PREDICTION OF THE STIFFNESS OF ASPHALT TREATED WITH SURFACTANT-BASED WARM MIX ADDITIVE

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ABSTRACT

The tonnage of asphalt pavements constructed with warm mix technologies has increased rapidly in the U.S. in recent years. Yet, some practical aspects of warm mix asphalt pavement construction remain incompletely defined. For example, compaction temperatures for many warm mix technologies cannot be estimated using standard equiviscous methods common to hot mix asphalt. This paper reports the preliminary results of research to develop a method for predicting the stiffness (G/sin δ) of binder treated with surfactant-based warm mix additive as a function of mix production temperature, mix storage and haul time, and warm mix additive dosage. Asphalt binders were treated in the laboratory with varying levels (0.0, 0.5, and 1.0%) of surfactant-based warm mix additive and heated in a rolling thin-film oven at 130, 145, and 163°C for 0, 25, 55, 85, and 115 minutes. Regression analyses of the lab data yielded equations, which with good fit correlated binder stiffness with the formulation (dosage) and process variables (aging temperature and time). The predictive value of these lab-developed equations was found to be good when the measured stiffness of binder extracted from field mix obtained at the paver was compared to binder stiffness calculated with the laboratory-developed equations using the plant mix temperature, total storage and haul time, and surfactant dosage*

Keywords: Additives, Compaction, Density, Gyratory, Warm Asphalt Mixture

1. INTRODUCTION

In congressional testimony on the U.S. asphalt paving industry's key strategic initiatives to address surface infrastructure improvement and reform, it was reported that in 2010, 46 million tons of warm mix asphalt were produced in the U.S., up from 13 million tons in 2009 (1). This two-year increase of 254% reflects the rapid adoption of WMA technologies nationwide. The magnitude of this growth is further amplified by considering the fact that in 2005, there were only seven experimental test sections and demonstration projects in place in all of North America. Thorough explanations (2, 3) of the reasons behind this unprecedented growth have been offered by many authors and mainly include reduced environmental impact, less human exposure to potentially hazardous jobsite vapor emissions, and a wide range of economic and performance benefits to both the paving contractor and agency alike (4, 5, 6, 7).

Despite this rapid growth in deployment of WMA construction practices, many aspects of WMA technologies remain poorly understood, especially when compared to conventional HMA. WMA mix design guidelines were only recently formalized via the output of NCHRP 9-43. Many ongoing research programs aim to elucidate some of the basic properties of warm mix technologies, such as the function of WMA additives in production and construction and the role of asphalt foam in mix production and pavement construction (8, 9). Other current studies (for example, NCHRP 9-47 and 9-49) target comparisons of the long-term performance properties of HMA pavements and pavements constructed with any of the 22 WMA technologies offered commercially in the U.S. (10, 11). Numerous programs have looked at the deformation properties of WMA pavements (12).

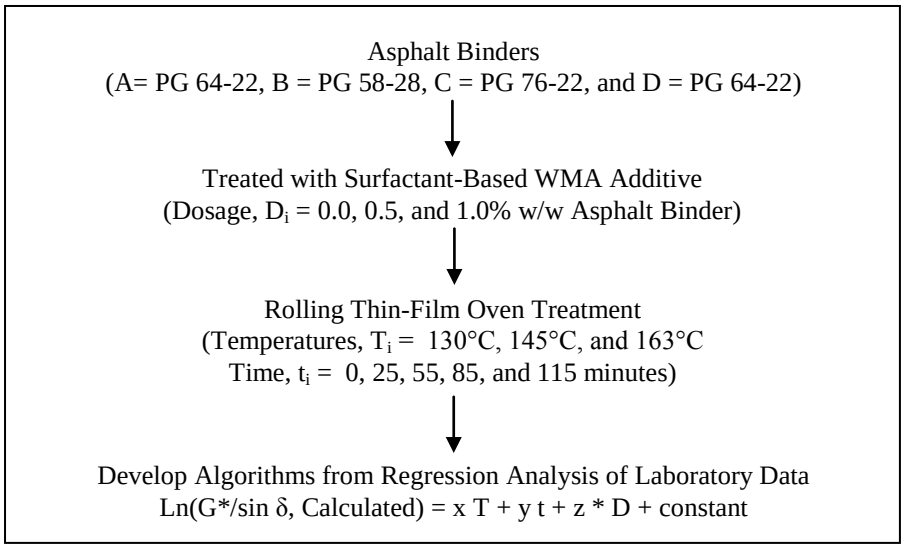
Identification of mix and compaction temperatures for WMA mixtures is an area that has not lent itself to the equiviscous methodology typical used for HMA in accordance with AASHTO T 316 (13). The transient nature of foamed WMA technologies makes rotational viscometry at mix and compaction temperatures impossible. Many WMA chemical additives do not affect viscosity, but rather affect binder lubricity (8) and/or the normal force response of binder to shear in or beyond the normal linear viscoelastic region (14). The difficulty in forecasting compaction temperatures for WMA mixtures based on binder properties has led to the development of workability tests that characterize the entire mix (15).

