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Field Evaluation of Asphalt Film Thickness as a Design Parameter in Superpave Mix Design

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Abstract: Research shows that asphalt film thickness (AFT) is related to mix performance. The use of AFT as a mix design parameter has always been a challenge because of the complexity of estimating AFT based on mix parameters. The aggregate surface area and the effective volume of asphalt are important components in the calculation of AFT. This study compares the voids in mineral aggregate (VMA) and AFT as mix design parameters against the field performance of Superpave mixes. Film thickness was estimated by different formulas using calculated aggregate surface area. Data on early flushing sections of Superpave mixes was used to correlate film thickness to distress development and other mix design parameters. The pavement sections considered for the study were observed to have undergone flushing and rutting problems. Field cores from flushed and non-flushed sections were obtained and verified for compliance with Superpave specifications. The results of this research related AFT to mix design parameters but showed that depending on the method of calculation, AFT, as a mix design parameter, may or may not be helpful in explaining specific field performance distresses such as rutting or bleeding.

***Key words**: Asphalt film thickness; Superpave mix design; VMA.*

Background

Research has shown that asphalt film thickness (AFT) could be related to asphalt mix durability, making film thickness an important mix design criterion. Adequate film thickness around the aggregate particles is required to ensure mix durability. Similar to the specification on other mix design parameters, a limit or a range needs to be imposed as a film thickness requirement for the mix. If the aggregates have an affinity to water, thin asphalt films are more easily penetrated by water, causing stripping or de-bonding of the asphalt binder from the aggregate [1]. The rupture of the asphalt film reduces the effective film thickness and causes moisture damage. Inadequate film thickness also creates a lack of cohesion between aggregate particles ending with dry mix. Thicker film thickness increases the lubrication effect of asphalt [2]. Increased film thickness in dense graded mixes can cause the aggregate particles to repel one another, contributing to rutting and/or flushing under critical conditions. Increased film thicknesses will improve resistance to aging, but contributes to fat spots and rutting [1]. Apart from bleeding, high film thickness tends to move the aggregate particles apart and breaks the tightly interlocked aggregate particles, making the structure unstable.

There have been issues regarding the calculation of AFT. AFT is known to be related to aggregate surface area, specific gravity, and effective volume of the binder. The Asphalt Institute method is widely used for calculating surface area. The effective specific gravity (G_{se}) is used to calculate AFT as it incorporates the volume of the aggregate particles (voids minus the volume of voids absorbed with asphalt). This specific gravity is used to calculate the amount of asphalt absorbed by the aggregate particles. Effective asphalt film, which contributes to early pavement failure, requires precise calculation of absorbed asphalt. Surface texture, presence of fines, pore size distribution, specific gravity, and aggregate gradation affect absorption. The AFT calculation is based on the assumption that each aggregate particle is spherical and covered with the same film thickness [3]. Calculating the film thickness is based on different formulas by different agencies, depending on the local aggregate and binder.

Different criteria are used to evaluate mix design performance. Voids in mineral aggregate (VMA) is one of the volumetric parameters used in Superpave mix design procedure. Replacing VMA criteria with the average AFT in mix design is proposed by researchers as it correlates better with field performance than VMA [3]. This paper investigates the correlation between AFT and other mix design parameters and with field performance of Superpave mixes.

Objectives

The objective of this study is to examine the possibility of relating AFT to volumetric mix design parameters and field performance of Superpave mixes. VMA and AFT are compared as design parameters in Superpave mix design. Various techniques of film thickness calculation have been used. The possibility of using AFT to regulate or replace VMA is investigated.

Voids in Mineral Aggregate vs. Asphalt Film Thickness

VMA was introduced when McLeod pointed out in 1950 that the basic criteria for both design and analysis of asphalt pavement

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Table 1. Surface Area Factors, m^2/kg, Used by Hveem [5].

