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The effects of rejuvenating agents on recycled aged CRM binders

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The recycling of asphalt pavements containing crumb rubber modifier (CRM) modified binders is increasing in areas having these types of asphalt pavements more than 10 or 15 years old. The performance and physical and rheological properties of the blends of aged CRM binders containing rejuvenating agents due to the presence of CRM have not been considered in detail. In this study, two CRM binders and one control binder of PG76-22 were artificially aged and then used as recycled materials by adding different rejuvenating agents, i.e. a rejuvenator and a softer binder. The properties of the blends of the three aged binders containing various percentages of the rejuvenating agents were evaluated using Dynamic Shear Rheometer (DSR), Bending Beam Rheometer (BBR) as well as viscosity tests. The test involved three different aging states of the blends: original, RTFO residual and RTFO + PAV residual. Results from this study show that: (1) the aged CRM binders can be rejuvenated back to a targeted PG grade; (2) the rejuvenating agents investigated are effective in changing the properties when used with the aged CRM binders; (3) the presence of crumb rubber in the modified binders enhances their aging resistance; (4) the target grade is more easily reached by adding the rejuvenating agents to the aged CRM binders rather than the aged control PG76-22.

Keywords: Rubberized asphalt; Recycling; DSR; BBR; Rejuvenating agents

1. Introduction

In some areas in the United States and in various other countries, there is an increasing interest in using crumb rubber modifier (CRM) modified binders in asphalt pavements because of their improved performance (Bahia and Davies 1994, Thomson 2004). This improved performance is the result of the interaction between CRM particles and the base binders. For example, the absorption of the light molecule fractions of the base binders into the CRM particles affects the properties of the mix, causing it to be stiff and exhibit a high ability to resist rutting (Stroup-Gardiner *et al.* 1993, Abdelrahman and Carpenter 1999). An additional advantage, obviously, is an environmental benefit, potentially using millions of scrap tires. Although introduced four decades ago, CRM binders have been seen more frequently in use in asphalt pavement in the past 15 years. New specifications and the research and technical services available promote the increasing use of these materials (Amirkhanian 2003). Given the amount of asphalt pavement in the field for more than 15 years, there is a need for research into the recycling issues involved with these materials. This study presented here addresses several of the more pressing issues related to this topic.

The presence of CRM affects not only the properties of the mix but also the process of aging of the binders (Liang and Lee 1996). Because of interaction with CRM particles, the binders change their composition, resulting in a decrease in the portion of small molecule fractions (i.e. saturates and aromatics) and an increase in the portion of large molecule fractions (i.e. asphaltens and resins) (Airey *et al.* 2002). The aging of the CRM binders does not occur in the same way as that of unmodified asphalt binders due to the presence of the CRM. Both the CRM and the residual binder left after the interaction with CRM will experience aging. However, limited data is available on whether recycling of aged CRM binders can follow the same process as those for unmodified binders and various other modified binders. Rejuvenating agents are introduced in the recycling of the aged normal binders to compensate for the decrease in the small molecular

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fractions (saturates and aromatics). These added rejuvenating agents in the RAP containing rubberized binders, however, may change not only the residual binders but also the aged CRM particles. It is not clear if existing rejuvenating agents are applicable to aged CRM binders for the recycling process. To address this issue, this laboratory study was designed to investigate if the rejuvenating agents used for aged unmodified binders will also work for the recycling of aged CRM binders.

CRM binders are not able to be evaluated as precisely as neat binders using standard Superpave binder test procedures (Tory *et al.* 1996), in part, because of the thick coating around the perimeter of RTFO bottles and the veil of materials falling across the bottles during the RTFO aging of the CRM binders, (McGennis 1995). In addition, several potential problems including stiffness-related problems, plate slip and equipment limitations were reported during DSR testing (Stroup-Gardiner and Newcomb 1995). Some modifications of the test procedures for modified binders have been attempted, such as using a glass rod in the RTFO bottle to make the stick modified binders roll inside the glass bottles and not creep out of the bottle, and increasing the gap of the plates to accommodate the high percentage and the coarse particle size of the CRM (NCHRP 2001, Kim *et al.* 2001). However, since there is still no recommended Superpave protocol for CRM binders, the evaluation of the CRM binders is limited to using the Superpave binder tests with some modifications (Lougheed and Papagiannakis 1996, Hanson and Duncan 1995).

