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ABSTRACT

Voids in the mineral aggregate (VMA), together with the voids in the total mix (VTM), are considered important parameters in hot mix asphalt (HMA) mix design. It is believed that a minimum VMA requirement is necessary to ensure that the HMA mix is not deficient in asphalt cement (so the mix is durable), and/or in VTM (to prevent flushing and/or rutting). Current VMA requirements are based largely upon the work done during 1950 to 1960. However, the literature reviewed as part of this study did not indicate the existence of any significant rational data correlating the durability of HMA pavements with the minimum VMA values specified for mix design.

This study was undertaken (a) to reexamine the rationale behind the minimum VMA values currently being used, and (b) to quantify the relationship between various asphalt film thicknesses and the aging characteristics of the HMA mix, so that an optimum film thickness desirable for satisfactory mix durability could be established. The optimum film thickness could then be used to establish VMA requirements.

Mixes prepared with asphalt binder film thickness ranging from about 4 to 13 microns, were subjected to accelerated aging using Strategic Highway Research Program (SHRP) procedures to simulate both short and long term aging. Both the aggregate (RD) and the asphalt

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cement (AAM-1) used in this study were obtained from the SHRP Materials Reference Library. The aged, compacted mix was tested for tensile strength, tensile strain at failure and resilient modulus. The aged asphalt cement was recovered and tested for penetration, viscosity, complex between various asphalt film thicknesses and the aging characteristics of the HMA mix, so that an optimum film thickness desirable for satisfactory mix durability could be established. The optimum film thickness could then be used to establish modulus and phase angle. Aging indices were obtained from these tests, and the relationship between film thickness and the aged mix/aged asphalt cement properties were determined using regression analysis. For the particular aggregate/asphalt cement combination used in this study, it was found that accelerated aging would occur if the asphalt binder film thickness was less than 9-10 microns in an HMA mixture compacted to 8°/0 air void content. The minimum VMA required to accommodate this optimum asphalt film thickness and 4°/0 air void content, was also calculated.

KEY **WORDS** : VMA, voids in mineral aggregate, hot mix asphalt, HMA, asphalt concrete, asphalt paving mixture, film thickness, durability.

EVALUATION OF VOIDS IN THE MINERAL AGGREGATE FOR HMA PAVING MIXTURES

INTRODUCTION

The concept of voids in the mineral aggregate (VMA) is considered fundamental in the design of dense-graded hot mix asphalt (HMA) mixtures. The term VMA describes that portion of the space in a compacted HMA pavement or specimen which is not occupied by the aggregate. Current mix design procedures including Superpave are largely based upon the need for selecting and proportioning the various materials to meet certain volumetric properties such as VMA. A minimum VMA requirement (based on the maximum nominal size of the aggregate) is used to ensure that the HMA mix is not deficient in asphalt cement (thereby ensuring mix durability) and/or in the voids in the total mix (VTM) to prevent bleeding or rutting.

The minimum requirements for VMA have been questioned by many researchers because there is a lack of significant research data correlating the VMA with the HMA mix performance in terms of durability.

OBJECTIVES

This study was undertaken to achieve ihe following objectives:

1. Review available literature to re-examine the rationale behind the minimum VMA requirements currently being used.

2. Determine the optimum asphalt binder film thickness in an HMA mixture to minimize short and long term aging of the asphalt binder, thus providing reasonable durability of the HMA mix. The optimum film thickness can then be used to establish minimum VMA requirements.

LITERATURE REVIEW

Minimum VMA Requirements

In a paper presented to the Highway Research Board in 1956 [1], McLeod pointed out that the basic criteria for both the design and analysis of paving mixtures should be on a volumetric basis and not on the basis of weight. Most specifications in those days tended to specify a range of asphalt content by weight along with grading bands or limits for the aggregate, which in effect required a design on the basis of weight.

McLeod [1] illustrated the volumetric relationship between the total asphalt binder, air voids between the coated aggregate particles, and the total aggregate in a compacted paving mixture. He based the compaction requirements upon the Marshall test procedure, with 75 blows on each side of the briquette. He also recommended that the VMA, which is the volume of voids between the aggregate particles, should be restricted to a minimum value of 15°/0, the volume of the air voids (within the VMA) should lie between 3 and 5%, which in turn restricted the volume of asphalt cement in the compacted mixture to a permissible minimum of 10% by volume. Therefore, his proposal for a specification of a minimum 15% VMA, along with 5% air voids, automatically establishes a minimum asphalt content of about 4. 5°/0 by weight (10% by volume).

His calculations were based upon a bulk specific gravity of 2.65 for the aggregate and 1.01 for the asphalt cement. No asphalt absorption was considered in the volumetric analysis.

Another paper presented by McLeod in 1959 [2] to the American Society of Testing and Materials, advocated the use of bulk specific gravity of the aggregate for calculating both the VMA and the air voids. Absorption of the asphalt cement into the aggregate was also taken into account in the volumetric analysis. McLeod recommended again that the lowest permissible asphalt content in a HMA mix should be 4. 5°/0 by weight, to ensure mix durability. This amounts to about 10°/0 asphalt cement by volume. No HMA performance data were presented to support the minimum asphalt content of 4.5°/0 on which the minimum VMA requirement was based. In this paper, McLeod also proposed a relationship between the minimum VMA and the nominal maximum particle size of the aggregate, which was adopted by the Asphalt Institute in 1964 [3]. He based this relationship upon the bulk specific gravity of the aggregate and an air voids content of 5°/0 for the compacted mix. However, the background data for relating the minimum VMA requirements to the nominal maximum size of the aggregate was not given [2].

During the last 30 years or so, most asphalt paving technologists did not realize that these minimum VMA requirements were based on 5°/0 air void content (and not 4°/0 air void content generally used for mix design) and 75-blow Marshall compaction. Obviously, the minimum VMA requirements corresponding to 4°/0 air void content would be 10/0 lower than those recommended in earlier editions of Asphalt Institute MS-2 [3]. This was recognized in 1993 and the Asphalt Institute MS-2 was revised [4] to give minimum VMA requirements corresponding to 3, 4, and 5% air void contents. These revised minimum VMA requirements have also been incorporated in Superpave mix design procedures.

Asphalt Binder Film Thickness in Durability Considerations

It is generally agreed that high permeability, high air voids, and thin asphalt coatings on the aggregate particles are the primary causes of excessive aging of the asphalt binder which contributes to the lack of durability of the HMA mixes often encountered in the field. However, the concept of an "average film thickness" for dense-graded asphalt mixtures is not easily understood. How much validity can be assigned to a film thickness, calculated simply by dividing the total surface area of the aggregate (obtained from its gradation) by the effective asphalt content? It is highly unlikely that all the particles in a mix have the same film thickness of asphalt coating. Fine aggregate particles may have a much thicker coating as compared to the coarse aggregate particles, and in fact, for all practical purposes, some very fine particles might simply be embedded in the asphalt cement/filler mortar system. Therefore, the term "film thickness" is elusive and difficult to define. However, for the purpose of calculation later in this paper, we shall assume that the concept of the "average film thickness" is indeed valid, and proceed with the calculations. Surface area will be calculated using the procedure outlined in the Asphalt Institute's MS-2 [4].

Campen, Smith, Erickson and Mertz [5] presented the relationship between voids, surface area, film thickness and stability for dense graded HMA. The authors recognized that thicker asphalt binder films produced mixes which were flexible and durable, while thin films produced mixes which were brittle, tended to crack and ravel excessively, retarded pavement performance, and reduced its useful service life. On the basis of the data they analyzed, average film thicknesses ranging from 6 to 8 microns were found to have provided the most desirable pavement mixtures.

