	0.06
Tensile Strength	0.05	0.07	-0.07

Figure C5 summarizes the percent change in asphalt binder properties. The graph relating film thickness to the percent change in penetration shows a good level of R^2 using the third-order polynomial regression curve. The change in penetration increases at low film thickness values and decreases at high film thickness values. This trend agrees with the expectation that higher values of film thickness will slow the rate of binder aging. The standard and INDEX Model regression curves are very similar. The VIRTUAL Model regression curve tightens the range of film thickness, but tends to initiate the high and low curves at approximately the same points (8 and 10 microns) as the other to groups.

There is no correlation of film thickness to percent change in viscosity using the data generated in the Florida study.

Very good regression curves were formed with the data comparing film thickness and percent change in Complex Modulus. However, the shape of the curve suggests that the binder change is constant at the lower and higher levels of film thickness and transitions through the intermediate film thickness values. The breaks in the curves generally occur at 8 and 10 microns, similar to the change in penetration. The R^2 for the VIRTUAL Model regression curve (0.70) is well below the R^2 for the other two curves (0.90 and 0.92) and, unlike most of the other graphs, is similar in shape.

Even though the correlation value for the phase angle was above 0.80, the R^2 values for the regression curves are not as good. The trend in the percent change in phase angle meets general expectation, but the third-order polynomial curves for the standard and INDEX Model are relatively smooth. The regression curve for the VIRTUAL Model film thickness values compares well with the penetration data regression curves.

As noted, only one of the six data sets for percent change in mixture properties generated a good correlation value in the initial assessment. Figure C6a and C6b exam the individual pairs of film thickness and mixture response and found a similar lack of identifiable trends in the graphs. The plot of change in M-value created a reasonable regression curve, but the spread of the percent change in M-value is wide.

Conclusions of the Durability Analysis

The Auburn and Florida reports were selected for the durability analysis because both studies measured the short-term aged properties and long-term aged properties of the mixture and recovered binder. Each report contained sufficient data on the materials in the mixtures to calculate alternative film thickness values based on the INDEX Model and VIRTUAL Model. The following conclusions are drawn.

- The Auburn study used a single gradation and varied the binder content. The correlation of film thickness to mixture and binder properties was very good. The Florida study examined multiple gradations and set the binder content to obtain 4 percent voids. The correlation of film thickness to asphalt binder properties was good, but there was no correlation with most of the mixture properties. Film thickness can be used to measure the durability of HMA mixture, but differences in mixture composition and structure make it difficult to use mixture tests for measuring durability with multiple mixtures.
- Testing of extracted and recovered binders gave consistent results. This conclusion may not be valid for modified binders.

- Third-order polynomial regression curves properly expressed the expected trend in durability. They identified rapid aging at low film thickness and slow aging at high film thickness. Some curves expressed change at both ends with little change in the middle. Other curves expressed constant values at both ends with a transition in the middle. The shape of each curve may be relative to the type of test performed and the test temperature used.
- The INDEX Model did not substantially change the durability regression curves. Both studies used single aggregate source mixtures, so the differences in film thickness associated with varying aggregate specific gravity were not present. The VIRTUAL Model tended to compress the film thickness values and tighten the durability regression curves.
- For both studies, film thickness values above 10 microns provided the best durability. Film thickness values below 8 microns showed poor durability.

Comparison with Rutting and Fatigue Studies

Durability studies provide a target minimum film thickness value to achieve a desirable level of durability. Rutting and fatigue studies provide maximum (rutting) and minimum (fatigue) relationships to achieve proper HMA mixture performance under traffic. Can these studies further bracket the film thickness range to satisfy mixture stiffness and flexibility requirements? Using the Auburn and Florida studies, can we define these film thickness limits?

The Auburn study measured the Resilient Modulus and Tensile strength of one mixture at multiple binder contents. The regression curves comparing film thickness to these mixtures properties were very uniform. As the film thickness increased, these mixture properties decreased. The desirable level of Resilient Modulus and Tensile strength will be dependent on the intended mixture's use (for example, base or surface). We could not arbitrarily require 6000 Kpa and 10 microns of film thickness for this mixture. Mixture characteristics, in addition to binder content, would have to change to meet 6000 Kpa and 10 microns.

The Florida study better demonstrates the complexity of achieving durability and the ability to carry traffic load. Figure 22 shows graphs comparing film thickness to measured mixture properties of the six different gradations from a single aggregate source. Two mixtures can have equal load carrying values and different film thickness values or different load carrying values and equal film thickness. Resilient Modulus values for mixes C1, C2, and F2 are about the same after short-term aging, but the film thickness values range from 7 to 11 microns. At the same time, mixes F2, F3/C4, and C3 have about the same film thickness, but the Resilient Modulus ranges from 8.5 to 12 MPa. Similar trends can be seen in the Tensile Strength and Failure Strain graphs.

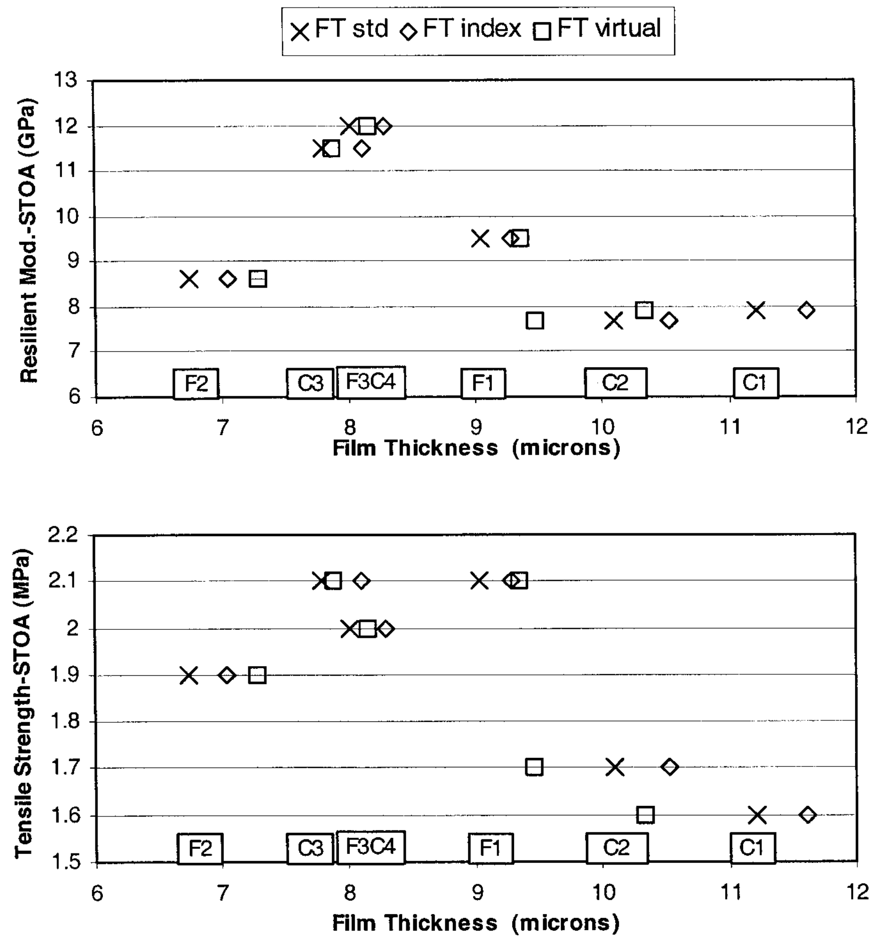


Figure 22 – STOA Mixture Properties from Florida Study

Pellinen (19) examined the behavior of a wide variety of mixtures. The study compared the volumetric mix design criteria to mechanical performance test results. While the study did not focus on mixture durability, it did compare the mixture requirements to satisfy stiffness and strength. The report concludes…*"**A key to the successful mix design is the balance between the volumetric composition and the used raw materials at the specific climatic and traffic conditions.**"* Figure 5(a) in Pellinen's report, provided here as Figure 23, displays the competing mixture performance criteria.

Can we further bracket the film thickness range to satisfy mixture stiffness and flexibility requirements? No. Film thickness alone cannot bracket the intended level of rutting or fatigue characteristics for a HMA mixture. In concert with other mixture characteristics (like gradation, CAA, FAA, and density), film thickness may be one of a group of input parameters for other mixture performance criteria. It is easy to demonstrate that mixtures with lower binder contents (low film thickness) generally have relatively high rutting resistance. And mixtures with higher binder contents (high film thickness) have better fatigue resistance. But as the Florida study showed, two different mixtures with reasonably equivalent binder contents do not have the same rutting and fatigue properties.

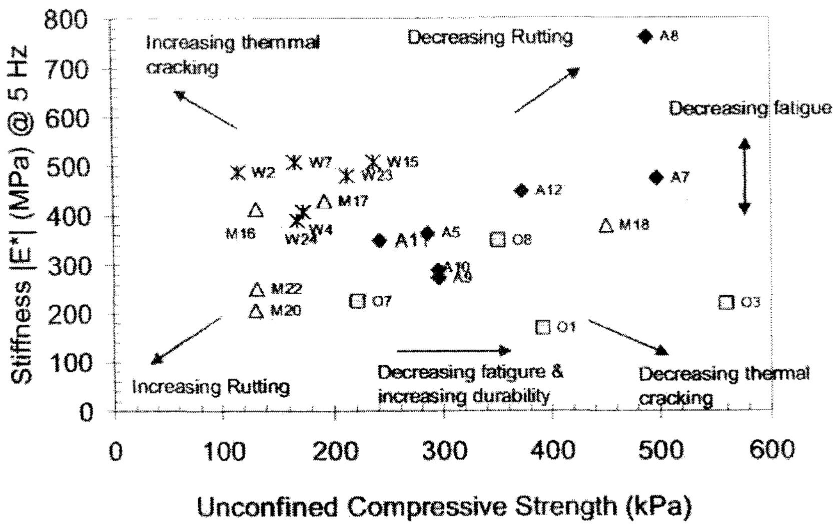


Figure 23 – Conceptual Stiffness/Strength Criteria for Asphalt Mixtures (19)

Phase II Summary

If the new models better represent the aggregate/binder relationship of the HMA, then we should see improvements in the correlation of film thickness to test results measuring the durability of mixtures. The studies selected for this phase measured the properties of HMA mixes and the extracted asphalt binders after both short-term aging and long-term aging. The Auburn study isolated binder content was the primary variable. The INDEX Model computed higher film thickness values and the VIRTUAL Model flattened the film thickness range. The new film thickness values did not improve the correlation with measured durability related tests, but the VIRTAUL Model did change the shape of the trend as binder content increased. The Florida study isolated the aggregate gradation as the primary variable. The INDEX Model computed higher film thickness values and the VIRTUAL Model flattened the film thickness range for the change in gradation similar to the change in Auburn's study of binder content. With only one binder content for each mixture in the Florida study, The correlation between film thickness and durability was limited, particularly with mixture tests. The new film thickness values did not improve the correlations.

The multiple gradations in the Florida study demonstrate the complexity of balancing HMA durability and HMA strength. Two mixtures can have equal measured strength and different film thickness values or different strength and equal film thickness. A matrix of gradation and binder combinations should be studied to see if there is a relationship between film thickness and HMA mixture properties.

CHAPTER 5. Film Thickness Related to Iowa Mix Designs

Phase I developed the INDEX Model and VIRTUAL Model to replace the standard film thickness equation. Phase I further demonstrated how the new equations responded to changes in mixture characteristics. Phase II applied the new equations to two HMA durability studies. The first durability study used one mixture and the second used six mixtures. The results of Phase II showed that the multiple variable studies (the second study) have difficulty clearly identifying mix durability. Durability is not a single parameter performance characteristic and the common compacted mixture test methods give different responses for different mixtures. If we examine a large population of mixtures for durability, we would expect to have the same difficulty distinguishing durability from other mixture performance characteristics.

The impact of the new film thickness equations on field mix designs cannot examine the desired limits of mixture durability, but can look at how the new film thickness values compare to the current film thickness values using "real" mix designs. How will the new film thickness equations change the preparation of mix designs? If the INDEX Model or VIRTUAL Model is used for mix design, will the range of film thickness values change from the current 8 to 15 microns?

Actual hot mix asphalt mix designs represent a broad spectrum of mixtures. Mix designs for low volume pavements are different than mix designs for Interstate pavements. Typically low volume mixes have higher amounts of sand. High traffic mixes require more compaction energy and tend to have lower amounts of asphalt binder. Numerous mixture characteristics will influence the final computed film thickness value.

This phase of the study started with 348 approved mix designs for projects on Iowa highways and roads. The list included mixes for all traffic levels in all six districts of the State from the 2002 and 2003 construction seasons. The software used in Iowa for all mix designs is known as SHADES. One component of this software measures the accuracy and precision of several components of the laboratory mix design process. Each mix design is given a rating of excellent, good, fair, or poor. To get a better understanding of the impact of the new film thickness equations, only 280 of the mixtures with a good or excellent rating are used. This reduces the variability of the results due to laboratory error. The group of 280 mixtures was further reduced to 268 by eliminating the nine 100K mixtures and three incomplete mix designs. Table 10 summarizes the breakdown of the 348 mix designs.

For the purposes of this study, the 268 mix designs represent the "total" population of mixtures used in Iowa. The Iowa DOT database does not include the individual gradations of each aggregate source used in the mix. To accomplish the Phase III objective, the database was supplemented with complete mix design reports for 40 of the 268 mix designs. Ten mix design reports were randomly selected from each of the four primary traffic (ESAL) levels to produce a stratified random sample. Only mix designs with the SHADES excellent rating for laboratory mix design process were considered for the 40 mix sample to reduce the affect of laboratory variation.

Table 10 – Summary of Iowa Mix Designs

Mix Design Rating	No. of Mixes	Mix Design Level	Number of Mix Ratings Excellent or Good	
			total	used
Excellent	106	100K ESALs	9	0
Good	174	300K ESALs	58	58
Fair	52	1M ESALs	85	84
Poor	16	3M ESALs	81	79
		10/30M ESALs	47	47
total	348	total	280	268

This Phase III effort compares the INDEX Model and VIRTUAL Model film thickness values of the selected 40-mixture sample to the normal range of film thickness values of the 268-mixture population. The steps taken in this analysis included:

1) determine the descriptive statistics of the population,
2) determine the descriptive statistics of the four traffic subsets of the population,
3) compute the INDEX and VIRTUAL film thickness values for the 40 mix designs,
4) determine the descriptive statistics of the 40-mix sample,
5) determine the descriptive statistics of the four traffic subsets of the sample,
6) compare the population and sample statistics
7) draw conclusions regarding the impact of the INDEX and VIRTUAL models.

The film thickness values of the population set are representative of the range of film thickness commonly achieved in Iowa. The database of 268 mixtures includes the film thickness value prescribed by the Iowa DOT specifications. This film thickness value FT(DOT) applies Equation 5, which is a simplified version of the standard equation (Eq-2). To expand the analysis, the standard film thickness values FT(std) for the population were added. As expected, the FT(DOT) values are always slightly lower than the FT(std) values. A summary of the statistics of the population is given in TABLE 11. The mean (10.27 & 10.58 microns) and median (10.10 & 10.43 microns) values are well above the Iowa specification minimum limit of 8.0 microns. Because the median values are slightly lower than the mean, the population has a slight positive skew. The skew is also reflected in the range, 7.7-14.8 and 7.9-15.3, which is 2.5 microns lower and 4.5 microns higher than the mean. The histogram in Figure 24 visually graphs the distribution of FT(DOT) population. A majority of the values range between 8.5 and 11.5 microns.

