

Submitted for the International Conference on Perpetual Pavement, September 13–15, 2006

**EVALUATION OF OXIDATION IN ASPHALT PAVEMENT TEST SECTIONS
AFTER FOUR YEARS OF SERVICE**

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Submitted June 16, 2006

Word count = 4,201
10 Tables and Figures * 250 = 2,500
Total = 6,701

ABSTRACT

This paper is concerned with a hot-mix asphalt pavement validation site constructed in Arizona in 2001. Four asphalts from different sources but of similar Superpave performance grade were used to construct the sections at the site. The crude oil source used to produce the asphalts is the only significant variable from section to section. Sampling and testing at the Arizona site is ongoing with the objective being to evaluate the physiochemical changes that occur in-situ. For this study, four-year old field aged cores collected in 2005 were sectioned into 13-mm increments and the viscosity of the extracted asphalts was compared to the predicted viscosity of each asphalt based on: (1) the Global Aging System, which is an integral part of the NCHRP 1-37A Mechanistic Empirical Design Guide; and (2) a Pressure Aging Vessel (PAV) model developed under NCHRP 9-23. The aging, in terms of extracted viscosity that has occurred over the four-year period is substantially greater than predicted by the Global Aging System, particularly in the top 13 mm of pavement. A methodology is suggested that allows for comparison of data obtained using the Global Aging System with that of the PAV model and the actual field aged viscosity.

INTRODUCTION

Western Research Institute (WRI), in cooperation with four state transportation departments and a number of contractors and suppliers, has built four field validation sites. The sites are located in Arizona, Kansas, Nevada, and Wyoming. At each site, multiple sources of asphalt of the same Superpave performance grade were used to construct the validation sections. In all cases, the crude oil source used to produce the various asphalts is the only significant variable from section to section. This paper is concerned with the Arizona site and reports on an evaluation of the short-term oxidative hardening that occurs in asphalt during construction and the long-term oxidative hardening that occurs in-situ near the surface of the pavement. Both short- and long-term hardening are important factors for predicting long-term pavement performance. As noted in the NCHRP 1-37A Design Guide (1), hardening near the surface can play a major role in causing top-down cracking. At the same time, hardening near the surface can result in lower stresses in the underlying pavement layers which decreases the potential for rutting.

The main objective of this paper is to compare how well the Global Aging System's (GAS) (2) predictive equations that are used in the NCHRP 1-37A Design Guide for determining mix/laydown and field aged asphalt viscosities compare to the actual viscosities obtained from a field trial site constructed in Arizona. An additional objective is to evaluate how well viscosity data obtained using a Pressure Aging Vessel (PAV) model (3) developed under NCHRP 9-23 compares to the viscosities from the Arizona site and the GAS.

TEST SITE AND MATERIALS

The Arizona site is located on the south bound lane of US 93, approximately 50 miles north of Wickenburg, Arizona at about milepost 153. The contractor's asphalt and asphalt from three other sources were used to construct the site. The four asphalts are generically identified here as AZ1-1 thru AZ1-4. AZ1-1 was produced from a West Texas intermediate sour blend; AZ1-2 from a Venezuelan crude; AZ1-3 from a Rocky Mountain blend; and AZ1-4 from a Canadian crude. AZ1-1, AZ1-3, and AZ1-4 were classified as performance grade PG 76-16, and AZ1-2 as PG 76-22.

High resolution liquid-state nuclear magnetic resonance (NMR) measurements were made on the four asphalts to determine whether they were modified with polyphosphoric acid or

with polymers. Phosphorous NMR measurements did not detect the presence of polyphosphoric acid in any of the asphalts. Proton NMR measurements did not detect the presence of any SBS type polymers in the asphalts. The NMR detection limits for phosphorous and polymers were estimated to be 0.1 and 0.5 wt%, respectively.

The project consisted of new four-lane construction of two 63-mm lifts using a 19-mm nominal maximum size dense graded aggregate with an asphalt content of 4.7% and 1.0% hydrated lime. The two 63-mm lifts were followed by a 19-mm lift of a rubber-modified asphalt friction course. The comparative asphalts were used in both 63-mm lifts, but not in the 19-mm friction course.

The project asphalt and the three comparative asphalts were used in the southbound driving lane and in the outside shoulder area of the project. The rubber-modified asphalt friction course was only applied to the driving and passing lanes of the project, thus leaving the outside shoulder areas exposed to the environment. Construction of the site occurred November 12-17, 2001.

The Mean Annual Air Temperature (MAAT) estimated from data obtained at the weather station nearest the project location is 61°F (average 2000 to 2004).

SAMPLE COLLECTION AND TESTING

Samples of all construction materials were collected during the actual time of construction. Loose mix samples were collected either from the windrow in front of the paver or from the paver hopper. Asphalt samples were collected from the sample collection port of the hot-mix plant, generally when the state DOT was also collecting asphalt samples. Asphalt samples were collected when it was certain that a specific asphalt source was being used and not during any transition periods between sources.

On November 17, 2005, three cores from the south bound lane shoulder were collected from each of the sections. The cores were shipped to WRI in Laramie, Wyoming and selected cores were sectioned as shown in Figure 1.

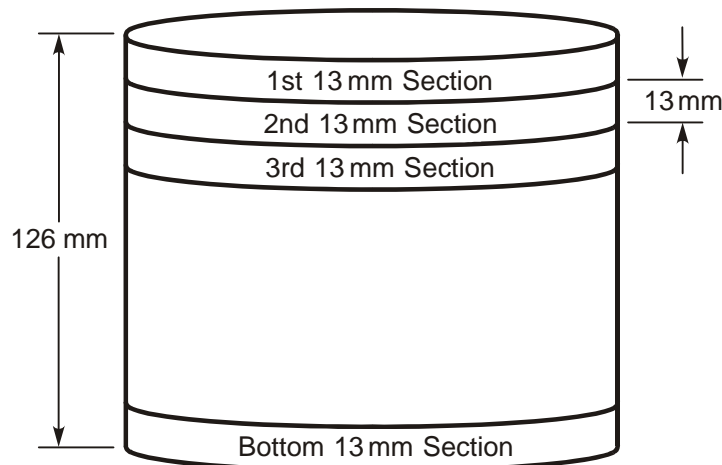


Figure 1 Sketch of sectioned field core.