2. Experimental Plan

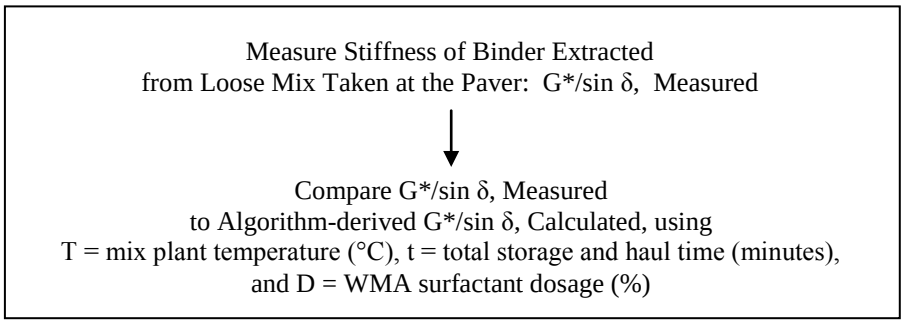
Figure 1 illustrates the two-step experimental plan used to generate algorithms in the lab using rolling thin-film oven (RTFO) to characterize the change in binder stiffness as a function of WMA additive dosage (0, 0.5, and 1.0% w/w binder) and RTFO conditioning temperatures and times. Very simply, the WMA-treated binder samples were placed in the RTFO at three different conditioning temperatures, T_i, for five incrementally increasing time periods, t_i. Four asphalt binders were treated in this manner: A, a Venezuelan-based PG 64-22; B, a Canadian-crude based PG 58-28; C, a PG 76-22; and D, a PG 64-22 job binder from a Midwest terminal.

FIGURE 1. Experimental Plan

Step 1. Algorithm Development



Step 2. Evaluate Predictive Value of Algorithm



3. Results of Rolling Thin-Film Oven Conditioning

Table 1 shows typical results of analysis of the change in stiffness of Venezuelan-based binder A doped with three levels of surfactant-based WMA additive and aged in the RTFO under varying conditions of time and temperature.

Table 1: G*/sin δ Change with WMA Surfactant Dosage and RTFO Conditioning Time and Temperature

WMA Dosages (%)	RTFO Temperatures (C)	RTFO Durations (min)	G*/sin(delta)		Average G*/ sin (delta)
0.00	130	0	1.96E+03	1.93E+03	1943.96
0.00	130	25	1.93E+03	2.15E+03	2038.48
0.00	130	55	2.21E+03	2.35E+03	2278.75
0.00	130	85	2.54E+03	2.39E+03	2467.63
0.00	130	115	2.69E+03	2.61E+03	2650.02
0.00	145	0	1.96E+03	1.93E+03	1943.96
0.00	145	25	2.35E+03	2.16E+03	2253.00
0.00	145	55	2.61E+03	2.66E+03	2637.49
0.00	145	85	2.98E+03	3.18E+03	3079.41
0.00	145	115	3.72E+03	3.83E+03	3775.76
0.00	163	0	1.96E+03	1.93E+03	1943.96
0.00	163	25	2.26E+03	2.07E+03	2166.31
0.00	163	55	3.31E+03	3.12E+03	3218.25
0.00	163	85	4.35E+03	4.30E+03	4323.65
0.00	163	115	5.39E+03	5.32E+03	5358.19
0.50	130	0	2.02E+03	1.94E+03	1976.82
0.50	130	55	2.29E+03	2.23E+03	2261.06