Table 11 – Film Thickness Population Statistics for Iowa Mix Designs

Film Thickness Model>	Total population		300K ESAL sub-group		1M ESAL sub-group		3M ESAL sub-group		10/30M ESAL sub-group	
	DOT	std	DOT	std	DOT	std	DOT	std	DOT	std
Mean	10.27	10.58	10.25	10.61	10.12	10.43	10.03	10.33	10.94	11.23
Median	10.10	10.43	10.06	10.37	9.95	10.27	9.98	10.35	10.65	10.87
Standard Dev.	1.27	1.33	1.17	1.27	1.10	1.15	1.17	1.21	1.62	1.69
Skew	0.66	0.63	0.42	0.44	0.28	0.27	0.39	0.35	0.60	0.60
Minimum	7.73	7.91	8.39	8.64	8.24	8.45	7.73	7.91	8.28	8.53
Maximum	14.78	15.31	13.44	14.06	12.67	13.08	12.95	13.36	14.78	15.31
Count	268	268	58	58	84	84	79	79	47	47

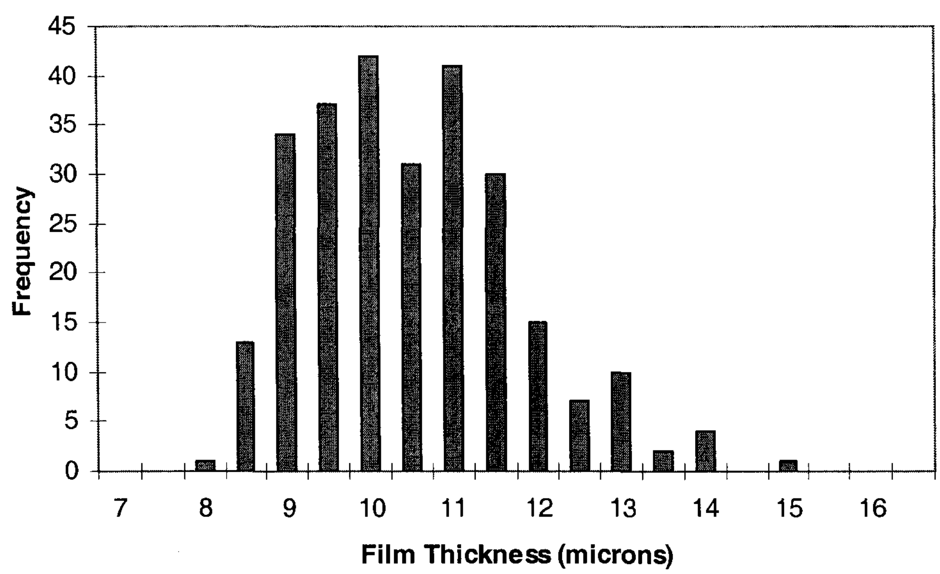


Figure 24 – Histogram of Film Thickness Population

The population is further divided into the four traffic (ESAL) categories. These categories have different mix design criteria, so it is appropriate to examine the film thickness values of each category. With the same component materials, the proportion of each component will change to satisfy the desired level of mix design criteria. Therefore, the general range of film thickness values should change with each traffic category. TABLE 11 provides a summary of the statistics for each population sub-group. In general, the shape of the data distribution (slight positive skew) for each sub-group is similar to the entire population. The standard deviation decreases as a result of the tighter range of values, even though the smaller data set could cause the standard deviation to increase. As shown in FIGURE 25, the trend in the mean film thickness values for the 300K, 1M and 3M groups reflects the reduction in asphalt binder content associated with higher amounts of compaction effort in the design process. The dramatic increase in the 10/30M group is associated with two mix parameters, cleaner gradations (less fine aggregate) and the need to lubricate the mix during compaction.

The study population uses the Iowa DOT's mix design database which only provided details of the combined gradation. To generate the INDEX Model and VIRTUAL Model film thickness values, the complete mix design reports were recovered to obtain the details of the gradation for each aggregate source used in the mix design. With the gradation details, the INDEX Model film thickness value FT(INDEX) and VIRTUAL Model film thickness FT(VIRTUAL) were computed for each of the 40 mix designs in the sample database. The film thickness values of the 40-mix sample set are listed in TABLE 12. The sample is plotted in FIGURE 26 with the FT(std) values as the basis (x-axis value) for comparison. Overall, the trends between the four film thickness values are very similar to trends observed in the generic mix sensitivity analysis in Phase I.

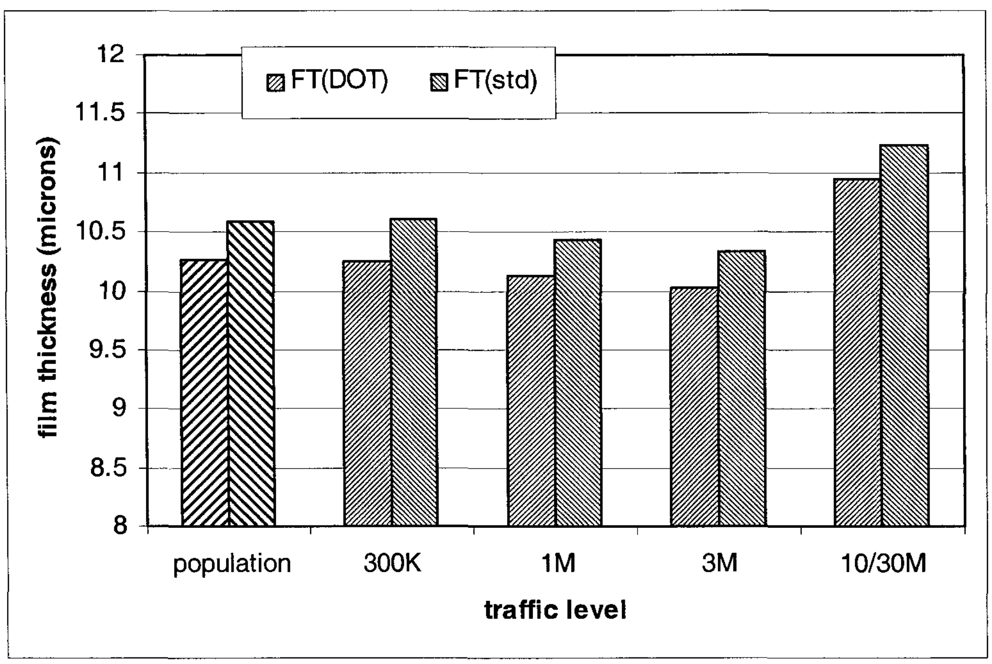


Figure 25 – Population and Traffic Level Mean Film Thickness

Table 12 – Film Thickness Values for 40-Mix Sample

JMF	ESAL	LAYER	FT (DOT)	FT (Standard)	FT (INDEX)	FT (VIRTUAL)	DOT diff	INDEX diff	VIRTUAL diff
ABD2-2008	300K	INTER	10.60	11.11	12.78	11.43	-0.51	1.67	0.32
1BD3-017	300K	INTER	12.10	12.73	14.55	13.17	-0.63	1.82	0.45
ADB2-2029	300K	INTER	8.40	8.78	10.18	10.24	-0.38	1.40	1.46
ABD3-5030	300K	SURF	9.66	10.16	11.90	10.47	-0.50	1.74	0.31
ABD3-6012	300K	SURF	9.44	9.51	11.13	9.83	-0.07	1.62	0.32
ABD3-2012	300K	SURF	13.48	14.07	16.48	13.86	-0.59	2.41	-0.21
ABD3-2009	300K	SURF	10.51	10.87	12.59	11.35	-0.36	1.72	0.48
ABD3-2005	300K	SURF	11.33	11.84	13.97	12.22	-0.51	2.13	0.38
1BD3-015	300K	SURF	9.77	10.15	11.63	10.99	-0.38	1.48	0.84
SWI3-18	300K	SURF	11.8	11.56	12.91	11.94	-0.48	1.36	0.38
4BD3-7	1M	BASE	10.75	11.03	12.52	11.57	-0.28	1.49	0.54
ABD3-5021	1M	INTER	8.78	8.87	10.05	9.12	-0.09	1.19	0.25
4BD3-11	1M	INTER	9.36	9.77	11.27	10.11	-0.41	1.50	0.34
ABD3-17M	1M	SHLD	8.46	8.58	9.88	9.38	-0.12	1.30	0.80
4BD3-17	1M	SHLD	8.41	8.53	9.75	9.25	-0.12	1.22	0.72
4BD3-16	1M	SHLD	11.28	11.56	12.94	11.89	-0.28	1.38	0.33
ABD3-5034	1M	SURF	9.36	9.64	10.97	9.94	-0.28	1.34	0.30
4BD3-8	1M	SURF	10.11	10.29	11.62	10.81	-0.18	1.32	0.52
4BD3-21	1M	SURF	10.49	10.80	12.07	10.83	-0.31	1.26	0.03
4BD3-18	1M	SURF	11.40	11.70	13.47	11.44	-0.30	1.77	-0.26
SWI3-16	3M	BASE	10.85	11.04	12.93	11.41	-0.19	1.88	0.37
ABD3-5004	3M	INTER	10.43	10.60	12.35	10.74	-0.17	1.75	0.14
ABD3-5006	3M	INTER	11.67	12.00	13.98	12.09	-0.33	1.98	0.10
ABD3-2015	3M	INTER	11.04	11.08	12.79	10.65	-0.04	1.71	-0.43
ABD3-5005	3M	SURF	9.48	9.52	10.74	9.83	-0.04	1.22	0.32
ABD3-5009	3M	SURF	10.09	10.49	11.31	10.13	-0.40	0.82	-0.35
ABD3-5007	3M	SURF	11.62	12.03	13.84	11.87	-0.41	1.81	-0.16
ABD2-2032	3M	SURF	10.20	10.64	11.99	10.37	-0.44	1.35	-0.27
SWI3-21	3M	SURF	10.46	10.74	11.93	11.23	-0.28	1.20	0.49
ABD3-2004	3M	SURF	8.34	8.65	9.75	9.38	-0.31	1.10	0.72
ABD3-2017	10M	BASE	9.42	9.63	11.00	9.73	-0.21	1.38	0.10
SWI3-25	10M	BASE	10.43	10.71	12.05	11.05	-0.28	1.34	0.35
SWI3-27	10M	INTER	10.74	11.00	12.92	10.99	-0.26	1.92	-0.01
ABD3-2026	10M	SURF	12.72	13.10	14.88	12.73	-0.38	1.78	-0.38
4BD3-19	10M	SURF	12.52	12.80	14.32	11.76	-0.28	1.52	-1.03
ABD3-6004	30M	BASE	8.23	8.48	9.77	8.57	-0.25	1.29	0.09
3BD3-3026	30M	INTER	14.08	14.45	16.01	12.86	-0.37	1.57	-1.59
ABD3-6005	30M	INTER	9.85	10.18	11.53	10.06	-0.33	1.35	-0.12
ABD3-2032	30M	INTER	9.41	9.32	10.84	9.46	0.09	1.51	0.14
ABD3-6006	30M	SURF	10.61	10.96	12.47	10.54	-0.35	1.51	-0.41

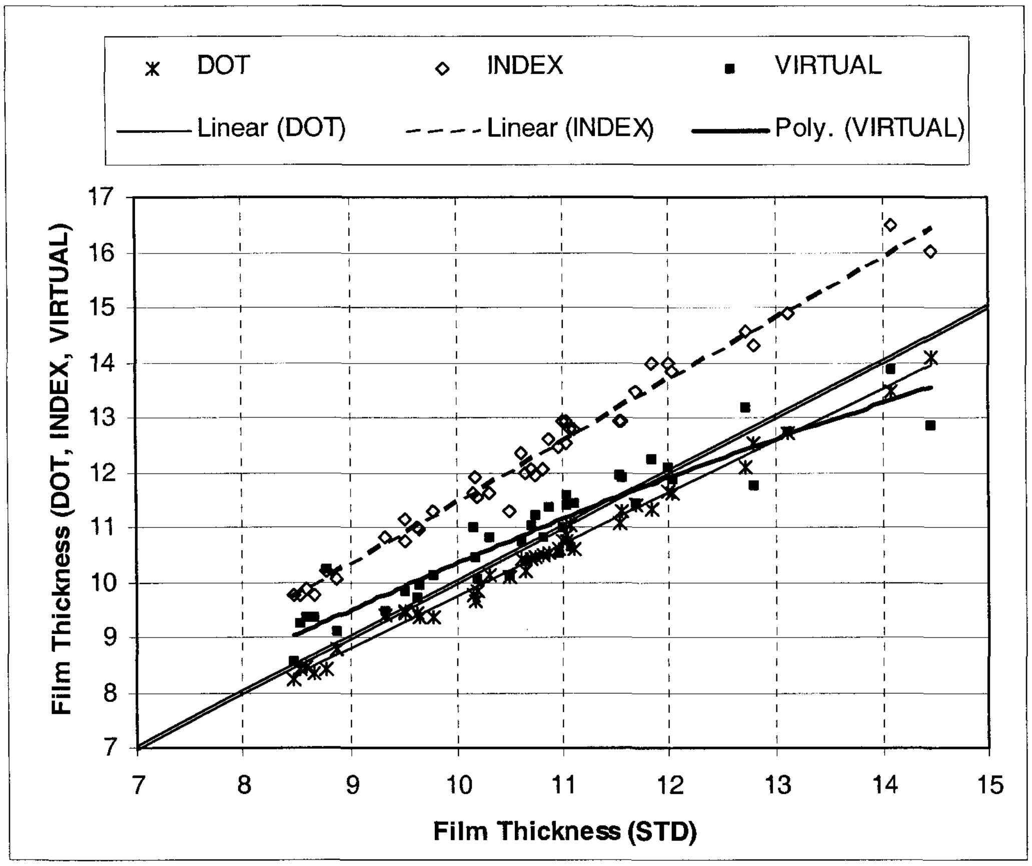


Figure 26 – Film Thickness Comparison for 40-Mix Sample

Like the 268-mix population, the 40-mix sample was analyzed for general descriptive statistics. The summary of the sample's descriptive statistics is shown in TABLE 13. The mean values differ for each film thickness model. The FT(DOT) is lower than the FT(std) as expected. The FT(INDEX) mean value is 1.5 microns above the FT(std) as expected. And the FT(VIRTUAL) is between the FT(std) and FT(INDEX), which fits the general trend for the VIRTUAL model. The median values are very close to the mean for three of the four models, but all four sets of data shown some degree of positive skew (0.36-0.57). The range of the 40 values is lowest for the VIRTUAL model (5.3 microns) and highest for the INDEX Model (6.7 microns). Only the range of film thickness values for the INDEX Model (9.7-16.5) would not fit within the Iowa DOT specification limits of 8 to 15 microns.

Table 13 – Film Thickness 40-Mix Sample Statistics

	FT(DOT)	FT(std)	FT(INDEX)	FT(VIRTUAL)
Mean	10.42	10.72	12.25	10.88
Median	10.45	10.72	12.06	10.82
Standard Deviation	1.37	1.45	1.66	1.19
Skew	0.57	0.55	0.55	0.36
Minimum	8.23	8.48	9.75	8.57
Maximum	14.08	14.45	16.48	13.86
Count	40	40	40	40

The 40-mix sample set is further divided into four 10-mix subsets for each of the traffic (ESAL) levels. While it is possible to create a list of descriptive statistics for each subset, the number of values in each set is too small to realistically measure the shape of the distribution. It is appropriate to limit the examination to the mean and median values for general trends between the film thickness models. TABLE 14 provides a summary of the sample subset means and median values. The median values are lower than, or equal to, the mean values. The trend between the means of the film thickness equation models shows the FT(DOT) always as the lowest values and the FT(INDEX) as the highest values. The FT(VIRTUAL) values are higher than the FT(std) values. The trend across traffic levels shows the 1M mixes have the lowest film thickness, but the ranking of the FT(INDEX) and FT(VIRTUAL) values varies for each traffic level.