The asphalt binder material from each section was extracted using an 85:15 (v/v) mixture of toluene and 95% ethyl alcohol. After extraction, the solution was centrifuged and filtered to remove the fine aggregate material. The solvent was removed using a rotary evaporator with an argon gas purge to eliminate the exposure of the asphalt material to oxygen during solvent removal. The final stage of solvent removal was accomplished using reduced pressure and an elevated temperature. An oil bath set at 120°C was used to heat the flask containing the extracted asphalt binder. Infrared spectroscopy (IR) was used to confirm the removal of solvent.

Complex shear modulus and phase angle of original, laboratory aged, and extracted asphalts were measured using a Rheometrics Model RDA II Dynamic Analyzer (Research-Grade Dynamic Shear Rheometer, DSR). In general, DSR tests were performed at 10 degree intervals over a temperature range of 0 to 80°C and a frequency range of 0.01 to 100 radians/second. Carbonyl content was measured using a PerkinElmer Spectrum One Fourier Transform Infrared Spectrometer.

MODELS

Global Aging System

The GAS models were developed from an extensive database consisting of viscosity measurements using capillary viscometers, and penetration and softening point measurements converted to viscosity over a broad range of temperatures (2). The change in viscosity with temperature is characterized by the method described in ASTM D2493 (4). This method characterizes temperature susceptibility as the slope of the log log viscosity versus log temperature. The temperature-viscosity relationship is described as

$$\log \log \eta = A + VTS \log T_R \quad (1)$$

where η is the viscosity, T_R is the temperature at which the viscosity is estimated, and A and VTS (viscosity temperature susceptibility) are regression parameters.

The following equation was developed several years after the GAS models were developed to convert DSR data to viscosity in order to ensure that the GAS models continued to be a practical tool (5),

$$\eta = \frac{|G^*|}{10} \left(\frac{1}{\sin \delta} \right)^{4.8628} \quad (2)$$

where $|G^*|$ is the binder complex shear modulus in Pascal determined at an angular frequency of 10 radians/sec, δ is the binder phase angle in degrees, and η is the viscosity in centipoise.

The basis for the above relationship is the Cox-Merz rule (6). The Cox-Merz rule can be used to convert from steady-state viscosity, η , to complex viscosity $|\eta^*|$, where the complex viscosity is defined in terms of the real and imaginary parts of $|G^*|$. The approximation is

$$\eta \sim |\eta^*| = |G^*|/\omega \quad (3)$$

and ω is the angular frequency. However for this rule to apply for asphalt, the phase angle (δ) must be close to 90°, i.e., the asphalt must exhibit essentially Newtonian behavior. The

$(1/\sin \delta)^{4.8638}$ component in equation 2 is an adjustment factor for non-Newtonian behavior at lower temperatures where δ significantly departs from 90° .

PAV Model

AASHTO R28-02 (7) is a laboratory procedure to accelerate asphalt aging by means of pressurized air and elevated temperatures and simulates in-service oxidative aging and hardening. It is reported in the test procedure that the RTFOT/PAV residue may be used to estimate the physical or chemical properties of asphalt binders after five to ten years. Houston et al. (3) among others have pointed out several limitations of the test procedure. For example, the range of five to ten years is rather broad and the procedure doesn't allow prediction of aging outside the estimated range. Also, the test method doesn't account for the influence of air voids on asphalt aging.

To address these limitations Houston et al. (3) developed the following model that relates t_{aging} , field aging time in months, to T_{PAV} , PAV aging temperature in $^\circ\text{C}$.

$$t_{aging} = \exp \left(\frac{\left(\frac{T_{PAV}}{0.445445 \times VA_{orig}^{0.378370}} \right) - 109.9632 + 78.2945 \times (\log \log \eta_{RTFO,60^\circ\text{C}})^2}{2.132432 + 0.193560 \times (\log \log \eta_{RTFO,60^\circ\text{C}})^2 \times MAAT} \right) \quad (4)$$

where VA_{orig} is the initial air voids in percentage after field compaction, $\eta_{RTFO,60^\circ\text{C}}$ is the RTFOT (Rolling Thin Film Oven test) viscosity at 60°C , and MAAT in $^\circ\text{F}$. The above model is referred to here as the PAV model.

It is interesting to point out that during the development of the PAV model it was found that the viscosity of the sectioned cores from the field trial sites evaluated did not vary significantly with depth. Other research has reported significant changes in viscosity with depth (8) and generally it is thought that the significant change in viscosity with depth is in the top 25 mm. The NCHRP 1-37A Design Guide, in defining the pavement structure layer properties, only models asphalt aging for the top 13 mm of the pavement and states the largest change in stiffness due to aging occurs only in the top half inch and the aging gradient for layers other than the top layer is not significant.

GLOBAL AGING SYSTEM MODEL APPLICABILITY

The original (tank), RTFOT, mix/laydown, and extracted field aged viscosity-temperature relationships for AZ1-1 are shown in Figure 2. The linear relationships were estimated using simple linear regression analysis. AZ1-1 has essentially a straight line relationship over the entire temperature range (0 to 80°C) except below about 30°C where there is slight non-linearity. The non-linearity below 30°C becomes more pronounced for the RTFOT, mix/laydown, and field aged asphalts. In a similar manner, but to a lesser extent, AZ1-2, AZ1-3, and AZ1-4 also show increasing nonlinearity below about 30°C for the RTFOT, mix/laydown, and field aged asphalts.