Sieve #	#4	#8	#16	#30	#50	#100	#200
Sieve Size (*mm*)	4.75	2.36	1.18	0.60	0.30	0.15	0.075
Surface Area Factors	0.41	0.82	1.64	2.87	6.14	12.29	32.77

mixtures should be based on volumetric considerations rather than on weight [4]. VMA controls the minimum asphalt content in the mixture to ensure stability. There have been difficulties in achieving the VMA requirement in Superpave mixes, especially coarse graded mixes. There exist many cases in which various, otherwise good performing mixtures were rejected when they did not conform to the minimum VMA requirement. The VMA requirement, which is based on the Nominal Maximum Aggregate Size (NMAS), does not strongly correlate with the gradation of the mixture or the specific gravity of the aggregate. AFT, on the other hand, is related to aggregate surface area and effective volume of asphalt. Minimum VMA requirements decrease with increased NMAS. VMA is generally based on the coarse aggregate in a mix, whereas the fine aggregate governs film thickness. At a given air void content, a coarse mixture has the same VMA requirement as the fine mixture, but may have a different film thickness, as more asphalt is required for fine gradation mixes to have the film thickness of coarse graded mixtures. Therefore, to provide the same durability at a maximum aggregate size, the minimum VMA requirement for a fine graded mixture should be greater than the coarse graded mixture. As the VMA requirements established by McLeod and Superpave were based upon dense graded mixes, Kandhal pointed out that the Superpave VMA requirements unfairly penalize coarse mixtures with low VMA [4]. Superpave VMA calculations are based on the aggregate bulk specific gravity, which accounts for the absorbed asphalt in the mixture that does not contribute to the durability. AFT depends on the aggregate gradation and is unique for each mix design. While AFT is an important parameter relating to pavement durability, it can be accepted as a mix design parameter when it can be correlated and compared with other volumetric parameters. Current methods of calculating film thickness assume an average thickness, but not every aggregate particle is going to have the same thickness. Fine particles have a thicker film of asphalt when compared to the coarse aggregate. Moreover, dust particles can be embedded in the asphalt cement. As AFT increases, the volume per unit mass of the mixture also increases. If this change in volume can be calculated, a measure of film thickness can be obtained.

Calculations of Surface Area of Aggregate Particles

Film thickness is inversely proportional to surface area and decreases as the surface area of the aggregate increases. Small particles have a greater specific surface area than large particles. In existing models, specific surface area is calculated by assuming a specific gravity and assuming that the aggregate is spherical or cube shaped. The surface area calculations are not exact but mostly approximate.

Several methods are proposed to calculate aggregate surface area. In this study the Edward-Hveem method is used to calculate the surface area per unit mass for aggregate blend. This procedure is outlined in the Asphalt Institute's MS-2 [5]. The surface area (SA) is calculated by summing the product of the surface area factor times the percent material passing each sieve size, as presented in Eq. (1). The surface area factors used by Hveem are presented in Table 1.

$$SA = \sum SF_i \times P_i \tag{1}$$

SA = Surface area, m^2/kg,
SF_i = Surface factor for sieve i, and
P_i = Percent passing sieve i, in decimal form.

Experimental Considerations

The mixes considered for this paper are early Superpave trials constructed from 1999 to 2002 on Highway 56 and Highway 23 in Nebraska. Distresses on these sections, including flushing and rutting, were observed from 2000 to 2002. Records indicate that the construction of these sections was normal and all quality assurance/quality control, QA/QC, tests were in the acceptable ranges. During construction, QC data by the contractors and QA data by the Nebraska Department of Roads (NDOR) showed compliance with the then current specifications of Superpave mixes. All sections had scattered flushed areas, up to 200.0*ft* (60.96*m*) long with one, or both, wheel paths flushed. None of the affected sections were fully flushed. The distress was observed not to be region specific. Cores were drilled from the distressed sections and analyzed for volumetric details and mix design parameters. Each core was split into two 2.54*cm* sections and tested as top and bottom specimen. Mix parameters were determined for each 2.54*cm* layer and an average of these mix parameters was taken for analysis representing the core sample. Binder content for the volumetric analysis was based on the average of the two 2.54*cm* halves.

