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Effect of Reclaimed Asphalt and Virgin Binder on Rheological Properties of Binder Blends

N. Paul Khosla[1], Harikrishnan Nair[2+], Beth Visintine[1], and Glen Malpass[1]

Abstract: With the introduction of the Superpave mix design, many questions were raised about the proper method of incorporating Reclaimed Asphalt Pavement (RAP) in Superpave. During service, the blend of aggregates and binders undergoes various physical and rheological changes that have to be considered in the design process to ensure that HMA mixtures with RAP will perform very well. The issue of the resulting blended binder stiffness is very important for designing mixes. The binder that is recovered from the RAP is stiffer than virgin binder due to the aging that has occurred during its service life. Because of this, the blended RAP-virgin binder will increase in stiffness. The objective of this paper is to investigate the rheology of RAP–virgin binder blends. Three virgin binder grades, a PG 52-28, PG58-28 and PG64-22 were blended with two different RAP binder concentrations, 20% and 40% by total binder mass. The results of the Dynamic Shear rheometer (DSR) testing of the unaged, Rolling Thin Film Oven (RTFO) and Pressure Aged Vessel (PAV) aged binder blends showed similar trends in that as the concentration of RAP binder increased from 20 to 40 percent, the stiffness of the blend increased 150 to 200 percent for the blends containing PG52-28 and PG58-28 virgin asphalts. Results also shows that virgin asphalt grade used in a particular blend seemed to have an effect on the stiffness increase of the resulting asphalt blends as the RAP binder concentration increased.

***Key words**: Binder; RAP; Rheology; Superpave.*

Introduction

It is a widely accepted fact that the use of Reclaimed Asphalt Pavement (RAP) in the construction of new asphalt pavements can be beneficial, as it provides both cost savings and reduction of environmental effects. However, the development of Superpave did not consider the use of RAP when determining the criteria for mix and pavement design. Therefore, various researches has been conducted in order to determine a procedure to measure the effects of the addition of RAP to Superpave mixtures, which resulted in guidelines developed by the Federal Highway Administration [1]. Despite the potential benefits of RAP, a legitimate concern is that since RAP contains aged asphalt binder, it may not perform as well as mixes with virgin binder. However, several studies have indicated that the structural performance of properly designed RAP mixes can be equal to and in some instances better than that of conventional HMA mixes [2, 3]. Solaimanian and Kennedy [4] showed that the variability in RAP material greatly affects the variability of the asphalt content and gradation of the production mixture, especially at higher percentages of RAP. While up to 80% RAP has been reportedly used in hot-mix asphalt pavements [5], 10-50% RAP is more typically used [6].

With the introduction of the Superpave mix design, many questions were raised about the proper method of incorporating RAP in Superpave. During service, the blend of aggregates and binders undergoes various physical and rheological changes that have to be considered in the design process to ensure that HMA mixtures with RAP will perform very well. When used at intermediate to higher percentages, an aged binder can significantly influence the properties of the blend and may affect the resultant binder grade. As asphalt binder reacts and loses some of its components during the aging process, its rheological behavior will naturally differ from virgin materials. This suggests the importance of controlling the blending process between recycled and virgin binders. If the old binder is too stiff, the blend of old and virgin binders may not perform as expected. At small percentages (up to 20%), an aged binder does not significantly affect the properties of the blend of virgin and RAP binder [7]. However, when used at intermediate to higher percentages, an aged binder can significantly influence the properties of the blend and may affect the resultant binder grade. Asphalt binder ages and hardens through various mechanisms. The level of aging that asphalt binder experiences during production and service also depends on the void content of the HMA. Recovered binder from porous HMA has shown significantly greater stiffness than regular HMA [8]. Stockpiling also accelerates binder aging as the material is more prone to air exposure and oxidation [9]. Oliver [10] investigated the blending process between aged and virgin asphalt binders using mechanical testing. Based on the results, authors postulated that aged and virgin binders might not fully blend in HMA containing RAP materials due to the formation of agglomerates of aggregate and filler, making it harder for the fresh binder to penetrate. Therefore, incomplete mixing between virgin and aged binder was expected to result in areas with soft binder. This results in an overall softer binder than regular HMA. Huang *et al*. [11] conducted a study to investigate the blending between aged and virgin binders in HMA containing RAP. To assess the blending due to pure mechanical mixing, RAP materials were blended with virgin aggregates only (*i.e.*, no virgin binder was added). After mixing, it was determined that the asphalt

[1] North Carolina State University, Raleigh, NC 27695, USA.
[2] Virginia Center for Transportation Innovation and Research, 530 Edgemont Road, Charlottesville, VA 22903, USA.
[+] Corresponding Author: E-mail Harikrishnan.Nair@vdot.virginia.gov
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binder content in RAP materials was reduced by about 11% due to pure mechanical mixing. The properties of aged binder are also affected by the level of moisture damage on the existing pavement prior to recycling. In principle, stripped HMA should not be recycled due to the probability of reoccurrence of this distress in the new HMA [12]. However, when a small percentage of RAP is used (15 to 20%) together with an anti-strip agent, samples with moisture-damaged HMA provided a comparable strength and moisture resistance to samples made with virgin materials [13]. Among the factors affecting performance of HMA with RAP, the percentage of RAP in the mixture plays a critical role. It has been reported that asphalt mixture with relatively low and medium percentage of RAP, usually referred to less than 25%, could perform as well as or even better than mixtures made of new materials [14, 15].