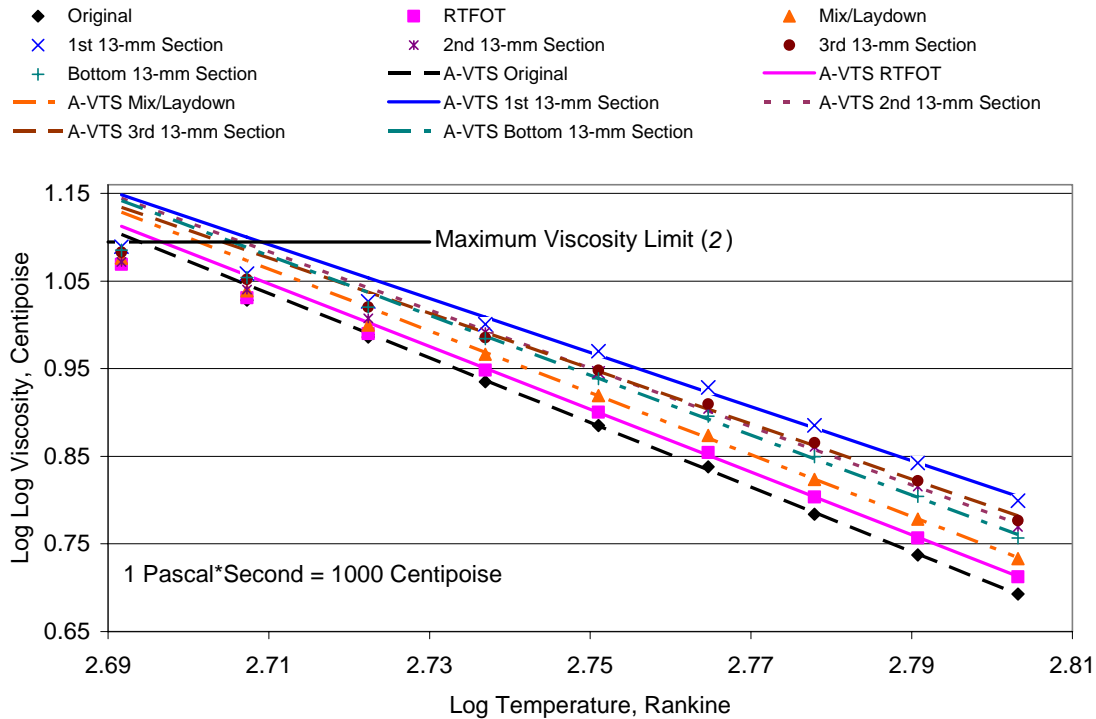


Figure 2 Viscosity – temperature relationships for original and aged AZ1-1.

The degree of non-linearity is an important consideration. According to Mirza and Witczak (2), the fundamental basis of the GAS aging models is the log log viscosity versus log temperature linear relationship. The linear relationship was developed by Mirza and Witczak from data (4 to 149°C) for not only the original, but also the mix/laydown, and field aged asphalts contained in the database used to develop the GAS models. These linear or straight line Class “S” asphalts were non-modified, and Mirza and Witczak advised the GAS models should not be used for modified asphalts, Class “W” (waxy) or Class “B” (blown) asphalts. The S, B, and W designations were originally developed by Heukelom (9) who observed the linear and nonlinear relationships of asphalts using the Bitumen Test Data Chart developed in the 1960’s. “S” refers to the straightness of the line and according to Heukelom is typical of cracked asphalts or asphalts with limited wax content.

The nonlinearity of the RTFOT, mix/laydown, and field aged asphalts is somewhat similar to the nonlinearity observed in blown asphalts. This is perhaps to be expected since the change in viscosity of aged and blown asphalts can be attributed primarily to oxygen uptake. As shown in Figure 3, carbonyl content for AZ1-1 is significantly greater than that for the other three asphalts and this appears to correlate with the greater non-linearity observed for the AZ1-1 asphalt.

It’s uncertain to what extent the non-linearity, particularly for the AZ1-1 asphalt, may reduce the applicability of the GAS models. To establish the mix/laydown A-VTS parameters, linear regression was typically performed from 30 to 80°C to avoid the nonlinearity. A-VTS parameters for the original, RTFOT, mix/laydown, and 13-mm sections for all four asphalts are listed in Table 1.

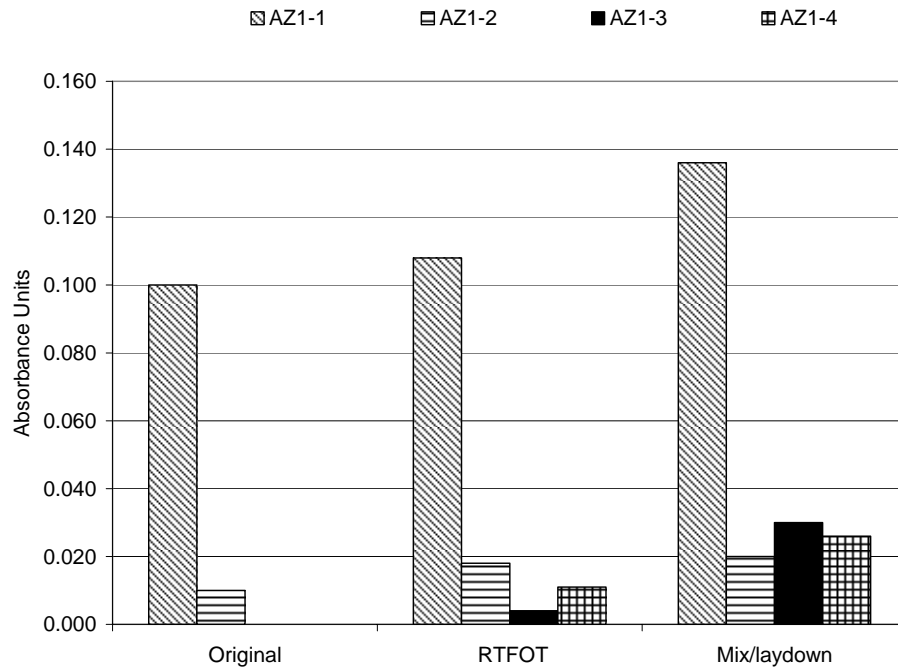


Figure 3 Carbonyl content.