They also concluded that the film thickness decreases as the surface area of the aggregate is increased. However, the asphalt binder requirement of a mix is not directly proportional to its surface area. The asphalt binder requirement was found to increase as the surface area was increased, but at a rate much lower than that guided by a relationship of direct proportionality [5].

Goode and Lufsey [6] also did some significant work in relating asphalt hardening to voids, permeability and film thickness. They recognized that the hardening of the asphalt binder in a mix was a function of air voids, film thickness, temperature, and time. On the basis of their work they concluded that a minimum value of 0.00123 for ‘bitumen index’ (which corresponds to a value of 6 microns of average film thickness) could be included as a criterion in all mix design procedures. The ‘bitumen index’ was defined as pounds of asphalt cement per square foot of surface area. They used the concept of bitumen index to avoid the implication that all particles were coated with the same uniform thickness of asphalt cement. Their study indicated that a combined factor of the ratio of the air voids to the bitumen index could be satisfactorily related to the asphalt binder hardening characteristics in the HMA mixture. They suggested that the Marshall method of mix design could be improved by incorporating a maximum value of voids-bitumen index ratio in place of a maximum value of air voids alone, and suggested a value of 4 as the maximum for this ratio, to ensure reasonable resistance to aging.

Kumar and Goetz [7] studied the asphalt binder hardening as related to HMA permeability and asphalt film thickness. They stated that the best procedure for predicting the resistance of hardening of asphalt binder in a single-sized HMA mix was to calculate the ratio of the film thickness factor to permeability. The film thickness factor was defined as the ratio of the percent asphalt content available for coating the aggregate to the surface area of the aggregate. They indicated that for dense-graded mixtures, the concept of an average film thickness is at best dubious, if not totally erroneous. For dense-graded mixtures, permeability was stated to be the best measure of the resistance to hardening. However, at the design value of 4°/0 air voids as is common for most dense-graded HMA mixtures, the effect of permeability of the mix was determined to be quite insignificant.

TESTING PROGRAM

This testing program was carried out with the following objectives:

- To evaluate the changes in the theological properties of the asphalt cement due to aging in relation to the asphalt film thickness. Both short term (during HMA production and construction) and long term (during service life) aging were considered.
- To determine an optimum range for the asphalt film thickness, if possible, which would minimize aging of the asphalt binder. This optimum film thickness can then be used in developing minimum VMA requirements for HMA mixtures.

Material Used

Aggregate and asphalt cement samples were obtained from the SHRP Material Reference Library (MRL). Only one aggregate (SHRP MRL Designation **RD**): Frederick Limestone was used in this study. Table 1 gives the physical properties of the total aggregate obtained from SHRP MRL. Table 2 gives the washed gradation of the aggregate used in the HMA mixture.

An asphalt cement (SHRP MRL Designation **AAM-1)** was used in this study. This asphalt cement was selected because it had one of the highest propensities to age in the HMA mix based on the work done in SHRP A-003A by Sosnovski et al [8]. Its physical and chemical properties as obtained from SHRP are given in Table 3.

Test Procedures Used

The surface area of the aggregate was calculated using the surface area factors given in MS-2 [4]. For the aggregate gradation used (Table 2) the surface area was calculated to be 27.626 ft^2/lb (5.662 m^2/kg).

HMA mixtures were prepared at each of the following six effective asphalt film thicknesses: 3.7, 5.6, 7.4, 9.3, 11.1, and 13.0 microns. The film thicknesses originally targeted for experimental design were 4, 6, 8, 10, 12 and 14 microns. However, certain errors in the calculations were discovered after the mixes had actually been prepared. The actual values of asphalt film thicknesses used were then recalculated.

A value of 0.20'% asphalt absorption was used for the RD-AAM-1 combination as determined and reported in [9]. This required six asphalt contents (by weight of the total mix) as follows: 2.2, 3.2, 4.2, 5.1, 6.1 and 7.1 percent to obtain asphalt film thickness ranging from 3.7 to 13.0 micron as mentioned above.

All six HMA mixtures were prepared at the mixing temperature of 143 ± 3°C. The testing sequence for each mix is given in Figure 1.

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The loose HMA mix samples were subjected to short term aging following SHRP #1025 procedures [10] The process involves aging of the loose HMA mix in a forced draft oven for 4 hours at a temperature of 135°C. The loose mix is placed in a baking pan and spread to an even thickness that produced about 21 kg/m^2. This procedure is designed to simulate the aging that the loose HMA mix undergoes during the construction phase of the pavement. Three samples of the aged HMA mix were subjected to Abson method of recovering asphalt binder. The recovered asphalt binder was tested for penetration at 25°C and viscosity at 60°C. The complex modulus (G*) and phase angle (δ) were also determined at 64°C for the recovered asphalt cement using the Dynamic Shear Rheometer. The temperature of 64°C was used because just after construction, rutting factor ($G^*/\sin\delta$) is critical at high pavement temperatures. This temperature would be used for testing a Superpave PG 64-34 binder after subjecting it to rolling thin film oven (RTFO) which simulates short term aging.

Five 100-mm diameter specimens were compacted from each mix type after short term aging. The compacted specimens were prepared to give a target air void content level of 8 ± 1 %. The Corps of Engineers Gyratory Testing Machine (GTM) was used for this purpose. The resilient modulus (M_R) of all the compacted specimens was determined at 25°C. Total number of samples tested= 6 (film thicknesses) x 5 (replicates) =30.

The 30 compacted specimens were subjected to long term aging following SHRP #1030 procedures [11]. The procedure consists of placing the compacted specimens on a rack in a forced draft oven for 120 hours, and at a temperature of 85°C. This procedure was designed to simulate the aging that the compacted HMA pavement undergoes during its 5-10 years service life. An air void content of 8 ± 1 percent in compacted specimens is used to simulate compaction at the time of construction. Lower air void contents may also not provide interconnected voids which are essential for this accelerated aging test.

The following tests were conducted on the compacted specimens after long term aging:

1. Resilient modulus (M_R) at 25°C.
2. Tensile strength (S_T), along with the strain at failure, at 25°C using a strain rate of 50 mm (0.05 m) per minute.
3. Abson recovery of aged asphalt binder from all 30 broken specimens. The recovered asphalt binders were tested for penetration at 25°C, viscosity at 60°C, complex modulus (G*) at 19"C, and phase angle (δ) at 19°C.

Complex modulus and phase angle were measured using Superpave test procedures [12]. The temperature of 19°C was used because the fatigue factor (G*sinδ) is critical at mid service pavement temperatures according to Superpave performance graded (PG) binder specifications [12]. After long term aging HMA mixes become stiff and, therefore, fatigue cracking becomes the primary distress of concern affecting the HMA durabil ity. The temperature of 19°C would be used to test a Superpave PG 64-34 binder after aging it in RTFO and pressure aging vessel (PAV).

ANALYSIS OF TEST RESULTS

Table 4 gives the compacted HMA's physical properties (such as resilient modulus at 25°C and tensile strength at 25°C) after short and long term aging corresponding to asphalt film thickness ranging from 3.7 to 13.0 micron. Table 5 gives the conventional properties (such as penetration at

25°C and viscosity at 60°C) of the recovered asphalt binders after short term and long term aging. Table 6 gives Superpave binder properties (such as complex modulus G*) for these recovered asphalt binders.

The concept of polynomial regression has been used as a tool to fit the observed data to curve, which quantify the relationship between the independent and the dependent variables. The independent variable, in most cases, is the asphalt film thickness, against which are plotted the values of the recovered asphalt cement properties like penetration, viscosity, and complex modulus, or the measured properties of the compacted HMA mix, like tensile strength and resilient modulus. The relationship between the measured properties and the film thickness has been quantified for mixes which have been subjected to both short and long term aging. All dependent variables whose values are given in Tables 4, 5 and 6 were analyzed, the detailed analyses are given elsewhere [13]. A selected number of dependent variables are discussed below.