Experimental Investigation and Objectives

The issue of the resulting blended binder stiffness is very important for designing mixes and has been at the forefront of many research projects. The binder that is recovered from the RAP is stiffer than virgin binder due to the aging that has occurred during its service life. Because of this, the blended RAP-virgin binder will increase in stiffness. The increased stiffness increases the rut resistance of the pavement but decreases the fatigue and thermal resistance in most cases. The amount of blending that occurs between the RAP binder and virgin binder affects the amount the stiffness increases. Literature review shows that only little research work has been performed on the relative difference in RAP characteristics between source stockpiles. As first part of this study [16] material property characteristics and the associated variability of different RAP sources with respect to RAP binder content, binder stiffness, aggregate gradation and aggregate particle shape and texture were undertaken. For this study, RAP samples were obtained from asphalt plant stockpiles in four different locations in North Carolina: East Raleigh (Source A), Statesville (Source B) West Raleigh (Source C) and Castle Hayne (Source D). These RAP samples represent stockpiles managed by different contractors, with the RAP samples processed by different methods such as screening, milling and/or grinding. These RAP stockpiles may contain a majority of roadway pavement millings, while some may consist entirely or in part from parking lot demolition debris. Some stockpiles may also contain some percentage of asphalt plant rejection material, material fail to meet one or more of the designers or state agencies mixture specifications and would be rejected back into a RAP stockpile. Stockpile sources of RAP selected also represent different aggregate types. Each RAP sample was pulled from the stockpile using a front-end loader to obtain material in the middle of the stockpile height in order to reduce the effects of particle segregation. Approximately 300 to 500 kilograms (600 to 1000 pounds) of RAP material was obtained from each site. Binders were recovered from each RAP source and the rheologic properties were evaluated using the Dynamic Shear and Bending Beam Rheometers in accordance with the procedures in AASHTO TP1 and TP5. Major conclusions from this study were (i) while there were similarities in some measured characteristics such as binder content, aggregate gradation and binder stiffness between two or even three of the RAP sources, data from these tests indicate that the characteristics of RAP materials in general cannot be assumed to be similar for the purposes of asphalt mixture design and (ii) general assumptions, such as the grade of virgin binder to be used in a mixture containing RAP does not need to be modified or shift downward in stiffness if the percentage of RAP to be used in a mixture is less that 15% by weight, should be used with caution. Indeed the results of binder rheological testing in this study showed that the measured stiffness of the hardest extracted RAP binder is more than twice that measured for the softest sampled RAP binder. This study also revealed [16] that the properties of the aggregate and binder in RAP materials should be evaluated completely before design and regularly during the production of asphalt mixtures containing RAP to ensure the satisfactory performance of the constructed pavement.

The objective of this paper is to investigate the rheology of RAP–virgin binder blends. Three virgin binder grades, PG 52-28, PG58-28 and PG64-22 were blended with two different RAP binder concentrations, 20% and 40% by total binder mass. During the rheologic characterization of the reclaimed RAP binder performed [16], it was determined that the binder reclaimed from the Statesville RAP (Source B) was the hardest of the four RAP sources sampled, while the binder from the Raleigh East RAP (Source A) source was the relative softest of those sampled. It was decided that only the binders reclaimed from these two sources were blended with the virgin binders to investigate the effects of RAP binder concentration on the stiffness of a RAP–virgin binder blend. The blended binders were tested in the DSR as unaged as well as after artificially aging using the RTFO and PAV. All the blended binder treatments were tested using the same sequential increasing temperature sweep test procedure, covering the same range of temperatures.

Results and Discussion

DSR Testing of Unaged and RTFO Blended Binders

The results of the DSR testing of the unaged blended binders are summarized in Table 1. These results show that doubling the RAP binder concentration from 20% to 40% resulted in an increase in stiffness of about 200 to 300 percent for blends containing PG52 virgin binder. The stiffening effect from the addition of reclaimed RAP binder was less pronounced as the stiffness of the virgin binder increased. Doubling the concentration of reclaimed RAP binder for blended binders containing PG64 virgin binder resulted in a stiffness increase of about 150%. The addition of 20% of RAP binder increased the stiffness of the binder blend one grade higher than that of the virgin binder. As the RAP binder concentration increased to 40% the stiffness of the blend increased 2 grades higher than that of the virgin binder.

DSR testing of the RTFO results are also summarized in Table 1. The trends were similar to those of unaged blended binder. Doubling the RAP binder concentration from 20% to 40% resulted in an increase in binder stiffness of about 200 to 300 % for RTFO aged blends containing PG52 virgin binder and about 150 to 200 % for RTFO aged blends containing PG64 virgin binder, respectively. The addition of 20% of RAP binder increased the stiffness of the RTFO aged binder blend one grade higher than that of the virgin

Table 1. Result of DSR Testing of Unaged and RTFO Aged Blended Binders.

Aging	Virgin Binder Grade	RAP Source	% RAP	Average $G^*/\sin\delta$ at Test Temperature				
				52°C	58°C	64°C	70°C	76°C
Unaged	PG52-28	Source A	20	3.38	1.51	0.68	0.33	0.17
			40	9.27	4.02	1.81	0.85	0.42
		Source B	20	3.01	1.32	0.62	0.30	0.16
			40	6.99	3.08	1.40	0.67	0.34
	PG58-28	Source A	20		2.66	1.25	0.63	0.33
			40		5.87	2.86	1.36	0.69
		Source B	20		2.47	1.18	0.60	0.32
			40		4.43	2.10	1.08	0.56
	PG64-22	Source A	20			2.85	1.34	0.67
			40			4.39	2.10	1.06
		Source B	20			2.48	1.19	0.58
			40			4.62	2.20	1.05
RTFO	PG52-28	Source A	20	10.75	4.63	2.10	0.97	0.49
			40	30.87	13.45	5.89	2.73	1.26
		Source B	20	8.54	3.70	1.66	0.78	0.38
			40	25.21	10.97	4.91	2.24	1.11
	PG58-28	Source A	20		10.61	5.06	2.47	1.24
			40		25.23	13.89	6.69	3.26
		Source B	20		9.12	4.36	2.11	1.08
			40		20.71	9.85	4.81	2.34
	PG64-22	Source A	20			9.39	4.35	2.12
			40			18.01	8.40	4.02
		Source B	20			7.41	3.51	1.73
			40			14.72	6.96	3.41

Table 2. Results of DSR Testing of PAV Aged Blended Binders.