Table 1 A-VTS parameters and air voids.

| Description | | AZ1-1 | AZ1-2 | AZ1-3 | AZ1-4 |
|--|----------------|--------|--------|--------|--------|
| Original | A | 11.013 | 9.981 | 10.535 | 10.663 |
| | VTS | -3.682 | -3.315 | -3.512 | -3.557 |
| | R ² | 1.00 | 1.00 | 1.00 | 1.00 |
| RTFOT | A | 10.756 | 9.678 | 10.686 | 10.743 |
| | VTS | -3.583 | -3.198 | -3.560 | -3.578 |
| | R ² | 1.00 | 1.00 | 1.00 | 1.00 |
| Mix/Laydown | A | 10.639 | 9.609 | 11.036 | 10.915 |
| | VTS | -3.533 | -3.173 | -3.683 | -3.633 |
| | R ² | 1.00 | 1.00 | 1.00 | 1.00 |
| 1st 13-mm Section | A | -3.086 | 8.971 | 10.413 | 9.795 |
| | VTS | 9.455 | -2.922 | -3.444 | -3.209 |
| | R ² | 1.00 | 1.00 | 1.00 | 0.99 |
| 2nd 13-mm Section | A | 10.102 | 9.233 | 10.483 | 10.163 |
| | VTS | -3.328 | -3.032 | -3.476 | -3.352 |
| | R ² | 1.00 | 1.00 | 1.00 | 1.00 |
| 3rd 13-mm Section | A | 9.633 | 9.756 | 10.299 | 10.864 |
| | VTS | -3.157 | -3.212 | -3.408 | -3.611 |
| | R ² | 1.00 | 0.99 | 1.00 | 1.00 |
| Bottom 13-mm Section | A | 10.342 | 9.076 | 10.864 | 10.599 |
| | VTS | -3.418 | -2.969 | -3.617 | -3.508 |
| | R ² | 1.00 | 0.99 | 1.00 | 1.00 |
| Air Voids (%), average of top three 13-mm sections | | 7.3 | 6.6 | 6.4 | 7.8 |

GLOBAL AGING SYSTEM MODEL FOR SHORT-TERM AGING

The GAS short-term aging model (2) is expressed as

$$\log \log(\eta_{t=0}) = a_0 + a_1 \log \log(\eta_{orig}) \quad (5)$$

$$a_0 = 0.054405 + 0.004082 \times code$$

$$a_1 = 0.972035 + 0.010886 \times code$$

where $\eta_{t=0}$ is the mix/lay-down viscosity in centipoise, η_{orig} is the original viscosity in centipoise, and the *code* is the hardening resistance.

The purpose of the hardening code is to increase the accuracy of the short-term aging model by adjusting for a particular asphalt's tendency to age during mixing, hauling, and compaction. Suggested code values were recommended by Mirza and Witczak (2) and vary from -1, representing a good to excellent resistance to hardening, to +2, representing a poor hardening resistance. A code of 0 represents an average condition. The hardening ratio, defined as the ratio of the log log mix/laydown viscosity to the log log original viscosity provides guidance on which code to use. For example, a ratio greater than 1.1 suggests a code of 2, and a ratio less than 1.03 suggests a code of -1. In the typical application, it is assumed the mix/laydown viscosity for a particular asphalt would be monitored on several projects to establish the hardening ratio and related hardening code.

In this research, the mix/laydown viscosities are known and the hardening ratios and corresponding hardening codes can be assigned. The hardening code is -1 for AZ1-2, and 0 for AZ1-1, AZ1-3, and AZ1-4 at 60°C. Figure 4 shows that the predicted mix/laydown viscosities for the AZ1-1 and AZ1-4 asphalts are significantly lower than the actual mix/laydown viscosities, the reverse is true for AZ1-3. For AZ1-2 the predicted and actual mix/laydown viscosities are similar. Overall, for all four asphalts the average predicted mix/laydown viscosity is within about 20% of the average actual mix/laydown viscosity.

An alternative approach to the hardening ratio defined above, is to assume the RTFOT viscosity is equivalent to the mix/laydown viscosity. The hardening ratio can then be defined as the ratio of log log RTFOT viscosity to the log log original viscosity. Using the RTFOT viscosity to determine the hardening ratio is more practical since the RTFOT viscosity is simple to establish. In defining equation 5 in the NCHRP 1-37A Design Guide, the RTFOT viscosity is used in place of the mix/laydown viscosity to determine the hardening ratio and related hardening code.

The hardening code is -1 for all four asphalts using a hardening ratio of log log RTFOT viscosity to log log original viscosity at 60°C. For two of the other three asphalts (AZ1 and AZ1-4), the difference between predicted and actual viscosity is significantly increased using a hardening code of -1 compared to a hardening code of 0, as shown in Figure 4.

The hardening codes were determined based on measured viscosities at 60°C. Since the RTFOT VTS and mix/laydown VTS are not the same as the original asphalt for any of the four asphalts, the hardening ratios are not constant with varying temperature; therefore the hardening codes may vary with temperature. For example, the ratio of log log RTFOT viscosity to log log original viscosity for AZ1-2 at 60°C is 1.028 resulting in a hardening code of -1, while at 70°C the ratio is 1.031 resulting in a code of 0.

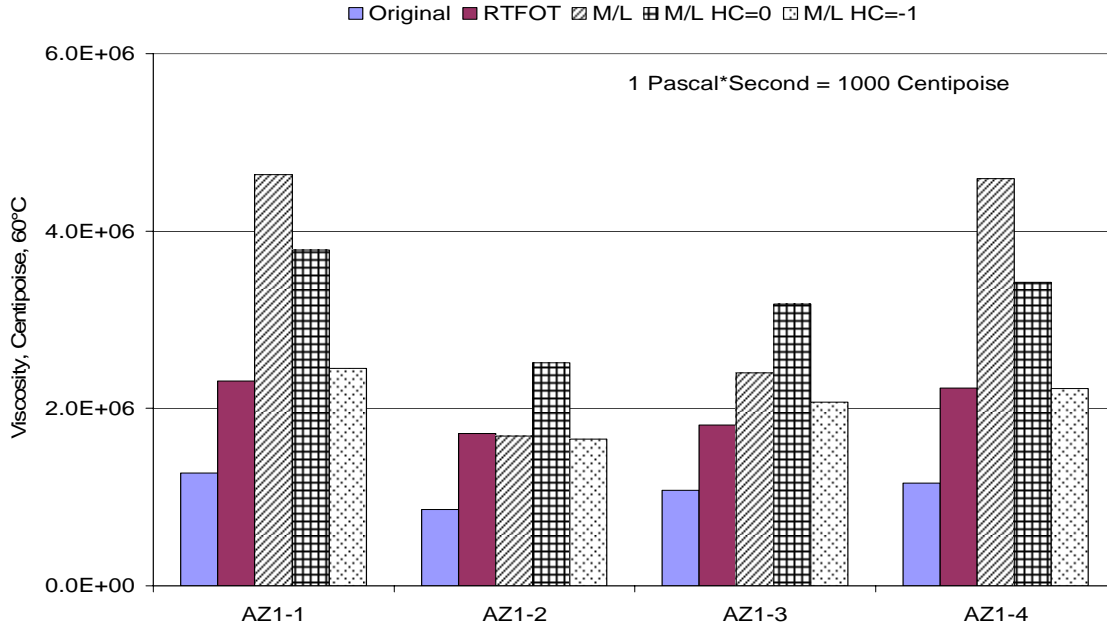


Figure 4 Relationship between original, RTFOT, mix/laydown, and GAS short-term predicted mix/laydown viscosities.

