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Laboratory Evaluation of Unmodified and Polymer-Modified Performance-Grade Binders with Anti-Stripping Additives

Selvaratnam Selvamohan, Former Research Assistant, The University of Oklahoma, selva@ou.edu
Musharraf Zaman, David Ross Boyd Professor and Aaron Alexander Professor, Associate Dean for Research, College of Engineering, The University of Oklahoma, zaman@ou.edu
Joakim Laguros, David Ross Boyd Professor Emeritus, The University of Oklahoma, joakim.g.laguros-1@ou.edu

Abstract

To prevent stripping, amine-based liquid anti-stripping additives are commonly added to asphalt binders. The effect of these anti-stripping additives in each PG binder type is not known. The objective of this research is to measure and compare the changes in introduced namely, PG 70-28, PG 76-28 and PG 64-22, when two selected anti-stripping additives are added. Performance grade of Oklahoma PG 64-22 binder exhibited insignificant grade change compared to the other two polymer modified binders with different percentages of anti-stripping additives. The maximum change in high grade temperatures for PG 64-22 was 1.5°C except at 1.00% Perma Tac Plus. PG 70-28 underwent a grade change of 3.2°C while PG 76-28 showed 3.6°C. Given PG 76-28 was close to a PG 82-28.

Introduction

Some specific types of pavement distresses namely, raveling, cracking, rutting and stripping are related to the rheological properties of asphalt binders. In general, pavements can experience reduced service life when exposed to moisture penetration. When the bond between asphalt binder and aggregate is broken, the asphalt pavement weakens and exhibits various types of macroscopic failures as mentioned above. Anti-stripping additives have been developed to address the issue of poor pavement performance and high maintenance costs experienced by moisture-susceptible pavements. These additives, whether solid or liquid, are used to promote adhesion of asphalt binder to the aggregate surface. Liquid anti-stripping agents are chemical compounds that contain amines. Amine-based liquid additives are commonly added to asphalt binders either at the refinery or at the site to chemically improve the adhesion between the asphalt binders and aggregate (Kennedy, 1983). Most agents reduce surface tension between the asphalt binder and aggregate in a mixture (Tunnicliff and Root, 1984). When surface tension is reduced, increased adhesion of asphalt binder to the aggregate is promoted. Thus, most liquid anti-stripping agents are surface-active agents (Roberts et al., 1996). Apart from these traditional trends, the newly developed concept, Surface Free Energy (SFE) measurements of asphalt binders can be used to predict the fatigue and moisture-induced damage (Elphingstone, 1997).

Effects of commercially available liquid anti-stripping agents on asphalt binders were evaluated by Anderson et al. (1982). It was shown that the addition of liquid anti-stripping additives can alter the physical characteristics and composition of asphalt binder, sometimes increasing asphalt binder viscosity to the point of non- compliance with the standard specifications. However, if an additive is used incorrectly or when not needed, adverse affects may occur, including increased cost and early maintenance and/or rehabilitation (Tunnicliff and Root, 1984). So far, there is no instrument to measure precisely the amount of anti-stripping additive in an asphalt pavement after the material has been added. Although there are some indirect ways to measure existence of additives through the performance of the asphalt pavement such as AASHTO T-283, the method takes days for the test results to be available. Due to the lack of proper testing methodology, ensuring the amount of additives in a mixture is often considered a difficult task in analysis and design. The typical dosage by weight of asphalt binder ranges between 0.25 and 0.75% (Kennedy, 1983).

Different anti-stripping additives are generally used with asphalt binders polymer-modified or unmodified, in pavement construction. However, it is currently not known to what extent these anti-stripping additives change the performance grade of different binders. Therefore, it is important to evaluate the changes in the "Performance Grade" of commonly used binders due to additives. The high and low grade temperatures of performance grade binders are verified with the Superpave specified Dynamic Shear Rheometer (DSR) and Bending Beam Rheometer (BBR). To this end, it is useful to identify the changes in asphalt binder grades by adding different percentages of selected anti-stripping additives. The findings of this study are expected to help state agencies and pavement designers to better specify asphalt binders, in terms of their performance grade, for bidding and construction purposes.

Objectives and Scope

The specific objectives of this study are listed below:
(1) Evaluate the changes in high grade temperature of binders with additives.
(2) Evaluate the changes in low grade temperature of binders with additives.
(3) Determine the optimum percentage of additives.
(4) Analyze and compare findings of the test results and draw conclusions and recommendations.

This experimental study evaluates and compares the changes in the "Performance Grade" of three asphalt binders commonly used in Oklahoma. Polymer modified PG 70-28 and PG 76-28 and the unmodified PG 64-22 were tested after the inclusion of anti-stripping additives namely, Perma Tac Plus and Adhere HP-Plus. It is believed that the findings of this study would enhance the study of SFE characteristics of asphalt binders.