Virgin Binder Grade	RAP Source	% RAP	Average $G^*\sin\delta$ at Test Temperature				
			16°C	19°C	25°C	28°C	31°C
PG52-28	Source A	20	5887	3966	1785	1169	770.1
		40	9871	6970	3511	2360	1509
	Source B	20	5547	3631	1566	1012	656.6
		40	7884	5413	2609	1748	1173
PG58-28	Source A	20		5637	2760	1862	1191
		40		8932	4841	3465	2476
	Source B	20		5511	2670	1793	1194
		40		3966	4022	2876	1952
PG64-22	Source A	20			4957	3401	2339
		40			6021	4210	2954
	Source B	20			4469	2795	1638
		40			5172	3410	2526

binder used in the blend. As the RAP binder concentration increased to 40% the stiffness of the RTFO aged blend increased three grades higher in the case of the blends with PG52 and PG58 virgin binders and approximately two grades in the case of the blend containing the PG64 virgin binder.

DSR Testing of PAV Aged Blended Binders

Table 2 presents the DSR testing of PAV aged blended binders. An increase in binder concentration from 20% to 40% saw an increase in PAV aged binder stiffness of about 160% to 200% for blended binders containing PG52 virgin binders, while doubling the concentration in blended binders containing PG64 virgin binder showed an increase in binder stiffness for the blend of about 100% to 150%. Again, the grade of the virgin binder seemed to affect the overall stiffness increase in a RAP–binder blend as the concentration of RAP binder increased. A blend containing 20% RAP binder yielded measured stiffness values comparable to one grade higher than the grade of the virgin binder used in the blend. The binder blend containing a PG52-28 virgin binder and 20% RAP binder met the grading requirements of $G^*(\sin\delta) \leq 5{,}000$ kPa at 19°C, which is required by AASHTO MP1 for a PG58-28. A binder blend of PG52-28 and 40% reclaimed RAP binder meets the grade requirements of a PG64-22 ($G^*\sin\delta \leq 5{,}000$ kPa at 25°C), which

Table 3. BBR Test Results for PAV Aged Blended Binders at –12°C.

Virgin Binder Grade	RAP Source	% RAP	Average S, MPa (std. dev.)	Average m (std. dev.)
PG - 22	Source B	20	15	0.339
		40	181	0.33
	Source A	20	165	0.334
		40	193	0.348
PG - 28	Source B	20	91.2	0.383
		40	135	0.329
	Source A	20	98.6	0.364
		40	148	0.316

was two grades higher than the virgin binder. However, the blend of PG64-22 and 40% RAP binder met the requirements of a PG70-22 ($G^*\sin\delta \leq$ 5,000 kPa at 28°C), which was one grade higher than the virgin binder used in the blend.

BBR Testing of PAV Aged Blended Binders

Table 3 shows the results of BBR testing for PAV aged blended binders. For the blended binders based on –22 virgin grade binder, doubling the RAP binder concentration from 20 to 40 percent increased the stiffness of the blend by about 120%. For the blends based on the –28 virgin binder grade, the same increase in RAP binder caused a stiffness increase of about 150%. It should also be noted that all of the PAV aged binder blends fulfilled the low temperature grading requirements for a PAV aged binder graded as a –22, regardless of virgin binder grade, RAP source or RAP concentration.

Binder Blending Charts

The rheological properties of the virgin -RAP binder blends were combined with those of virgin and RAP binders to construct blending curves for unaged and PAV aged binders with respect to RAP binder concentration over a range of temperatures.

Blending Charts for Unaged Binders

For a given test temperature, the RAP content that yields $G^*/\sin\delta$ = 1.00 kPa can be thought of as the minimum RAP binder content needed to satisfy the high temperature rheological stiffness requirements for an unaged binder. The blending charts for the virgin binders of PG52-28, PG58-28 and PG64-22 are shown in Fig. 1. An exponential model was fit to the data to provide a numerical relation between stiffness and RAP binder concentration. Table 4 shows the numeric models and the RAP binder concentration that satisfied $G^*/\sin\delta$ = 1.0 kPa for each virgin binder grade and test temperature used in this testing. The binder blends containing the Source A reclaimed RAP binder always yielded a binder blend that had a higher $G^*/\sin\delta$ value that a binder blend containing the Source B RAP, therefore the minimum RAP content required to meet the minimum requirements of $G^*/\sin\delta$ = 1.00 was always more if the Source B RAP binder was used. This observation suggests that if the relative age or hardness of a RAP is in question, for design purposes