The bulk specific gravity (G_{mb}) of the extracted core was estimated before breaking it down for the Rice test. The Rice test was performed to determine the maximum theoretical specific gravity (G_{mm}) of the asphalt sample. Quantitative extraction process (ASTM D-2172/ASTM T-164) was used to separate aggregate and binder. Sieve analysis was performed on the aggregate sample to obtain aggregate gradation. The aggregate gradation was required to calculate the surface area of the sample. The details of experimental work and studied sections can be found in a published report by Abdelrahman [6] in NDOR.

Asphalt Film Thickness Calculations

Six formulas to calculate film thickness were incorporated in the study to compare with the different methods of estimating AFT. The equations are shown in Table 2. East Valley Asphalt Committee (EVAC) calculates the film thickness using the presented empirical Eq. (2) [7]. Roque et al. [8] assumes that the overall fine aggregate content of the mixture (percent passing through sieve No. 8) appears to best reflect the age hardening rate of binder in asphalt mixtures [8]. Eq. (3) was developed assuming that fine aggregate has an access to all the asphalt in the mix. Therefore instead of using the P_s (total aggregate content), P_{Fagg} (percent fine aggregate by mass of total mixture) was used. Kandhal et al. proposed Eq. (4) as a method to calculate the film thickness [9]. This method can be proven based

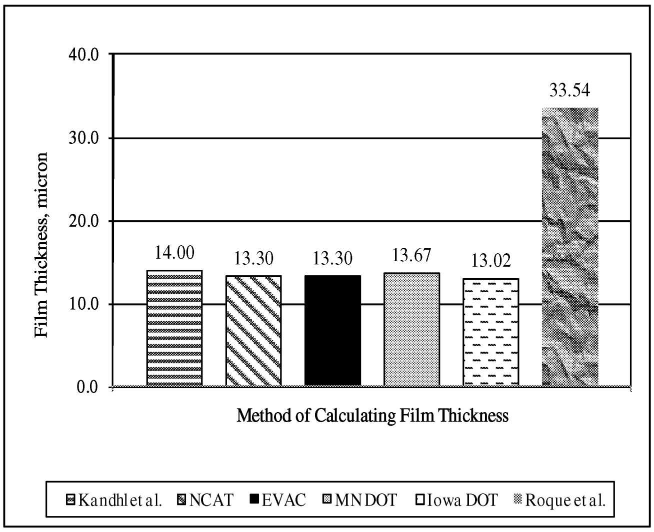

Fig. 1. Asphalt Film Thickness Calculated by Different Methods.

Table 2. Film Thickness Formulas.

Film Thickness, References are Provided in Parenthesis	Equation	
EVAC [7]	$T_F = 4876.8 \times (P_{be})/(SA \times P_s \times G_b)$	(2)
Roque et al. [8]	$T_F = [V_{be} / (SA \times P_{Fagg} \times G_b)] \times 1000$	(3)
Kandhal et al. [9]	$T_F = W_{b/agg} / (SA \times \rho_w \times G_b)$	(4)
NCAT [10]	$T_F = (Vasp / (SA \times W)) \times 1000$	(5)
Iowa DOT [11]	$T_F = 10 \times (P_{be}/SA)$	(6)
Minnesota DOT [12]	$T_F = (P_{be} \times 4870) / (100 \times Ps \times SA)$	(7)

Note: Units may vary depending on the equation. Please refer to the manuscript for the exact unit for each equation. Where:
T_F = Average film thickness
P_{be} = Effective asphalt content, percent by total weight of mix
SA = Specific surface area of aggregate
P_s = Aggregate content, percent by total weight of mix
G_b = Binder specific gravity
$V_{asp} = V_{be}$ = Effective volume of asphalt
P_{Fagg} = Percent of fine aggregate in total mix
$W_{b/agg}$ = Weight of asphalt per kilogram of aggregate
W = Weight of aggregate
ρ_w = Unit weight of water