1.1 Objectives

The objectives of the study are as follows:

(1) To investigate the effectiveness of conventionally used rejuvenating agents on the aged CRM binders.
(2) To study the possibility of rejuvenating the aged CRM binders back to a target PG grade.

1.2 Scope

Three aged binders including two aged CRM binders and one aged control were mixed separately with two rejuvenating agents, i.e. a rejuvenator and a softer binder, at various percentages, and subsequently evaluated using DSR, BBR and viscosity tests. The testing was conducted on all blends of the three aged binders containing rejuvenating agents in three states: original (no aging), RTFO residual and RTFO + PAV residual. The three aged binders were produced artificially using an accelerated aging process on two CRM binders and one control. The two CRM binders were generated with a target grade of PG76-22 by mixing two different binder sources of PG64-22 with one CRM source at one percentage. The control binder selected was a commercially available PG76-22 (one of the two base binders mixed with 3% SBS).

2. Materials and testing procedures

Two sources of base binder and one type of CRM were used in the laboratory to produce two CRM binders with a target grade of PG76-22 for the production of aged CRM binders. One commercially available binder of PG76-22, product one of the two base binders mixed with 3% SBS, was selected as control. The properties of the two base binders together with the control binder are shown in table 1.

The CRM (-40 mesh of 425 μm) used for this project was produced in ambient temperature. The CRM binders were produced under the following conditions: the mixing temperature was 177°C (350F); 10% CRM was added by weight of the binder; the mixing time was 30 min; and the mixing speed was 700 rpm. After being produced, the two CRM modified binders were then graded to ensure that the same grade as the control binder (PG76-22) was obtained. Two rejuvenating agents were used in this study: a PG52-28 softer binder and a commercially available material (table 2).

Aged binders were artificially produced through a series of accelerated aging processes, namely 85 min of RTFO aging followed by 20 h of PAV aging. The properties of the two aged CRM binders and the aged control (PG76-22) were tested using DSR and BBR (table 3). After being produced, these three aged binders were then mixed completely with the rejuvenator at 0, 5 and 10%, and with the softer binder (PG52-28) at 100 and 200% by weight of the aged binders, respectively. A total of 45 blends of the aged binders containing rejuvenating agents were prepared and tested (figure 1). The maximum percentages of the rejuvenating agents were selected by referring to a previous

Table 1. Properties of two base binders (PG64-22) and one control binder (PG76-22).

Aging states	Test properties	Source I PG64-22	Source C PG64-22	Control PG76-22
Unaged binder	Rotational viscosity at 135°C (Pa-s)	0.39	0.583	1.80
	$G*$/sin(delta) at 64°C (kPa)	1.28	2.030	–
	$G*$/sin(delta) at 76°C (kPa)	–	–	1.984
RTFOT aged residue	$G*$/sin(delta) at 64°C (kPa)	2.87	4.940	–
	$G*$/sin(delta) at 76°C (kPa)	–	–	3.579
PAV aged residue	$G*$/sin(delta) at 25°C (kPa)	3229	1429	3156
	$G*$/sin(delta) at 31°C (kPa)	–	–	1898
	Stiffness at -12°C (MPa)	257	103	171
	m-value at -12°C	0.312	0.376	0.335

Table 2. Properties of the rejuvenator used in the study.

Test properties	Values
Specific gravity, 15.6/15.6°C	0.98–1.02
Viscosity, 60C CST	200–500
Flash point, COC, (°C)	204 Min
RTFO-C 163°C, Weight loss %	4.0 Max
RTF-C, Viscosity ratio	2.5 Max
Compatibility, PC/S Ratio	0.5 Min
Saturates, w%	28 Max
Chemical compatibility	0.2–1.2

work and current practice in the USA. The aged binder in the RAP was recovered to a target PG grade after the addition of 10% of the rejuvenator (Shen and Amirkhanian 2004). The softer binder percentages of 100 and 200% were selected considering the fact that 30–50% RAP is usually incorporated in virgin HMA in many states.

The properties of these blends were evaluated through Superpave binder test procedures as shown figure 1. A viscosity test (AASHTO T316-1), BBR (AASHTO T313-02), DSR (AASHTO T315-02: with the plate gap adjusted to 2 mm) were performed. The plate gap adjustment was to eliminate the influence of rubber particle size on the results as suggested by most of the research on CRM binders. Two duplicated samples were tested by DSR and BBR, and three duplicate samples by the viscosity test. The results were reported as the average of the trials.