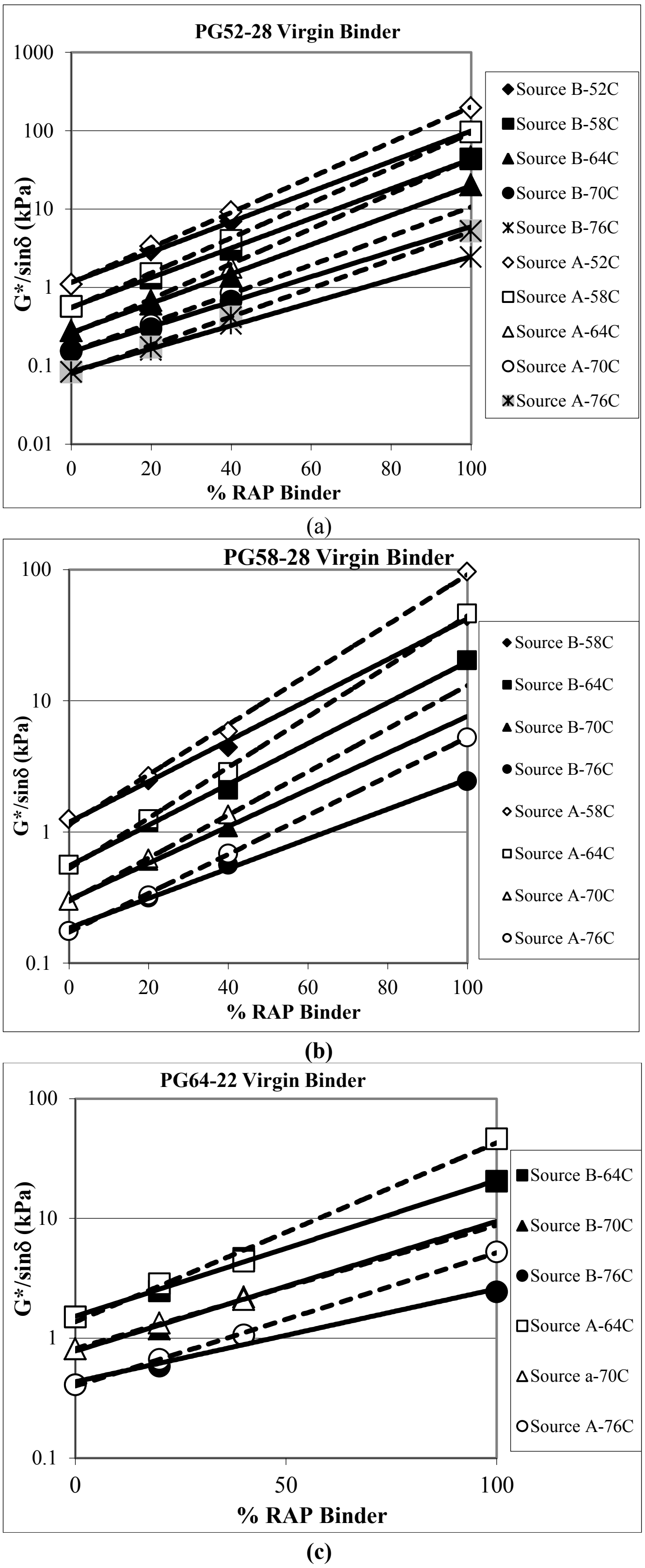


Fig. 1. Blending Charts for Unaged Binders Containing PG 52-28 (a), PG 58-22 (b), and PG64-22 (c) Virgin Binders.

it is more conservative to assume that binder is relatively soft and to increase the RAP concentration to ensure fulfilling the rheological requirements of AASHTO MP1 for unaged binders.

Table 4. Minimum Percentage of RAP Binder to Satisfy $G^*/\sin\delta = 1.00$ for Unaged Binders.

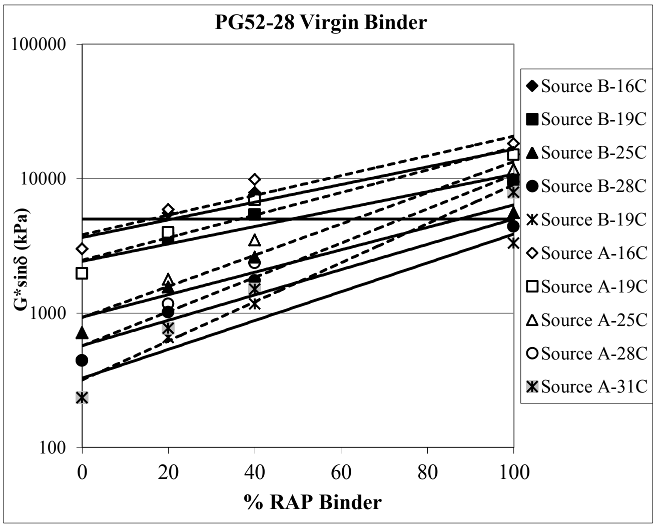
Virgin Binder Grade	RAP Source	Temperature °C	$G^*/\sin\delta = Ae^{B(\%RAP)}$ A	B	Minimum %RAP
PG52	Source B	52	---	---	0
		58	0.5588	0.0435	13.37
		64	0.2648	0.0431	30.83
		70	0.151	0.0368	51.37
		76	0.0842	0.0338	73.21
	Source A	52	---	---	0
		58	0.548	0.514	11.70
		64	0.2549	0.515	26.54
		70	0.1505	0.0426	44.45
		76	0.796	0.0418	60.54
PG58	Source B	58	---	---	0
		64	0.5519	0.0358	16.60
		70	0.3041	0.0322	36.96
		76	0.1855	0.0261	64.55
	Source A	58	---	---	0
		64	0.5268	0.0444	14.43
		70	0.2972	0.0378	32.10
		76	0.1724	0.0342	51.40
PG64	Source B	64	---	---	0
		70	0.7818	0.0249	9.88
		76	0.4332	0.0179	46.73
	Source A	64	---	---	0
		70	0.8190	0.0237	8.42
		76	0.3989	0.0256	35.90