on the basic concept of film thickness. Theoretically, average film thickness is the ratio between binder volume to the aggregate surface area. The disadvantage of this method is that it ignores the absorbed asphalt so it overestimates the asphalt film thickness. National Center for Asphalt Technology (NCAT) calculates the film thickness using Eq. (5) [10].This method considers the absorbed asphalt. That is the reason it uses only the effective volume of asphalt cement instead of using the total volume of binder. In Iowa, the Department of Transportation (DOT) has for many years relied on the use of film thickness to limit binder content [11]. The Iowa DOT uses empirical measure of film thickness. Eq. (6) presents the film thickness formula used by the Iowa DOT and is defined as a composite measure of effective binder volume and the normal surface area of the blended aggregate [11]. The Minnesota DOT uses Eq. (7) to calculate the film thickness in microns [12]. The constant 4870 is used to get the film thickness in microns while the surface area of aggregate (SA) is in ft^2/lb.

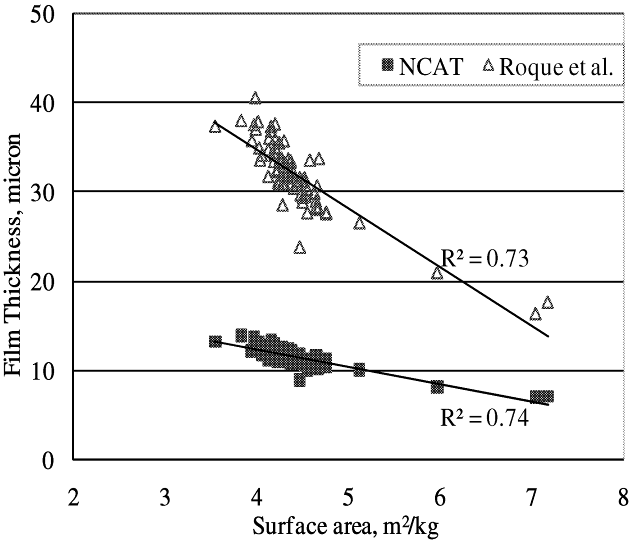

Fig. 2. Asphalt Film Thickness as Related to Surface Area.

Fig. 1 presents a comparison between the film thickness values obtained by different calculation methods. Examining Fig. 1 and the presented equations, it could be easily noticed that there is not much difference between the empirical and theoretical equations as they both give approximately the same values. The only different equation is the Roque equation as it is based on the percentage fine aggregate in the mix. For this reason, in the following sections of the paper the Roque equation will only be compared with NCAT method. The reason for choosing the NCAT method among the rest of available equations is because it is proved theoretically and it depends on the effective binder content. Fig. 2 shows the relationship between the surface area and asphalt film thickness. This relationship agrees with the literature that AFT is not directly proportional to aggregate SA, as R^2 is nearly 0.70. Fig. 2 shows that

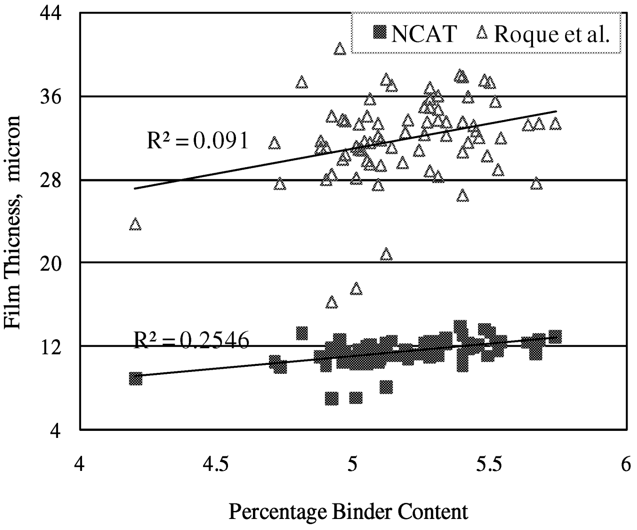

Fig. 3. Asphalt Film Thickness vs. Binder Content, QA/QC Samples.