Table 14 – Film Thickness Sample 10-Mix Subset Statistics

	FT(DOT)		FT(std)		FT(INDEX)		FT(VIRTUAL)	
	mean	median	mean	median	mean	median	mean	median
300K ESAL	10.64	10.55	11.07	10.99	12.81	12.69	11.55	11.39
1M ESAL	9.84	9.74	10.08	10.03	11.45	11.45	10.43	10.46
3M ESAL	10.42	10.44	10.68	10.69	12.16	12.17	10.77	10.69
10/30M ESAL	10.80	10.52	11.06	10.83	12.58	12.26	10.77	10.77

With this information about the population and sample of film thickness values, can we use the results of the sample to hypothesize the impact of the INDEX Model and VIRTUAL Model on the film thickness of the population of mix designs? The first question that must be answered is whether the sample is a representative subset of the population. The mean values of the FT(DOT) sample and FT(std) sample are slightly higher than the population values. The median values of the sample are almost equal to the sample mean, unlike the population; but, the sample shows a similar level of data skew (population ~0.64 and sample ~0.56). The amount of standard deviation is comparable between the population and sample statistics and the standard deviation is substantially greater than the difference between the means. Using a standard two-tailed t-test for equal means of the FT(std) population and FT(std) sample, the probable variation of the mean ($t = 0.53$) falls well below the critical variation ($t = 1.97$) for 95 percent confidence. From this comparison, we can conclude that the sample is representative of the population. Therefore the INDEX Model and VIRTUAL Model values from the sample can be viewed as representative of their impact on the population of film thickness values.

How would the INDEX Model and VIRTUAL Model impact Iowa's film thickness values. One approach looks at the differences between the new models and the FT(std) values. This difference can be expressed as FT(x)-FT(std). FIGURE 27 shows the histogram of the differences for the DOT, INDEX and VIRTUAL values against the FT(std) values. As expected, the FT(DOT) values are very tightly grouped and slightly lower than the FT(std) values. Generally in the range of –0.6 to 0.0 microns. The FT(INDEX) values are also tightly grouped and positively skewed in the general range of 1.2 to 2.0 microns. The FT(VIRTUAL) values show a much broader distribution with typical values between –0.6 and +1.0 microns. These FT(VIRTUAL) differences demonstrate the power of the VIRTUAL Model to reflect the uniqueness of each mix design better than the standard two-dimensional approach currently used.

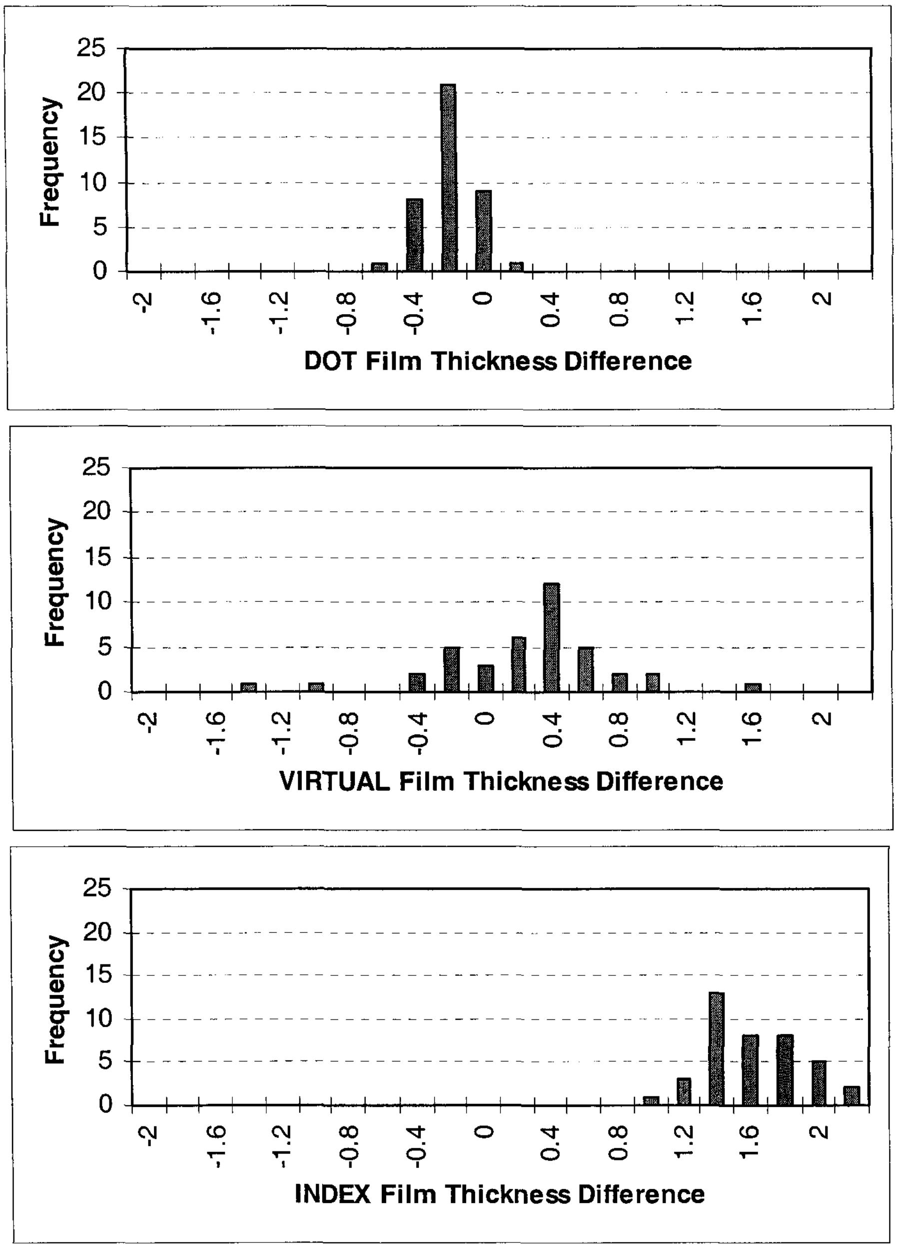


Figure 27 – Histogram of Film Thickness Change

Another approach to examine the impact starts with the mean values of the sample subsets. The trend of mean values in the sample subsets is not the same as the trend in the population subsets, but the range of mean values for FT(DOT) and FT (std) are generally the same (10 to 11 microns). Since the number of values in the sample subset is only 10, the standard deviation values are not strong indicators. To establish a reasonable range for the sample subset, the standard deviations from the total sample are used. Figure 28 shows the nominal range of all four film thickness models based on the sample subset means plus/minus twice the sample standard deviation. Superimposed over the shaded box representing the specification range (8 to 15 microns), the INDEX Model would require an increase in the upper limit of the specification range for three of the four traffic levels. The VIRTUAL Model ranges are within the current specification range and are generally between 8.5 and 13 microns in three of the four levels. Taking a conservative approach, a specification range of 8 to 14 microns would be sufficient to cover the expected range of VIRTUAL Model film thickness values based on the sample database. The range for the INDEX Model would be 8 to 16 microns.

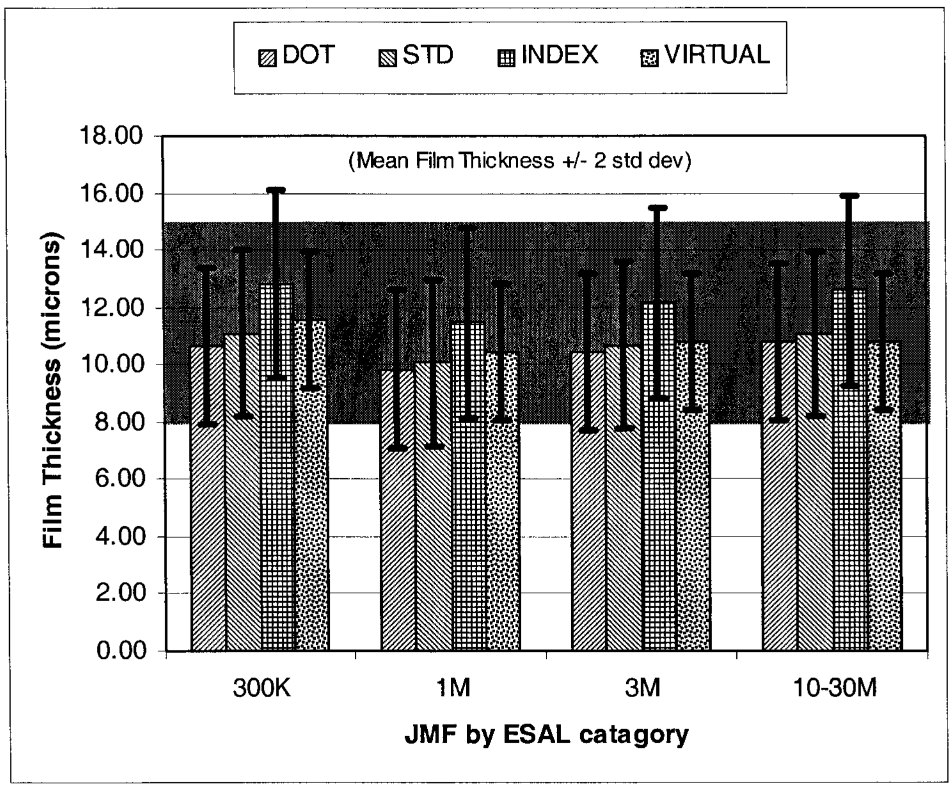


Figure 28 – Statistical Range of Film Thickness for Sample-Traffic Level Subgroups

A similar approach compares the population of FT(DOT) and FT(std) values to the sample FT(INDEX) and FT(VIRTUAL) values. The analysis already demonstrated that the sample database is statistically similar to the population. Since the Iowa DOT specification range for film thickness does not distinguish between traffic levels, the analysis based on the range of each Model is a reasonable approach. In addition, the statistics are stronger for the sample (40 data points) than for the sample subsets (10 data points each). Figure 29 shows the range of each Model based on the mean value plus/minus two standard deviations. The background shading represents the current film thickness specification limits. The figure shows that the current range of film thickness values for the

DOT and standard models generally falls between 8 and 13 microns. The INDEX Model ranges between 9 and 15.5 microns. The VIRTUAL Model is a slightly narrower range from 8.5 to 13.5 microns.

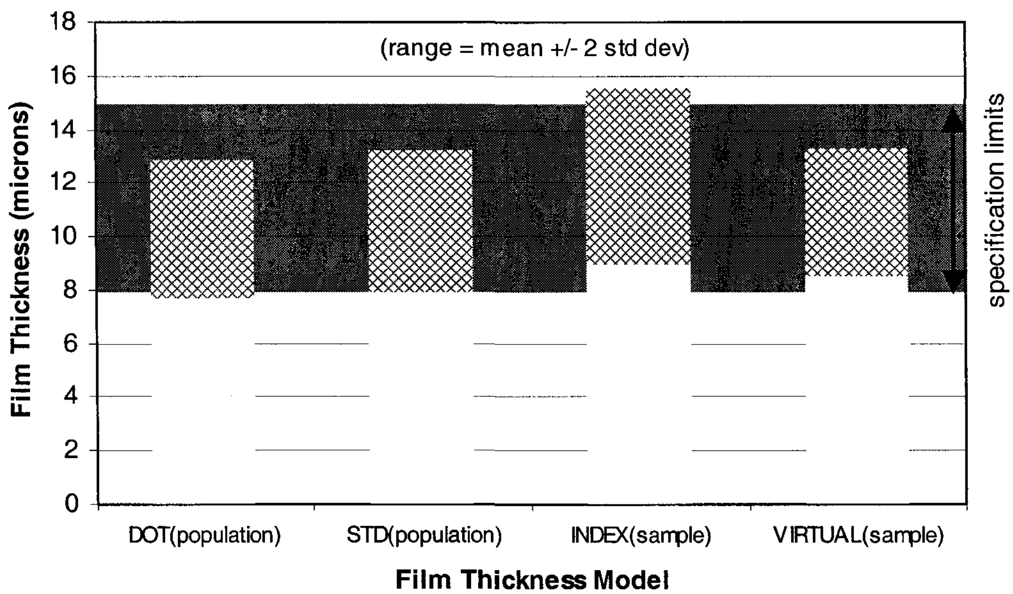


Figure 29 – Film Thickness Range on Population Basis

As the plotted sample data in Figure 26 shows, we would expect the INDEX range to be higher and broader than the DOT and standard model. The linear trend is 1.5 microns higher at lower film thickness values and 2.0 microns higher near the upper film thickness range. The extent of the INDEX range is reflected in the higher standard deviation (1.66) and the increased slope of the linear trend. The shape of the VIRTUAL trend in Figure 26 is not linear. Similar to the sensitivity study in Phase I, the VIRTUAL Model computes film thickness values above the standard model at lower film thickness levels, but tends to flatten and generate lower values at the higher film thickness level. The standard deviation for the VIRTUAL Model sample (1.19) is smaller than the standard model and is reflected in the flatter slope of the VIRTUAL second-order polynomial trend.

Phase III Summary

This phase of the study uses the statistical distribution of a sample of 40 mix designs used on Iowa DOT projects to predict the nominal range of film thickness values for the entire population of Iowa mixes. Although the specification limits are 8 to 15 microns, the typical range of film thickness values applying the standard and DOT models is 8 to 13 microns. Very similar to the results of the Phase I sensitivity study, the impact of the INDEX Model on current specification limits would increase both the lower and upper limits to 9 to 15.5 microns. The unique shape of the trend of VIRTUAL Model film thickness values would increase the lower limit to 8.5 microns. The upper limit is similar to the observed values for the standard model and could be set at 13.5 microns.

Chapter 6. Summary and Conclusions

The current standard model for calculating film thickness is not sufficiently detailed to adequately reflect differences in hot mix asphalt mixtures; and therefore, has limited value as a tool to evaluate research or mix designs. Modifications to the model (or replacement of the model) would give practitioners a better tool to assess the durability potential of a hot mix asphalt mixture. This study provides the asphalt community with new models with improved approaches to calculating film thickness that better reflect the unique properties of each hot mix asphalt mixture. The study examines the historical development and application of the standard film thickness model. The proposed film thickness models account for the individual aggregate source gradations, specific gravities and particle shape that comprise the hot mix asphalt blend. The study provides a practical approach to the significant contribution of the mineral filler as both an aggregate and asphalt binder extender. These parameters were not adequately accounted for prior to this study. Based on the analysis in this study, future studies of hot mix asphalt durability will have a more accurate perception of film thickness to compare differences in hot mix asphalt durability.

Film thickness is a computed, not measured, value that defines the thickness of the effective asphalt binder coating on each particle in the mixture and is used to insure that the HMA has adequate asphalt binder to achieve a desired level of mix durability. The procedure for computing the surface area was derived from the 1940's Hveem mix design process used to determine a "target" asphalt binder content and only requires the weighted proportion of the combined aggregate on each sieve. Any differences in aggregate particle specific gravity, shape, and texture are not taken into account. The film thickness value ***"assumed that all the asphalt exists in the form of uniform films as long as appreciable air voids exist."*** (9) The authors recognized that this assumption was not totally correct, but it was adequate for the purpose of their study. This research was undertaken to replace the standard model using the knowledge and tools available today.

Most of the current HMA research efforts focus on rutting and fatigue. Durability is the third key mixture performance criteria. The contractor is focused on keeping the asphalt binder content to a minimum, but the agency/owner's interest should insure that the finished pavement is durable (adequate asphalt binder content). Film thickness is one computed parameter to define sufficient asphalt binder for durability. Both film thickness and VMA are products of durability research in the mid-1950s, but later studies report that neither approach to define mixture durability was founded on extensive research. Research in the 1960s and 1970s conclude that durability is a function of film thickness, air voids, and permeability. Recent studies, starting in the mid-1990s, developed mixed results regarding the correlation between film thickness and mixture durability. Although some studies questioned the film thickness equation, they all used the 1942 Hveem table to determine aggregate surface area and applied Campen's 1959 approach for determining film thickness.

The current procedure for determining surface area of the total aggregate blend only requires the gradation expressed as the total percent (by weight) passing on each sieve. Each percent passing value represents all particles smaller than that sieve. Therefore, the surface area values are not a direct expression of total surface area for aggregate particles on a specific sieve and do not account for differences in aggregate particle specific gravity. Studies that examine differences in film thickness values in an attempt to identify trends in HMA mixture performance are not comparing equivalent film thickness values when the mixtures have aggregates with dissimilar specific gravities. The procedure for computing the film thickness value should account for known characteristics of the aggregate and may lead to a better understanding of the impact of film thickness on mixture performance.