Blending Charts for PAV Aged Binders – DSR Test Results

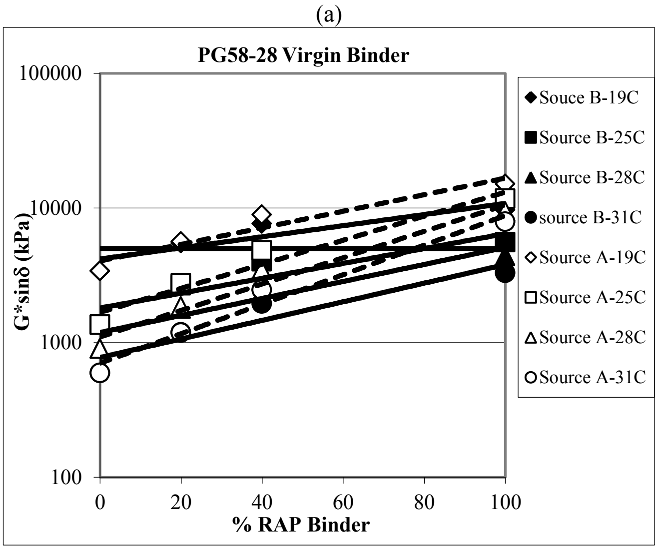
For PAV aged binders, Fig. 2 provides the blending charts for the virgin binders of PG52-28, PG58-28 and PG64-22, respectively. The virgin binder, RAP binder concentrations and temperature combinations that fulfilled the rheological performance requirement for PAV aged binders ($G^*\sin\delta \leq 5000$ kPa) can be seen in these figures. Table 5 gives the maximum RAP binder concentration allowed in the blend so as not to exceed $G^*\sin\delta$ = 5000 kPa requirement for each virgin binder grade and test temperature used in this testing. The trends of both RAP sources were similar to those of unaged binders.

Blending Charts for PAV Aged Binders – BBR Test Results

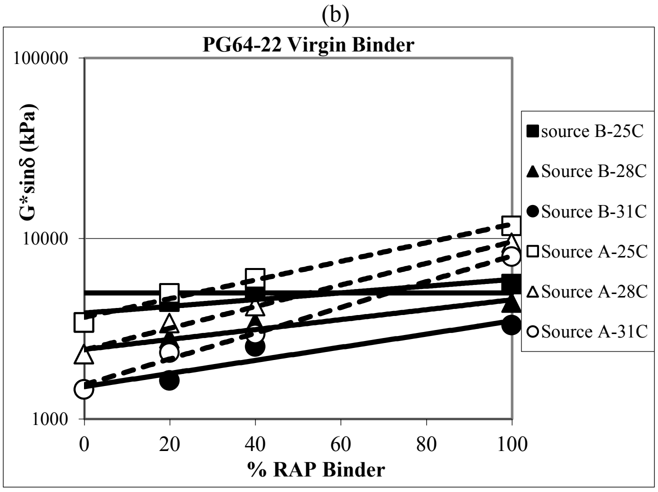
Figs. 3 and 4 show the relation of creep stiffness and m-values to RAP binder concentration. The figures indicate that the binders containing source A and source B were similar in stiffness through all RAP concentrations and that at –12°C, all RAP concentrations satisfied the creep stiffness ≤300 MPa specification requirements, which are shown on the charts as a bold horizontal line. The figures show that the specification requirements for m – value ≥ 0.300, which is again depicted on the charts as a bold horizontal line, are fulfilled at –12°C at RAP concentrations of less than about 60% for



(a)



(b)



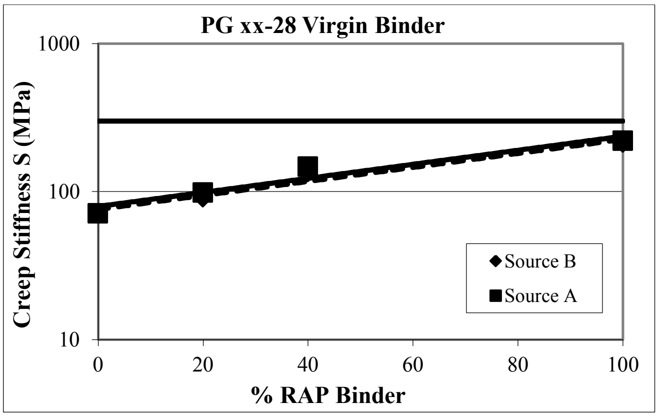
(c)

Fig. 2. Blending Charts for PAV Binders Containing PG 52-28 (a), PG 58-22 (b), and PG64-22 (c) Virgin Binder.

binders containing the Source A RAP binder and at a maximum of 75% for binders containing Source B RAP. It can then be assumed from this data that the low temperature grading requirement with respect to the BBR is not the controlling specification for the

Table 5. Maximum Percentage of RAP Binder to Satisfy $G^*\sin\delta = 5000$ kPa for PAV Binders.