0.50	130	85	2.27E+03	2.52E+03	2396.78
0.50	130	115	2.81E+03	2.50E+03	2651.59
0.50	145	0	2.02E+03	1.94E+03	1976.82
0.50	145	25	2.37E+03	2.22E+03	2292.83
0.50	145	55	2.57E+03	2.51E+03	2542.46
0.50	145	85	3.30E+03	3.19E+03	3246.31
0.50	145	115	4.00E+03	4.37E+03	4181.16
0.50	163	0	2.02E+03	1.94E+03	1976.82
0.50	163	25	2.43E+03	2.31E+03	2367.46
0.50	163	55	3.16E+03	3.26E+03	3206.32
0.50	163	85	4.21E+03	4.22E+03	4216.66
0.50	163	115	5.63E+03	5.78E+03	5708.13
1.00	130	0	1.75E+03	1.81E+03	1779.56
1.00	130	25	2.01E+03	1.84E+03	1926.36
1.00	130	55	2.00E+03	2.09E+03	2040.87
1.00	130	85	2.23E+03	2.25E+03	2238.72
1.00	130	115	2.36E+03	2.33E+03	2345.64
1.00	145	0	1.75E+03	1.81E+03	1779.56
1.00	145	25	2.25E+03	2.37E+03	2307.24
1.00	145	55	2.56E+03	2.80E+03	2677.37
1.00	145	85	2.94E+03	3.21E+03	3071.94
1.00	145	115	3.49E+03	3.61E+03	3554.41
1.00	163	0	1.75E+03	1.81E+03	1779.56
1.00	163	25	2.35E+03	2.16E+03	2256.49
1.00	163	55	2.77E+03	3.03E+03	2898.66
1.00	163	85	3.92E+03	3.86E+03	3891.44
1.00	163	115	5.31E+03	4.98E+03	5144.21

The RTFO aging behavior of binder A (measured as a function of WMA dosage, temperature, and time) also was plotted to show graphically the relationship between stiffness and the formulation variable (dosage) and the two process variables (temperature and time). Figure 2 shows the plot of stiffness, G*/sin δ, as a function of RTFO temperature and time for binder A, the Venezuelan-based PG 64-22, treated with 0% of the surfactant-based WMA additive. Figure 3 shows the plot of G*/sin δ over the same RTFO aging conditions (temperature and time) for binder A treated with 0.5% of the surfactant-based WMA additive. Figure 4 shows the change in G*/sin δ under the same aging conditions for binder A treated with 1.0% of the surfactant-based WMA additive. Exponential curves were fit to the data at each conditioning temperature.

Graphically, it is clear that over the range of RTFO conditions of temperature and time, the stiffness varied exponentially. R-squared values for exponential curve fit were excellent for at all dosages and at all RTFO conditions.

Figure 2: Binder A, PG 64-22, with 0.0% WMA Additive: Stiffness with Varying RTFO Temperature and Conditioning Time

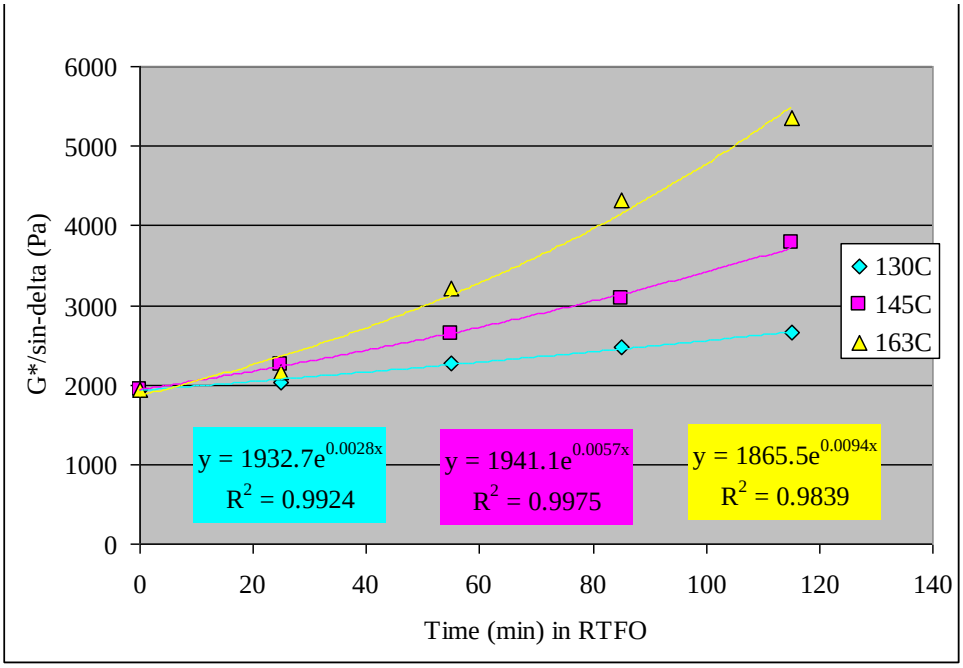


Figure 3: Binder A, PG 64-22, with 0.5% WMA Additive: Stiffness with Varying RTFOs Temperature and Conditioning Time