Experimental Program

Materials Description

Three performance grade asphalt binders used in this study were supplied by the Valero refinery in Ardmore, Oklahoma. Unmodified PG 64-22 is commonly used in base mixes by state agencies and pavement contractors in Oklahoma. Both PG 70-28 and PG 76-28 used in this study are polymer modified binders with the elastomer modifier called, Styrene Butadiene Styrene (SBS). The anti-stripping additives Adhere HP-Plus and Perma Tac Plus were received from the ARR MAZ Custom Chemicals, Inc., Florida and the AKZO NOBEL surface chemistry LLC, Chicago, Illinois, respectively. Physical properties of these additives are given in Table 1.

Aging of Asphalt Binder

The Rolling Thin Film Oven (RTFO) test simulates the asphalt binder aging (short-term) during the manufacture and construction of HMA pavements. The AASHTO T-240 standard test method requires that the RTFO continuously expose asphalt binder to both heat (163^{o}C) and air flow (4000ml/min) for 85 minutes to achieve the accelerated aging of the binder. The Pressure Aging Vessel (PAV) test simulates aging of an asphalt binder during the first 5-10 years of pavement service life. The AASHTO R-28 standard test method requires that the RTFO residue be subjected to high pressure, 2.1MPa (300psi), and high temperature (90-110oC) over a 20-hour period in the PAV to achieve the accelerated aging of the asphalt binder.

Laboratory Testing

Laboratory testing involved two polymer-modified and an unmodified asphalt binders and two anti-stripping additives. Three different percentages of each additive (0.25%, 0.50% and 0.75% for Adhere HP-Plus and 0.50%, 0.75% and 1.00% for Perma Tac Plus) were selected for the experimental study based on the literature. Each asphalt binder sample was mixed with the selected percentages of additive and tested in accordance with the AASHTO M 320 test method (AASHTO T - 315). The high grading temperatures were determined by evaluating the Superpave specified $G^*/\sin(\delta)$, and phase angle, δ, of unaged and RTFO-aged binders. To determine the high and low grades, four different test temperatures were chosen in and around the grading temperature for each binder. The temperatures ranged from 3^{o}C below to 6^{o}C above the grading temperatures of each binder. i.e., the test matrix in determining high grade of PG 64-22 includes test temperatures 61^{o}C, 64^{o}C, 67^{o}C and 70^{o}C. The low grading temperatures were determined by evaluating the stiffness, S(t) and m-value (AASHTO T – 313) of PAV-aged binders.

The calculated low grading temperatures were verified with that of DSR test results of PAV-aged binders. Each of these tests was repeated three times to ensure the repeatability of the results. Finally, the true grade of each asphalt binder was calculated, compared and documented.

Table 1: Properties of Anti-Stripping Additives

Description	**Adhere HP-Plus**	**Perma Tac Plus**
Dosage	0.20% – 0.75%	0.10% – 1.00%
Physical State	Brown to Dark Brown Liquid	Brown to Dark Brown Liquid
Viscosity	225cps at 25^{o}C	350cps at 25^{o}C
Flash Point	> 148^{o}C	> 200^{o}C
Boiling/Condensation	> 150^{o}C	> 150^{o}C
Melting/freezing	< 0^{o}C	< 0^{o}C
Density	0.95g/cm3	0.95g/cm3
Solubility	Partially soluble in cold water	Partially soluble in cold water

Experimental Results

Unmodified PG 64-22 and Anti-Stripping Additives

A summary of the DSR test results for unaged and RTFO-aged PG 64-22 at different temperatures is presented in Table 2. The DSR and the BBR results of the above binder after PAV aging are summarized in Table 3. After the inclusion of additives, the test temperatures at which the binders met the specified criterion were evaluated and are summarized in Table 4. Consequently, the true grade temperatures of PG 64-22 after the inclusion of additives were calculated for each case and are given in Table 5

Table 2: Average G*/sin(δ) for Unaged and RTFO-Aged PG 64-22

G*/sin(δ)/(kPa) for PG 64-22 Asphalt Binder														
Unaged								RTFO-aged						
T (^{o}C)	Pure	Adhere HP-Plus (%)			Perma Tac Plus (%)			Aged	Adhere HP-Plus (%)			Perma Tac Plus (%)		
		0.25	0.50	0.75	0.50	0.75	1.00		0.25	0.50	0.75	0.50	0.75	1.00
61	1.71	1.65	1.56	1.55	1.68	1.53	1.27	4.41	4.16	3.92	3.75	3.92	3.70	3.52
64	1.13	1.08	1.03	1.02	1.11	1.01	0.85	2.84	2.74	2.44	2.39	2.55	2.42	2.24
67	0.73	0.71	0.68	0.68	0.72	0.69	0.59	1.92	1.81	1.65	1.52	1.70	1.60	1.51
70	0.49	0.48	0.46	0.48	0.47	0.45	0.41	1.30	1.22	1.15	1.12	1.12	1.08	1.02