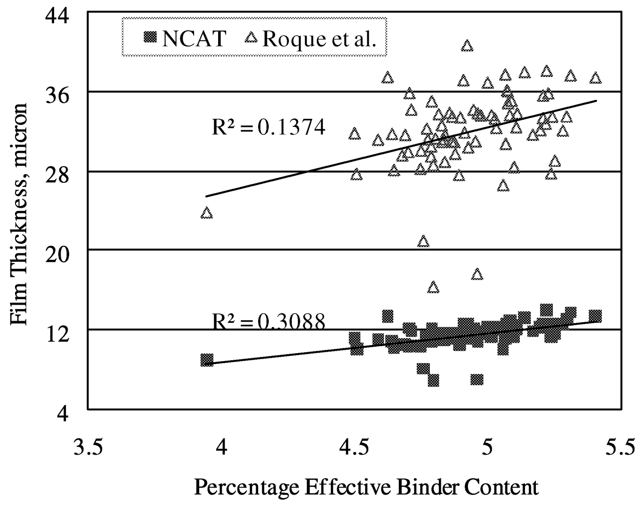

Fig. 4. Asphalt Film Thickness vs. Effective Binder Content, QA/QC Samples.

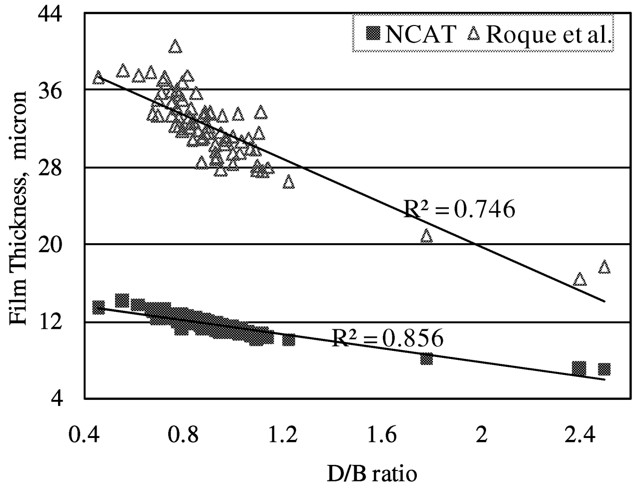

Fig. 5. Asphalt Film Thicknesses vs. D/B Ratio, QA/QC Samples.

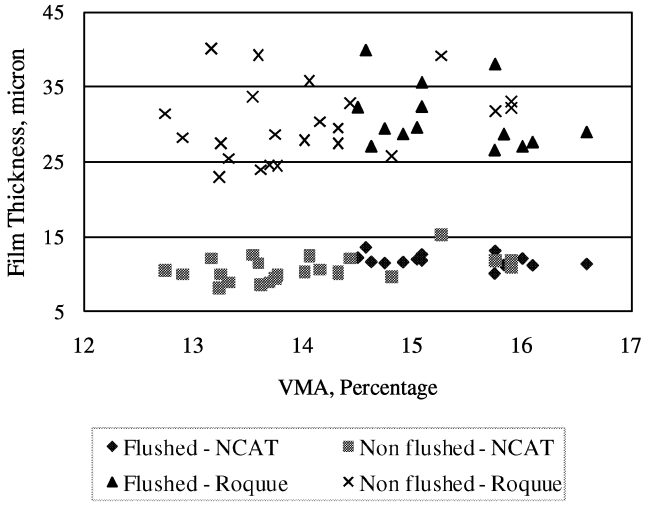

Fig. 6. Asphalt Film Thickness vs. % VMA, Field Cores.

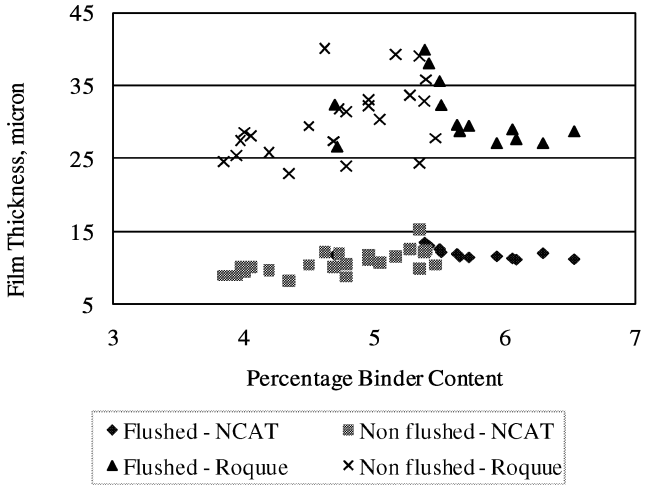

Fig. 7. Asphalt Film Thickness vs. % Binder Content, Field Cores.