Virgin Binder Grade	RAP Source	Temperature °C	$G^*/\sin\delta = Ae^{B(\%RAP)}$ A	B	Maximum % RAP
PG52 - 28	Source B	16	3645.8	0.0151	20.9
		19	2424	0.0149	48.6
		25	931.7	0.0192	87.5
		28	572.2	0.0217	99.9
		31	327.1	0.0247	----
	Source A	16	3819.5	0.0169	15.9
		19	2470.3	0.0193	36.5
		25	925.1	0.0267	63.2
		28	569.72	0.0293	74.1
		31	317.5	0.0335	82.3
PG58 -28	Source B	19	4182.8	0.0095	18.8
		25	1807.4	0.0127	80.1
		28	1190.3	0.0145	98.9
		31	775.6	0.0159	---
	Source A	19	4049.6	0.0142	14.8
		25	1679.7	0.0206	52.9
		28	1104.6	0.0226	66.8
		31	703.7	0.0252	77.8
PG64 -22	Source B	25	3863.1	0.0043	60.0
		28	2431.6	0.0063	---
		31	1513.8	0.0084	---
	Source A	25	3660.2	0.0119	26.2
		28	2416.2	0.0138	52.7
		31	1549.6	0.0164	71.4



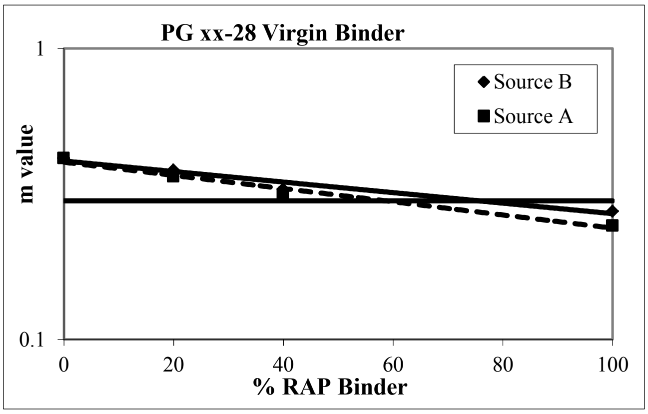
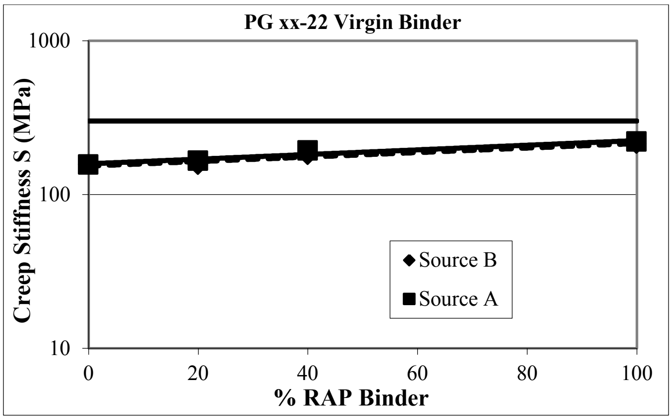


Fig. 3. Creep Stiffness and m-value for PAV Aged BinderContaining PG xx-28 Virgin Binder.



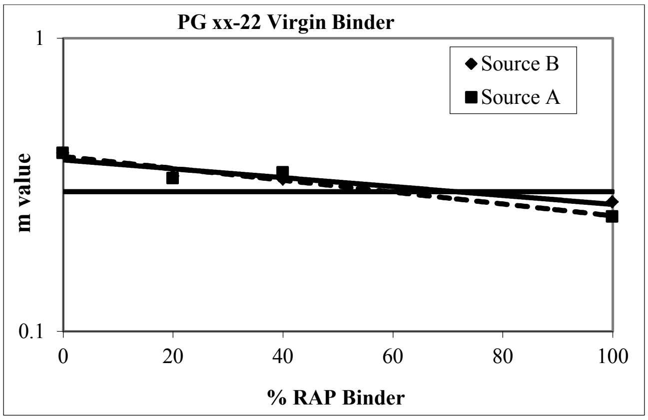


Fig. 4. Creep Stiffness and m-value for PAV Aged Containing PG xx-22 Virgin Binder.

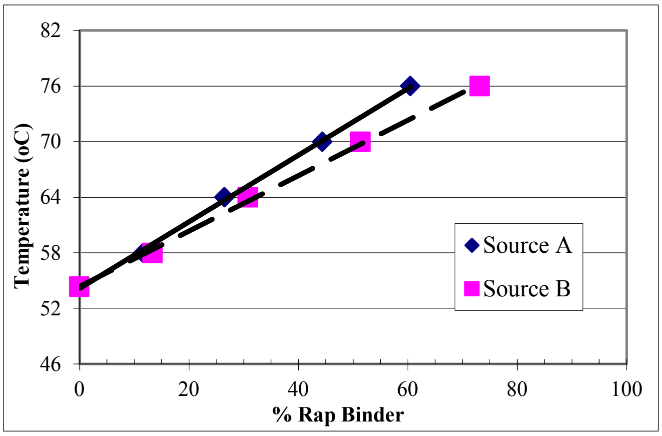
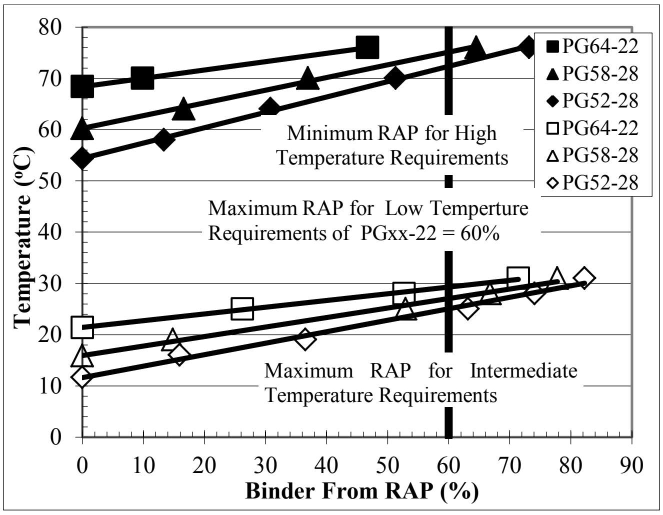


Fig. 5. Iso-Stiffness Chart for Unaged Binder Blends Containing PG58-28 Virgin Binder.