Table 3: Average G*.sin(δ), Stiffness and m-Value for PAV-Aged PG 64-22

PAV-aged PG 64-22 with Anti-Stripping Additives								
Description	T (^{o}C)	Aged	Adhere HP-Plus (%)			Perma Tac Plus (%)		
			0.25	0.50	0.75	0.50	0.75	1.00
G*.sin(δ)/(MPa)	19	7.06	6.84	6.26	6.16	6.87	6.00	5.69
	22	5.29	5.08	4.62	4.48	4.94	4.47	4.19
	25	3.71	3.56	3.18	3.10	3.46	3.09	2.88
	28	2.50	2.42	2.12	1.96	2.27	2.05	1.91
S(t) / (MPa)	-9	108.9	93.3	92.1	91.0	106.8	99.0	82.4
	-12	145.7	143.6	137.2	128.4	142.1	132.0	125.6
	-15	185.4	177.4	173.5	170.7	172.6	168.0	164.8
m-value	-9	0.330	0.322	0.325	0.330	0.328	0.342	0.335
	-12	0.346	0.322	0.318	0.320	0.335	0.351	0.328
	-15	0.292	0.277	0.275	0.280	0.285	0.279	0.289

Table 4: Test Temperatures at which PG 64-22 Reached Critical Values

Binder	**DSR (^{o}C)**	**RTFO-DSR (^{o}C)**	**PAV-DSR (^{o}C)**	**S(t) (^{o}C)**	**m-value (^{o}C)**
PG 64-22	64.9	66.0	22.6	<-28	-24.6
0.25% Adhere HP-Plus	64.8	65.5	22.1	<-28	-23.5
0.50% Adhere HP-Plus	64.2	64.7	21.3	<-28	-23.3
0.75% Adhere HP-Plus	64.1	64.5	21.1	<-28	-23.6
0.50% Adhere HP-Plus	64.8	65.1	22.0	<-28	-24.1
0.75% Adhere HP-Plus	64.0	64.7	21.0	<-28	-24.0
1.00% Adhere HP-Plus	62.8	64.2	20.4	<-28	-24.2

Table 5: True Grade of PG 64-22 with Anti-Striping Additives

Binder	**High Grade (^{o}C)**	**Low Grade (^{o}C)**	**Performance Grade**
PG 64-22	64.9	-24.6	64.9-24.6
0.25% Adhere HP-Plus	64.8	-23.5	64.8-23.5
0.50% Adhere HP-Plus	64.2	-23.3	64.2-23.3
0.75% Adhere HP-Plus	64.1	-23.5	64.1-23.5
0.50% Perma Tac Plus	64.8	-24.1	64.8-24.1
0.75% Perma Tac Plus	64.0	-24.0	64.0-24.0
1.00% Perma Tac Plus	62.8	-24.0	62.8-24.0

Polymer modified PG 70-28 and Anti-Stripping Additives

A summary of the DSR test results for unaged and RTFO-aged PG 70-28 with Adhere HP-Plus and Perma Tac at different temperatures is given in Table 6. Table 7 summarizes the DSR and BBR results of PAV-aged PG 70-28. The specified test temperature (intermediate temperature) for PAV-aged 70-28 is 25^{o}C. Since the initial tests of PAV-aged binders indicated relatively small values in G*.sin(δ), it was decided to run the DSR tests at lower temperatures. Table 8 gives the test temperatures at which the bender met the specified criteria. The true grade of PG 70-28 was calculated and is given in Table 9. Again, it is clear that effects on high and low grading temperatures are relatively higher for Adhere HP-Plus than for Perma Tac Plus.

Table 6: Average G*/sin(δ) for Unaged and RTFO-Aged PG 70-28

G*/sin(δ)/(kPa) for PG 70-28 Asphalt Binder														
Unaged								RTFO-aged						
T (^{o}C)	Pure	Adhere HP-Plus (%)			Perma Tac Plus (%)			Aged	Adhere HP-Plus (%)			Perma Tac Plus (%)		
		0.25	0.50	0.75	0.50	0.75	1.00		0.25	0.50	0.75	0.50	0.75	1.00
67	1.82	1.71	1.68	1.60	1.62	1.51	1.40	4.25	3.49	3.20	3.23	3.45	3.47	3.27
70	1.37	1.28	1.24	1.19	1.21	1.13	1.04	3.24	2.64	2.42	2.42	2.61	2.61	2.46
73	1.04	0.96	0.93	0.90	0.92	0.85	0.78	2.47	2.00	1.82	1.81	1.97	1.96	1.85
76	0.80	0.73	0.71	0.68	0.70	0.66	0.60	1.89	1.53	1.39	1.38	1.50	1.49	1.40