New Models

The current surface area factors are a product of a period time when engineers developed charts, tables and nomographs to simplify the calculations. Any new approach to measuring film thickness should account for today's common practice that the aggregate gradation is a blend of multiple aggregates from different sources and that the as-constructed density is different than the mix design density. The proposed INDEX Model uses the fundamental principles of weight, volume, specific gravity, and particle geometry to calculate a theoretical surface area of each aggregate particle. The resulting aggregate surface area is a better approximation of the true surface area. The VIRTUAL Model approach is a further improvement using theoretical techniques to place the particles in a virtual three-dimensional matrix, fills the void space with effective asphalt, and measures the thickness of the asphalt from the particle surface to the air void space. The VIRTUAL Model requires knowledge of the HMA mixture volumetrics.

Both models account for multiple aggregate sources, including differences in gradation and specific gravity. The INDEX Model also accounts for particle shape, but cannot reflect the impact of as-constructed air voids. The VIRTUAL Model accounts for as-constructed air voids, but does not adjust for different particle shapes.

A large portion of the aggregate surface area is attributed to the mineral filler. For this study, particles less than 10-micron size are not included in the determination of particle surface area, but are considered asphalt binder extender. The volume of these particles is added to the asphalt binder in the VIRTUAL Model.

The study ran a series of analyses on a family of generic mixes and examined the differences between the current film thickness "Standard Model" (Eq 2), the proposed INDEX Model (Eq 10), and the proposed VIRTUAL Model (Eq 11).

- Gradation - The Standard Model film thickness increases as the gradations change from fine blends to coarse blends. The INDEX Model shows a similar increasing trend, but the film thickness is greater than the Standard Model and reflects the change in treatment of mineral filler. The VIRTUAL Model shows a similar increasing trend for the fine graded blends, but the trend becomes relatively flat as the gradation becomes coarser. The visual break in the trend corresponds to the change in the slope of the fine aggregate portion of the gradation.

- Specific Gravity - The Standard Model does not directly account for differing aggregate specific gravities. When the asphalt binder content is held constant, both the INDEX Model and VIRTUAL Model show that the film thickness increases as aggregate specific gravity increases; but this analysis is not accurate. The correct analysis held the volume of aggregate and asphalt binder constant and reflected the difference in aggregate specific gravity in the weight proportions of the materials. The computed film thickness using the Standard Model shows a decreasing film thickness as the Gsb increases. The INDEX Model correctly computes the same film thickness.
- Mineral Filler Content and Gradation - Most HMA mix designers have no detailed information on the composition of the mineral filler, but it is the gradation of the mineral filler that has a significant impact on the calculated surface area. All three models react similarly to the quantity of mineral filler. A one percent change in the amount of mineral filler changed the film thickness by approximately 0.5 micron. The Standard Model does not show any change in film thickness due to the gradation of the mineral filler. There is a 4 micron film thickness difference between the fine and coarse mineral filler gradations for both the INDEX Model and VIRTUAL Model. The practicality of measuring mineral filler gradation may limit the use of this feature.
- Particle Shape - . The INDEX Model is the only model that has the ability to account for differences in particle shape. The INDEX Model shows that the film thickness of spherical shape particles is higher than cubical shaped particles and a general increasing trend in the film thickness value as the particles become elongated.
- Degree of compaction - The Standard Model and INDEX Model compute a theoretical film thickness without regard to the orientation of the particles. The VIRTUAL Model reflected an increase in the film thickness as the density increased (lower VMA and air voids) and a diminishing decrease in film thickness as the density decreased. Through the use of the VIRTUAL Model, it would be possible to define the minimum required film thickness on the basis of the level of compaction when the mixture is placed.
- Multiple Aggregate Source Blends – Two gradation blends using four aggregate sources and two aggregate specific gravities were combined into 32 unique mixtures. Mix design software was used to estimate the mixture's volumetric properties. The Standard Model film thickness does not change over the series of 16 test mixtures for each gradation. The INDEX Model

and VIRTUAL Model film thickness values reflect changes to the combined aggregate specific gravity, proportion of sources, and blended gradation.

The INDEX Model is still an "index" that measures the thickness of the asphalt film with the simplifications that the aggregate particle surface area coated by the asphalt binder is a flat surface, not 3-D surface, and each particle is separately, uniformly, and equally coated. Converting the three-dimensional (3-D) particle surface area to a 2-D surface generates errors in the actual film thickness. The 2-D approximation is reasonably accurate for particles down to the 1.18-mm sieve, but below the 1.18-mm sieve, the difference increase dramatically. If a film thickness model used the 3-D shell volumes, the analysis would require an iterative process to match asphalt binder volume to accumulated film thickness shell volume and the impact of the mineral filler particles would be even greater. This study did not pursue this approach.

Research Comparisons

The INDEX Model and VIRTUAL Model were applied to previous HMA durability studies to determine if the improvements in the computed film thickness would improve the correlation between film thickness and HMA durability. The two selected studies subjected the HMA to both short-term aging and long-term aging and measured the properties of the aged mixes and aged binders.

The Auburn study involved six mixtures using a single gradation and six binder contents. Most of the correlations of the standard film thickness to mixture properties (like resilient modulus) and recovered binder properties (like penetration) are very sound and agree with general engineering expectation. Injecting the new film thickness values into the study's data created similar well-correlated parameters. The INDEX Model film thickness tends to provide higher values than the standard equation and the VIRTUAL Model cuts across the other two film thickness values. The reduction in film thickness at high binder contents reflects the ability of the VIRTUAL Model to account for three-dimensional distribution of the binder and aggregate.

Collectively, the measured response of the recovered binder follows the expected trend, but the comparison of the correlation and regression values for the three film thickness datasets showed no practical change or improvement. Resilient Modulus was used as a non-destructive test to measure the response of the same set of mixture specimens and the short-term aged and long-term aged regression curves agreed with the expected trend. The results of the IDT to failure are only provided for the long-term aged condition and the results are very similar to the Resilient Modulus testing.

The University of Florida study examined the affect of gradation on mixture durability. The study used six mixtures with different gradations from one aggregate source and the binder content varied to achieve 4 percent air voids at the same compaction effort. The film thickness values computed by the INDEX Model are higher than the standard values. The values computed by the VIRTUAL Model are higher for thin film, finer gradations and lower for thick film, coarser gradations.

While there are differences between the mixtures, we can examine the recovered binder properties because they are isolated from the influence of the aggregate. In every analysis group, the standard and INDEX Model correlation values are better than the VIRTUAL Model correlation values. The consistency of the penetration, viscosity, and Complex Modulus data trends, even at relatively nominal levels of correlation, could conclude that film thickness is a factor in determining the durability of different mixtures, but this is a weak conclusion in light of the very small database in this study.

The key to examining the data is comparing the rate of measured property change between the short-term aged value and long-term aged value. This was done for both the extracted binder and mixture properties. The trend for change in binder properties agrees with the expectation that higher values of film thickness will slow the rate of binder aging. Only one of the six data sets for percent change in mixture properties generated a good correlation value in the initial assessment.

Third-order polynomial equations were used to create most of the "best-fit" regression curves for sets of data. The third-order regression curves modeled the changes to the values associated with low and high film thickness mixtures

Durability studies provide a target minimum film thickness value to achieve a desirable level of durability. The Florida study demonstrates the complexity of achieving durability and the ability to carry traffic load. Film thickness cannot bracket the intended level of rutting or fatigue characteristics for a HMA mixture. In concert with other mixture characteristics (like gradation, CAA, FAA, and density), film thickness may be one of a group of input parameters for other mixture performance criteria.

Mix Design Criteria

The third phase of the study examined the impact of the new film thickness equations on field mix designs to determine if the range of film thickness specification criteria would change. The study started with a population of good or excellent mix designs. The distribution of film thickness values for the population was compared to a randomly selected sample set of 40 mixtures. Film thickness values using the INDEX Model and VIRTUAL Model were computed for the 40 sample mix designs.

The trends for the 40-mix sample set between the film thickness values of all four models are very similar to trends observed in the generic mix sensitivity analysis in Phase I.

The standard model film thickness sample data set was determined to be statistically representative. Therefore the INDEX Model and VIRTUAL Model values from the sample can be viewed as representative of their impact on the population of film thickness values. The film thickness values of the INDEX model are tightly grouped and higher than the standard model and the VIRTUAL values are much broader distributed above and below the standard model. Two other approaches compared the current specification limits to the statistical range of the new film thickness models. The INDEX Model would require an increase in the upper limit of the specification range. The VIRTUAL Model range is generally narrower than the current specification range. The current range of film thickness values for the standard model generally falls between 8 and 13 microns. The INDEX Model ranges between 9 and 15.5 microns. The VIRTUAL Model is a slightly narrower range from 8.5 to 13.5 microns.

The VIRTUAL Model reflects the uniqueness of each mix design better than the standard two-dimensional approach currently used. A specification range of 8 to 14 microns would be sufficient to cover the expected range of VIRTUAL Model film thickness values.

Future Study

Durability is a key component of HMA performance, but does not get sufficient research effort to better define differences between good and poor mixtures. Meaningful durability studies must isolate the rate of binder aging (durability). This will require careful mixture preparation, short-term and long-tern aging, non-destructive mixture testing, careful asphalt binder extraction and recovery, and performance grade binder testing. Laboratory studies should include multiple binder contents for each mix to best measure the value of film thickness as an indicator of mixture durability.

Film thickness is a key component of mixture durability. New durability studies should apply the INDEX Model and VIRTUAL Model to better account for differences between mixtures.

The INDEX Model and VIRTUAL Model should be validated by laboratory studies. The sensitivity study described in the model development phase should be replicated with a series of real mixtures. A better understanding of the gradation of mineral filler would improve the computed film thickness value and better distinguish between coated particles and binder extender. The shape factors applied to the INDEX Model would be better quantified using the Aggregate Imaging System.

It is possible that new durability studies of multiple mixtures will still conclude that film thickness alone does not adequately quantify mixture durability. Previous studies have hypothesized that mixture durability relative to coarse aggregate is different from mixture durability relative to fine aggregate. The VIRTUAL Model suggests that there are relationships between the fine aggregate gradation and the binder content. New studies should take an in-depth look at defining the mastic component of a mixture (asphalt binder and a portion of the fine aggregate). How does mixture durability relate to the coarse aggregate fraction? To the fine aggregate fraction? And to the mastic fraction? Does one of these fractions dominate durability or does each play a role with different criteria?

Appendix A – Building New Models

Table A1 – General Gradations for Film Thickness Sensitivity Study

													pass P.075				VOLUME FACTORS			SURFACE AREA FACTORS		
GRADATION (percent passing)													90	70	50							
MIX	BLEND PERCENT	25	19	12.5	9.5	4.75	2.36	1.18	0.600	0.300	0.150	0.075	0.040	0.020	0.010	Gsb	CA >9.5	c-FA 9.5-1.18	f-FA <1.18	CA >9.5	c-FA 9.5-1.18	f-FA <1.18
A	100.0	100	100	96	90	74	57	40	28.0	18.0	12.0	6.0	5.40	4.20	3.00	2.550	1	1	1	1.1	1.1	1.1
B	100.0	100	100	96	88	68	48	32	22.0	15.0	10.0	6.0	5.40	4.20	3.00	2.550	1	1	1	1.1	1.1	1.1
C	100.0	100	100	95	85	60	40	26	17.0	12.0	9.0	6.0	5.40	4.20	3.00	2.550	1	1	1	1.1	1.1	1.1
D	100.0	100	100	93	81	52	34	22	14.5	10.0	8.0	6.0	5.40	4.20	3.00	2.550	1	1	1	1.1	1.1	1.1
E	100.0	100	100	91	75	45	30	20	13.0	9.0	7.0	6.0	5.40	4.20	3.00	2.550	1	1	1	1.1	1.1	1.1
SPEC LIMITS	MAX			100	90		58					10										
	MIN		100	90			28					2										

Table A2 – Film Thickness Values for Gradation and Aggregate Specific Gravity Sensitivity (for equal weight mixes)

	Gsb 2.450			Gsb 2.550			Gsb 2.650			Gsb 2.750		
GRADATION	std	index	virtual	std	index	virtual	std	index	virtual	std	index	virtual
A	6.40	6.79	7.00	6.40	7.07	7.30	6.40	7.35	7.61	6.40	7.62	7.94
B	7.24	7.72	7.66	7.24	8.03	8.00	7.24	8.35	8.35	7.24	8.66	8.74
C	8.06	8.63	8.29	8.06	8.98	8.67	8.06	9.34	9.08	8.06	9.69	9.53
D	8.77	9.44	8.48	8.77	9.82	8.83	8.77	10.21	9.21	8.77	10.60	9.62
E	9.35	10.10	8.59	9.35	10.52	8.92	9.35	10.93	9.28	9.35	11.34	9.65

Table A3 – Gradation Fineness Ratios

		Sieve Ratio (CA/FA)						AASHTO T 27
	CA	4.75	4.75	4.75	2.36	2.36	1.18	Fineness Modulus
Gradation	FA	1.18	0.6	0.3	0.6	0.3	0.3	
A		1.85	2.64	4.11	2.04	3.17	2.22	3.81
B		2.13	3.09	4.53	2.18	3.20	2.13	4.17
C		2.31	3.53	5.00	2.35	3.33	2.17	4.51
D		2.36	3.59	5.20	2.34	3.40	2.20	4.785
E		2.25	3.46	5.00	2.31	3.33	2.22	5.01

Table A4 - Film Thickness Values for Aggregate Specific Gravity Sensitivity (for equal binder volume mixes)

Gsb	2.45		2.55		2.65		2.75	
Pbe	4.50		4.33		4.17		4.03	
Pbe	5.60		5.39		5.20		5.01	
MIX	SA (std)	FT (std)	SA (std)	FT (std)	SA (std)	FT (std)	SA (std)	FT (std)
A	7.199	6.40	same	6.14	same	5.91	same	5.69
B	6.364	7.24	same	6.95	same	6.69	same	6.44
C	5.715	8.06	same	7.74	same	7.44	same	7.17
D	5.249	8.77	same	8.43	same	8.11	same	7.81
E	4.927	9.35	same	8.98	same	8.63	same	8.32
	SA (index)	FT (index)	SA (index)	FT (index)	SA (index)	FT (index)	SA (index)	FT (index)
A	6.781	6.79	6.515	6.79	6.269	6.78	6.041	6.79
B	5.97	7.71	5.736	7.71	5.519	7.70	5.318	7.71
C	5.336	8.63	5.127	8.62	4.933	8.62	4.754	8.62
D	4.879	9.44	4.688	9.43	4.511	9.42	4.347	9.43
E	4.558	10.10	4.38	10.10	4.214	10.09	4.061	10.09

Table A5 – Mineral Filler Gradation Summary

	Percent Passing (mm)					
Gradation	0.075	0.050/ 0.038	0.02	0.01	0.005	0.001
coarse	100	80	50	25	15	5
dense	100	90	70	50	30	10
fine	100	95	85	70	50	15
average	100.0	96.3	72.9	49.1	27.3	6.6
median	100.0	97.8	78.0	47.9	26.4	6.5
std dev	0.0	3.0	16.4	16.0	12.4	3.4

Table A6 – Film Thickness Values for Mineral Filler Sensitivity

		FT (std)	FT (index)	FT (virtual)
Mineral Filler Quantity (percent passing 0.075-mm)	4.5	8.82	9.79	9.48
	5	8.55	9.51	9.18
	5.5	8.30	9.24	8.91
	6	8.06	8.98	8.67
	6.5	7.83	8.74	8.44
	7	7.62	8.52	8.23
	7.5	7.42	8.30	8.04
Mineral Filler Gradation	coarse	8.06	7.30	7.08
	dense	8.06	8.98	8.67
	fine	8.06	11.34	10.77
Analysis based on gradation C, Gsb=2.55				
All MF passing the 0.010 sieve is considered binder extender. Binder extended is included with binder volume for INDEX Model.				