Fig, 6. Iso-Stiffness Blending Chart.

selection of RAP content to be used in an asphalt mixture.

ISO-Stiffness Binder Blending Charts

The information compiled in Tables 4 and 5 gives either maximum or minimum RAP binder concentrations that satisfied the applicable rheological binder requirements for the test method (and aging condition) for each test temperature used in this study. The various combinations of temperature and RAP binder combinations provided the same resulting stiffness for a given test method and aging condition; $G^*\sin\delta$ = 1.00 kPa for unaged binders, $G^*\sin\delta$ = 2.2 kPa for RTFO aged binders, $G^*\sin\delta$ = 5000 kPa for PAV aged binders and so on. Fig. 5 shows the temperature- RAP concentration relationship for unaged binders of Source A and Source B reclaimed RAP binders blended with PG52-28 virgin performance graded asphalt. The two trend lines through the data points for the Source A and B reclaimed RAP binders represent an estimate of the temperature – RAP binder concentration needed to satisfy $G^*\sin\delta$ = 1.00 kPa. To use the iso-stiffness curves for the design of mixtures containing RAP, it would be necessary to construct these lines for unaged binder blends ($G^*\sin\delta$ = 1 kPa), RTFO aged blends ($G^*\sin\delta$ = 2.2 kPa), PAV aged blends ($G^*\sin\delta$ =5000 kPa, S = 300 MPa and m – value = 0.300) for the virgin binder blend and RAP binder source to be used for a specified project.

To further simplify the design of mixtures containing RAP using these iso-stiffness charts, several assumptions and observations must be pointed out:

- For binder specifications that require a minimum value for a certain rheologic property (*i.e.* $G^*/\sin\delta \geq$ 1 kPa) it is more conservative to construct iso-stiffness curves for the softest reclaimed RAP binder encountered in this study, which was the RAP from Source B. In other words, for a given virgin binder grade and RAP concentration, if it is assumed that the reclaimed RAP binder is generally not as age hardened as most other reclaimed RAP binders; then if the minimum rheological requirements are met using this softer binder, the minimum requirement will also be satisfied for harder reclaimed binders.
- For a given virgin binder grade and RAP concentration, the minimum percentage of RAP required to meet the rheologic requirements for unaged binders ($G^*/\sin\delta \geq$ 1 kPa) is always higher than the minimum binder content required to meet the rheological requirements of RTFO aged binders ($G^*/\sin\delta \geq$ 2.2 kPa) for all binder blends tested in this study. If the requirement for unaged binders is satisfied assuming a soft reclaimed RAP binder, then the requirements for RTFO aged binders are also satisfied.
- All of the reclaimed RAP binders tested in this study fulfill the creep stiffness (S) ≤ 300 MPa at –12°C, meaning they meet these requirements for binders low temperature graded as PGxx – 22. Therefore, all binder blends containing any concentration of these reclaimed RAP binders should also meet this specification.
- The only low temperature rheological parameter that was found to restrict the amount of RAP binder in a given blend was the m-value, which must be greater than 0.300 at –12°C in order for a binder to be graded as a PGxx-22. Regardless of the low temperature grading of the virgin binder (either –28 or –22 in this research) the maximum concentration of RAP allowed for a binder to satisfy the m - value requirements was 60%.

With these observations in mind, a simplified iso-stiffness chart was constructed as shown in Fig. 6. This chart can give either the maximum and minimum RAP concentration for different virgin binder grades, or the virgin binders that will be required for a range of RAP concentrations. For example, if a contractor wishes to use a PG64-22 virgin graded asphalt for a construction project that requires that same grade of binder, but would like to determine what percentage of RAP can use and still fulfill the binder grading requirements for the project, they could first check the minimum amount of RAP required to meet the specifications. They locate 64°C on the y-axis of the chart and move horizontally until they intersect the line for a PG64-22 virgin asphalt binder. In this case, the iso-stiffness line for a PG64-22 intersects the y-axis at a temperature higher than 64°C, meaning there is no minimum required RAP content in this case. To determine the maximum RAP binder content, the user selects 25°C on the y-axis, which is the intermediate temperature requirement for a PG64-22, and moves horizontally across the chart until intersection with the intermediate temperature iso-stiffness line for a PG64-22 binder. The percentage of RAP binder that corresponds to that intersection point on the x-axis is the maximum allowable percentage of RAP allowed in order to fulfill the intermediate temperature requirements, which is 27%. This percentage is less than the maximum allowed to satisfy the low temperature requirements for a PGxx-22 graded binder, which is 60%; so the contractor can use between 0% and 27% RAP binder and fulfill the binder specification requirements for the project.

Summary and Conclusions

The rheological properties were determined for binder blends containing three different grades of virgin binders (PG52-28, PG58-28 and PG64-22), two concentrations of reclaimed RAP binder (20 and 40 percent by mass) from two different RAP sources.