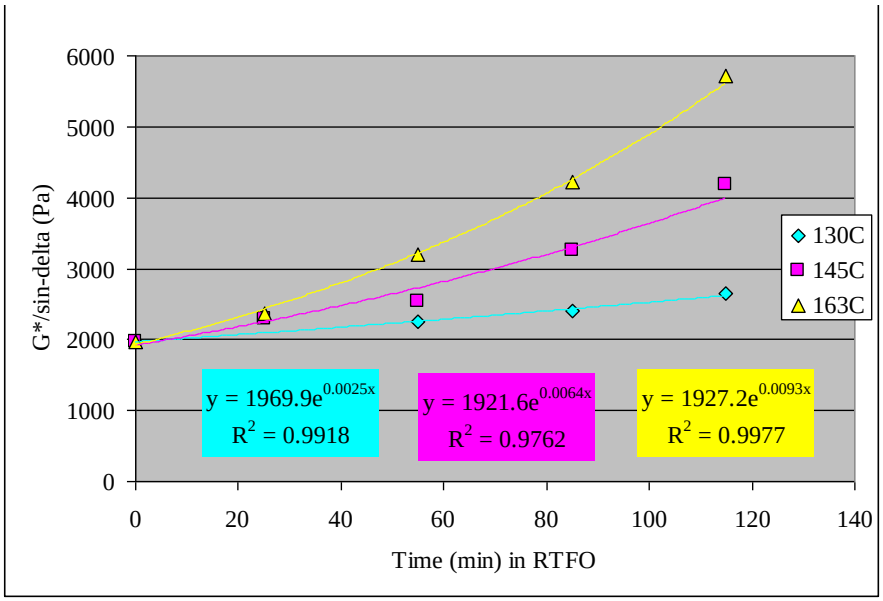
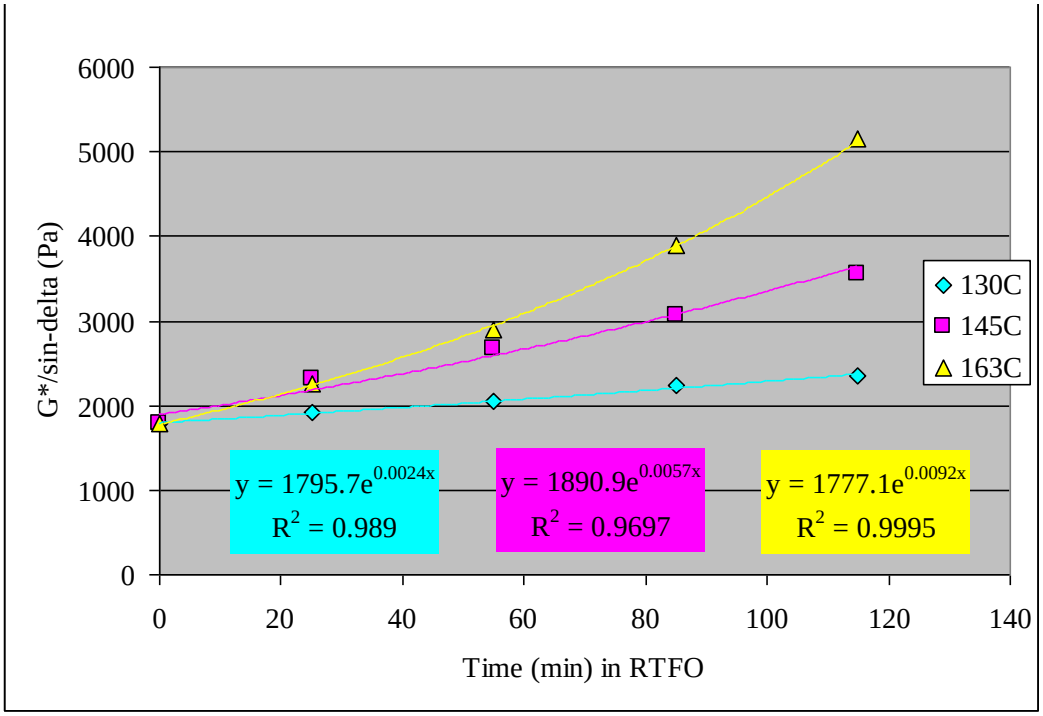


Figure 4: Binder A, PG 64-22, with 1.0% WMA Additive: Stiffness with Varying RTFO Temperature and Conditioning Time



Identical analyses were performed for the other binders. The coefficients and exponents of the equations, which fit the aging behavior of the other binders, are given in Table II, along with the R-square values. The data show that the aging behavior was very regular for all four binders evaluated in this study.