Table A7 – Film Thickness Values for Particle Shape Sensitivity

Shape	Shape Factor		FT (std)	FT (index)	FT (virtual)
	Volume	Surface Area			
Cube 1:1	1.0	1.2	8.06	8.67	8.67
Cube 2:1	2.0	2.1	8.06	9.15	8.67
Cube 3:1	3.0	2.9	8.06	9.44	8.67
Sphere 1:1	1.0	1.0	8.06	9.32	8.67
Sphere 2:1	2.5	2.0	8.06	10.09	8.67
Sphere 3:1	4.0	3.0	8.06	10.30	8.67

Table A8 – Film Thickness Values for Degree of Compaction Sensitivity

Air Voids	VMA	FT (std)	FT (index)	FT (virtual)
2	11.73	8.06	8.98	10.04
3	12.63	8.06	8.98	9.17
4	13.50	8.06	8.98	8.67
5	14.36	8.06	8.98	8.33
6	15.20	8.06	8.98	8.11
8	16.83	8.06	8.98	7.79
10	18.40	8.06	8.98	7.58
Pb = 5.6 Pbe = 4.5 Gb = 1.035				

Table A9 – Film Thickness Values for Fine Blend-Multiple Source Sensitivity

Mix No.	VMA	FT (std)	FT (index)	FT (virtual)
1	15.2	8.24	9.45	8.84
2	15.4	8.24	9.86	9.14
3	15.2	8.24	9.47	8.87
4	15.5	8.24	9.88	9.14
5	15.3	8.24	9.47	8.86
6	15.6	8.24	9.88	9.13
7	15.4	8.24	9.49	8.86
8	15.7	8.24	9.90	9.13
9	15.4	8.24	9.72	9.04
10	15.7	8.24	10.15	9.33
11	15.5	8.24	9.74	9.04
12	15.8	8.24	10.17	9.33
13	15.6	8.24	9.73	9.03
14	15.8	8.24	10.17	9.36
15	15.6	8.24	9.76	9.07
16	15.9	8.24	10.19	9.36
Va = 4 Pb = Pbe = 5.0 Gb = 1.02				

Table A10 – Film Thickness Values for Coarse Blend-Multiple Source Sensitivity

Mix No.	VMA	FT (std)	FT (index)	FT (virtual)
1	15.0	9.17	10.48	9.09
2	15.0	9.17	10.54	9.13
3	15.0	9.17	10.50	9.10
4	15.0	9.17	10.55	9.14
5	15.3	9.17	10.53	9.10
6	15.3	9.17	10.59	9.14
7	15.3	9.17	10.54	9.12
8	15.4	9.17	10.60	9.12
9	15.3	9.17	10.92	9.34
10	15.3	9.17	10.98	9.38
11	15.3	9.17	10.94	9.35
12	15.3	9.17	11.00	9.40
13	15.6	9.17	10.97	9.36
14	15.7	9.17	11.03	9.37
15	15.7	9.17	10.99	9.34
16	15.7	9.17	11.05	9.39
Va = 4 Pb = Pbe = 4.9 Gb = 1.02				

Table A11 – 2D to 3D Film Thickness Reduction Factors

Sieve (mm)	19	12.5	9.5	4.75	2.36	1.18	.600	.300	.150	.075	.038	.020	.010	.005
Avg.Part.Dia.	22	15.7	11	7.12	3.55	1.77	.890	.450	.225	.112	.056	.029	.015	.007
FT (microns)														
20	1.00	1.00	1.00	0.99	0.99	0.98	0.96	0.92	0.86	0.77	0.65	0.53	0.41	0.29
15	1.00	1.00	1.00	1.00	0.99	0.98	0.97	0.94	0.89	0.81	0.70	0.58	0.46	0.34
12	1.00	1.00	1.00	1.00	0.99	0.99	0.97	0.95	0.91	0.84	0.74	0.62	0.50	0.37
10	1.00	1.00	1.00	1.00	0.99	0.99	0.98	0.96	0.92	0.86	0.77	0.66	0.53	0.41
8	1.00	1.00	1.00	1.00	1.00	0.99	0.98	0.97	0.94	0.88	0.80	0.70	0.58	0.44
6	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.97	0.95	0.91	0.84	0.75	0.63	0.50
Factor = a multiplier to FT (std) or FT (index) value to adjust the film thickness to the actual film of a 3D particle														

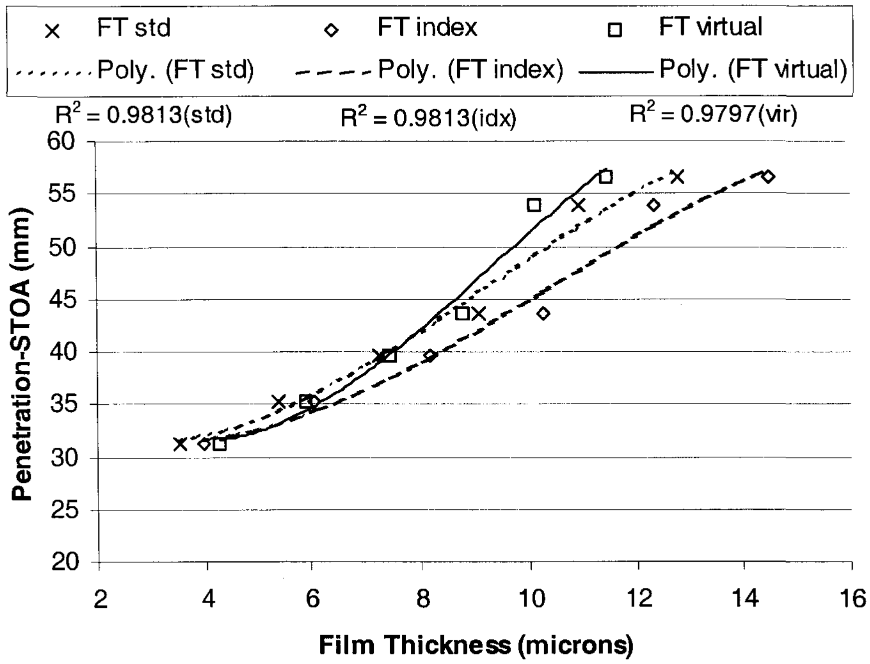
Appendix B – Data for Auburn Study

Table B1 – Measured Asphalt Binder Properties (STOA and LTOA)

FT (reported)	Penetration		Viscosity		Complex Modulus		Phase Angle	
	STOA	LTOA	STOA	LTOA	STOA	LTOA	STOA	LTOA
microns	0.1 mm	0.1mm	poises	poises	Pa	MPa	degrees	degrees
3.71	31.3	24.6	12,621	47,444	*2,090	2,500	*81.84	36.54
5.57	35.3	25.7	8,099	46,584	3,590	2,250	79.08	36.51
7.42	39.6	27.3	5,261	43,472	2,270	1,740	78.60	37.88
9.28	43.6	29.0	4,346	39,401	2,460	1,530	82.42	36.89
11.15	54.0	33.6	2,763	30,633	1,310	1,220	84.27	40.19
13.01	56.6	34.3	2,367	28,976	1,220	*1,710	84.56	*39.80
* possible outlier								

Table B2 – Measure HMA Properties (STOA, LTOA, ratio)

FT (reported)	Resilient Modulus			Indirect Tensile		
	STOA	LTOA	LT/ST	strength	strain	Modulus
microns	MPa	MPa		MPa	Percent	MPa
3.71	8,184	12,293	1.50	1.524	0.440	3.464
5.57	6,357	9,398	1.48	1.373	0.545	2.519
7.42	4,027	5,240	1.30	1.076	0.657	1.638
9.28	2,910	3,716	1.28	0.942	0.738	1.276
11.15	2,572	2,696	1.05	0.734	0.927	0.792
13.01	1,958	2,020	1.03	0.62	1.245	0.498



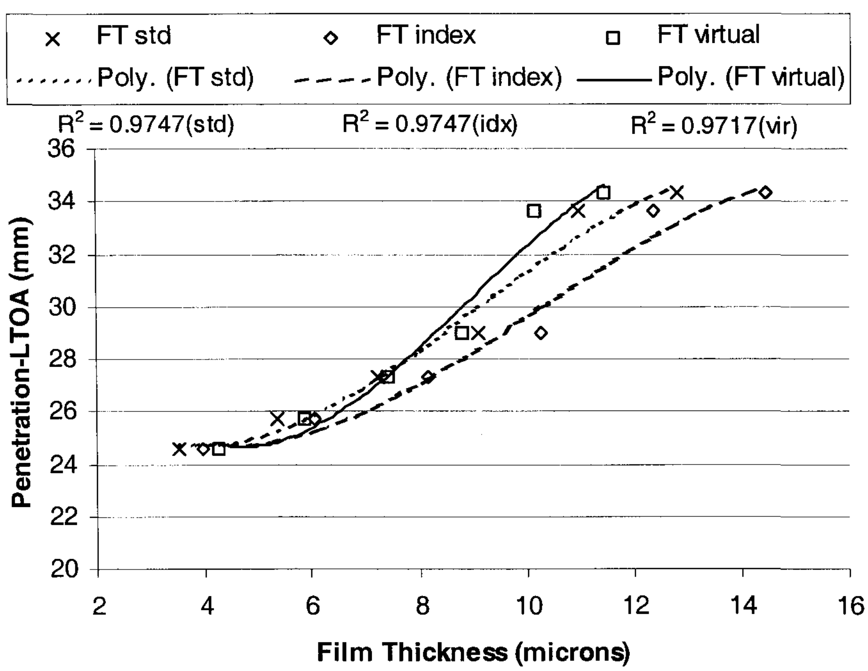
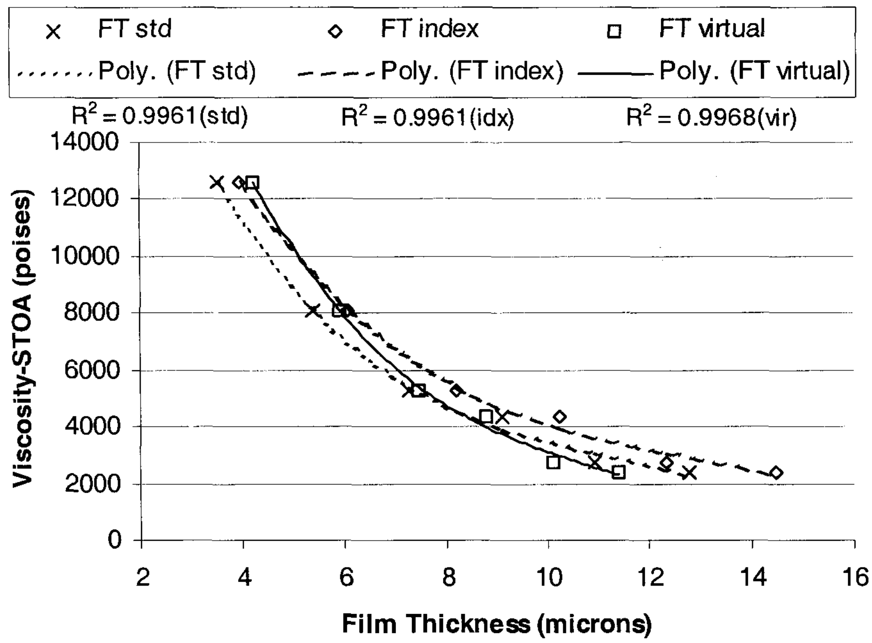


Figure B1 – Impact of STOA and LTOA on Penetration of Binder



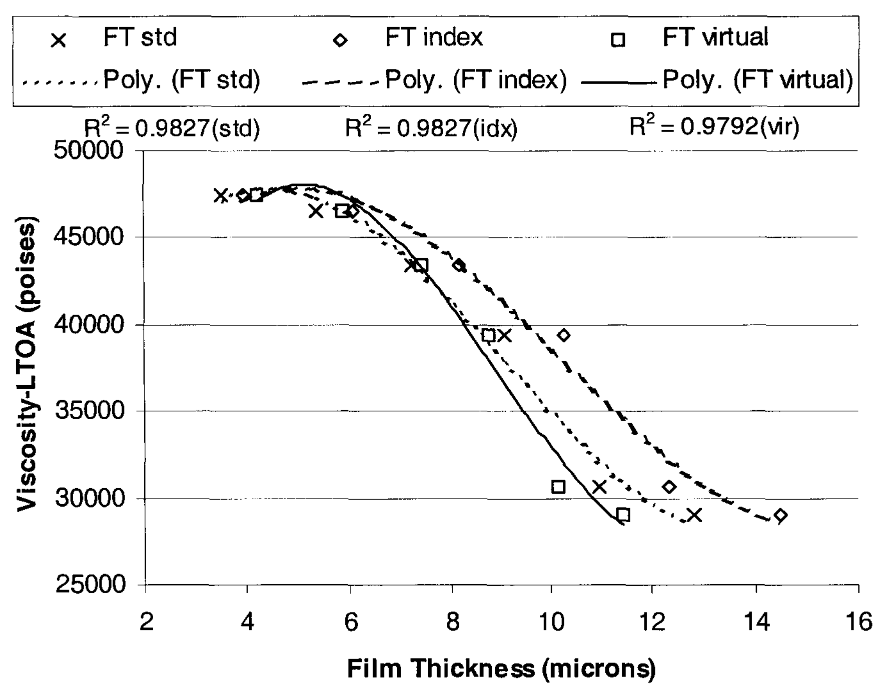
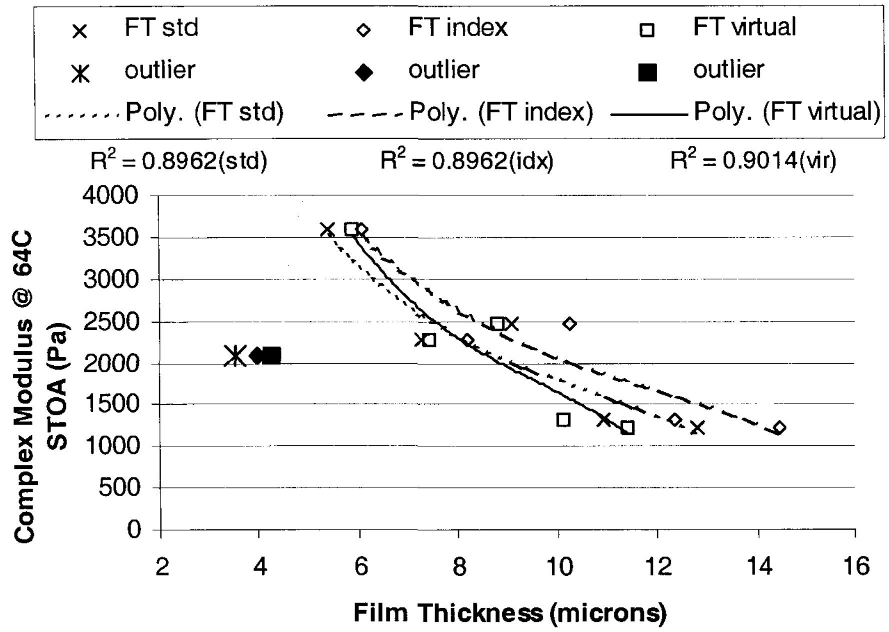