Table 7: Average G*.sin(δ), Stiffness and m-value for PAV-aged PG 70-28

PAV-aged PG 70-28 with Anti-Stripping Additives								
Description	T (^{o}C)	Aged	Adhere HP-Plus (%)			Perma Tac Plus (%)		
			0.25	0.50	0.75	0.50	0.75	1.00
G*.sin(δ)/(MPa)	13	NA	NA	NA	6.84	NA	NA	NA
	16	5.58	5.39	4.99	4.97	5.36	5.10	5.07
	19	4.31	3.84	3.60	3.58	3.92	3.72	3.68
	22	3.30	2.66	2.49	NA	2.68	2.55	2.49
S(t) / (MPa)	-15	98.6	100.7	100.5	95.2	104.3	101.8	98.5
	-18	139.8	145.5	138.6	149.8	150.2	145.8	148.1
	-21	203.4	212.1	210.4	202.9	216.1	210.5	209.1
m-value	-15	0.319	0.305	0.310	0.309	0.320	0.309	0.312
	-18	0.302	0.294	0.299	0.301	0.299	0.291	0.301
	-21	0.271	0.266	0.254	0.259	0.259	0.251	0.257

Table 8: Test Temperatures at which PG 70-28 Reached Critical Values

Binder	**DSR (^{o}C)**	**RTFO-DSR (^{o}C)**	**PAV- DSR (^{o}C)**	**S(t) (^{o}C)**	**m-value (^{o}C)**
PG 70-28	73.4	74.3	17.4	<-28	-18.3
0.25% Adhere HP-Plus	72.6	72.0	16.4	<-28	-18.0
0.50% Adhere HP-Plus	72.3	71.1	16.0	<-28	-17.4
0.75% Adhere HP-Plus	71.8	71.1	16.0	<-28	-17.9
0.50% Perma Tac Plus	71.9	71.9	16.8	<-28	-18.3
0.75% Perma Tac Plus	71.8	71.9	16.2	<-28	-18.0
1.00% Perma Tac Plus	71.3	71.3	16.2	<-28	-18.0

Table 9: True Grade of PG 70-28 with Anti-Stripping Additives

Binder	**High Grade (^{o}C)**	**Low Grade (^{o}C)**	**Performance Grade**
PG 70-28	73.4	-26.7	73.4-26.7
0.25% Adhere HP-Plus	72.0	-26.3	72.0-26.3
0.50% Adhere HP-Plus	71.0	-26.7	71.0-26.7
0.75% Adhere HP-Plus	71.1	-26.4	71.1-26.4
0.50% Perma Tac Plus	71.9	-25.7	71.9-25.7
0.75% Perma Tac Plus	71.8	-26.1	71.8-26.1
1.00% Perma Tac Plus	71.3	-26.0	71.3-26.0

Polymer modified PG 76-28 and Anti-Stripping Additives

A summary of the DSR test results of unaged and RTFO-aged PG 76-28 with anti-stripping additives is given in Table 10. A summary of the DSR and BBR test results of PAV-aged PG 76-28 with additives is given in Table 11. The test temperatures at which PG 76-28 with different percentages of Perma Tac Plus and Adhere HP-Plus met the Superpave specified criterion are summarized in Table 12. The true grades of PG 76-28 with additives are given in Table 13.

Table 10: Average G*/sin(δ) for Unaged and RTFO-aged PG 76-28

G*/sin(δ)/(kPa) for PG 76-28 Asphalt Binder														
Unaged								RTFO-aged						
T (^{o}C)	Pure	Adhere HP-Plus (%)			Perma Tac Plus (%)			Aged	Adhere HP-Plus (%)			Perma Tac Plus (%)		
		0.25	0.50	0.75	0.50	0.75	1.00		0.25	0.50	0.75	0.50	0.75	1.00
73	2.01	1.94	1.69	1.74	1.74	1.66	1.63	4.56	3.76	3.68	3.57	3.62	3.61	3.47
76	1.56	1.54	1.36	1.37	1.38	1.28	1.23	3.56	3.01	2.88	2.85	2.90	2.88	2.86
79	1.23	1.22	1.09	1.11	1.11	1.01	0.95	2.73	2.40	2.29	2.27	2.41	2.42	2.36
82	1.00	0.99	0.91	0.92	0.96	0.82	0.73	2.12	1.91	1.82	1.81	1.89	1.90	1.88