Equation 5 and the hardening codes are discussed in the NCHRP 1-37A Design Guide, but they are not currently programmed into the design guide software (10). A predicted mix/laydown viscosity is not calculated, but rather the RTFOT viscosity is assumed to represent the mix/laydown viscosity. The mix/laydown viscosity is an important variable in the GAS model that predicts aged viscosity (equation 6). As shown in Figure 5, when there is a significant difference between RTFOT and mix/laydown viscosity, as is the case for AZ1-1, it can result in a significant difference in predicted aged viscosity. The GAS model for predicting aged viscosity is discussed further in the next section.

GLOBAL AGING SYSTEM MODEL FOR PREDICTING AGED VISCOSITY AND COMPARISON TO THE PAV MODEL

The GAS model for predicting aged viscosity with time is hyperbolic in the form

$$\log \log(\eta_{aged}) = \frac{\log \log(\eta_{t=0}) + At}{1 - Bt} \quad (6)$$

where η_{aged} is the aged viscosity in centipoise and represents the viscosity at an assumed depth of 0.25 in. (6.3 mm), $\eta_{t=0}$ is the viscosity at mix/laydown in centipoise, t is the time in months, and A and B define the shape of the curve. A is a function of the MAAT, the mix/laydown viscosity, and the temperature of interest; and B is solely a function of the temperature of interest. A and B are fully defined elsewhere (2).

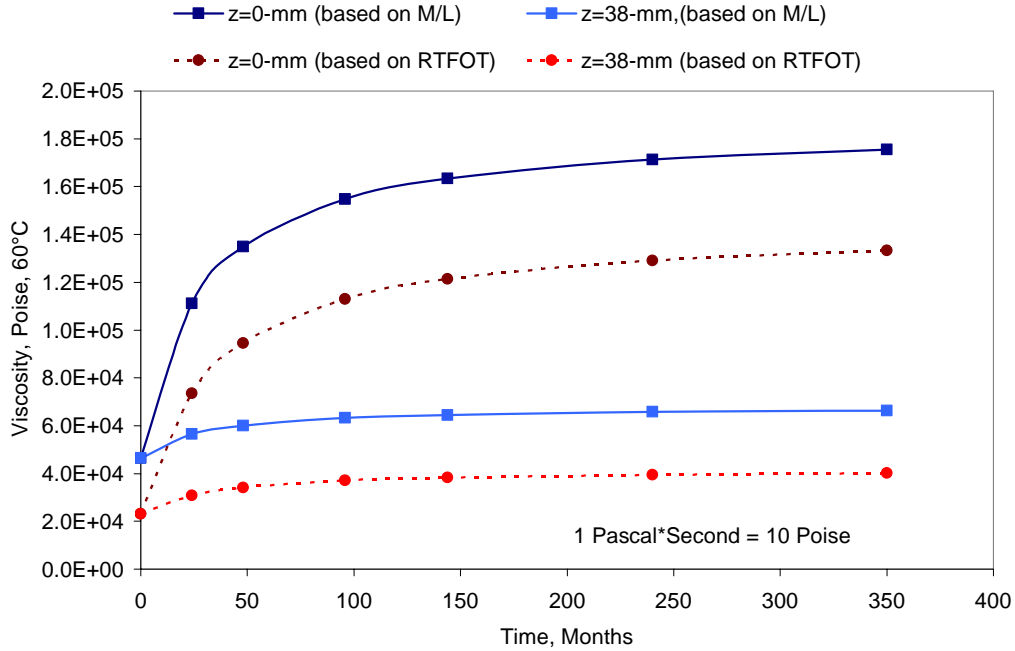


Figure 5 Differences between the GAS predicted aged viscosity (equation 6) using RTFOT viscosity to represent $\eta_{t=0}$ and mix/laydown viscosity to represent $\eta_{t=0}$ for AZ1-1 asphalt.

According to Mirza and Witczak (2), a minimum of two and preferably four to five temperatures can be selected between a range of 25 and 135°C to predict the aged viscosity at any given time and climatic environment. Linear regression can then be used with the aged viscosities to determine the regression coefficients of the following equation.

$$\log \log(\eta_t) = A_t + VTS_t \text{Log}T_R \quad (7)$$

Solving equation 6 at one degree intervals with $t = 48$ months and MAAT = 61°F, reveals the relationship of log log aged viscosity to log temperature in Rankine is not linear. Based on recent correspondence with the GAS principal author (Mirza) the best way to establish the A-VTS parameters in equation 7 is to calculate the aged viscosity at three temperatures (25, 60, and 135°C) and then perform the linear regression to determine the A-VTS parameters. Mirza advised the main reason for this is because most of the available data was at these three temperatures; for intermediate temperatures the data was very limited and was not used in the analysis.

The GAS model for predicting aged viscosity with depth is expressed as

$$\eta_{t,z} = \frac{\eta_t(4 + E) - E(\eta_{t=0})(1 - 4z)}{4(1 + Ez)} \quad (8)$$

$$E = 23.82e^{(-0.0308MAAT)}$$

where $\eta_{t,z}$ is the viscosity at time t in months and depth z in inches, and E is a function of the MAAT.