Table 1: Exponential Aging Equations: Intercepts, Slopes, and R-Square Values (G*/sin δ = Y-intercept x e ^ (Slope x time)

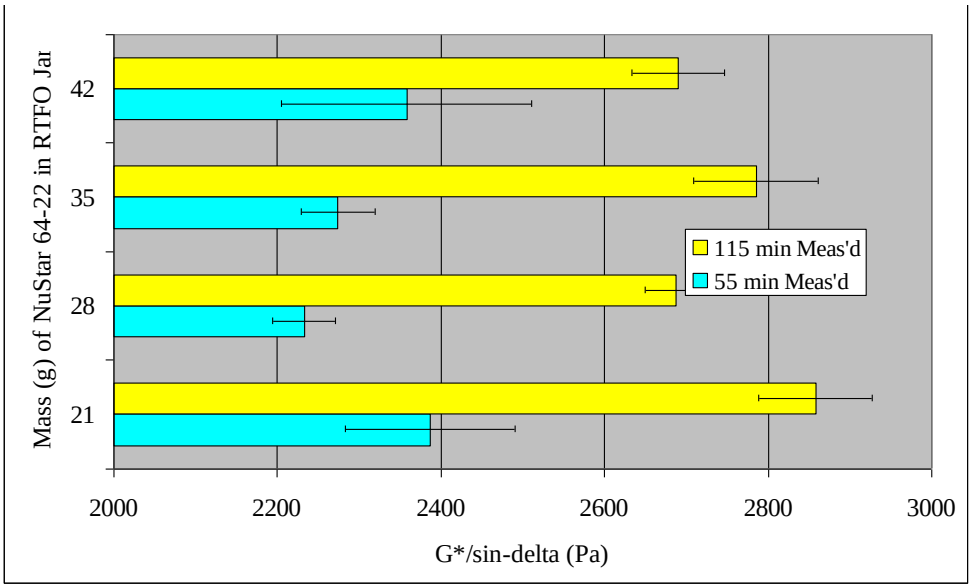
Binder	WMA Dosage, D (%)	RTFO Temp., T (°C)	Y-intercept (coefficient)	Slope (exponent)	R-squared
A	0	130	1932.7	0.0028	0.9924
		145	1941.1	0.0057	0.9975
		163	1865.5	0.0094	0.9839
	0.5	130	1969.9	0.0025	0.9918
		145	1921.6	0.0064	0.9766
		163	1927.2	0.0093	0.0077
	1	130	1795.7	0.0024	0.9890
		145	1890.9	0.0057	0.9697
		163	1777.1	0.0092	0.9995
B	0	130	1210.6	0.0042	0.9665
		145	1246.8	0.0061	0.9948
		163	1299.0	0.0083	0.9814
	0.5	130	1172.7	0.0041	0.9483
		145	1273.7	0.0055	0.9901
		163	1308.3	0.0080	0.9864
	1.0	130	1156.8	0.0038	0.9757
		145	1182.4	0.0057	0.9976
		163	1196.3	0.0083	0.9990
C	0	145	1637.4	0.0031	0.9920
		163	1611.8	0.0070	0.9980
		175	1643.3	0.0097	0.9959
	0.5	145	1296.1	0.0028	0.9387
		163	1293.9	0.0073	0.9886
		175	1399.9	0.0083	0.9834
	1.0	145	1297.6	0.0032	0.9968
		163	1244.8	0.0078	0.9902