AFT decreases as SA increases. This reflects the fact that AFT is controlled by both aggregate surface area and effective binder content.

Asphalt Film Thickness as Related to Mix Design Parameters

AFT was plotted and compared against various mix design parameters. Cores were extracted from flushed and non-flushed sections from low volume Superpave pavements. Figs. 3 to 5 show the relation between AFT and mix parameters based on QA/QC records for cored samples from both flushed and non-flushed sections from Highway 23 and Highway 56. The figures show that the film thickness would vary depending upon the used equation. Relating the film thickness to aggregate or mix properties has to be verified with actual lab measurements.

An increase in dust to binder (D/B) ratio for a mix implies either more dust material (passing No. 200) or less binder. In both cases film thickness reduces. A good correlation is observed between D/B ratio and the film thickness. Film thickness is expected to be directly related to the binder content in the mix (effective binder content). Based on the R^2 values, it could be observed that for the current study the binder content and the film thickness are not well correlated. The reason could be related to the loss of oil from flushed cores. A small amount of asphalt may also be lost while preparing the sample for the Rice test. The film thickness calculation method proposed by Roque et al [8] assumes only fine aggregate as a measure to calculate film thickness. It shows a very low correlation between AFT and binder content.

R^2 values for the straight line relationships between AFT and different mix parameters based on QA/QC data showed good correlation between D/B ratio and film thickness (R^2 varies from 0.74 to 0.84). On the other hand, it showed poor correlation between AFT and VMA (R^2 varies from 0.14 to 0.18).

Asphalt Film Thickness as Related to Superpave Mix Field Performance

Figs. 6 to 8 present the relationships between AFT and mix parameters based on cores extracted from both flushed and non-flushed sections. The parameters related to the voids in asphalt mix, i.e. total air voids, asphalt content, D/B ratio, VMA, and voids filled

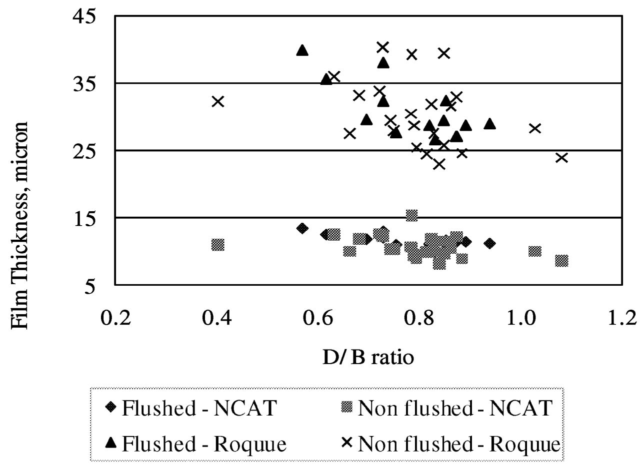

Fig. 8. Asphalt Film Thickness vs. D/B Ratio, Field Core.

Table 3. Summery of Statistical Analysis for Mix Parameters and Asphalt Film Thickness in Flushed vs. non Flushed Sections.

Variable	t-Value	$P_r > \|t\|$	Comment
VMA	4.47	<0.0001	Significant difference
Binder Content	5.15	<0.0001	
D/B Ratio	-0.09	0.927	Not significant
AFT (NCAT)	2.50	0.017	Significant difference
AFT (Roque et al.)	0.40	0.3078	Not significant

with asphalt (VFA), were analyzed. QC and QA data showed compliance with specifications for Superpave mixes. The derived mix parameters were compared to the specification provided for Superpave mixes by NDOR.