Table 11: Average G*.sin(δ), Stiffness and m-value for PAV-aged PG 76-28

PAV-aged PG 76-28 with Anti-Stripping Additives								
Description	T (^{o}C)	Aged	Adhere HP-Plus (%)			Perma Tac Plus (%)		
			0.25	0.50	0.75	0.50	0.75	1.00
G*.sin(δ)/(MPa)	10.0	6.24	6.15	6.03	5.61	5.37	5.19	5.02
	13.0	4.92	4.71	4.58	4.29	4.14	3.98	3.81
	16.0	3.72	3.55	3.38	3.14	3.03	2.73	2.46
S(t) / (MPa)	-15	61.4	59.4	53.4	53.9	59.3	59.5	56.4
	-18	99.1	93.7	89.2	87.6	87.3	86.0	81.2
	-21	112.7	106.7	100.8	101.6	111.5	109.8	106.6
m-value	-15	0.322	0.322	0.311	0.318	0.313	0.317	0.315
	-18	0.309	0.309	0.302	0.301	0.306	0.306	0.301
	-21	0.268	0.261	0.257	0.252	0.260	0.249	0.248

Table 12: Test Temperatures at which PG 76-28 Reached Critical Values

Binder	**DSR (^{o}C)**	**RTFO-DSR (^{o}C)**	**PAV- DSR (^{o}C)**	**S(t) (^{o}C)**	**m-value (^{o}C)**
PG 76-28	82.0	81.6	12.9	<-34	-18.6
0.25% Adhere HP-Plus	81.8	80.2	12.4	<-34	-18.6
0.50% Adhere HP-Plus	80.4	79.5	12.2	<-34	-18.1
0.75% Adhere HP-Plus	80.6	79.4	11.4	<-34	-18.1
0.50% Perma Tac Plus	81.1	80.3	10.9	<-34	-18.4
0.75% Perma Tac Plus	79.0	80.2	10.5	<-34	-18.3
1.00% Perma Tac Plus	78.4	79.9	10.1	<-34	-18.0

Table 13: True Grade of PG 76-28 with Anti-Stripping Additives

Binder	**High Grade (^{o}C)**	**Low Grade (^{o}C)**	**Performance Grade**
PG 76-28	81.6	-28.6	81.6-28.6
0.25% Adhere HP-Plus	80.2	-28.6	80.2-28.6
0.50% Adhere HP-Plus	79.5	-28.1	79.5-28.1
0.75% Adhere HP-Plus	79.4	-28.1	79.4-28.1
0.50% Perma Tac Plus	80.3	-28.4	80.3-28.4
0.75% Perma Tac Plus	79.0	-28.3	79.0-28.3
1.00% Perma Tac Plus	78.4	-28.0	78.4-28.0

Discussion of Results

Unmodified PG 64-22 and Anti-Stripping Additives

From Table 2 it was observed that the high grading temperatures consistently decreased with an increase in the additive percentages. The change in δ for unaged binder was less than 3^{o}C. Therefore, PG 64-22 is not expected to undergo any significant changes in terms of its viscous-elastic response during its early stage. However, δ decreased by approximately 4 to 5^{o}C, when it was subjected to short-term aging in the RTFO. Thus, short term aging appears to have a notable effect on the visco-elastic response of the asphalt binder. In view of these results, during and following short term aging, the asphalt binder may behave less like a viscous material under the application of load.

PG 64-22 with Adhere HP-Plus, exhibited a reduction in δ by approximately 50% after being subjected to long term aging in the PAV. Therefore, this additive has significant effect on visco-elastic response after long term aging. In general, δ increases slightly with an increase in additive percentage. However, no definite pattern in increase was observed. Considering G*.sin(δ), variation of low grade temperature was consistent with increase in Adhere HP-Plus percentage. It is also important to note from Table 3 that the G*.sin(δ) was lowered by approximately 200% when the test temperature increased by 9^{o}C (from 19^{o}C to 28^{o}C). Consequently, PG 64-22 is expected to show greater susceptibility to thermal cracking when the pavement temperature changes even within 10^{o}C during its service life.

Cracking caused by a single thermal cycle is related to the binder S(t) at the temperature at which cracking occurs and this temperature is referred as the “limiting temperature” (Roberts et al., 1996). From Table 3, it is clear that the S(t) increases when the test temperature is lowered. Therefore, for Adhere HP-Plus with PG 64-22, as S(t) increases, thermal stresses developed in the HMA pavements (due to thermal shrinking) increase, and thermal cracking be more likely to occur. However, it is important to note that the specified limiting S(t) of 300MPa could not be reached in this study. Accordingly, PG 64-22 with the same additive is expected to not to have significant thermal cracking even when the pavement temperature drops below low grade temperature by approximately 10^{o}C. Further, from Table 3, the maximum S(t) was 185MPa at -15^{o}C. It should be pointed out that by using the S(t), the specified limit of 300MPa would be reached at a very low temperature. Therefore, establishing a low grade temperature using the S(t) was not feasible in this study. However, it is safe to assume that it would be very low and the corresponding temperature grade would also be very low.

