Available online at www.sciencedirect.com

ScienceDirect

Construction and Building Materials 22 (2008) 1906–1913

Construction and Building MATERIALS

www.elsevier.com/locate/conbuildmat

Recycling of laboratory-prepared long-term aged binders containing crumb rubber modifier

Soon-Jae Lee *, Chandra K. Akisetty, Serji N. Amirkhanian

Department of Civil Engineering, Clemson University, Clemson, SC 29634-0911, United States

Received 17 May 2007; received in revised form 13 July 2007; accepted 16 July 2007
Available online 4 September 2007

Abstract

The use of conventional reclaimed asphalt pavement (RAP) has become routine in a number of states throughout the United States, and the satisfactory mix design procedures have been developed. The recycling of crumb rubber-modified materials has been an area of interest since crumb rubber modifier (CRM) was first used in asphalt paving materials over 40 years ago. Some state departments of transportation (DOTs) have used rubberized asphalt concrete (RAC) materials in limited recycling experiments or demonstration projects. The respective studies include different types of wet process binders and/or various gradations of CRM as an aggregate substitute (dry process). The results show that a wide range of CRM-modified paving materials can be successfully reclaimed and recycled.

Previous research on the recycling of RAC focused only on the mixture properties at the location of in-field paving. In the long-term performance characterizations, it is important to identify the aging properties of rubberized binders and the subsequent recycling properties of these aged rubberized binders. Without understanding these binder properties, it is difficult to predict the mixture performance and suggest guidelines for the recycling of RAC. To address this issue, this research was conducted to identify the performance properties of recycled aged CRM binders. Evaluation of the recycled aged CRM binders included the following testing procedures: viscosity at high temperature, rheological properties at high and intermediate temperatures, and cracking properties at low temperature. The results from this study indicated that the recycled aged CRM binders can result in satisfactory binder performance which meets current Superpave binder requirements.

Keywords: Crumb rubber; Recycling; Aging; Rubberized binders; Performance properties

1. Introduction

1.1. Background

Approximately 600 million scrap tires are generated each year in the United States and in Europe [1]. The disposal of these scrap tires has been a serious issue due to many reasons (e.g., lack of landfill space, environmental issues, etc.). Previous studies have reported that crumb rubber modifier (CRM) binders can produce asphalt pavements that exhibit increased pavement life, decreased traffic noise, reduced maintenance costs and resistance to rutting and cracking [2–5]. Because of these advantages, there is an increasing interest in using CRM binders in hot mix asphalt (HMA) pavements in some states in the Unites States and other countries [5,6].

Using CRM to modify asphalt binders in pavement engineering began more than four decades ago in the United States. The recycling for rubberized asphalt pavement is a very important issue because many of these pavements were built over 10–20 years ago and some of them may now be a candidate for recycling. Previous research on the recycling of rubberized asphalt concrete (RAC), which was

* Corresponding author.
E-mail addresses: soonjae93@gmail.com (S.-J. Lee), cakiset@clemson.edu (C.K. Akisetty), kcdoc@clemson.edu (S.N. Amirkhanian).

0950-0618/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.conbuildmat.2007.07.012

conducted primarily by some state departments of transportation (DOTs) [7–10], focused on investigating the in-field paving properties regarding the feasibility of recycling rubber-modified paving materials. The majority of the limited number of studies on the use of reclaimed rubberized materials in recycled asphalt paving mixtures indicate that these reclaimed materials can be successfully incorporated into other bituminous paving mixes [11]. However, it is important to be able to identify the aging and recycling properties of rubberized binders to predict the long-term performance of these mixtures and to suggest guidelines for the recycling of RAC.

1.2. Research objectives and scope

The main objective of this research was to investigate the performance properties of laboratory-prepared recycled aged crumb rubber modifier (CRM) binders through Superpave binder tests. The CRM binders were produced in the laboratory incorporating one CRM source (ambient) and one CRM percentage (10% by weight of asphalt binder) into three base binders. The CRM binders were artificially aged using rolling thin film oven (RTFO) + pressure aging vessel (PAV) aging procedures, and the aged CRM binders were recycled using two base binders (performance grade (PG) 64-22 for 0% and 15% long-term aged (LTA) binders, and PG 58-22 for 25% and 35% LTA binders). The recycled aged CRM binders were artificially aged using the same RTFO + PAV methods. The viscosity and rutting properties for recycled CRM binders in the original state, the rutting properties after RTFO aging process, and the cracking properties at intermediate and low temperatures after RTFO + PAV aging processes were evaluated. Fig. 1 shows a flow chart of the experimental design used in this study.