From the results of this study, the following conclusions are made:

1. The measured stiffness of the hardest extracted RAP binder was more than twice that measured for the softest sampled RAP binder. Assuming the stiffness of RAP binders are generally the same can lead to performance deficiencies if the stiffness of the RAP binder is not correctly measured or accounted for during design.
2. The results of the DSR testing of the unaged, RTFO and PAV aged binder blends showed similar trends in that as the concentration of RAP binder increased from 20 to 40 percent, the stiffness of the blend increased 150 to 200 percent for the blends containing PG52-28 and PG58-28 virgin asphalts. However, the doubling the RAP binder concentration over the same range saw a stiffness increase of about 100 to 150 percent for blends containing PG64-22 virgin asphalt. The virgin asphalt grade used in a particular blend seemed to have an effect on the stiffness increase of the resulting asphalt blends as the RAP binder concentration increased.
3. For binder specifications that require a minimum value for a certain rheologic property (*i.e.* $G^*/\sin\delta \geq 1$ kPa), it is more conservative to assume a softer reclaimed RAP binder. In other words, for a given virgin binder grade and RAP concentration, if it is assumed that the reclaimed RAP binder is generally softer than most other reclaimed RAP binders, then if the minimum rheological requirements are met using this softer binder, the requirement will also be satisfied for harder reclaimed binders.
4. For a given virgin binder grade and RAP concentration, the minimum percentage of RAP required to meet the rheologic requirements for unaged binders ($G^*/\sin\delta \geq 1$ kPa) is always higher than the minimum binder content required to fulfill the requirements of RTFO aged binders ($G^*/\sin\delta \geq 2.2$ kPa) for all binder blends tested in this study. If the requirement for unaged binders is satisfied assuming a soft reclaimed RAP binder, then the requirements for RTFO aged binders are also met.
5. All of the reclaimed RAP binders tested in this study fulfill the creep stiffness (S) $\leq$ 300 MPa at –12°C, meaning they satisfy these requirements for binders low temperature graded as PGxx – 22. Therefore, all binder blends containing any concentration of these reclaimed RAP binders should also meet this specification.
6. The only low temperature rheological parameter that was found to restrict the amount of RAP binder in a given blend was the m-value, which must be greater than 0.300 at –12°C in order for a binder to be graded as a PGxx-22. Regardless of the low temperature grading of the virgin binder (either –28 or –22 in this research) the maximum concentration of RAP allowed for a binder to satisfy the m - value requirements was 60%.

References

1. Bukowski, J.R. (1997). *Guidelines for the Design of Superpave Mixtures Containing Reclaimed Asphalt Pavements*, Superpave Mixture Expert Task Group, Federal Highway Administration, Washington, DC, USA.
2. Little, D.H. and Epps, J.A. (1980). Evaluation of Certain Structural Characteristics of Recycled Pavement Materials, *Association of Asphalt Paving Technologists Proceedings*, Vol. 49, pp. 219-251.
3. Brown, E.R. (1984). Evaluation of Properties of Recycled Asphalt Concrete Hot Mix, *Final Report No. CL-84-2*, U.S. Army Engineer Waterways Experiment Station.
4. Solaimanian, M. and Kennedy, T.W. (1995). *Production Variability Analysis of Hot-Mixed Asphalt Concrete Containing Reclaimed Asphalt Pavement*, Center for Transportation Research, Bureau of Engineering Research, The University of Texas, Austin, Texas, USA.
5. FHWA (1993). Recycling of Asphalt Pavements Using at Least 80 Percent Recycled Asphalt Pavements (RAP). *Report No. FHWA-RD-93-088*, Engineering and Environmental Aspects of Recycled Materials for Highway Construction, Environmental Protection Agency and Federal Highway Administration.
6. Flynn, L. (1992). Three States OK More RAP in Recycling Specs: Asphalt Recycling and Reclaiming, *Roads and Bridges.*
7. McDaniel R.S., Soleymani, H., Anderson, R.M., Turner, P., and Peterson, R. (2000). Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method, *NCHRP Web Document 30 (Project D9-12): Contractor's Final Report*, National Cooperative Highway Research Program.
8. Kemp, G.R. and Predoehl, N.H. (1981). A comparison of field and laboratory environments on asphalt durability, *Proceedings of the Association of Asphalt Paving Technologists*, No. 50, pp. 492-537.
9. McMillan, C. and Palsat, D. (1985). Alberta's experience in asphalt recycling, *Proceedings of the Canadian Technical Asphalt Association*, 30, pp.148-167.
10. Oliver, J.W.H. (2001). The Influence of the Binder in RAP on Recycled Asphalt Properties, *Road Materials and Pavement Design*, 2(3), pp. 311-325.
11. Huang, B., Li, G., Vukosavljevic, D., Shu, X., and Egan, B.K. (2005). Laboratory Investigation of Mixing Hot-Mix Asphalt with Reclaimed Asphalt Pavement, *Transportation Research Record*, No. 1929, pp. 37-45.
12. Karlsson, R., and Isacsson, U. (2006). Material-Related Aspects of Asphalt Recycling - State of the Art, *Journal of Materials in Civil Engineering*, 18(1), pp. 81-92.

13. Williams, B. and Amirkhanian, S.N. (1993). Recyclability of Moisture-Damaged Flexible Pavements, *Journal of Materials in Civil Engineering*, 5(4), pp. 510-530.
14. McDanial, R. and Nantung, T. (2005). Designing Superpave Mixes with Locally Reclaimed Asphalt Pavement: North Central States Jointly Fund Study, *TR News*, No. 239, pp. 28-30. Online http://gulliver.trb.org/publications/trnews/trnews239rpo.pdf, Last Accessed November 2010.
15. Newcomb, D.E., Brown, E.R., and Epps, J.A. (2007). Designing HMA Mixtures with High RAP Content: A Practical Guide, *Quality Improvement Series 124*, National Asphalt Pavement Association.
16. Khosla, N.P., Nair, H., Visintine, B., and Malpass, G. (2009). Material Characterization of Different RAP Sources. *International Journal of Pavements*, 8(1-2-3), pp.13-24.