From Table 4 , comparing both additives at the same dosage levels of 0.50% and 0.75%, the changes in both high and low grade temperatures are slightly higher for Adhere HP-Plus than Perma Tac Plus. It should also be noted that these changes in grades are relatively small for both additives. i.e., 0.7^{o}C and 0.1^{o}C for unaged samples; 1.3^{o}C and 0.9^{o}C for RTFO-aged samples at 0.50% of Adhere HP-Plus and Perma Tac Plus, respectively.

Polymer modified PG 70-28 and Anti-Stripping Additives

Referring to Table 6, at each temperature, the G*/sin(d) values exhibited a linear variation with the selected percentages of Adhere HP-Plus (r^2 = 0.9994). This correlation can be used to predict the G*/sin(δ) for an unknown Adhere HP-Plus percentage (between 0.25% and 0.75%) at a particular temperature, if two values of G*/sin(δ) are known. For example, provided the G*/sin(δ) at 64^{o}C with the addition of 0.25% and 0.75% Adhere HP-Plus, one can calculate the G*/sin(δ) for the addition of 0.60% without running a DSR test. Referring to Table 6 again, similar to Adhere HP-Plus, the G*/sin(δ) values for Perma Tac Plus indicated a r^2 of 0.9984. The high grade temperature of unaged PG 70-28 itself was 73^{o}C instead of 70^{o}C. For rutting resistance, a higher G*/sin(d) value is preferable (Anderson et al., 1991). Therefore, Oklahoma PG 70-28 even before adding any additives may show less susceptibility to permanent deformation or rutting.

The complex modulus, G*, also decreases with an increase in additive percentage. The higher the G* value, the stiffer the asphalt binder and thus more resistant to rutting (Roberts et al, 1996). Nevertheless, the specified parameter which is a combination of G* and δ as specified by the AASHTO M 320, G*/sin(δ), will govern the performance of pavement related to rutting at its early stage. The d exhibited an increasing trend with an increase in additive percentage. Further, the δ values were slightly higher for Perma Tac Plus than (0.5-1.0 deg.) for Adhere HP-Plus. For rutting resistance, a high G* and low δ are both desirable (Bahia et al., 1995). Also, it is important to note that factors such as cost and handling should also be considered in selecting a binder.

Referring to Table 7, the S(t) did not show any considerable variation with different percentages of Adhere HP-Plus. However, it showed significant variation with Perma Tac Plus. The maximum S(t) attained in this case was 212MPa at -21^{o}C for the addition of 0.25% Adhere HP-Plus. From Table 7, in general, S(t) indicated a decreasing trend with an increase in Adhere HP-Plus percentage, while Perma Tac Plus exhibited an increasing trend. With decreasing S(t), the thermal stresses developed in the pavement due to thermal shrinkage also decreases, and thermal cracking becomes less likely. The increase in S(t) for the addition of Perma Tac Plus clearly indicates that the pavement will undergo considerable thermal cracking.

Interestingly, it was not possible to calculate the low grading temperature using the S(t) values since they were relatively small. (Criteria: S(60) < 300MPa at -18^{o}C). However, by looking at the change in S(t), one can safely assume that it would be very low and the corresponding grading temperature would also be very low. In view of Table 8, the test temperatures at which the PAV-aged PG 70-28 reached the critical value with respect to DSR were significantly low (specified test temperature of 25^{o}C). Therefore, exact low grade temperatures could not be calculated (AASHTO M 320). However, it is safe to assume that it would be less than -40^{o}C (AASHTO M 320).

Polymer modified PG 76-28 and Anti-Stripping Additives

From Table 10, it was observed that G*/sin(δ) decreased with an increase in Adhere HP-Plus percentage. This indicates that PG 76-28 becomes relatively more prone to rutting when the percentage of Adhere HP-Plus increase. However, it was observed that the δ decreased with an increase in the additive percentage. This can be considered as a beneficial outcome, since asphalt binders behave more like an elastic material if the δ is small (Roberts et al., 1996) and hence more recoverable deformation under the application of load. Thus, it can be considered as a compensative effect for rutting. From Table 10, PG 76-28 itself exhibited a 6^o grade change based on its high grade (i.e., from 76^{o}C to 82^{o}C). In other words, PG 76-28 satisfied the unaged DSR criterion at 82^{o}C [Criterion: (G*/sin(δ) $\leq$ 1.0MPa].