In Highway 56 flushed cores showed an average of 5.9 % asphalt content when compared to the mix design value of 5% asphalt content (AC). QA/QC of non-flushed cores showed a lower asphalt content ranging between 4.4 and 5.2 %. VMA requirement specifies a minimum limit on the binder requirement but does not limit the excessive use of binder in the mix design. A mix design can have much higher asphalt content but still satisfy the VMA requirement. All the sections were designed with a D/B ratio of 0.5 to 0.6. Low D/B ratio combined with excessive binder content is a major cause of flushing. Gradation control points for percent passing No. 30 sieve size for all highway section was specified to be between 19 and 34%. QA/QC data and field cores showed a much lower value than the lower limit of 19%. This implies that the coarse materials were higher than specified in the mix design (less surface area). The VMA requirement of 14% was satisfied even when the D/B ratio and percentage passing No. 30 sieve did not meet the specifications. VMA is based on NMAS and does not take into consideration the aggregate gradation. Fine material requires more binder than coarse material to maintain the same film thickness. The air voids for the highway sections were designed for 4% with an acceptable range of 3 to 5%. The specification limits the VFA to a maximum of 78%.

Thicker film thickness does not oxidize enough during the initial years when the pavement is prone to rutting and bleeding. Apart from bleeding, high film thickness tends to move the aggregate particles apart and break the tightly interlocked aggregate structure, making it unstable. A major concern with AFT, as a mix design criterion in Superpave applications, is the method of calculating aggregate surface area. Adjustment factors or calibration techniques may be necessary.

Statistical Analysis

Statistical analysis was conducted to examine the differences between flushed and non-flushed sections in mix parameters. The t-test was used to analyze the data at 95% significant level using SAS 9.1 software to check the following hypothesis.

H_0: $\mu_{\text{flushed}} = \mu_{\text{non flushed}}$, H_a: $\mu_{\text{flushed}} \neq \mu_{\text{non flushed}}$

Where: μ is the population mean for VMA, Binder content, D/B ratio or AFT. Equality of variance assumption was checked and the appropriate method for analysis was selected. Table 3 presents a summary of the findings. Results indicate that D/B ratio did not show significant difference between flushed and non-flushed sections. On the other hand, VMA and binder content showed significant difference between flushed and non-flushed sections. The AFT had mixed results depending on the method used to calculate the film thickness. Using the NCAT method yielded significant difference in AFT between flushed vs. non-flushed sections, while the Rouque method indicated that there was no significant difference in AFT between flushed vs. non-flushed sections.

Discussion and Conclusions

The use of AFT as a mix design parameter has always been a challenge because of the complexity of estimating AFT based on mix parameters. The aggregate surface area and the effective volume of asphalt are important components in the calculation of AFT. Both parameters are aggregate source specific.

The comparison between the film thickness values obtained by different calculation methods indicates no significant differences between the empirical and theoretical equations as they both give approximately the same values. The only different equation is the Roque equation, as it is based on the percentage fine aggregate in the mix.

Comparing both flushed and non-flushed sections, the mix design parameters showed that there is a significant difference in the VMA and binder content, while there is no significant difference between D/B ratios. Increasing the dust in the mix increases the surface area which in turn reduces the film thickness. That may reduce the potential for flushing and rutting. D/B ratio showed a good linear relation with AFT as shown in Fig. 5. The same trend did not exist with film thickness when the analysis was based on distressed vs. non distressed sections, as shown in Fig. 8.

The estimation of AFT for flushed vs. non-flushed sections was dependent on the formula used in calculating the film thickness. AFT calculated by the NCAT method showed significant differences between flushed and non-flushed sections. AFT calculated by the Roque method did not show significant differences between flushed and non-flushed sections.

This research tried to relate AFT to mix design parameters, but the results show that AFT as a mix design parameter may or may not be helpful in explaining specific field performance distresses such as rutting or bleeding, depending on the method of calculation. On the other hand, the field cores satisfied the VMA requirements but were still prone to flushing.

To replace VMA with AFT, more research is needed to verify a method for calculating and/or measuring aggregate surface area and asphalt film thickness. Using a standard method for estimating aggregate surface area/asphalt film thickness is necessary before implementing AFT as a mix design criterion.

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