3. Results and discussions

3.1 Viscosity

Figure 2 shows the viscosity of the blends of the aged binders containing rejuvenating agents versus the percentage of the rejuvenator and the softer binder at 135°C. The viscosity of the blends containing the rejuvenator decreased linearly as the rejuvenator percentages increased (figure 2a). On the other hand, the viscosity of the blends decreased non-linearly as the percentage of the softer binder PG52-28 increased (figure 2b). The viscosity decreased rapidly for the first 100% of the softer binder added, and then decreasing very slowly with the further increase of the percentage. These relationships, if shown as a logarithmic scale, will appear more linearly if the percentage of the softer binder is defined as the ratio of the weight of the softer binder to the total weight of the blend, a relationship frequently used in viscosity blend charts for the recycling (figure 2c). The logarithmic form, often used for recycling purpose, can more easily determine the percentage of the softer binder needed by using a linear curve rather than a nonlinear curve.

The trends of the viscosity of the two aged CRM binders were similar to the aged control PG76-22, regardless of the rejuvenating agents used in the study. However, the difference in the slopes of the curves is discernible. The blends containing the aged control PG76-22 have the steepest slopes, whereas the blends containing aged CRM binder I have the flattest. These differences in the rate of change in viscosity can be attributed to the presence of the aged CRM in the binders.

The viscosities of the control PG76-22 and the CRM binders I and C were 1.80, 1.95 and 2.50 Pa.s, respectively, further increasing to 9.71, 4.37 and 8.52 Pa.s after the accelerated aging using RTFO. The fact that the aged control PG76-22 binder had a higher increase rate in viscosity (439%) than the aged CRM binders I (124%) and C (221%) suggests that the control PG76-22 experienced more severe aging under the same RTFO aging condition.

To meet the viscosity requirements set forth by Superpave (i.e., 3.0 Pa.s), 7.0, 12.5 and 10.0% of the rejuvenator need to be added to the aged modified binders I and C and the control PG76-22 (figure 2a), respectively. Similarly, the percentages of the softer binder needed are approximately 38.0, 70.0, 75.0% (figure 2b). These percentages of the softer binder in the blends equals, at maximum, 52.0, 30.0 and 25.0% of the RAP incorporated in the mixtures.

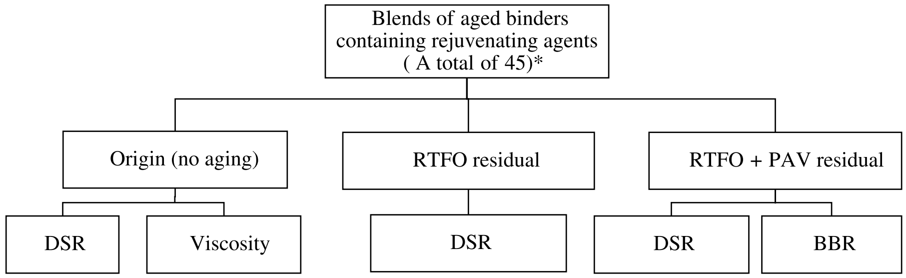
The results indicated that both the rejuvenator and the softer binder were effective in reducing the high viscosity of the aged CRM binders and the control binder. In addition, all blends easily met the superpave binder requirements.

3.2 Properties at high temperatures

Figure 3 shows the relationships between the failure temperatures of the blends of the aged binders containing the two rejuvenating agents and the percentage of either the rejuvenator or the softer binder, which were obtained from DSR on blends in original state (i.e. without aging). The failure temperatures of the blends decreased as the percentage of both the rejuvenator and the softer binder increased. When a rejuvenator was used, the failure

Table 3. Properties of aged CRM binders and aged control PG76-22.

	Failure temperatures (°C)			Stiffness (MPa)	m-value
Aging condition	No aging	RTFO residual	RTFO+PAV residual	RTFO+PAV residual	
Tests	DSR	DSR	DSR	BBR	BBR
Aged CRM I	89.7	86	18	147	0.272
Aged CRM C	99.6	88	21.9	114	0.306
Aged control PG76-22	98	98.6	29.4	197	0.253



(*3 aged binders × 2 rejuvenating agents × (32)/2 percentages ×3 aging stages=45)

Figure 1. The test combinations of the blends of the aged binders containing rejuvenating agents.

temperatures decreased in a good linear way, although there is a difference in the rate of change (failure temperature) of blends containing various binder sources. The effectiveness of the rejuvenator in causing the decrease in the high failure temperatures of the blends depended on the source of the aged CRM binder. When the softer binder is used as a rejuvenating agent, the relationships between the failure temperatures and the percentages of the softer binder are still well correlated. However, the failure temperatures of the blends decreased three to five grades when the content of the softer binder is added to 100%, whereas, the rate of change was not that severe for the softer binder increased from 100 to 200%. For example, figure 3 shows that only one grade change was observed for these blends.