Compacted HMA Mix Properties

The resilient modulus of the compacted HMA specimens was measured both after short term aging and after long term aging (Table 4). The loose mix had been subjected to short term aging before compaction, i.e., before the preparation of the compacted samples. The compacted samples were then subjected to long term aging. Resilient modulus testing was carried out at 25°C in the diametral or indirect tensile mode.

Figures 2 and 3 show the relationship between the film thickness and modulus values after short term and long term aging, respectively. Quadratic polynomial regression gave an acceptable model for this relationship as presented below:

After Short Term Aging

$$Mr_{st} \text{ “ } 2069.9 - 273.15\mu + 10.53\mu^2$$

$$R^2 = 0.99035$$

where, Mr_{st} = resilient modulus after short term aging (ksi)

(1 ksi = 6.895 Mpa)

μ = film thickness in microns

After Long Term Aging

$$Mr_{lt} = 3267.6 - 456.75p + 17.55\mu^2$$

$$R^2 = 0.9896$$

where, Mr_{lt} = resilient modulus after long term aging (ksi)

It can be seen in Figures 2 and 3 that at about a film thickness of 11 microns, the fitted curve tends to flatten out and does not change significantly with increasing film thickness. Also, the slope of the curve becomes steeper as the film thickness falls below a value of about 9 to 10 microns, which indicates that the stiffness (caused by aging) of the HMA mix starts to increase quite rapidly with a decrease in film thickness below about 9-10 microns. Also, there is a marked similarity between the curves obtained after short term and long term aging.

Some more information concerning the change in resilient modulus values with film thickness can be obtained from the graph in Figure 4 where the resilient modulus values after short term aging have been plotted against the corresponding moduli values after long term aging. Each point on the graph corresponds to one particular asphalt film thickness which decreases from left to right (because the resilient modulus values increase with decrease in film thickness). Regression analysis leads to a linear relationship in the data as modelled by the following equation:

$$Mr_{lt} = -198.12 + 1.675\, Mr_{st}$$

$$R^2 = 0.998$$

The very high value of R^2 indicates that a linear model almost exactly represents the relationship. From this it can be inferred that both short and long term aging of the HMA mix are affected in exactly the same way by the film thickness. This means thick asphalt films minimize the aging of the HMA mixes during construction as well as during service life.

As expected, the tensile strength at 25°C decreases and the tensile strain at failure increases as the asphalt film thickness in the HMA mix (after long term aging) is increased from 3.7 to 13.0 micron.

Recovered Asphalt Binder Properties

The measured values of viscosity of the recovered asphalt after short term and long term aging have been presented graphically in Figures 5 and 6, respectively. For samples subjected to short term aging, regression analysis leads to the establishment of a quadratic model defined by the following equation:

$$V_{st} = 22609 - 3268.8p + 132.8\mu^2$$

$$R^* = 0.988$$

where,

V_{st} = viscosity of asphalt cement after short term aging (poises)

(1 poise= 0.1 pas)

As can be seen from the data for short term aging (Fig. 5), as the asphalt film thickness decreases below a value of about 9-10 microns the fitted curve tends to steepen indicating an accelerated rate of increase in viscosity. On the other end, the same curve is seen to flatten out at about 11 microns film thickness, which indicates that the film thickness has lesser and lesser effect on the aging of the asphalt cement once it is increased above a value of about 11 microns.

For samples subjected to long term aging, regression analysis failed to produce a satisfactory model which could explain the nature of the relationship between film thickness and aged viscosity. Thus, no equation is available to define the relationship. Instead, the points on the graph have been connected together by a smooth curve. As can be seen from Figure 6, the viscosity increases at an accelerated rate once the asphalt film thickness decreases below a value of about 10 microns. The nature of the curves obtained when the viscosity ratio (Table 5) is plotted against film thickness, is

about the same as in the previous cases for short and long term aged conditions [13]. The viscosity ratio is defined as the ratio of the viscosity of the aged asphalt to the viscosity of the unaged/original asphalt.

Similar relationships were also observed between asphalt film thickness and penetration or retained penetration of asphalt cements after short and long term aging [13].

For asphalt cement subjected to short term aging, complex modulus G* and phase angle δ were measured at a temperature of 64°C, whereas for long term aged specimens, the testing of the asphalt cement was carried out at 19°C (Table 6). Since the stiffness of the asphalt binder is more critical after long term aging rather than short term aging from the durability (or resistance to fatigue) standpoint, the complex modulus G* and fatigue factor (G*sinδ) after long term aging will only be presented here. The relationship between asphalt film thickness and G* at 19°C after long term aging has been shown in Figure 7. Although the regression analysis of G* at 1 9°C and film thickness gave a quadratic model for the short term aged asphalt cement [13], a linear model (Figure 7) better expresses the relationship between asphalt film thickness and G* at 19°C after long term aging, as follows:

$$G*_{lt} = 3158521 - 176472.6p$$

R = 0.98

$G*_{lt}$ = complex modulus of asphalt cement subjected to long term aging (Pa)

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$$\mathbf{R = 0.98}$$

$G*_{lt}$ = complex modulus of asphalt cement subjected to long term aging (Pa)

As expected, values of the complex modulus G* decrease with increasing asphalt film thickness, both for short and long term aging. This indicates that the presence of thicker films of asphalt cement in the HMA mix minimizes aging of the asphalt binder. However, it is not apparent from the fitted curves as to what range of asphalt film thickness might prove to be optimum in minimizing asphalt cement aging.

The relationship between G*sinδ (fatigue factor) and film thickness has been presented in Figure 8, for asphalt cement recovered from mixes which had been subjected to long term aging. A linear model was obtained as follows:

$$GSD_{lt} = 1848404 - 98052.5p$$

$$R^2 = \mathbf{0.98}$$

where,

GSD_{lt} = G*sinδ (in pascals) for samples subjected to long term aging.

As is evident from the fitted curve (Figure 8), G*sinδ increases with decrease in the film thickness of the asphalt binder in the HMA mix. This indicates that the lower the asphalt binder film thickness present in a HMA mix, the more susceptible the pavement is to fatigue cracking in the long term.

SHRP has suggested a value of 5000 KPa as the upper limit for G*sinδ for asphalt cement subjected to accelerated aging in the Pressure Aging Vessel (PAV). PAV aging simulates the aging that the asphalt binder in a HMA pavement undergoes after about 5-10 years in service. As discussed earlier, this study employed a procedure (also developed by SHRP) to simulate long term aging of in-service pavements using compacted HMA samples, instead of j ust asphalt cement, as is used in the PAV test. Therefore, for asphalt cement recovered from compacted HMA samples subjected to accelerated long term laboratory aging procedures, 5000 kPa should be considered as the upper limit for G*sinδ. As is evident from the data presented in Figure 8, the maximum recorded value of G*sinδ is about 1500 kPa, which is much less than the limiting value of 5000 kPa. This indicates that the PAV aging of asphalt cement is much more severe in this limited laboratory study than that occurring in compacted HMA samples aged in forced draft oven at 85°C for 120 hours.