		175	1255.2	0.0089	0.9902
D	0.5	135	1737.1	0.0042	0.9502
		146	1743.4	0.0078	0.9921
		163	1712.2	0.0106	0.9800

4. Binder Viscosity at Reduced RTFO Temperature Did Not Affect Short-Term Aging

It has been postulated that rolling inefficiences might confound or even invalidate RTFO aging at temperatures typical of WMA applications (e.g., 130°C) (16). Figure 5 shows results of RTFO experiments in which the quantity of Venezuelan-based binder A added to the RTFO vessel was both decreased by 25% from the method-specified mass and increased to 50% above the method-specified mass. Additionally, the RTFO conditioning time was varied from 55 to 115 minutes in the experiments. Samples were analyzed for stiffness. If the viscosity at 130°C was causing rolling inefficiencies, which reduced the amount of binder surface area exposed to the air flow, then samples containing higher-than-specified masses would have shown reduced oxidative stiffening. Samples with the lowest mass charges would have shown higher stiffening. There was no correlation between the input variables (mass and time at 130°C) and the resulting binder stiffening. For the unmodified binders used in this study, the warm mix temperature did not affect the binder oxidation behavior.

Figure 5: Change in G*/sin-delta of Ven-Based Binder A PG 64-22 in 130°C RTFO – Not a Function of Mass (g) in RTFO Jar, Showing Viscosity Did not Affect Oxidation Rate



5. Regression Analyses to Generate Predictive Algorithms

The natural logarithm of the average stiffness values measured for binder A (enumerated in Table I and shown graphically in Figures 2, 3, and 4) were calculated. Linear regression analyses were conducted to correlate the ln(G*/sin δ) with the dosage, d, of the surfactant-based WMA additive and the RTFO conditioning temperatures, T, and times, t. For Binder A, Equation 1 shows the resulting regression equation. R-squared for this regression analysis was 0.8485.

Similar analyses were conducted for the other three binders. Equations 2, 3, and 4 show the results of these regression analyses for binders B, C, and D, respectively.

$$\mathbf{Ln(G^*/\sin\delta)_A = -0.02759 \times d + 0.01255 \times RTFO\ T + 0.004806 \times RTFO\ t + 5.7809} \quad \text{Eq. 1}$$

R-squared for the regression analysis of Venezuelan-based binder A aging = 0.8485.

$$\mathbf{Ln(G^*/\sin\delta)_B = -0.07560 \times d + 0.009043 \times RTFO\ T + 0.005955 \times RTFO\ t + 5.8298} \quad \text{Eq. 2}$$

R-squared for the regression analysis of PG 58-28 binder B aging = 0.9289.

$$\mathbf{Ln(G^*/\sin\delta)_C = -0.2563 \times d + 0.01158 \times RTFO\ T + 0.006453 \times RTFO\ t + 5.5084} \quad \text{Eq. 3}$$

R-squared for the regression analysis of PG 76-22 binder C aging = 0.8747.

$Ln(G^*/\sin\delta)_D = 0.0 \times d + 0.01180 \times RTFO\ T + 0.007521 \times RTFO\ t + 5.7096$ Eq. 4

R-squared for the regression analysis of PG 64-22 MidWest binder D aging = 0.8878.

The lab-developed algorithm for Binder D did not include a factor, d, for the additive dosage because it was known that the contractor was using 0.5%. This was thus a fixed value.

6. Predictive Value of Lab-Developed Algorithms

In field projects using binders A and D, binder samples were obtained by extracted of loose mix obtained from the paver auger box. The stiffness of the extracted binder was compared to the stiffness predicted using Equations 1 and 4.

Case 1. A 9.5-mm NMAS, dense-graded mix was produced at 135°C using binder A, which had been treated with 0.5% of a surfactant-based WMA additive package. Binder extracted from loose field mix collected at the auger box of the paver gave a stiffness value of

$G^*/\sin\delta$ (measured) = 5264 Pa.

Equation 1 requires the dosage of the surfactant warm mix additive (0.5%) and the mix production temperature (which in this case was 135°C). The time variable must be estimated from total storage and total haul time.

The combined time for storage (25 - 35 minutes) and hauling to the construction site (90 - 100 minutes) gives a total time at temperature of roughly 115 to 135 minutes.

Reasoning that the initial binder stiffness immediately out of the plant is approximated in the laboratory by the stiffness of the binder after 85 minutes of laboratory RTFO conditioning, then we may approximate a total time value (initial oxidation time + storage time + hauling time) to insert into Equation 1. That range of times is between 200 to 220 minutes total (200 = 85 + 115 and 220 = 85 + 135).

Substituting total lower time value of 200 minutes into Equation 1, the predicted stiffness is

$G^*/\sin\delta$ (predicted for t = 200, T = 135, and D = 0.5) = 4546 Pa.