The RTFO-aged PG 76-28 with higher percentage of Adhere HP-Plus did not show any significant variation in G*/sin(δ) values at higher temperatures (79-82^{o}C). This implies that the amount of Adhere HP-Plus added to PG 76-28 has little or no effect on the binder during and after the short-term aging. Specifically, both unaged and RTFO-aged PG 76-28 exhibited relatively higher values of G*/sin(δ) compared to the other asphalt binders used in this study. This may be attributed to the modification process of the asphalt binder itself. The polymer modified asphalt binder will be more resistant to deformation and exhibit enhanced elastic recoil (Collins et al., 1991). Therefore, an optimum use of Adhere HP-Plus with PG 76-28 is expected to provide better performance against rutting.

As given in Table 10, no significant variation in $G^*/\sin(\delta)$ was observed for PG 76-28 with Perma Tac Plus. This again indicates that Perma Tac Plus has very little to no effect on PG 76-28 during and after short term aging. The difference between $G^*/\sin(\delta)$ values, for RTFO-aged samples with additives and RTFO-aged samples without additive also gradually diminished. In addition, at higher temperatures (above 82°C), no noticeable effect on $G^*/\sin(\delta)$ for Perma Tac Plus was observed. One reason for this behavior is that at higher temperatures anti-stripping additives exhibits low heat stability (Taylor and Khosla, 1983).

Referring to Table 11, it was observed that PG 76-28 with Adhere HP-Plus indicated extremely low δ values. Two reasons can be attributed to these phenomena. First, samples used in this test were representing long-term aging effects, thus having a stiffer binder. Second, a polymer modified asphalt binder generally shows a lower phase angle (Collins et al., 1991). Therefore, PG 76-28 with Adhere HP-Plus would be more resistant to fatigue cracking at its intermediate temperatures. Because of this nature, PG 76-28 can be used in applications where high stresses are expected (e.g., high volume truck traffic, intersections etc.). Modified asphalt binders also have been used in extreme climatic conditions to reduce aging in desert climates and to help produce asphalt binders for low temperature applications (Angelo, 2004). Also, use of SBS in the modification process will generally both stiffen and increase the flexibility or stretchiness of the asphalt binder, improving both high and low temperature performance (Brown, 2004). In view of Table 11, the S(t) values of PG 76-28 with Adhere HP-Plus initially show little variations between the temperatures -21°C and -18°C. However, a sudden reduction in S(t) was observed when the test temperature increased from -18°C to -15°C. This indicates that, PG 76-28 will be more resistant to thermal cracking at temperatures higher than -18°C. It is also observed that the test temperatures at which the PAV-aged samples met the DSR criterion are very small. This demonstrates that PG 76-28 with these additives does not have any impact on fatigue cracking. Therefore, PG 76-28 with the selected additives is expected to have increased resistance to fatigue cracking.

The low grade temperature predicted for PG 76-28 based on the S(t) criterion is less than -34°C, as shown in Table 12. Thus, determination of true grade temperature was governed by the m-value criterion. A reduction in m-value indicates that the rate of stress relaxation also decreases (Bahia and Anderson, 1994). As indicated above, the m-values reduced with a reduction in test temperatures. This would reduce the ability of a pavement to relieve thermal stresses by flow at lower temperatures. However, the effect of these two specification parameters, S(t) and m-value, on thermal cracking is analogous to the effect of G^* and δ on rutting and fatigue cracking (Roberts et al., 1996). Therefore, PG 76-28 with selected additives is expected to enhance thermal cracking resistance.

Conclusions

From the results presented above, the following conclusions can be drawn:

1. Unmodified PG 64-22 satisfied all the Superpave Specified criteria within the selected percentages of Adhere HP-Plus. However, with 1.00% Perma Tac Plus the same binder did not pass the Superpave specified DSR criterion for unaged binder. Therefore, based on this study for PG 64-22, the use of Perma Tac Plus greater than the dosage level of 0.75% is not recommended.
2. Comparing both additives, the grade changes are higher for Adhere HP-Plus than for Perma Tac Plus. The optimum percentage of ant-stripping additives was verified to be 0.50% for both cases of PG 64-22. Further, the use of anti-stripping additives within the selected range does not significantly alter the performance grade of PG 64-22.
3. Polymer modified PG 70-28 passed the Superpave specified criteria with both additives within the prescribed percentages. For this binder, the maximum change observed in high grade temperature was 3.2°C, while it was 0.9°C in low grade temperature. In this case, the grade changes are relatively higher compared to unmodified PG 64-22.