Air Voids to Bitumen Index Ratio Analysis

The concept of the ratio of the air voids (percent) to bitumen index, as a measure of the aging susceptibility of a mix (whatever be its gradation), was discussed earlier. Goode and Lufsey [6] had proposed a maximum value of 4.0 for this ratio which they believed would prevent pavement distress by reducing the aging of the asphalt film coating the aggregate. Mathematically, what they stated was:

$$\frac{Air\ Voids\ (\%)}{Bitumen\ Index \times 10^3} = 4.0\ (maximum)$$

Noting that:

film thickness in microns= bitumen index x 4870

The previous expression can be reduced to a minimum film thickness requirement, varying with the air voids content of the given mix, as follows:

$$Film\ \ Thickness\ \ (microns).\ \ \frac{Air\ \ Voids\ \ (\%)\ \ \mathrm{x}\ \mathbf{4870}}{4 \times 10^{3}}\ \ \ (minimum)$$

A target value of 8’% for the air voids in the compacted HMA specimens was used in the present study, in conformance with the accelerated long term aging procedure developed in SHRP AO03-A Project. This corresponds to a minimum film thickness requirements of 9.74 microns (about 10 microns), based upon the above equation. As can be seen from Figures 2 and 3, the curves of the resilient moduli (for both short and long term aging conditions) versus film thickness tend to steepen as the film thickness decreases below the range of 9 to 10 microns. This indicates that the rate of aging of the asphalt cement is accelerated when the film thickness is less than 9- 10 microns. This accelerated aging rate can also be seen in the plots of viscosity versus film thickness (Figures 5 and 6). Therefore it can be concluded, on the basis of the piesent study, that a maximum value of 4.0 for the voids/bitumen index ratio is indeed reasonable, and might prove to be a better specification for design, at least as far as the aging of asphalt cement is concerned.

Based on the data presented in this limited study of one asphalt cement/one aggregate combination, let us assume that the optimum asphalt film thickness to minimize aging is 9 microns. The volume of asphalt cement binder can then be calculated based on this optimum film thickness and surface area of the aggregate in the HMA mix used. This volume of asphalt cement when added to 4% air void content (generally used in HMA mix design) should then give the minimum VMA required for this HMA mix to ensure reasonable durability. It is interesting to note that the minimum VMA requirement for the mix used in this study would be calculated at 15.6% based upon this procedure for a film thickness of 9 microns and an air voids content of 4%. As per the recommendations of the Asphalt Institute [4], the corresponding minimum VMA that has to be provided for this mix (with a maximum nominal size of 12.5 mm according to the new definition) is 14 percent. The nominal maximum size has now been defined as one sieve size larger than the first sieve to retain more than 10 percent. Therefore, the minimum VMA recommendation of the Asphalt Institute (also adopted in Superpave mix design) is about 1.5% less than that needed for obtaining an optimum asphalt film thickness based on this study. This difference is likely to vary if different gradation and/or different asphalt cement/aggregate combinations are used. It is also interesting to note that McLeod [14] had recommended in 1971 to increase all minimum VMA requirements in MS-2 by 2°/0 to obtain greater durability, although without providing any significant supporting data. However, it may not be possible to increase the VMA in many dense-graded HMA mixtures.

CONCLUSIONS AND RECOMMENDATIONS

This study was undertaken (a) to reexamine the rationale behind the minimum VMA requirements currently being used, and (b) to quantify the relationship between various asphalt binder film thicknesses and the aging characteristics of the HMA mix so that an optimum asphalt film thickness desirable for satisfactory mix durability could be established. The following conclusions were drawn and recommendations made:

1. The literature reviewed as part of this study did not indicate the existence of any significant rational data correlating the performance of HMA pavements with the VMA values currently specified for HMA mix designs.
2. The relationship between the asphalt film thickness and the aged properties (both short term and long term) of the HMA mixtures, such as tensile strength and resilient modulus, was quantified. A fairly good correlation was obtained between the asphalt film thickness and the resilient modulus of the aged HMA mixtures. An optimum film thickness of 9-10 microns was indicated from the data, below which the HMA mix (compacted to 8°/0 air void content) aged at an accelerated rate. This range appears to concur with the results obtained by Goode and Lufsey in terms of air voids/bitumen index ratio.
3. Relationships were also established between the asphalt film thickness and the aged asphalt binder properties (both short and long term) such as viscosity, penetration, and complex modulus. An optimum film thickness of 9-10 microns was generally indicated from the data, below which the asphalt binder aged at an accelerated rate. This film thickness corresponds to asphalt binder contained in an HMA mix compacted to 8°/0 air void content.
4. The minimum VMA for the HMA mix used in this study was calculated to be 15.6% to accommodate an optimum asphalt film thickness of 9 microns and 4°/0 air voids. The corresponding Asphalt Institute or Superpave recommendation for minimum VMA is 14°/0 for this mix (maximum nominal size of 12.5 mm). However, it may not be possible to achieve the desired VMA (15 .6°/0) in some dense-graded HMA mixtures of similar gradation.

5. The preceding conclusions are based on only one aggregate/asphalt cement combination. SHRP A-O03A and A-003B Projects have indicated that the aging phenomenon is influenced by the interaction between the aggregate and the asphalt cement. Therefore, the optimum asphalt film thickness indicated in this study needs to be confirmed by conducting more studies involving different aggregate/asphalt cement combinations. The minimum VMA requirement then could be based on the optimum asphalt film thickness which gives reasonable durability of the HMA mix.

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Table 1. Physical Properties of RD Aggregate (Frederick Limestone)

Property	Value
Bulk Specific Gravity	2.704
Water Absorption, percent	0.3
L. A. Abrasion (AASHTO T96)	
0/0 Wear	23.4
Flakiness Index, percent	34.7
Sand Equivalent (AASHTO T176)	69

Table 2. Washed Gradation of Aggregate Used in the HMA Mix

Sieve Size (mm)	Percent Passing
12.5	100
9.5	89
4.75	63
2.36	45
1.18	33
0.6	21
0.3	13
0.15	8
0.075	5

Table 3. Properties of Asphalt Cement (AAM-1) Used

Property	Value
ORIGINAL ASPHALT CEMENT	
Specific Gravity	0.993
Viscosity at 60°C, Pas	199.2
Viscosity at 135°C, cSt	569
Penetration at 25°C, 0.1 mm	64
Ductility at 4°C, cm	4.6
Softening Point (R&B), °C	51.7
Dynamic Shear Rheometer (DSR) data:	
G*/sinδ at 64"C, kPa	1.15
TFO RESIDUE	
Mass Change, %	0.00516
Viscosity at 60°C, Pas	394.7
Viscosity at 135"C, cSt	744
RTFO RESIDUE	
DSR data	
G*/sir-lb at 64°C, kPa	2.46
PRESSURE AGING VESSEL RESIDUE	
DSR data	
G*sinδ at 20°C, kPa	3,200
COMPONENT ANALYSIS	
Asphaltenes (n-heptane)	3.9
Polar Aromatics	50.3
Napthene Aromatics	41.9
Saturates	1.9
ELEMENT ANALYSIS	
Nitrogen %	0.50
Sulphur, %	2.40
Vanadium, ppm	60.0
Nickel, ppm	29.0

Table 4. Compacted HMA Properties after Short and Long Term Aging

Film Thickness (microns)	Resilient Modulus at 25°C, MPa		
	After STA[2]	After LTA[3]	LTA/STA Ratio
3.7	8,184	12,293	1.50
5.6	6,357	9,398	1.48
7.4	4,027	5,240	1.30
9.3	2,910	3,716	1.28
11.1	2,572	2,696	1.05
13.0	1,958	2,020	1.03

[1] All reported data are averages of five samples.
[2] STA = Short Term Aging
[3] LTA = Long Term Aging

Table 5. Recovered Conventional Asphalt Binder Properties after Aging[1]

Film Thickness (microns)	Viscosity at 60°C, Pa.s		Viscosity Ratio		Penetration at 25°C, 0.1 mm		Retained Penetration[5]	
	After STA[2]	After LTA[3]	After STA	After LTA	After STA	After LTA	After STA	After LTA
3.7	1262.1	4744.4	6.15	23.12	31.3	24.6	50.5	39.7
5.6	809.9	4658.4	3.95	22.70	35.3	25.7	56.9	41.5
7.4	526.1	4347.2	2.56	21.19	39.6	27.3	63.9	44.0
9.3	434.6	3940.1	2.12	19.20	43.6	29.0	70.3	46.8
11.1	276.3	3063.3	1.35	14.93	54.0	33.6	87.1	54.2
13.0	236.7	2897.6	1.15	14.12	56.6	34.3	91.3	55.3