The viscosity results show that the blends with the aged control PG76-22 had the steepest slopes (figure 2), while, conversely, the failure temperature was not affected as significantly as the two aged CRM binders containing both the rejuvenator and the softer binder.

The results show that adding approximately 11.0% of the rejuvenator will give a failure temperature of 76°C for the blends of the aged CRM binders I and C, whereas a much higher content of rejuvenator is necessary for the aged PG76-22 (figure 3a). Similarly, 87.5, 95.0 and 130% of the softer binder are needed for the two aged CRM binders C and I and the control PG76-22 to reach a failure temperature of 76°C, respectively. In other words, if as much as 53.0, 51.0 and 43.0% RAP containing modified binders I, C and PG76-22 are incorporated into virgin HMA, the recycled binders will achieve the target grade of PG76-22.

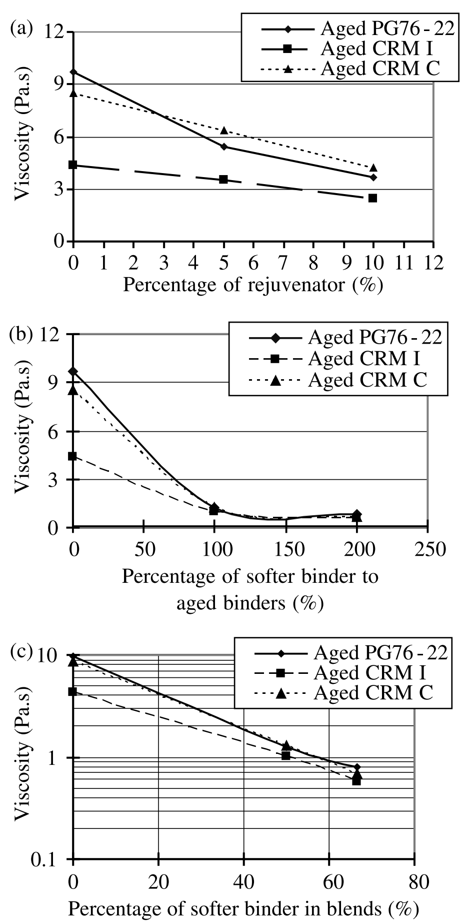


Figure 2. Viscosity at 135°C versus percentage: (a) rejuvenator; (b) softer binder; (c) softer binder (log basis).

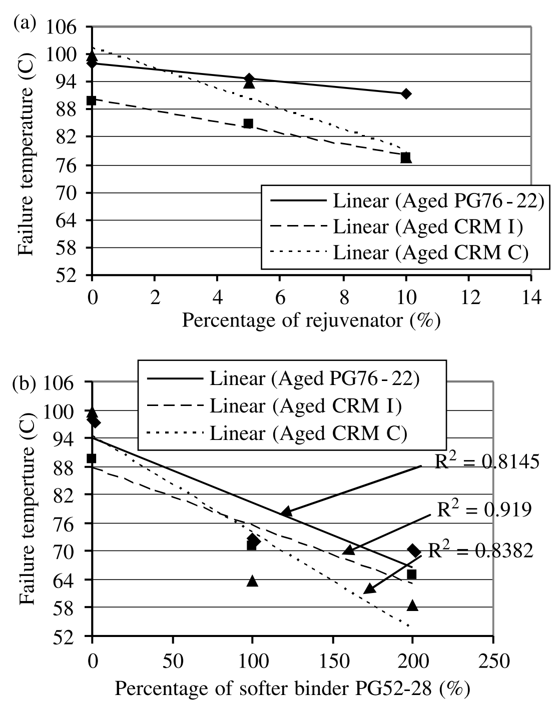


Figure 3. Failure temperatures of the blends (no aging) versus content of: (a) rejuvenator; (b) softer binder.