The GAS air void correction is of the form

$$F_v = \frac{1 + 1.0367 \times 10^{-4} (VA)(t)}{1 + 6.1798 \times 10^{-4} (t)} \quad (9)$$

$$\log - \log \eta'_t = F_v \log \log \eta_t$$

where F_v is the air voids adjustment factor, VA is the air voids in percent, and t is the time in months. F_v takes a value of one if no adjustment for the air voids is used in the GAS analysis. Figure 6 shows that the viscosities for the 13-mm sections at 48 months for all four asphalts are substantially higher than the predicted viscosities with or without the air void correction, particularly for the top 13-mm sections. VA was determined by averaging the air voids from the 1st, 2nd, and 3rd 13-mm sections of each core (see Table 1).

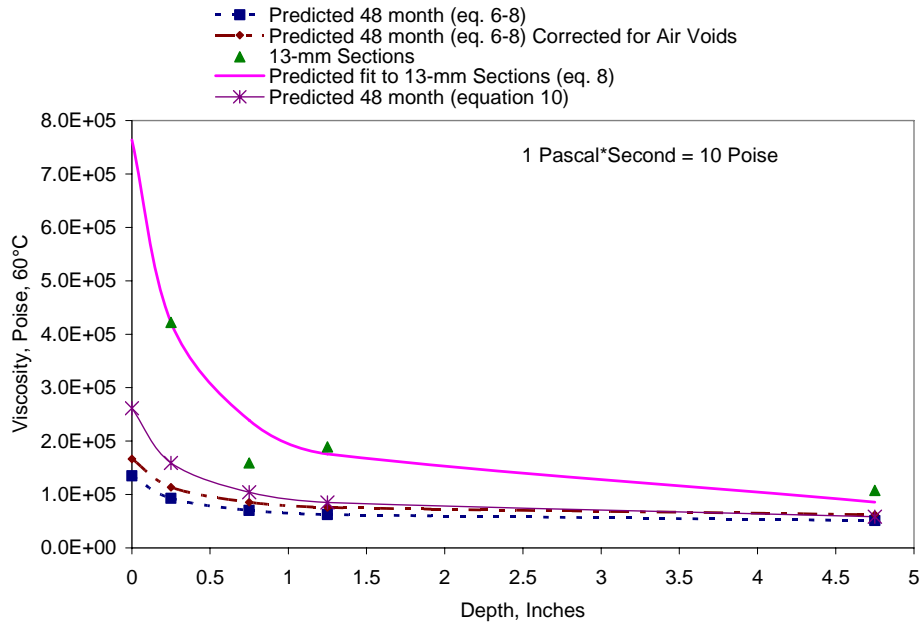
F_v was not included in the final general GAS model for predicting long-term aging because of limited air void data in the study (2). As with the GAS short-term model it is discussed in the NCHRP 1-37A Design Guide, but not programmed into the Design Guide software (10).

Equation 8 was fitted to the 13-mm section viscosities by assuming the top 13-mm section viscosity represents the aged viscosity at a depth of 0.25 in. (6.3 mm). The resulting curve shown in Figure 6 is a reasonable fit of the 13-mm section data, although for three of the four asphalts (AZ1-1, AZ1-2, and AZ1-4) the curve could be improved by increasing the degree of change or “kneeing” which could be accomplished by adjusting E .

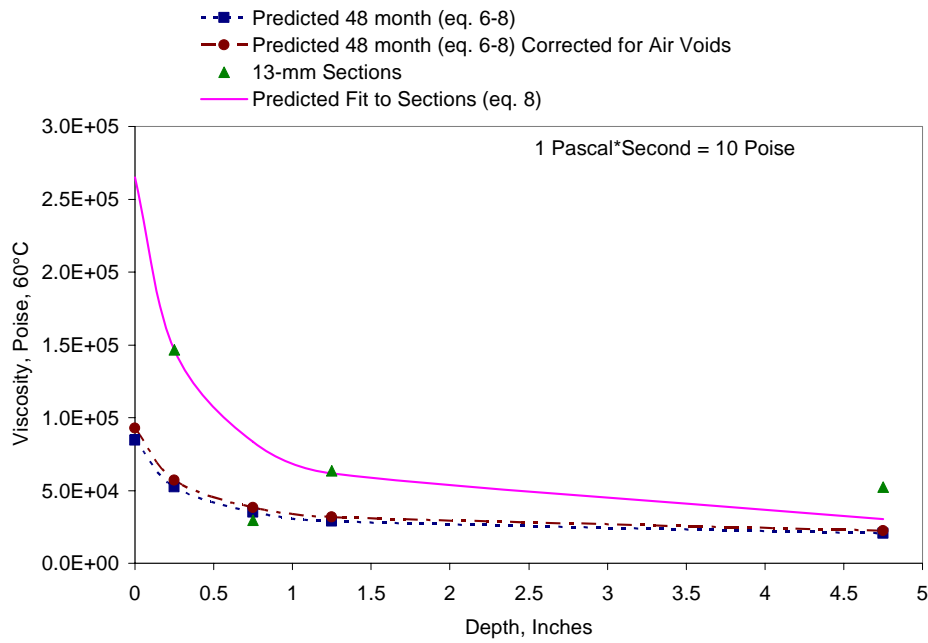
It was assumed the aged asphalt viscosities used to develop the GAS represented a depth of 0.25 in. (6.3 mm). Using a somewhat greater assumed depth, e.g. 1 in. (25.4 mm) and revising equation 8 accordingly, results in

$$\eta_{t,z} = \frac{\eta_t(1 + E) - E(\eta_{t=0})(1 - z)}{(1 + Ez)} \quad (10)$$