[1]All reported data are averages of three samples
[2]STA = Short Term Aging
[3]LTA = Long Term Aging
[4]Based on viscosity of original asphalt cement measured at NCAT (205.2 Pa.s)
[5]Based on penetration of original asphalt cement measured at NCAT (62)

Table 6. Recovered Superpave Asphalt Binder Properties after Aging[1]

Film Thickness (microns)	Complex Modulus, G* at 64°C, Pa	Complex Modulus, G* at 19“C, Pa	G*sinδ at 19“C, Pa
	After STA[2]	After LTA[3]	After LTA[3]
3.7	2090	2.50 E +06	1.488 E +06
5.6	3590	2.25 E +06	1.339 E +06
7.4	2270	1.74 E + 06	1.068 E +06
9.3	2460	1.53 E + 06	0.918 E + 06
11.1	1310	1.22 E + 06	0.787 E +06
13,0	1220	1.71 E + 06	1.094 E +06

[1] All reported data are averages of three samples
[2]STA = Short Term Aging
[3]LTA = Long Term Aging

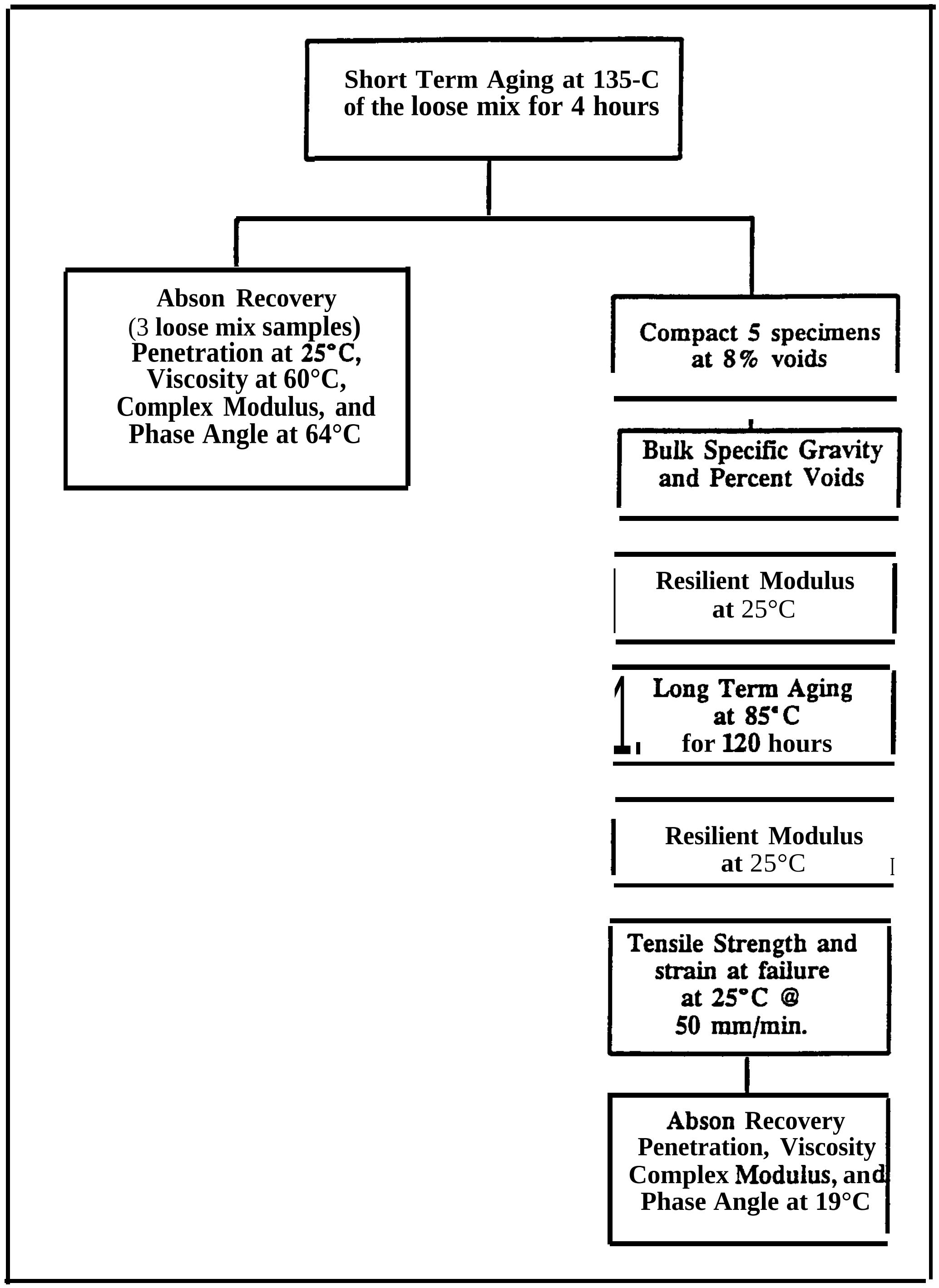


Figure 1. Test Sequence for Each Asphalt Content/Film Thickness

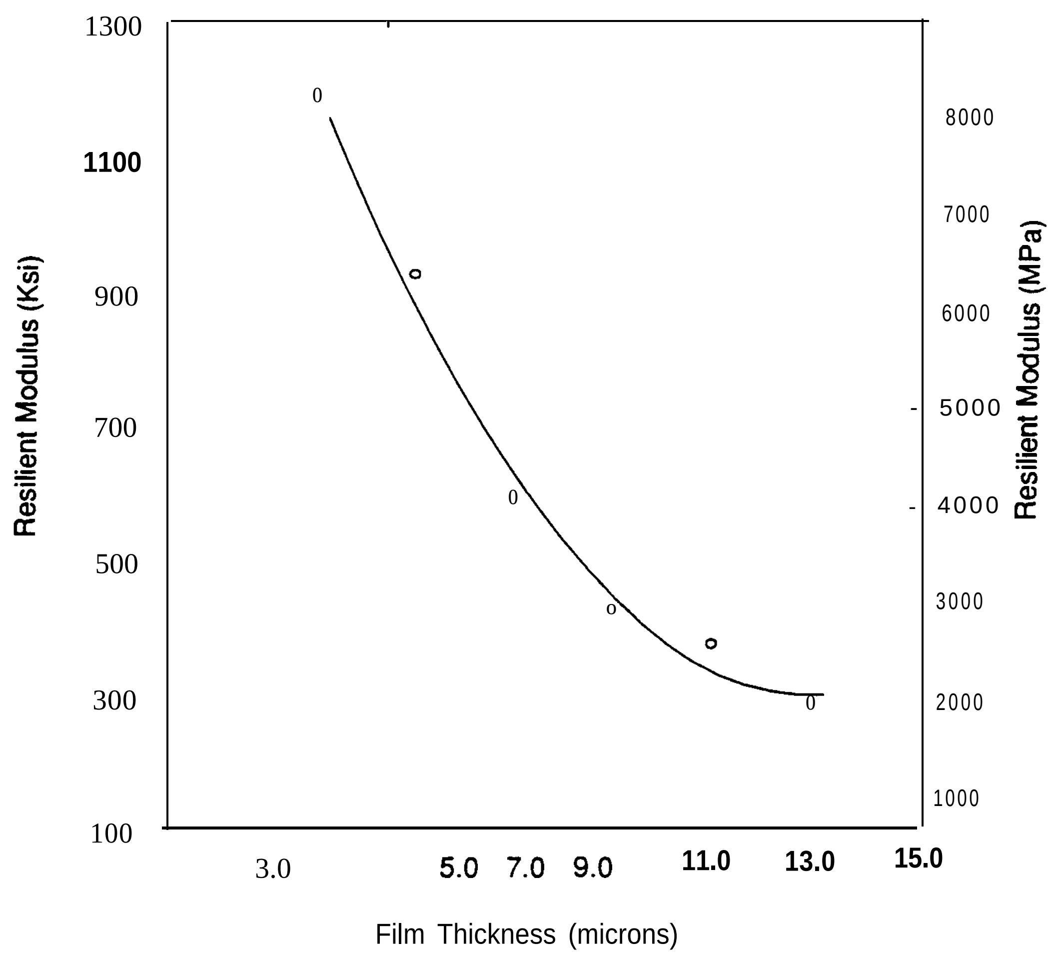


Figure 2. Asphalt Film Thickness vs. Resilient Modulus after Short Term Aging

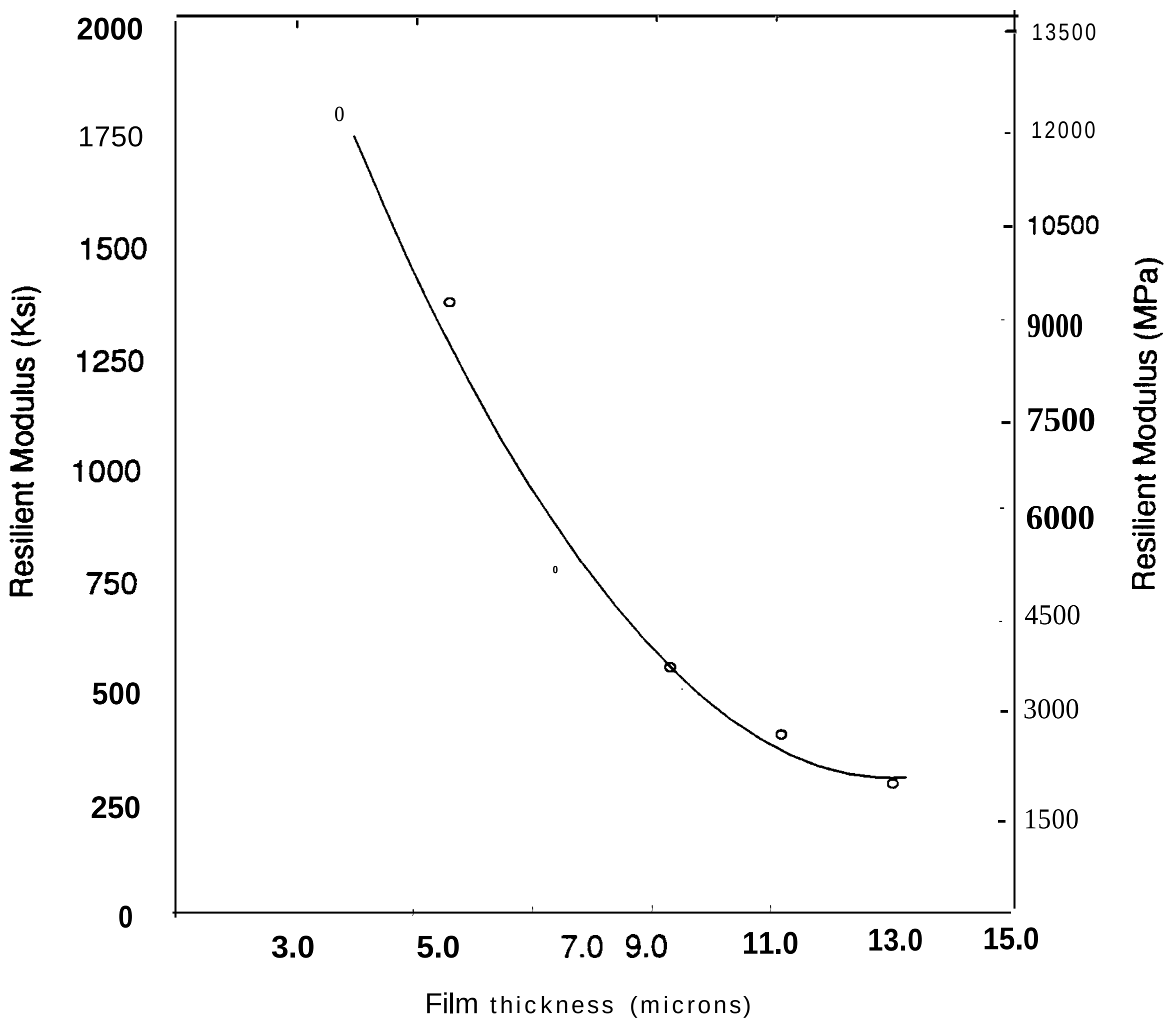
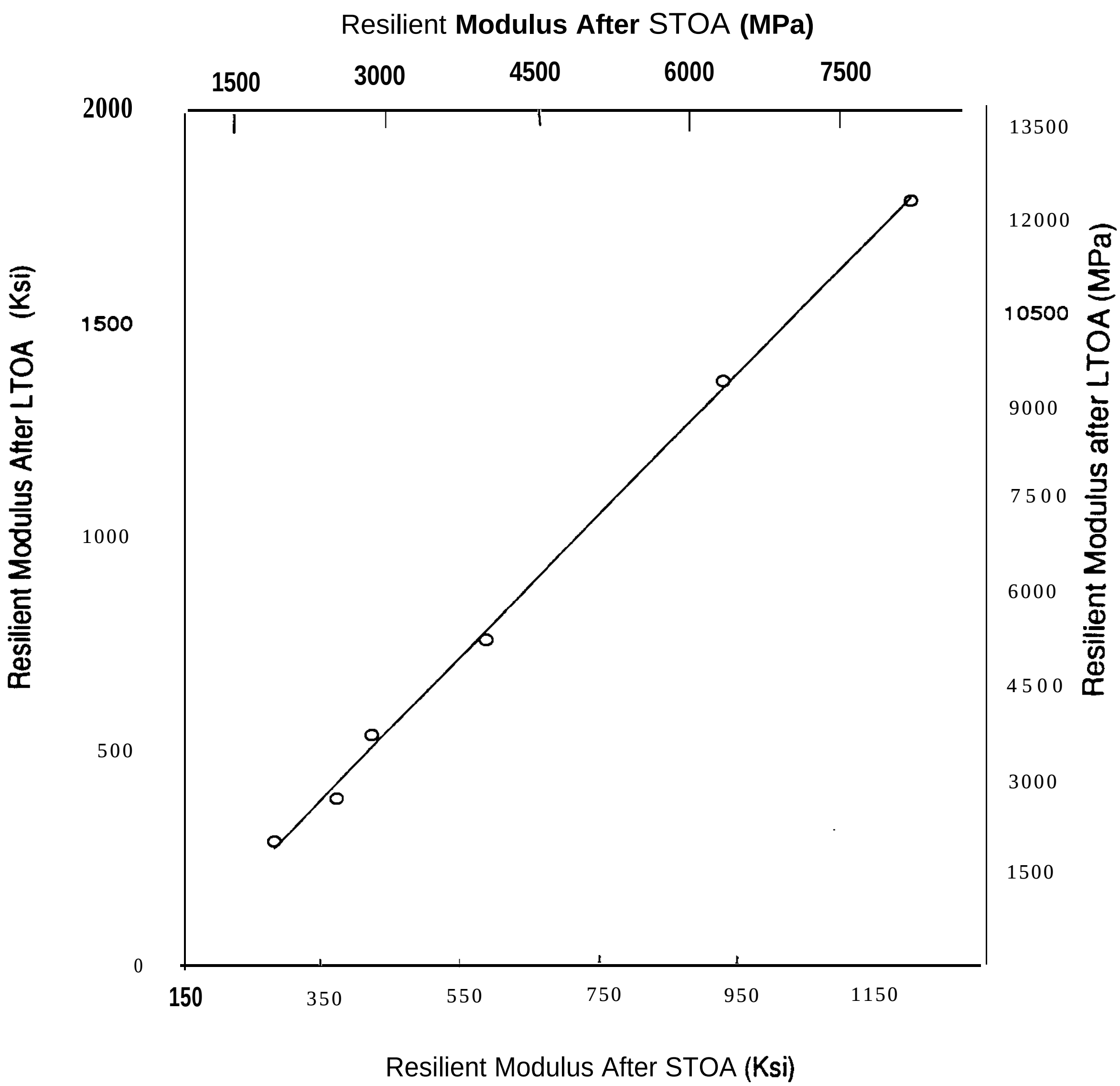