Figure B2 – Impact of STOA and LTOA on Viscosity of Binder



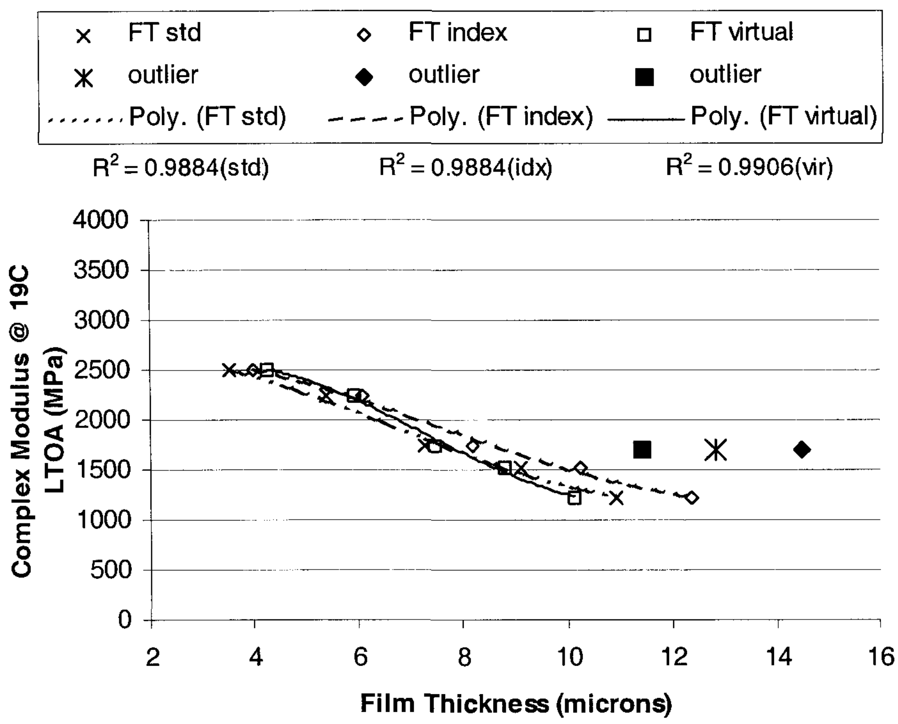


Figure B3 – Impact of STOA and LTOA on Complex Modulus of Binder

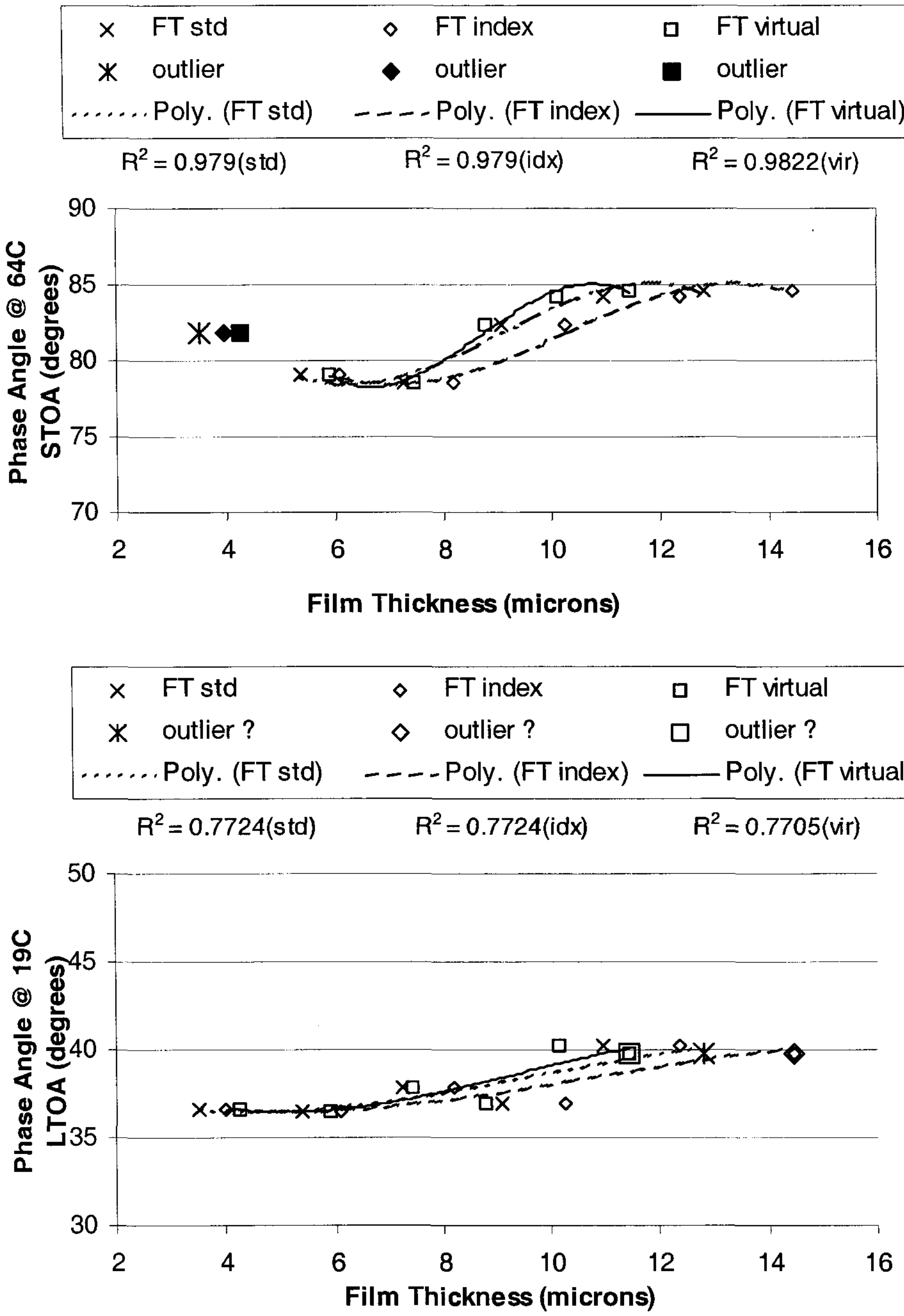


Figure B4 – Impact of STOA and LTOA on Phase Angle of Binder

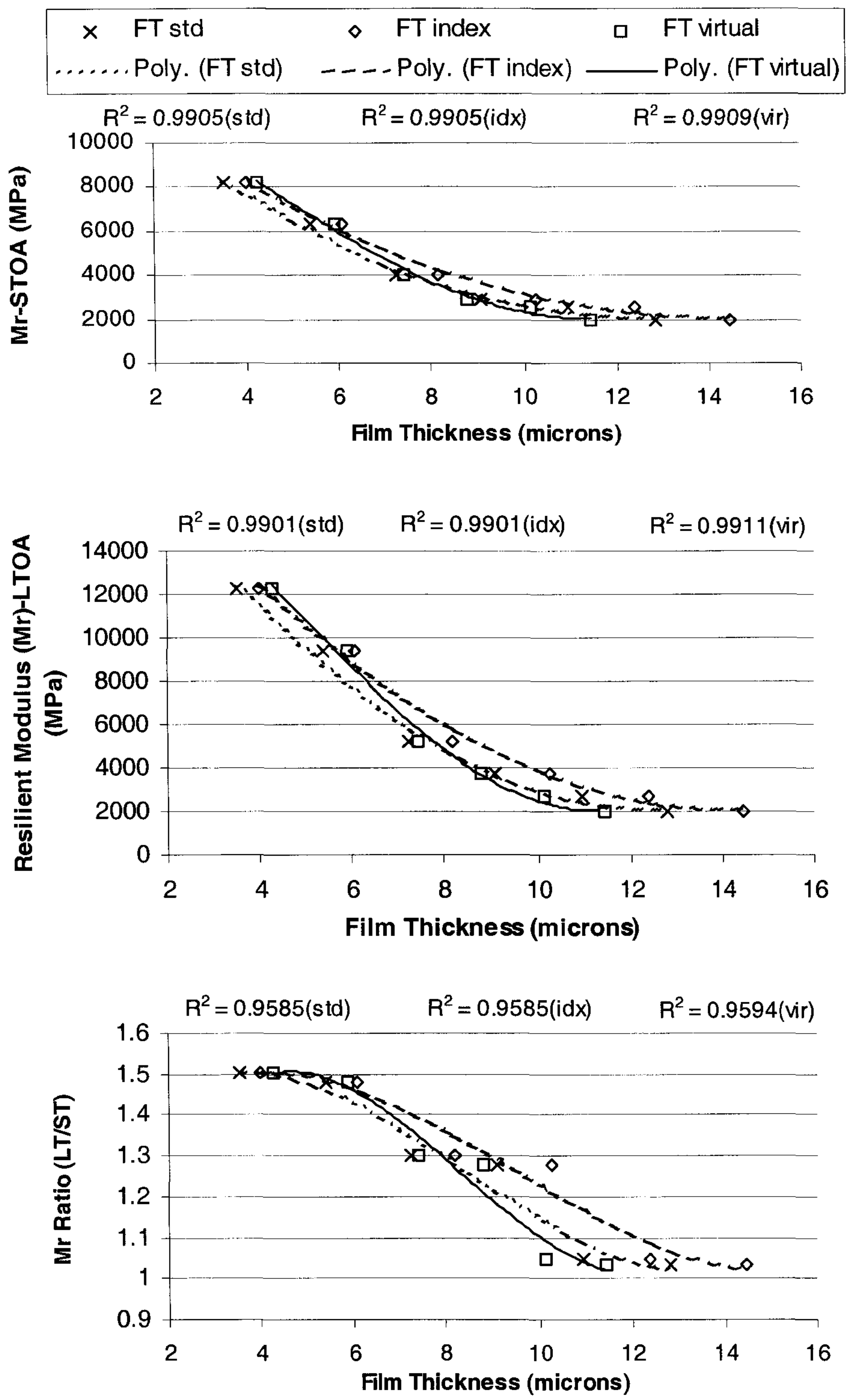


Figure B5 – Impact of STOA and LTOA on Resilient Modulus of Mixture

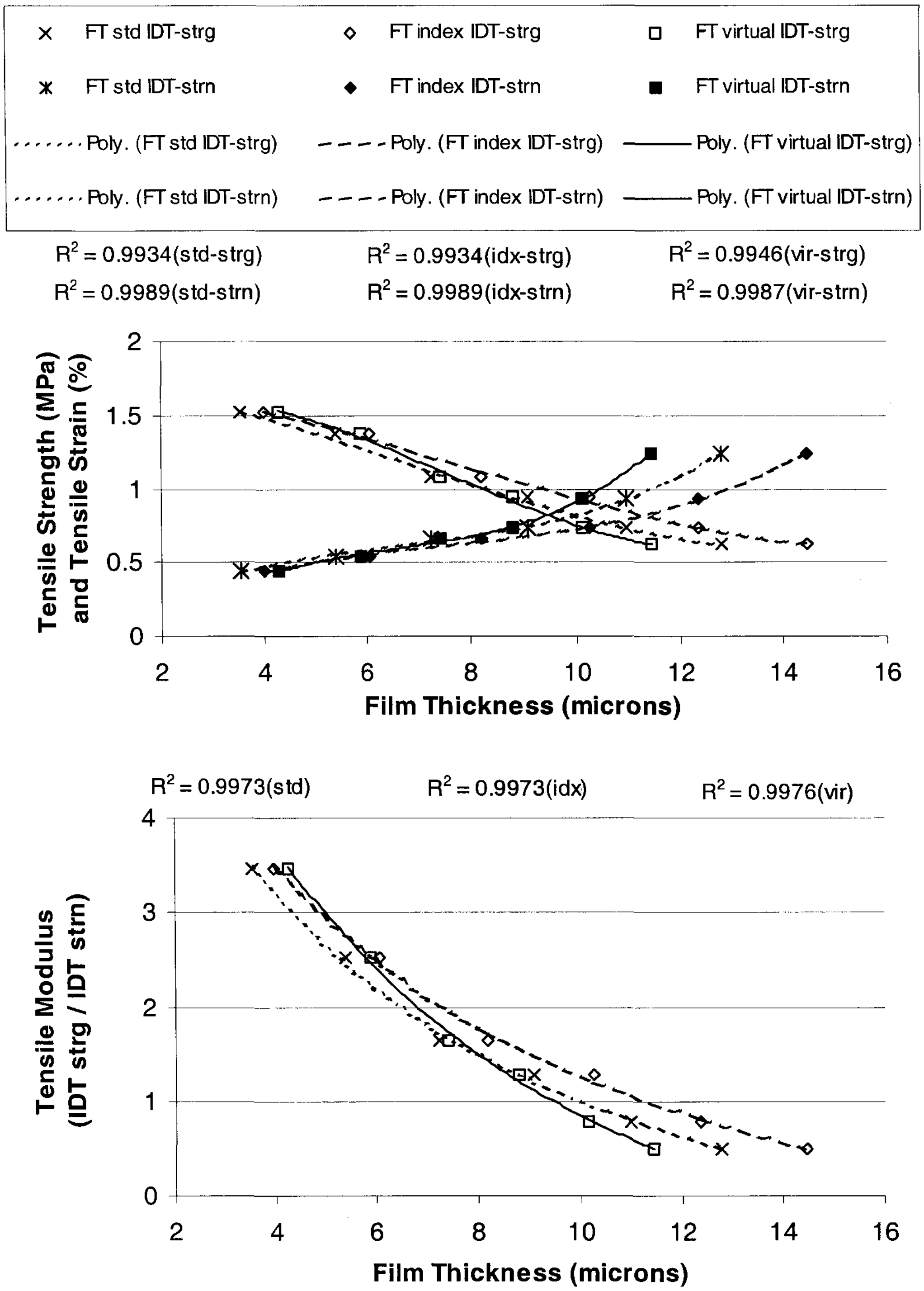


Figure B6 – Impact of STOA and LTOA on Indirect Tensile Strength, Strain, and Modulus of Mixture

Appendix C – Data for Florida Study

Table C1 – Gradations

Mix No.	19	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
C1	100	97.4	90.0	60.2	33.1	20.3	14.7	10.8	7.6	4.8
C2	100	91.1	73.5	47.1	29.6	20.2	14.4	10.4	6.7	4.8
C3	100	97.6	89.3	57.4	36.4	24.0	17.7	12.9	9.2	6.3
F1	100	95.5	85.1	69.3	52.7	34.0	22.9	15.3	9.6	4.8
F2	100	90.8	78.0	61.3	44.1	34.7	23.6	15.7	9.1	6.3
F3C4	100	94.5	84.9	66.5	36.6	26.1	20.5	13.6	8.6	5.8

Table C2 – Mixture Volumetric Properties (corrected)

Mix No.	Gmm	Gb	Gmb	Pb	Gsb	Gse	Pba	Pbe	VMA	Va	VFA	F:B
C1	2.3279	1.035	2.2349	6.5	2.469	2.549	1.320	5.266	15.37	3.995	74.0	0.852
C2	2.3466	1.035	2.2545	5.8	2.465	2.545	1.323	4.554	13.84	3.925	71.6	0.993
C3	2.3486	1.035	2.2535	5.3	2.474	2.528	0.897	4.451	13.74	4.049	70.5	1.340
F1	2.3378	1.035	2.2436	6.3	2.488	2.554	1.074	5.293	15.50	4.029	74.0	0.850
F2	2.3752	1.035	2.2814	5.4	2.489	2.565	1.229	4.238	13.29	3.949	70.3	1.406
F3C4	2.3466	1.035	2.2541	5.6	2.469	2.537	1.129	4.534	13.82	3.942	71.5	1.208

Table C3 - Measured Asphalt Binder Properties (STOA, LTOA, % diff)

Mix No.	Penetration			Viscosity		
	STOA 0.1 mm	LTOA 0.1mm	%diff	STOA poises	LTOA poises	%diff
C1	42	39	7.1	64,348	111,069	-72.6
C2	40	36	10.0	87,063	117,500	-34.9
C3	38	32	15.8	80,636	118,598	-47.1
F1	36	28	22.2	89,653	169,535	-89.1
F2	36	26	27.8	96,500	180,482	-87.0
F3C4	38	32	15.8	71,391	117,212	-64.2
	Complex Modulus			Phase Angle		
	STOA Pa	LTOA Pa	%diff	STOA degrees	LTOA degrees	%diff
C1	7,590,700	8,257,500	-8.8	48.4	46.5	3.9
C2	7,390,900	8,059,000	-9.0	49.9	48.0	3.8
C3	7,858,300	9,225,200	-17.4	47.9	45.7	4.6
F1	9,720,500	11,424,000	-17.5	47.5	45.0	5.3
F2	9,760,900	11,491,000	-17.7	46.2	43.6	5.6
F3C4	7,796,100	9,358,600	-20.0	47.9	45.5	5.0

Table C4 – Measure HMA Properties (STOA, LTOA, %diff)