4. For PG 76-28, the recommended optimum dosage level of both additives was verified to be 0.50%. Comparing both additives at the same dosage level, the changes in high and low grading temperatures are higher for Adhere HP-Plus than for Perma Tac Plus.
5. PG 76-28 passed the specified criteria with both additives within the tested range. The test results indicated that the binder submitted as a PG 76-28 was actually a PG 82-28. Test results indicated that the grade changes are significant compared to the other two asphalt binders. However, since the PG 76-28 itself showed a 6°C change, the subsequent changes due to the addition of additives were considered less significant. The optimum percentage was verified to be 0.50% for both additives.
6. The findings from this study are expected to be useful information in understanding the changes in performance grade of asphalt binders and their response to grade variation due to the addition of additives.

Recommendations

Three asphalt binders and two additives were examined in this study. Therefore, it is important to carry out similar study with a number of binders and additives so that researchers and highway agencies will have a better understanding of the consequences of these materials. The asphalt binders used were received from only one source. Thus, it is recommended to use asphalt binders from different sources since the quality of crude petroleum, refining process and impurities can greatly influence the quality of asphalt binders. Likewise, properties of liquid additives also vary significantly depending upon their chemical make-up and surface characteristics, among others. Therefore, it is recommended that different types of additives from several sources be used in future studies.

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References

Anderson, D. A., Christensen, D. W., and Bahia, H., (1991). Physical Properties of Asphalt Cement and the Development of Performance-Related Specifications. Asphalt Paving Technology Proceedings, Association of Asphalt Paving Technologists Session, Vol. 60, pp. 437-475.

Anderson, D. and Dukatz, E. (1982). The Effect of Anti-Stripping Additives on the Properties of Asphalt Cement. Association of Asphalt Paving Technologies, Vol. 51, pp. 298-317.

Angelo, J. D., (2004). Modified Binders and Superpave Plus Specifications. Superpave Technical Issues, Asphalt Institute.

Bahia, H. U., and Anderson, D. A., (1994). The Pressure Aging Vessel (PAV): A Test to Simulate Rheological Changes Due to Field Aging. ASTM Special Publication 1241.

Collins, J. H., Bouldin, M. G., Gelles, R., and Berker, A. (1991). Improved Performance of Paving Asphalts By Polymer Modification. Journal of the Asphalt Paving technologists technical Sessions, Vol. 60, pp. 43-79.

Huang, Y. H., (2004). Pavement Analysis and Design. 2nd Edition, Prentice Hall Inc, New Jersey, USA.

Ksaibati, K and Conner, G. L., (2004). Laboratory Evaluation of Bottom Ash Asphalt Mixes. Research Report, Department of Civil and Architectural Engineering, University of Wyoming.

Kennedy, T. W., Roberts, F. L. and Lee, K.W. (1983). Evaluation of Moisture Effects on Asphalt Concrete Mixtures. Transportation Research Record, 911. Washington D.C., National Academy Press, pp. 134-143.

Roberts, F.L., Kandahal, P.S., and Brown, E.R., (1996). Hot Mix Asphalt Materials, Mixture Design, and Construction. 2nd Edition. Lanham, Maryland: NAPA Education Foundation.

Robertson, E. R., Branthaver, F. J., Plancher, H., Duvall, J. J., Ensley, EK. E., Harnsberger, P. M., and Peterson, C. J., (1991). Chemical Properties of Asphalts and Their Relationships to Pavement Performance. Asphalt Paving Technology Proceedings, Association of Asphalt Paving Technologists Session, Vol. 60, pp. 413-436.

Selvamohan, S., Zaman, M. M., Gierhart, D.(2006). Performance Grade Changes in PG 64-22 Binder Due to Selected Additives, Accepted for Publication in the Proceedings of 7th International Congress on Advances in Civil Engineering, held in Istanbul, Turkey, October, 11-13.

Taylor, M. A. and Khosla, N. P. (1983) Stripping of Asphalt Pavements: State of the Art. Transportation Research Record 911. Washington D.C: National Academy Press. pp. 150-158.

Tunnicliff, D.G., and Root, R.E., (1984). Use of Anti-Stripping Additives in Asphalt Concrete Mixtures. National Cooperative Highway Research Program (NCHRP), Report 274.

Wasiuddin, N. M, Fogle, C. M., Zaman, M. M., and O’Rear, E. A., (2006). Effect of Anti-Stripping Additives on Surface Free Energy Characteristics of Asphalt Binders for Moisture-Induced Damage Potential. ASTM Journal of Testing and Evaluation, Vol. 35, Issue 1, pp. 36-44.

Zaman, M. M., Laguros, G, J., Wasiuddin, N. M., Coleman, J., (2005). Effect of Anti-Stripping Additives on Performance-Graded Binders in Oklahoma. Office of Research Administration Record, the University of Oklahoma (ORA 125-5259).