This is 16% lower than the measured stiffness.

Substituting the higher time value of 220 minutes into Equation 1 yields a predicted stiffness value of

$G^*/\sin\delta$ (predicted for t = 220, T = 135, and D = 0.5) = 5005 Pa.

This predicted value is within 5% of the measured value of 5264 Pa.

Case 2. A similar treatment was given to analysis of predictive value of the lab-developed algorithm using a 19-mm NMAS, dense-graded mix that was produced at 141°C using binder A. Again, binder A had been treated with 0.5% of a surfactant-based WMA additive package. Binder extracted from loose field mix collected at the auger box of the paver gave a stiffness value of

$G^*/\sin\delta$ (measured) = 5398 +/- 19 Pa.

As in Case 1, the surfactant WMA additive dosage was D = 0.5%. T = 141°C. Again, total time is estimated by adding initial oxidation time + storage time + hauling. In this example, the total time is estimated to range from t = 210 to 230 minutes.

Substituting total lower time value of 210 minutes into Equation 1, the predicted stiffness is

$G^*/\sin\delta$ (predicted for t = 210, T = 141, and D = 0.5) = 5146 Pa.

This predicted value is less than 5% lower than the measured stiffness of 5398 +/- 19 Pa.

Substituting the higher time value of 230 minutes into Equation 1 yields a predicted stiffness value of

$G^*/\sin\delta$ (predicted for t = 230, T = 141, and D = 0.5) = 5665 Pa.

This predicted value is again (as in Case 1) within less than 5% above of the value of 5398 +/- 19 Pa measured on the binder extracted from the loose 19-mm NMAS dense-graded mix.

Case 3. In a third evaluation of the correlation between the stiffness of binder extracted from loose plant mix obtained at the paver and stiffness predicted by the lab-developed algorithm, a and field observations. A 9.5-mm NMAS, dense-graded mix was produced at 157°C using binder D, the MidWest origin binder. (For surfactant-based warm mixes, production temperatures rarely reach 157°C. This was the trial production run with the technology in the contractor's plant, and so, the elevated temperatures were chosen as a starting point.) Binder extracted from loose field mix collected at the auger box of the paver gave a stiffness value of

$G^*/\sin\delta$ (measured) = 5885 +/- 550 Pa.

Equation 4 is repeated below.

$$\text{Ln}(G^*/\sin\delta)_D = 0.0 \times d + 0.01180 \times \text{RTFO T} + 0.007521 \times \text{RTFO t} + 5.7096 \qquad \text{Eq. 4}$$

Storage and hauling times in this trial were roughly 49 to 63 minutes. Again, it was reasoned that the initial oxidation of the binder out of the continuous mix plant was represented by the level of oxidation in the RTFO at 85 minutes, the total time value used to substitute into Equation 4 was calculated by summing the initial oxidation time + storage time + hauling time, which gives t = 134 to 148 minutes total (134 = 85 + 49; 148 = 85 + 63). Substituting T = 157 and the range of t values, the stiffness values calculated from Equation 4 are

$G^*/\sin\delta$ (predicted for t = 134 to 148 and T = 157) = 5294 to 5886 Pa.

These predicted stiffness values again range within about 10% of the measured value obtained from the extracted binder.

6. Conclusions and Recommendations

The results of this preliminary study suggest that it may be possible to estimate the stiffness of WMA binder (derived from surfactant-based WMA technology) in the field if the aging properties have first been characterized as a function of additive dosage and process conditions (temperature and time) in the RTFO.

The evaluation of other procedures for short-term binder aging are warranted. Analysis of plots of the RTFO test temperatures and slopes of the exponential aging equations indicates that no oxidation would occur for binder A at temperatures below about 116.2 to 118.0°C (the y-intercepts of trendlines) and for binder B below about 96.1 to 102.6°C. Figures 6 and 7 show that the y-intercepts when the slopes equal zero (that is, there is no oxidative stiffening of the binders in the RTFO). While oxidative stiffening would be slowed, it is not reasonable to believe it ceases. The apparent decrease to a slope of zero is likely an artifact of the RTFO testing procedures.

It is recommended that the predictive value of the algorithms developed for binder B (PG 58-28) and the polymer-modified binder (binder C, PG 76-22) be evaluated via the general method demonstrated in this study. Similarly, only drum plants were used in the three Cases discussed in this study. The role of plant type in affecting the stiffness of the binder during mix production in the field must be addressed.