Mix No.	Resilient Modulus			Creep Compliance		
	STOA	LTOA	%diff	STOA	LTOA	%diff
	0.1 mm	0.1mm		poises	poises	
C1	7.9	9.6	21.5	13.9	4.5	-67.6
C2	7.7	11.9	54.5	15.1	2.8	-81.5
C3	11.5	14.2	23.5	7.6	2.2	-71.1
F1	9.5	9.9	4.2	7.9	4.5	-43.0
F2	8.6	12.9	50.0	6	1.9	-68.3
F3C4	12	13.9	15.8	6.3	1.9	-69.8
	M-value			Fracture Energy		
	STOA	LTOA	%diff	STOA	LTOA	%diff
	Pa	Pa		degrees	degrees	
C1	0.7961	0.5480	-31.2	5.8	3.5	-39.7
C2	0.7729	0.5856	-24.2	4.8	2.9	-39.6
C3	0.6563	0.4977	-24.2	3.5	2.7	-22.9
F1	0.6560	0.5726	-12.7	4.2	2.8	-33.3
F2	0.5649	0.4955	-12.3	5.4	3.2	-40.7
F3C4	0.5817	0.5039	-13.4	3.7	1.7	-54.1
	Failure Strain			Tensile Strength		
	STOA	LTOA	%diff	STOA	LTOA	%diff
	Pa	Pa		degrees	degrees	
C1	4629.8	2224.4	-52.0	1.6	2.1	31.3
C2	3771.3	1896.7	-49.7	1.7	2.1	23.5
C3	2174.0	1468.3	-32.5	2.1	2.4	14.3
F1	2919.6	1833.3	-37.2	2.1	2.1	0.0
F2	3714.6	1526.2	-58.9	1.9	2.6	36.8
F3C4	2419.0	1174.7	-51.4	2	2.2	10.0

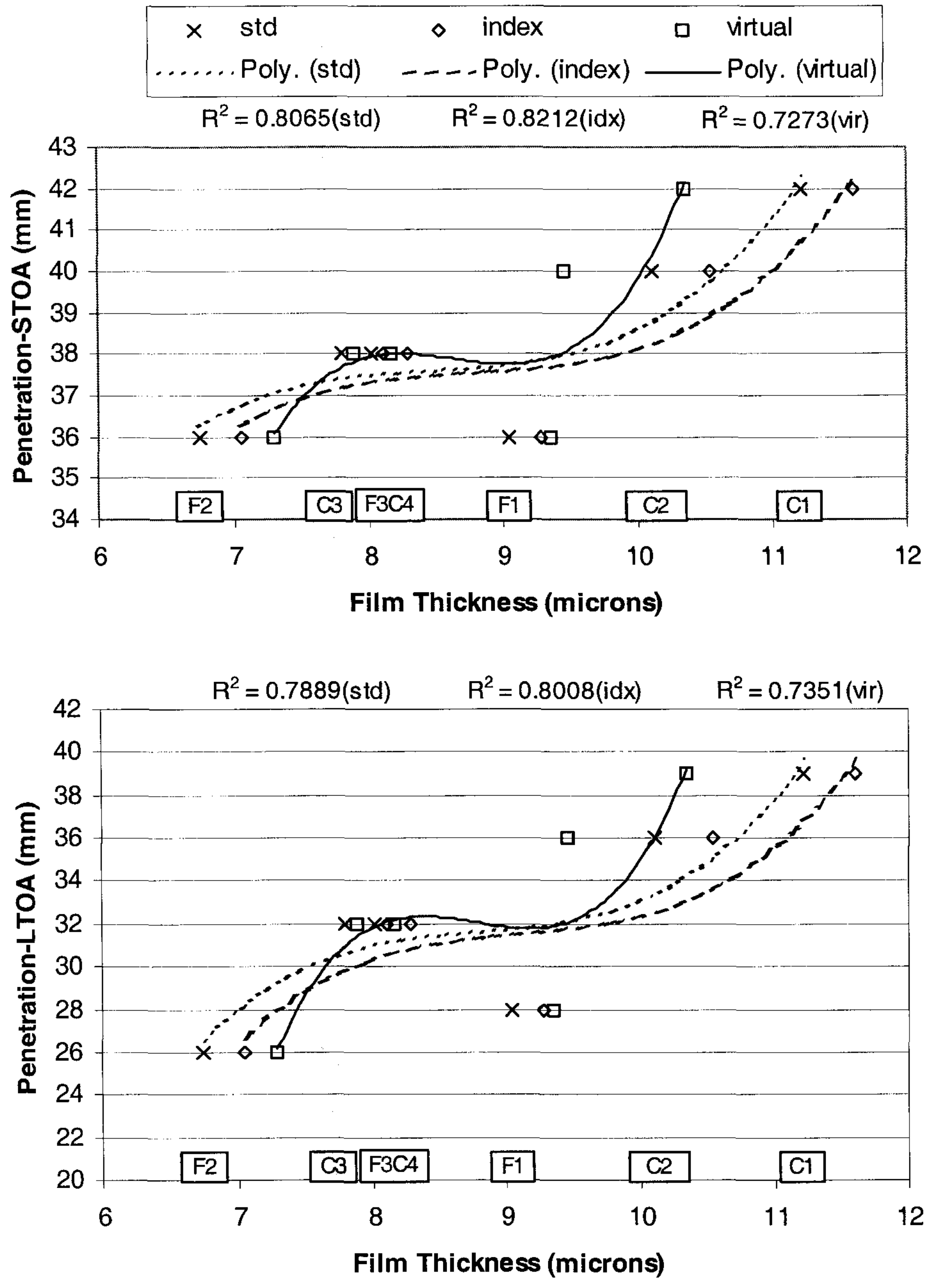
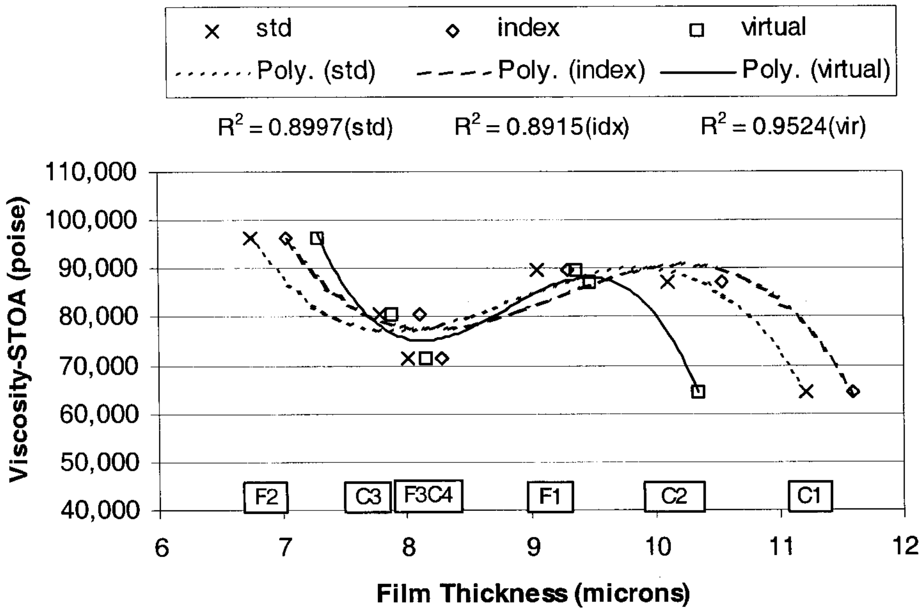


Figure C1 – Impact of STOA and LTOA on Penetration of Binder



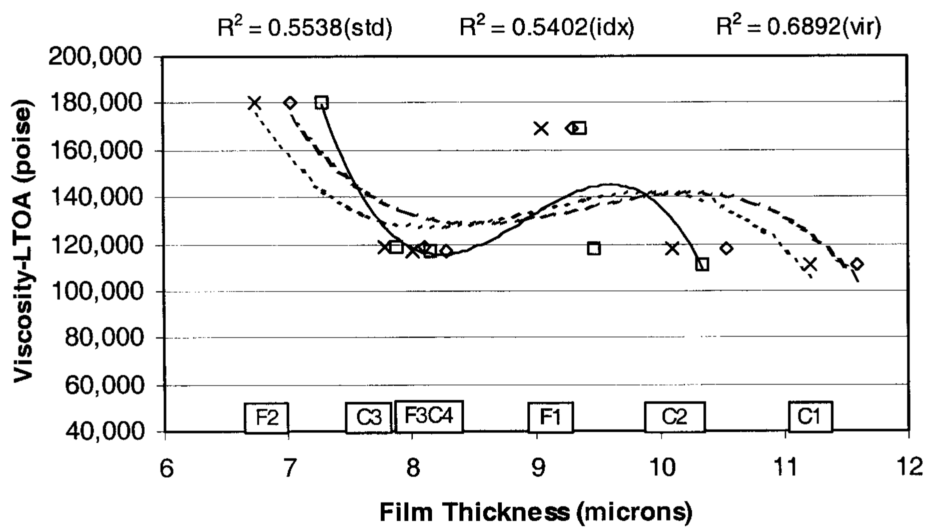
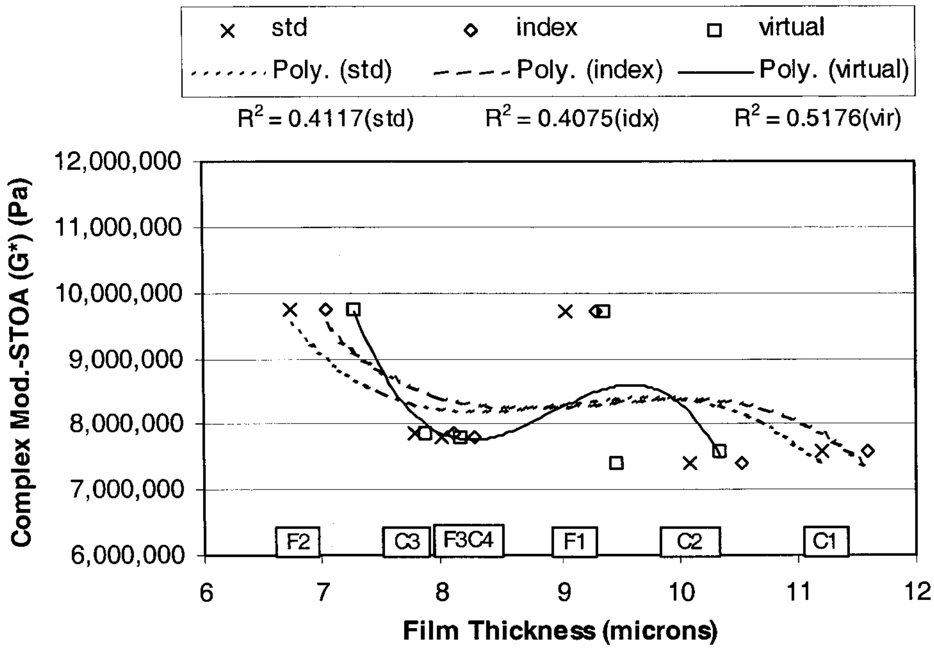