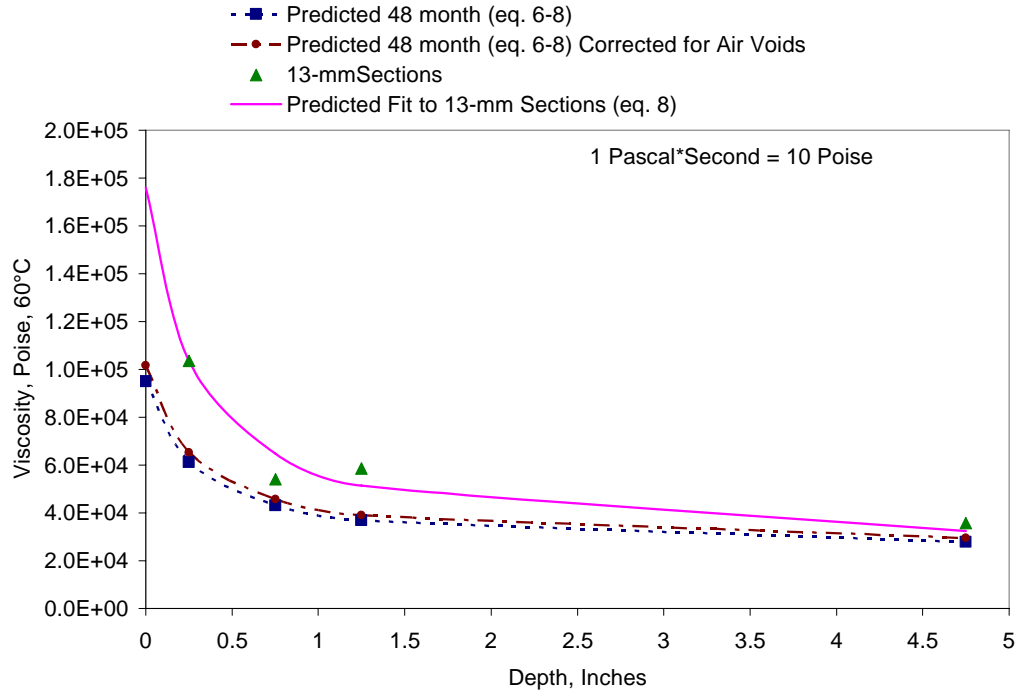
Figure 6a includes equation 10, which predicts viscosities closer to the actual 13-mm section viscosities than predicted by equation 8.



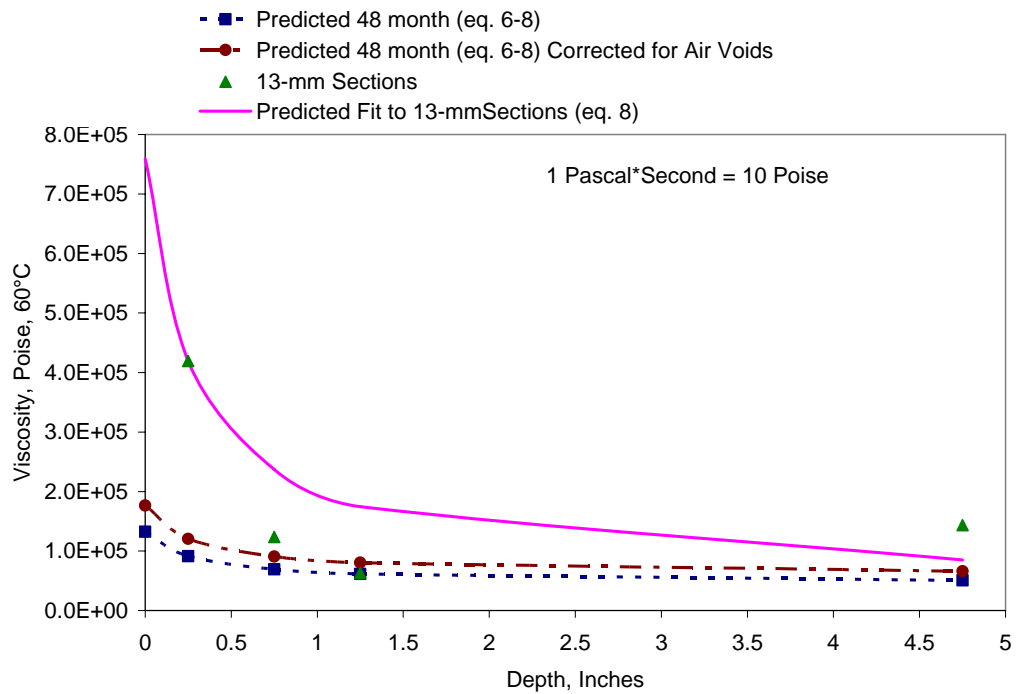
a.



b.



c.



d.

Figure 6 GAS predicted aged viscosity with depth at 48 months compared to 13-mm section viscosities: (a) AZ1-1, (b) AZ1-2, (c) AZ1-3, and (d) AZ1-4.

PAV Model Application

Figure 7 shows the 110°C RTFOT/PAV viscosity for three of the four asphalts is roughly equivalent to the corresponding extracted top 13-mm section viscosity. This suggests the depth in the pavement represented by the 110°C RTFOT/PAV viscosities is about 6.5 mm at a time of 48 months.

AZ1-1 was selected for testing at different PAV temperatures to evaluate the PAV model. Table 2 shows the viscosities after PAV aging at temperatures of 95, 100, and 110°C and includes the estimated field aging times based on the PAV model (equation 4).

The PAV model does not include a viscosity gradient with depth. As mentioned previously, during development of the PAV model it was found that the viscosity of asphalt recovered from sectioned cores taken from the field sites that were evaluated did not vary significantly with depth. The average extracted viscosity from the top 1-in. (25.4-mm) section was considered to be representative of a site (3).