A general trend found in figure 4 is similar to the one in figure 3. Adding a proper content of the rejuvenator and the softer binder produced the target high failure temperature needed for the aged CRM binders and control. Rejuvenator percentages of only approximately 7.5 and 10.0% were needed for CRM binders I and C to satisfy a grade of PG76-22, respectively. Similar to the original state, a much higher percentage of rejuvenator was necessary for the blend of aged control PG76-22 to obtain a failure temperature of 76°C. Adding approximately 63.0, 70.0 and 175.0% of the softer binder was needed for aged CRM binders I and C and aged PG76-22 to reach the target failure temperature of 76°C. In other words, if as much as 61.0, 58.8 and 36.0% RAP containing modified binders I and C and PG76-22 respectively, were incorporated into virgin HMA mixtures, the recycled binders will have a high failure temperature of 76°C.

Clearly, adding the rejuvenator and the softer binder will produce the target temperature of 76°C for the two aged CRM binders and the aged control regardless of their aging state. Adding approximately 7.5 and 10.0% of the rejuvenator will result in the aged CRM binders I and C obtaining a high temperature grade of 76°C, respectively. The softer binder can recycle about 50.0% of the RAP containing aged CRM binders with regard to the high temperature of 76°C. The two modified binders require less of the rejuvenating agents than the aged control binder.

3.3 Properties at intermediate temperatures

Figure 5 shows the relationships between the failure temperatures of the blends of the aged binders containing rejuvenating agents and the percentages of either the rejuvenator or the softer binder, which were obtained using DSR on RTFO + PAV aging residuals. The failure temperatures of the blends decreased linearly as the percentage of both the softer binder and the rejuvenator increased. The different slopes shown in figure 5, as was the case in figure 4, indicated that the rejuvenator and the softer binder have different effects on the aged CRM and control binders in changing the failure temperatures.

According to the Superpave binder standards, binders graded as PG76-22 require an intermediate failure temperature equal to or less than 28°C. For all cases, except the blend of aged control PG76-22, the lower failure temperatures were found to be less than 28°C in this study. By adding approximately 2.8 and 20.0% of the rejuvenator and softer binder, respectively, the blends with aged control PG76-22 will have a failure temperature of 28°C (figure 5). In other words, if as much as 83.0% of the RAP with aged control PG76-22 is incorporated into a typical HMA, a PG76-22 grade binder will be achieved. No rejuvenating agents need to be added to the aged CRM binders to obtain the temperature requirements in the intermediate temperature range.

These results suggest that the blends of the aged CRM binders and the rejuvenating agents exhibit good properties at intermediate temperatures, similar to the findings for the recycling of aged unmodified binders as reported in a previous paper (Shen and Ohne 2002). Furthermore, both the rejuvenator and softer binder can improve the properties of the blends of the aged CRM binders and the control PG76-22 at intermediate temperatures.

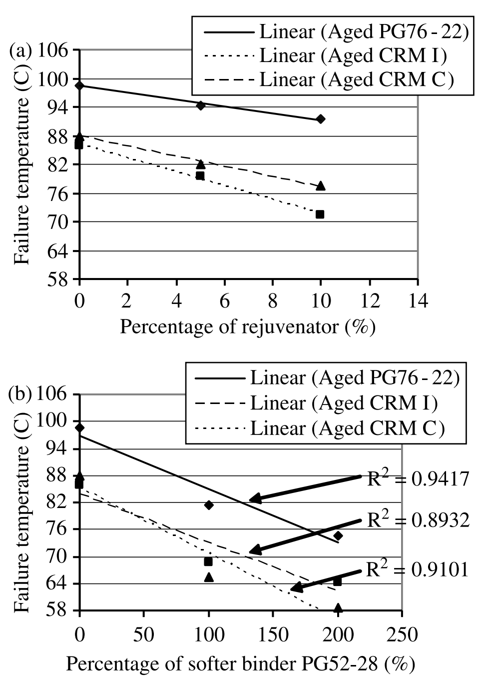


Figure 4. Failure temperatures of the blends (RTFO residual) versus content of: (a) rejuvenator; (b) softer binder.