Figure C2 – Impact of STOA and LTOA on Viscosity of Binder



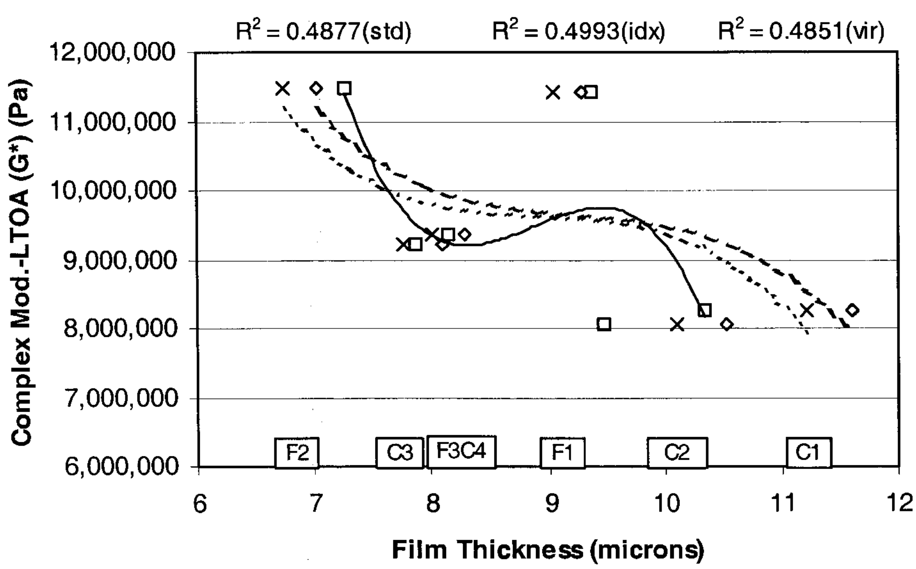


Figure C3 – Impact of STOA and LTOA on Complex Modulus

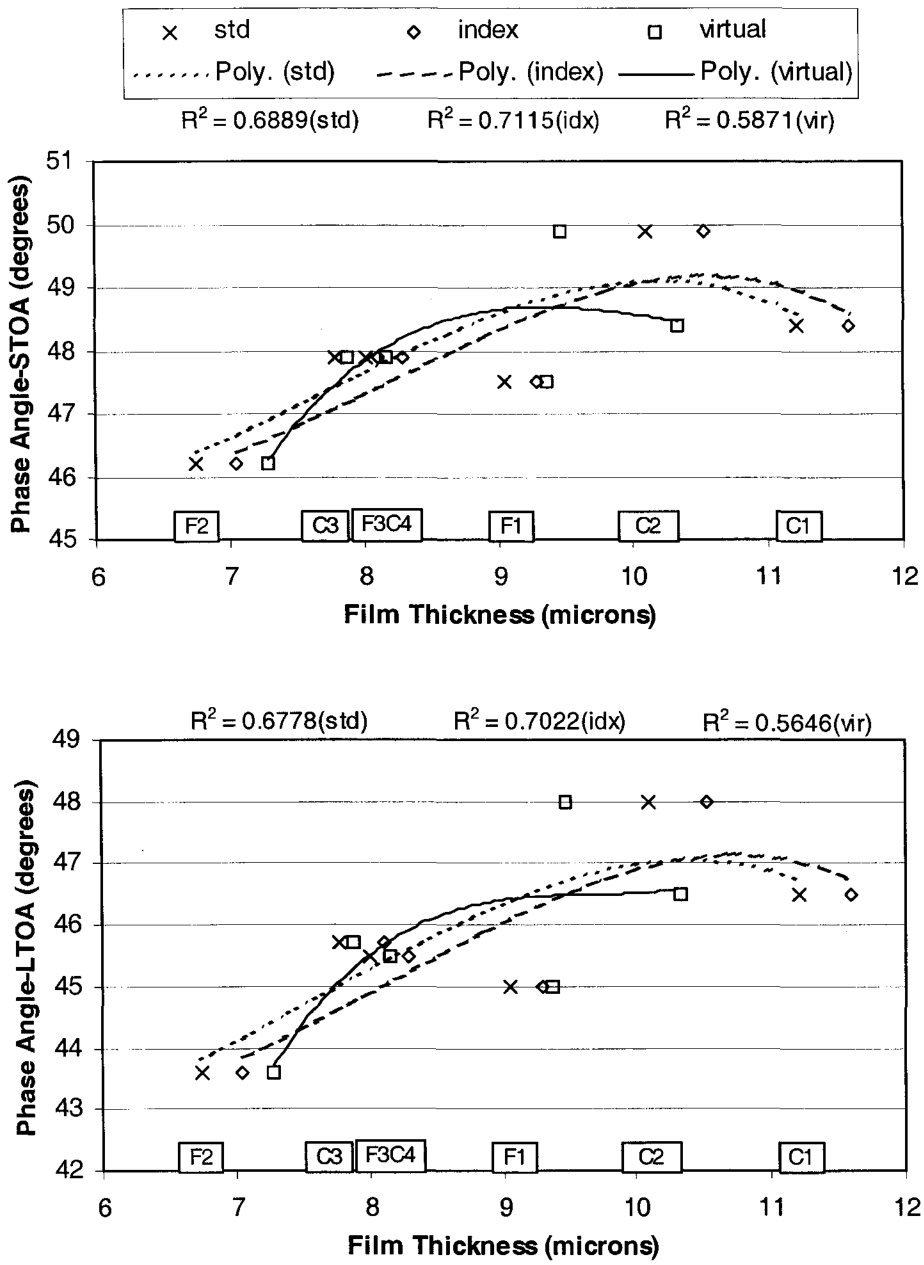


Figure C4 – Impact of STOA and LTOA on Phase Angle

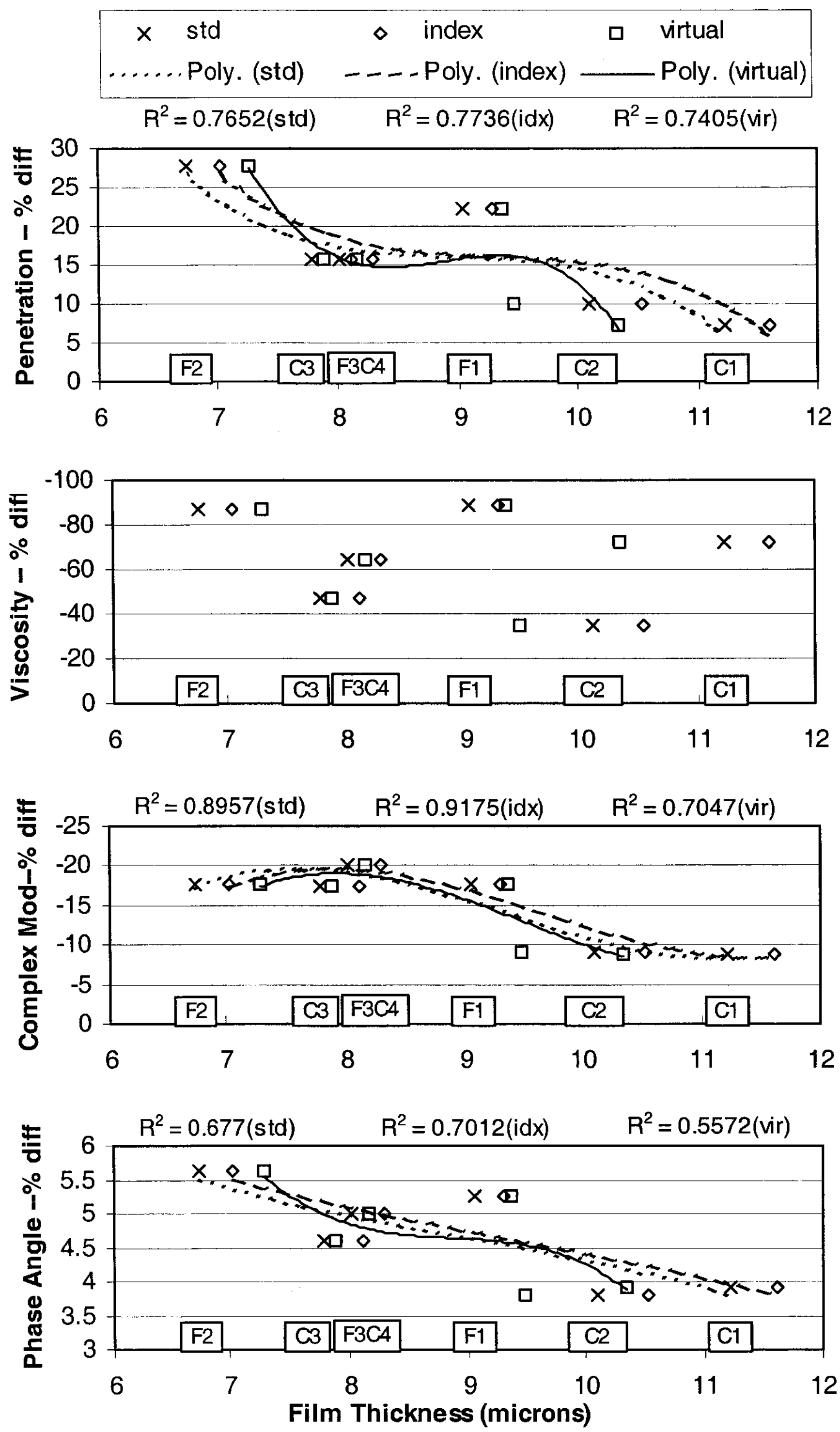


Figure C5 – Percent Change in Binder Properties

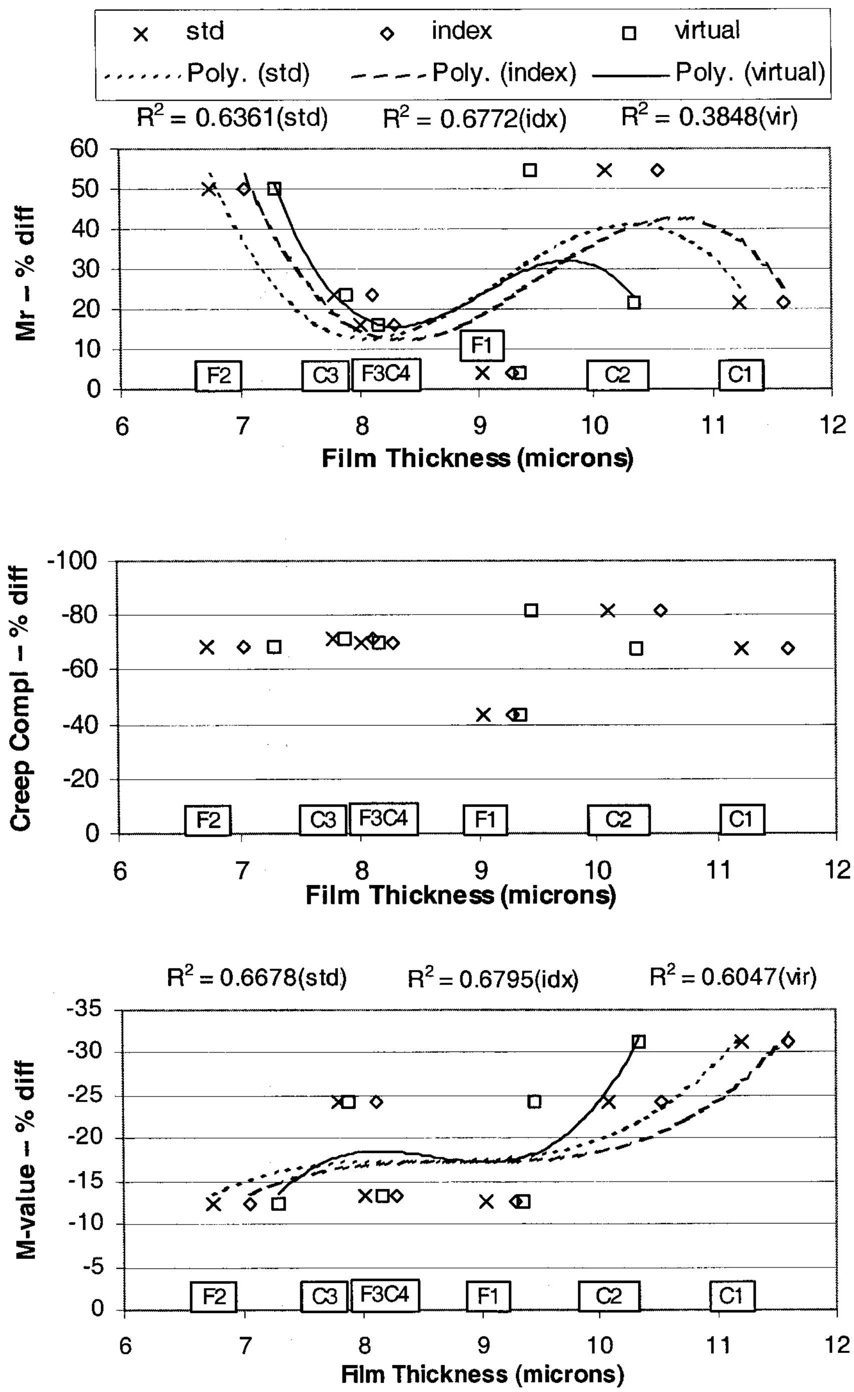


Figure C6a – Percent Change in Mix Properties

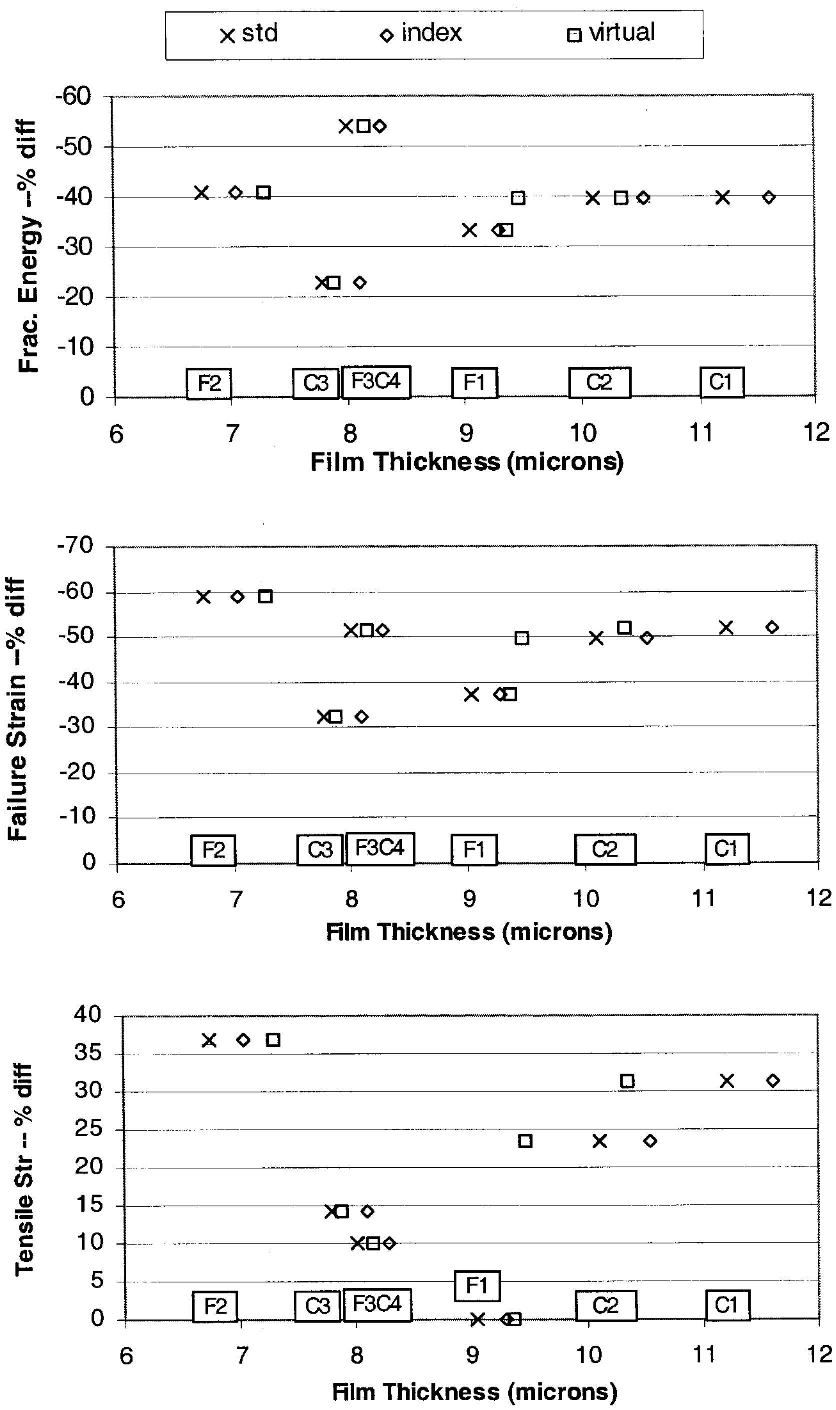


Figure C6b – Percent Change in Mix Properties

References

1. J.A. Hinrichsen and J. Heggen, "Minimum Voids in the Mineral Aggregate Based on Gradation and Volumetric Properties" Transportation Research Record 1545, TRB, Washington, D.C., 1996, pp.75-79
2. P.S. Kandhal, K.Y. Foo, and R.B. Mallick, "A Critical Review of VMA Requirements in Superpave" NCAT Report No. 98-1, NCAT, Auburn, Alabama, 1998
3. R.B. Leahy and R.B. McGennis, "Asphalt Mixes: Materials, Design and Characterization" Proceedings of the AAPT, Vol 68A, 1999 pp.70-127
4. Mix Design Methods for Hot-Mix Asphalt Paving, Manual Series No. 2, First Edition, April 1956, The Asphalt Institute, College Park, Maryland, Chapter III and V
5. J.K. McLaughlin and W.H. Goetz, "Permeability, Void Content, and Durability of Bituminous Concrete" Highway Research Board Proceedings, Vol. 34, TRB, Washington, D.C., 1955, pp.274-286
6. N.W. McLeod, "Relationship Between Density, Bitumen Content, and Voids Properties of Compacted Paving Mixtures" Highway Research Board Proceedings, Vol 35, TRB, Washington D.C., 1956
7. W.H. Campen, J.R. Smith, L.G. Erickson and L.R. Mertz, "The Control of Voids in Aggregate for Bituminous Paving Mixtures" Proceedings of the AAPT, Vol 26, 1957 pp.297-311
8. J. Lefebvre, "Recent Investigations of Design of Asphalt Paving Mixtures" Proceedings of the AAPT, Vol 26, 1957 pp.321-394
9. W.H. Campen, J.R. Smith, L.G. Erickson and L.R. Mertz, "The Relationships Between Voids, Surface Area, Film Thickness and Stability in Bituminous Paving Mixtures" Proceedings of the AAPT, Vol 28, 1959 pp.149-178
10. J.F. Goode and L.A. Lufsey, "Voids, Permeability, Film Thickness vs. Asphalt Hardening" Proceedings of the AAPT, Vol 34, 1965 pp.430-463
11. A. Kumar and W.H. Goetz, "Asphalt Hardening as Affected by Film Thickness, Voids and Permeability in Asphaltic Mixtures" Proceedings of the AAPT, Vol 46, 1977 pp.571-605
12. P.S. Kandhal and S. Chakraborty, "Effect of Asphalt Film Thickness on Short- and Long-Term Aging of Asphalt Paving Mixtures" Transportation Research Record 1535, TRB, Washington, DC, 1996 pp.83-90
13. B. Nukunya, R. Roque, M. Tia and B. Birgisson, "Evaluation of VMA and Other Volumetric Properties as Criteria for the Design and Acceptance of Superpave Mixtures" Proceedings of the AAPT, Vol 70, 2001 pp.38-69
14. B.E. Ruth, R. Roque and B. Nukunya, "Aggregate Gradation Characterization Factors and Their Relationships to Fracture Energy and Failure Strain of Asphalt Mixtures" Proceedings of the AAPT, Vol 71, 2002 pp.310-344
15. B. Radovskiy, "Analytical Formulas for Film Thickness in Compacted Asphalt Mixture" Transportation Research Record 1829, TRB, Washington DC, 2003 pp.26-32
16. Hot Mix Asphalt Materials, Mixture Design and Construction, Chapter 4, NCAT, Auburn, Alabama, pp.151-153
17. D.A. Anderson and J.P. Tarris, "Characterization and Specification of Baghouse Fines" Proceedings of the AAPT, Vol 52, 1983 pp.88-120
18. S. Chakraborty, "Evaluation of Voids in the Mineral Aggregate for HMA Paving Mixtures" Master of Science Thesis, Department of Civil Engineering, Auburn University, 1994
19. T.K. Pellinen, "The Effect of Volumetric Properties on Mechanical Behavior of Asphalt Mixtures" TRB 2003 Annual Meeting, Session 215, TRB, Washington DC, 2003 paper no. 03-4403