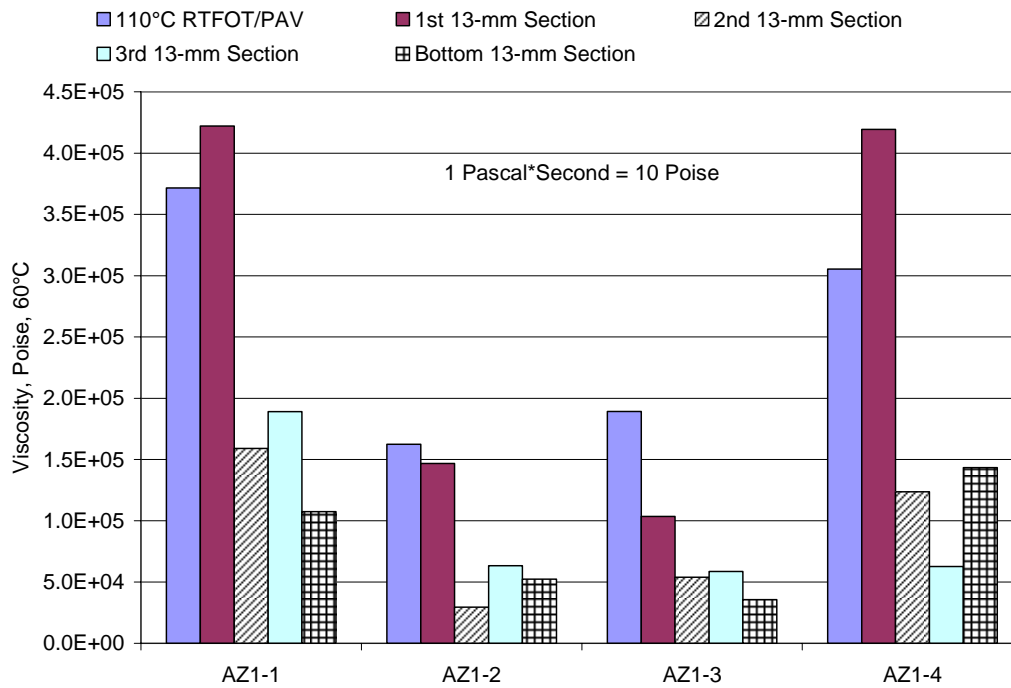


Figure 7 Relationship between RTFOT/PAV viscosity and 13-mm section viscosities.

Table 2 RTFOT/PAV estimated aging time (Equation 4).

| Asphalt | T _{PAV} , °C | RTFOT/PAV Viscosity, 60°C, Poise | Equation 4, Predicted Aging, Months |
|---------|-----------------------|----------------------------------|-------------------------------------|
| AZ1-1 | 95 | 1.64E+05 | 68 |
| AZ1-1 | 100 | 2.84E+05 | 117 |
| AZ1-1 | 110 | 3.72E+05 | 345 |

Since the extracted 13-mm section viscosities in this research show a viscosity gradient with depth and the GAS model (equation 8) includes an adjustment for viscosity with depth, the following approach was developed to assign an approximate depth to the AZ1-1 RTFOT/PAV viscosities shown in Table 2. In addition, this approach was used to compare the RTFOT/PAV viscosities to the predicted aged viscosities.

First the RTFOT/PAV viscosities and estimated field aging times from Table 2 were plotted and fitted as shown in Figure 8 with a rectilinear hyperbola of the form

$$\Delta y = \frac{t}{a + bt} \quad (11)$$

where t is time, and Δy is the change in the physical property with time or the difference between the zero life value and the value at any subsequent time. This form of a hyperbola for evaluating the physical changes that occur in asphalt, as measured by, e.g. softening point, due to age hardening was first proposed by Brown et al. (11). A plot of $t/\Delta y$ versus t is recognized as a straight-line relation and the parameters a and b are the y -intercept and slope respectively of a best fit linear regression.

The hyperbola, as shown in Figure 8, follows the surface ($z = 0$ mm) GAS predicted aged viscosity up to about 50 months and then diverges significantly from the GAS predicted aged viscosities. The hyperbola can be solved for the viscosity at 48 months, which yields 152,000 poise (15,200 Pa·s). Then, solving the GAS fit (equation 8) to the 13-mm section viscosities shown in Figure 6a using a viscosity of 152,000 poise (15,200 Pa·s) yields a depth of about 40 mm. This suggests the PAV model viscosities represent a depth of 40 mm in Figure 8. The limiting viscosity, as defined by $\eta_{t=0} + 1/b$, is 550,000 poise (55,000 Pa·s), which is about two-thirds of the predicted surface viscosity shown in Figure 6a.

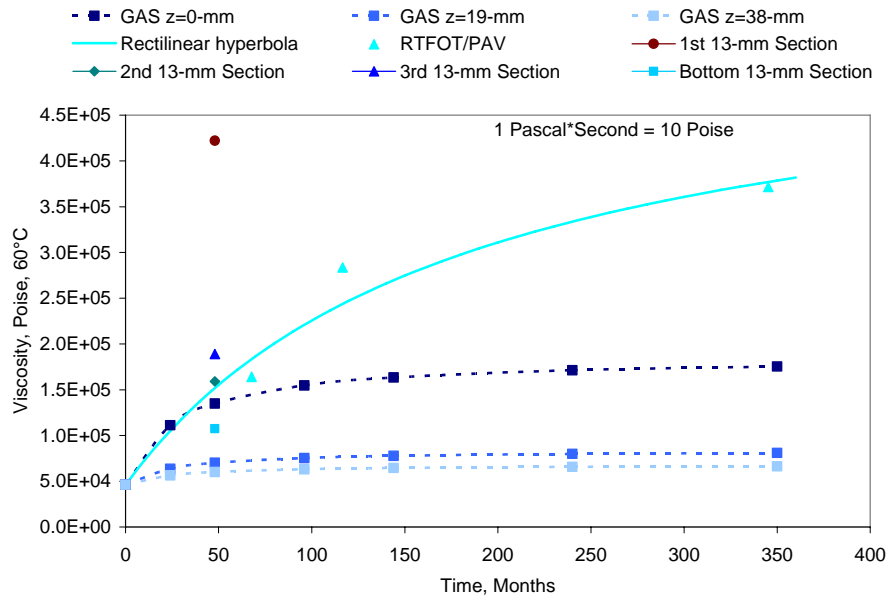


Figure 8 Comparison of GAS predicted aged viscosity with time to a hyperbolic fit of RTFOT/PAV viscosities at aging temperatures of 95, 100, and 110°C.

CONCLUSIONS

Based on the data obtained to date for the four asphalts studied:

- The reduction of extracted viscosity from the top 13 mm of pavement to the next 13 mm ranged from 48 to 70% and the average reduction was 65%.
- The magnitude of the differences between the extracted viscosity of the 2nd, 3rd, and bottom 13-mm sections was not large and for one of the asphalts the bottom viscosity was actually greater than the viscosity of the 2nd and 3rd sections.
- The aging, in terms of extracted viscosity, that has occurred over the four-year period is substantially greater than predicted by the Global Aging System, particularly in the top 13 mm of pavement.
- In a limited analysis of the PAV model, for the AZ1-1 asphalt, the depth of the RTFOT/PAV viscosity corresponding to 48 months was estimated at 40 mm.

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