Figure 3. Asphalt Film Thickness vs. Resilient Modulus after Long Term Aging



STOA = short term oven aging
LTOA = lons term oven aging

Figure 4. Resilient Modulus before vs. Resilient Modulus after LTOA

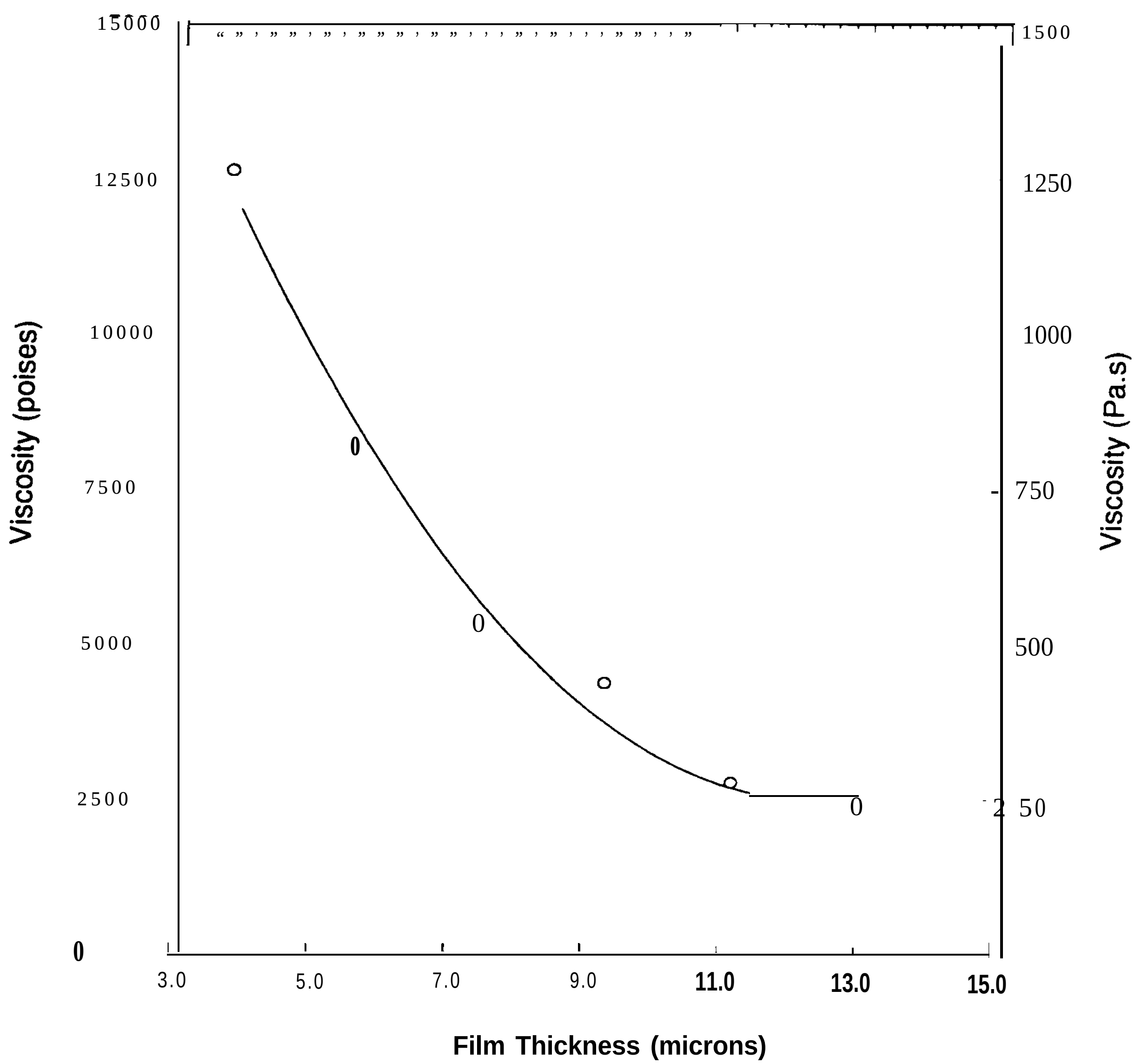


Figure 5. Asphalt Film Thickness vs. Viscosity after Short Term Aging