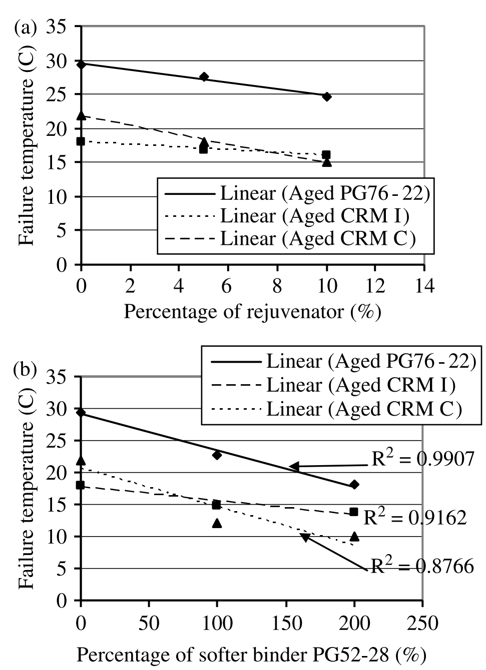


Figure 5. Failure temperatures of the blends (RTFO + PAV residual) versus content of: (a) rejuvenator; (b) softer binder.

Table 4. BBR results of the blends at −12°C and −18°C

Items	Recycling agents	Sources	Control PG76-22		CRM I		CRM C	
		Temp (°C)	−12	−18	−12	−18	−12	−18
Stiffness (MPa)	Rejuvenator	0	197	337	147	239	114	229
		5%	200	322	109.8	234.2	100	216
		10%	173	310	96.5	221	94.8	210
	Softer binder	100%	141	296	86	210	84	207
		200%	97.3	254	84.8	198	77	196
m-value	Rejuvenator	0	0.253	0.26	0.306	0.267	0.272	0.284
		5%	0.285	0.26	0.35	0.292	0.328	0.301
		10%	0.297	0.26	0.384	0.327	0.359	0.309
	Softer binder	100%	0.329	0.3	0.376	0.29	0.35	0.337
		200%	0.373	0.33	0.414	0.342	0.403	0.353

% by wt of aged binders

3.4 Properties at low temperatures

Table 4 shows the results of BBR test on the blends of the aged binders containing rejuvenating agents at −12 and −18°C. The BBR test results indicated the stiffness changed very little while the *m*-values increased significantly as the percentage of the rejuvenator increased (figure 6). The stiffness of all binders was much less than 300 MPa, the standard value for a Superpave binder. Therefore, an increase in the *m*-value is more important than an increase in stiffness in aged CRM binders for improving the low temperature properties of these blends. In addition, the rejuvenator is more effective to the aged CRM binders than to the aged control PG76-22 in terms of the *m*-value increase.

Both the stiffness decreased linearly and the *m*-value increased linearly as the percentage of the softer binders increased, see figure 7. The stiffness of all the blends was less than 300 MPa also. Improvement in the *m*-values of the blends is, again, more necessary than stiffness in terms of obtaining the required low temperature grade.

The results indicated that the addition of approximately 0, 2.0 and 10.0% of rejuvenator contents will result in the blends of the aged CRM binders I and C and the aged control PG76-22 obtaining a low temperature grade of −22°C, respectively. In addition, adding of 0, 35.0 and 70.0% of softer binder will make the aged CRM binders I and C and the aged control PG76-22 reach a low temperature grade of −22°C, respectively. In other words, if as much as 100.0, 74.0, and 59.0% RAP containing CRM binders I, C and PG76-22 are incorporated into a virgin HMA mixture, the recycled binders will have a low temperature grade of −22°C. The change of the low temperature properties of the blends with the percentage

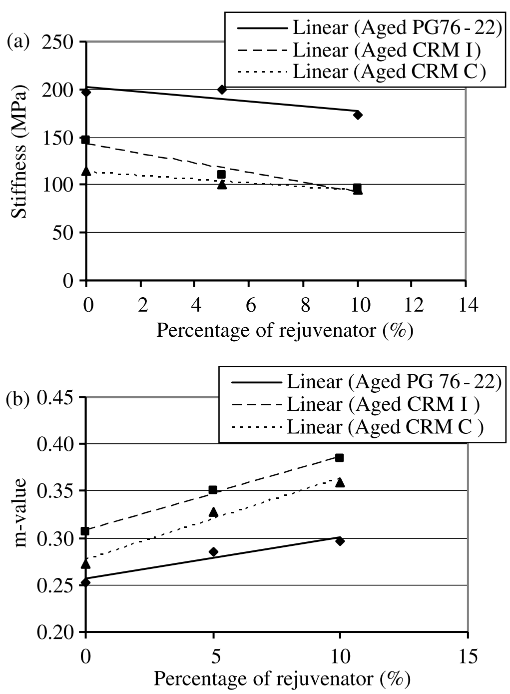


Figure 6. BBR results for the blends (RTFO + PAV residual) versus content of rejuvenator: (a) stiffness; (b) *m*-value.