Additionally, the role of reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) in these analyses must be evaluated for the technique to be of broad, practical value.

Figure 6: Change of Slope of RTFO Stiffness Curves with RTFO Temperature, Time, and WMA Additive Dose in Binder A, PG 64-22

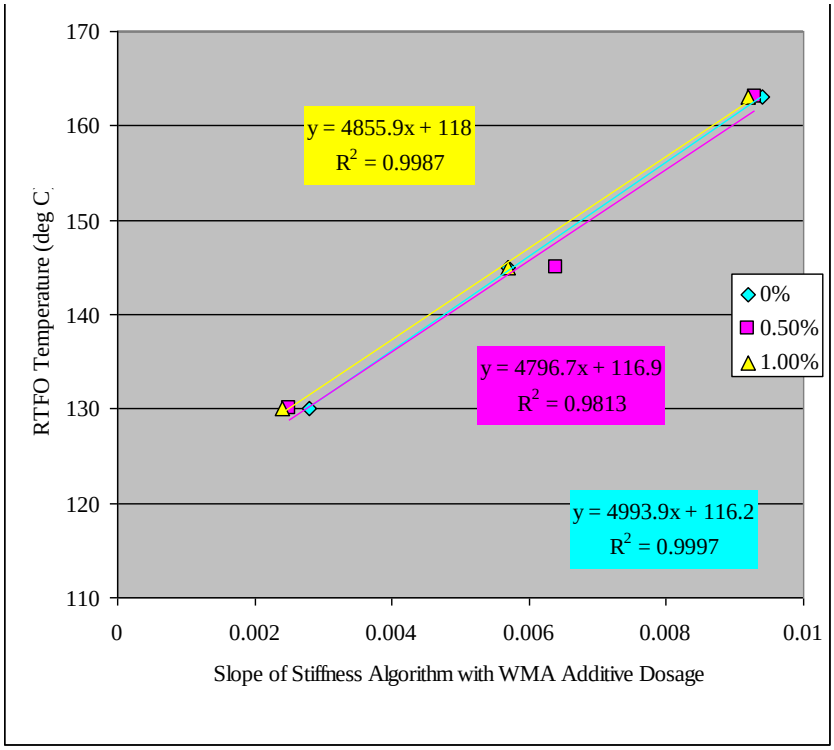
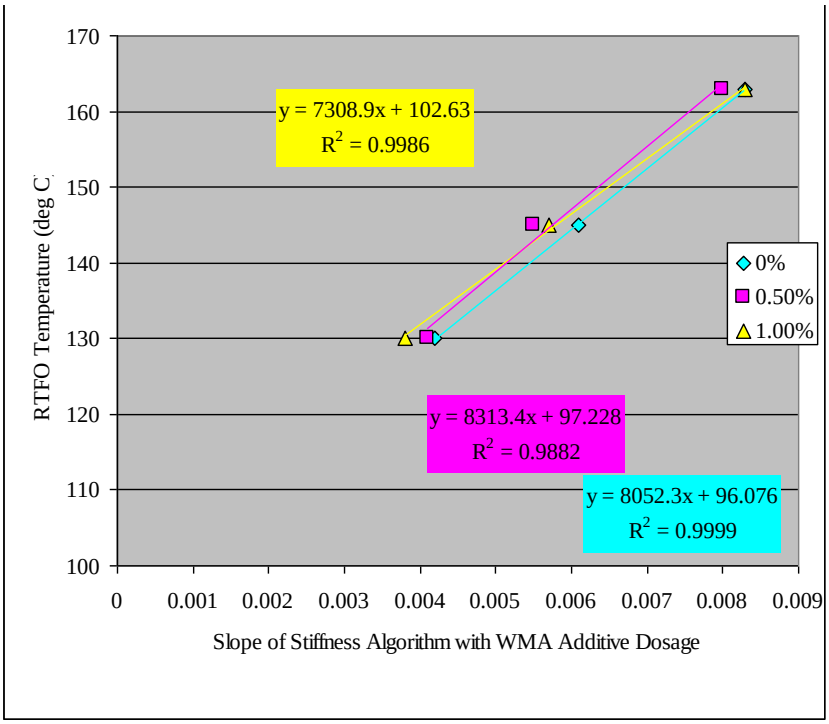


Figure 7: Change of Slope of RTFO Stiffness Curves with RTFO Temperature, Time, and WMA Additive Dose in Binder B, PG 58-28



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