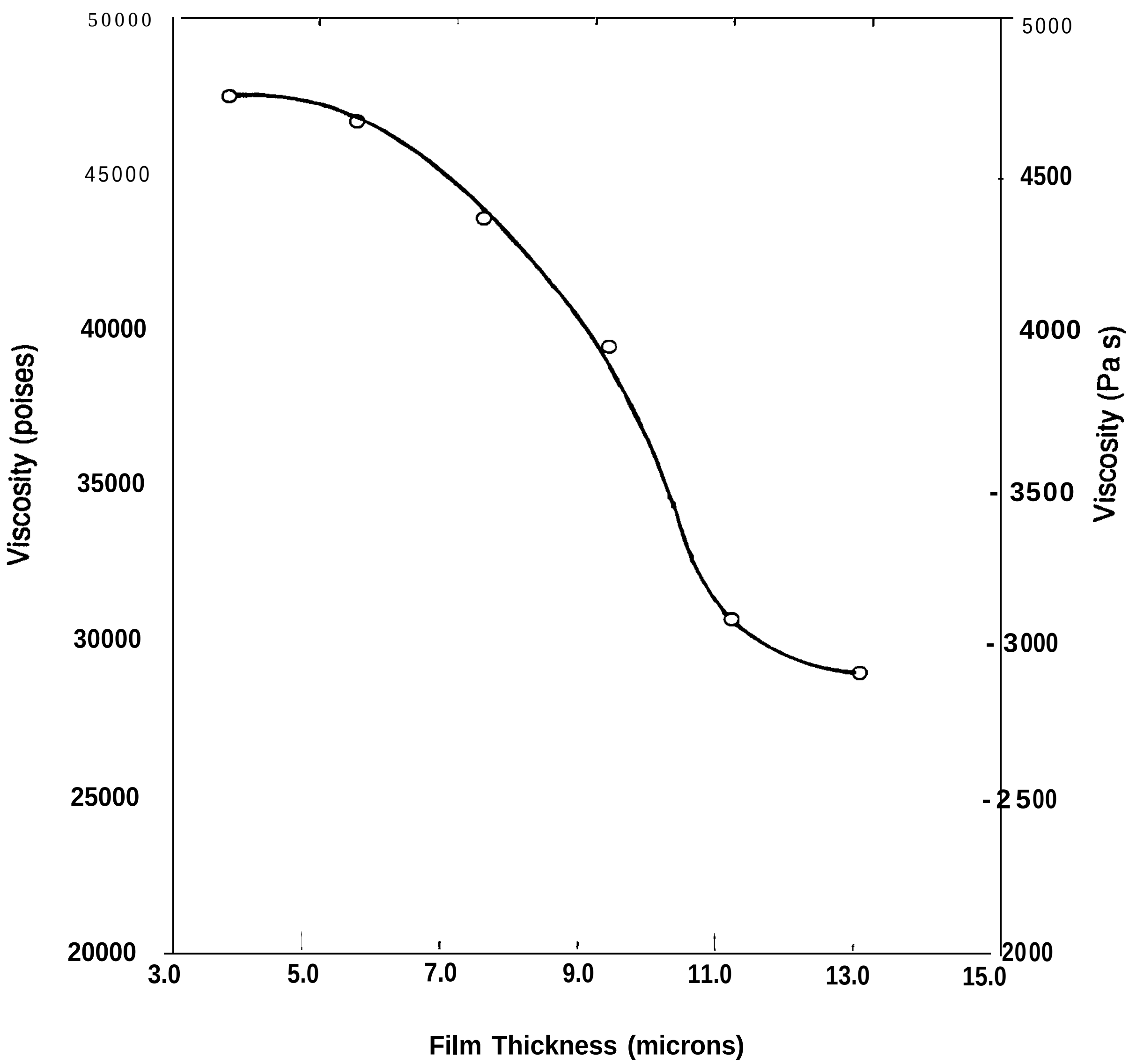


Figure 6. Asphalt Film Thickness vs. Viscosity after Long Term Aging

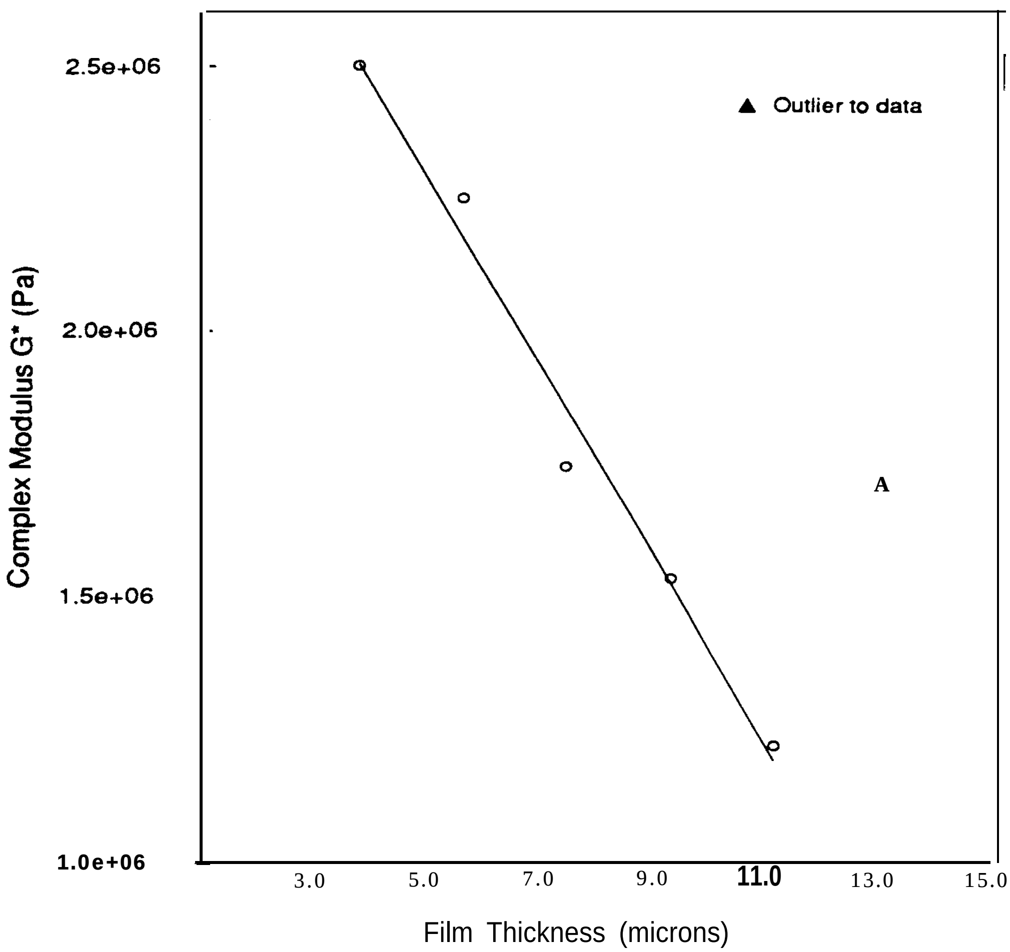


Figure 7. Asphalt Film Thickness vs. Complex Modulus (G*) After Long Term Aging

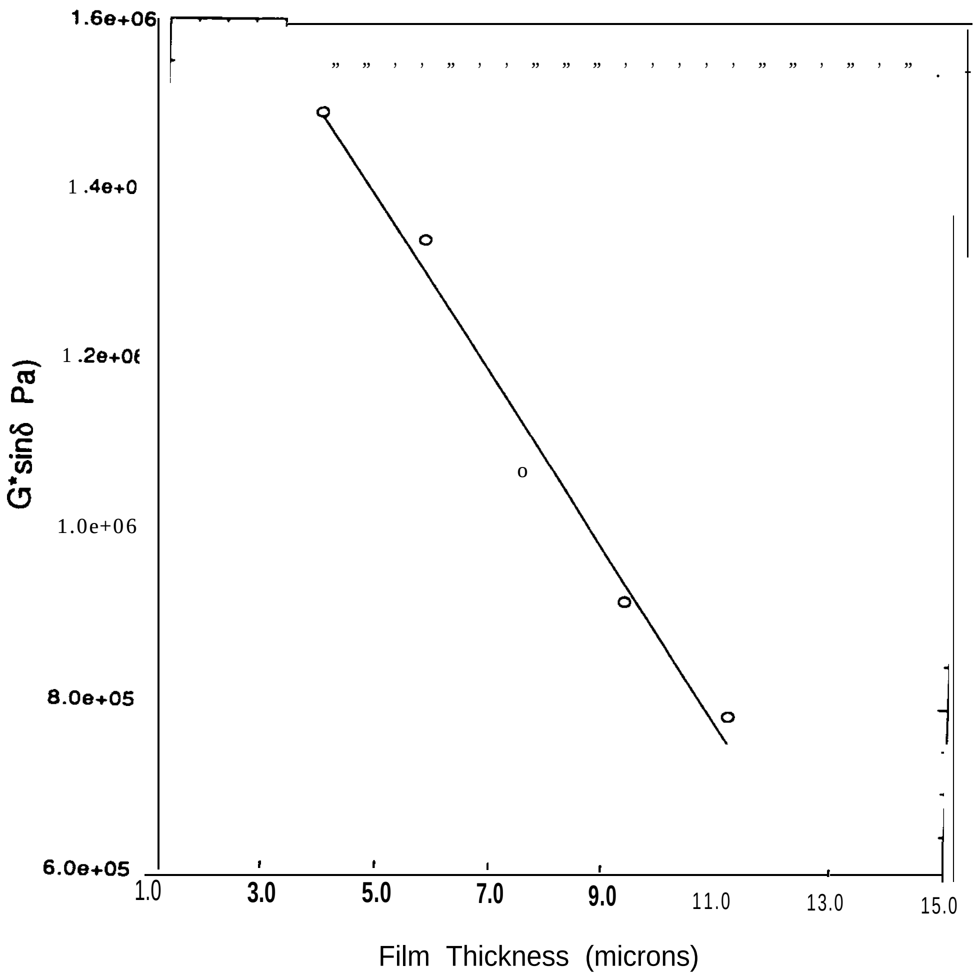


Figure 8. Asphalt Film Thickness vs. G*sinδ after Long Term Aging