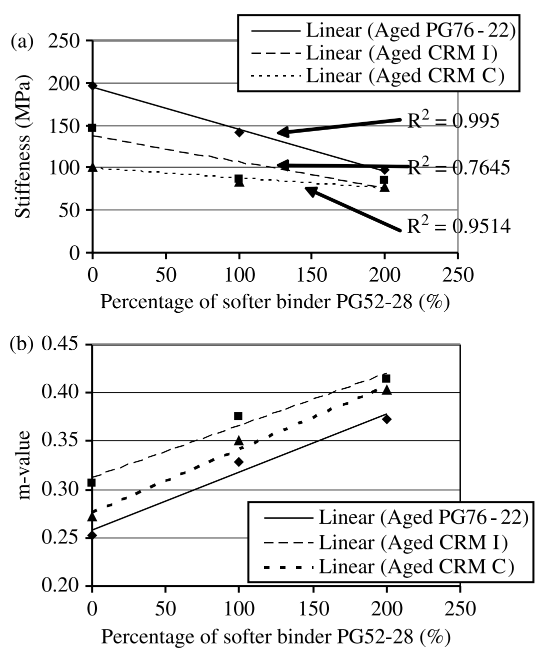


Figure 7. BBR results of the blends (RTFO + PAV residual) versus content of softer binder: (a) stiffness; (b) *m*-value.

of the rejuvenating agents at −18°C is similar for the test temperature of −12°C.

4. Summary and conclusions

In this study, the two aged rubberized binders and one aged control PG76-22 were rejuvenated by adding a rejuvenator and a softer binder. The results confirmed that the blends containing the two aged CRM binders as well as the blend containing the aged control binder can be rejuvenated to the target grade of PG76-22. This was the grade of the two CRM binders before aging. More specifically, the study found the following:

The viscosity of the blends of both aged CRM binders and the aged control PG76-22 decreased as the percentage of the rejuvenator and the softer binder increased. The increased viscosity rate was found to be higher for the control PG76-22 than for the two CRM binders after RTFO aging. Conversely, the viscosity of the blend of the aged control PG76-22 decreased more rapidly, with an increase in the percentage of the rejuvenating agents, than for the blends of the aged CRM binders I and C.

The high failure temperature of the blends of the three aged binders in both the original state (no additional aging) and after RTFO decreased linearly as the percentage of the rejuvenator increased. However, this value decreased rapidly when the softer binder content was less than 100%; and decreased at a slow rate as the percentage of the softer binder increased from 100 to 200%. Adding 10% of the rejuvenator and 100% of the softer binder decreased the PG grade 3–5 high temperature PG grades. Therefore, the percentage of both the rejuvenator and the softer binder should be carefully monitored so that the target PG grade will be achieved (e.g. 76°C).

The intermediate failure temperature of the blends after RTFO and PAV aging were improved as the percentage of the rejuvenator and the softer binder increased. The failure temperature of the blends was much lower than 28°C, an intermediate temperature specified for PG76-22 grade binder. In addition, the blends of the aged CRM binders exhibit lower failure temperatures than those of the aged control PG76-22 after the addition of the same amount of rejuvenating agents.

The BBR results indicated that both the rejuvenator and the softer binder effectively improved the low temperature properties. The stiffness of most of the blends tested at −12°C was much less than 300 MPa, thus improving the *m*-value that is crucial in enhancing the low temperature grade. The *m*-value of the two aged CRM binders increased at the same rate as that of the aged control PG76-22 after the addition of the softer binder. However, the rate of increase in the *m*-value of aged control PG76-22 was greater than when the rejuvenator was added. For the blends tested, it was possible to obtain the low temperature grade of −12°C by adding 2.5–10% of the rejuvenator or 0–35% of the softer binder.

Adding only 0–7.5% and 2.5–10.0% of the rejuvenator to the CRM aged binders I and C, respectively, resulted in reaching the target of PG76-22. In addition, all of the binders reached a PG76-22 grade after the addition of approximately 0–53%, 35–51% and 70–130% of the softer binder to the aged CRM binders I and C and the control PG76-22, respectively.

The two CRM binders achieved higher resistance to aging than the control PG76-22, a property attributed to the much higher viscosity increase rate found for the control PG 76-22.

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