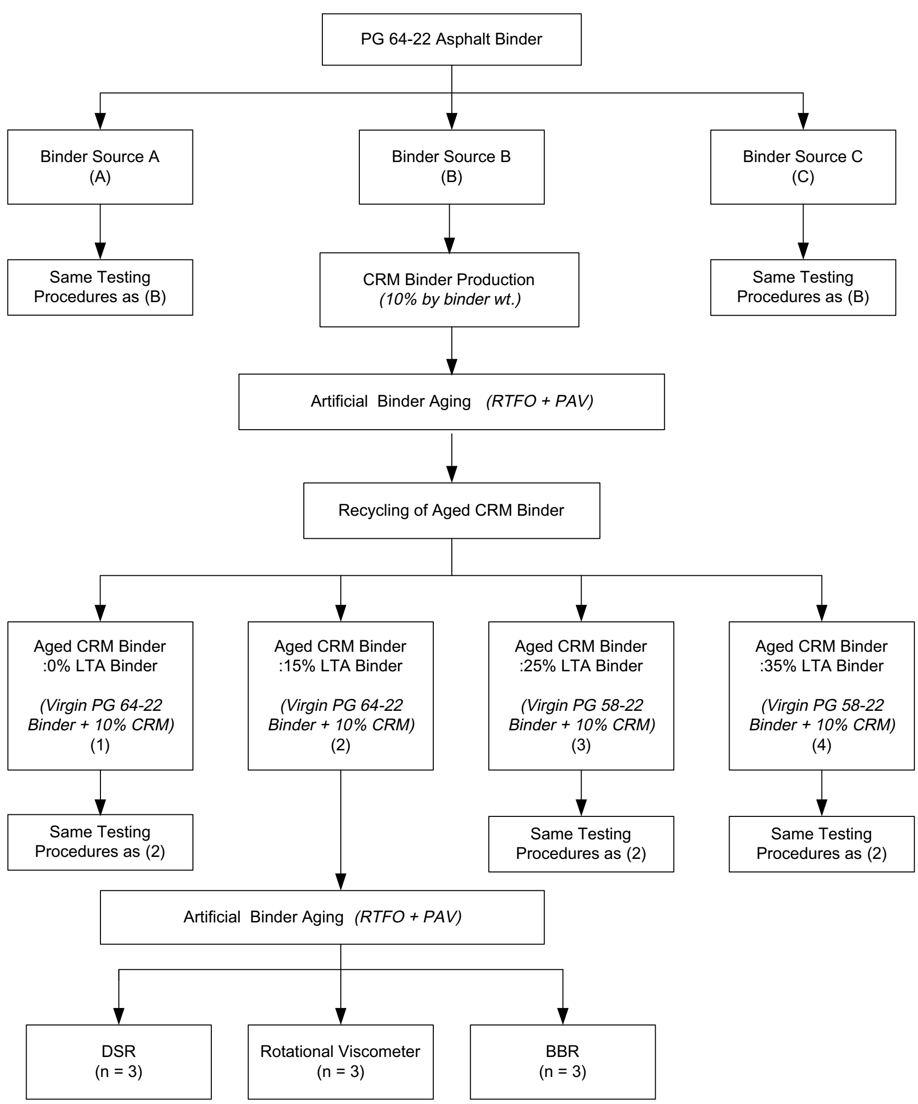

Fig. 1. Flow chart of experimental design procedures.

2. Materials and test program

2.1. Materials

2.1.1. Asphalt binders

Three PG 64-22 asphalt binders designated as A, B, and C from different crude sources were used in this study. Binder A was from a Venezuelan crude source, binder B was from a Middle Eastern source, and binder C was a mixture of several sources that could not be identified by the supplier. Each binder was graded in accordance with AASHTO M320 to verify the performance grade. Table 1 summarizes the properties of the three base binders included in this study.

2.1.2. Crumb rubber modifier (CRM)

The CRM produced by mechanical shredding at ambient temperature was obtained from one source: −40 mesh (−0.425 mm) and used with a gradation as shown in Table 2, which is widely used to produce the CRM mixtures in South Carolina. To ensure that the consistency of the CRM was maintained throughout the study, only one batch of crumb rubber was used in this study.

2.2. CRM binder production and aging

The binder mixing used in this study was the wet process, in which the CRM is added to the base asphalt binder before introducing it in the asphalt concrete matrix [12–14]. The CRM binder was produced in the laboratory at 177 °C for 30 min by an open blade mixer at a blending speed of 700 rpm [12,15]. The percentage of crumb rubber added for the CRM binder was 10% by weight of the base binder. This mixing condition matches the practices used in South Carolina to produce field mixtures [15].

The CRM binders were then artificially aged through a series of accelerated aging processes (RTFO aging for 85 min at 163 °C and PAV aging for 20 h at 100 °C) [16]. The effectiveness of the accelerated aging processes for CRM binders used in this study was evaluated in the previous studies using Superpave binder tests and gel permeation chromatography (GPC) technique [13,15,17]. From the previous studies, it was observed that CRM binders showed similar aging level with control binders (PG 64-22) after the RTFO + PAV aging.

Table 1
Properties of three base binders (PG 64-22)

Aging states	Test properties	Binder sources		
		A	B	C
Unaged binder	Rotational viscosity at 135 °C (Pa s)	0.609	0.470	0.409
	$G^*/\sin\delta$ at 64 °C (kPa)	1.943	1.237	1.194
	High failure temperature (°C)	69.7	66.9	65.7
RTFO aged residual	$G^*/\sin\delta$ at 64 °C (kPa)	4.402	2.230	2.334
	High failure temperature (°C)	71.7	65.3	65.9
RTFO + PAV aged residual	$G^*\sin\delta$ at 25 °C (kPa)	1907.1	2102.6	2335.0
	Stiffness at −12 °C (MPa)	128	195	187
	m-Value at −12 °C	0.339	0.318	0.337

Table 2
The gradation of crumb rubber used in this study

Sieve no. (μm)	Ambient CRM	
	% Retained	% Cumulative retained
30 (600)	0	0
40 (425)	9.0	9.0
50 (300)	31.9	40.9
80 (180)	32.9	73.8
100 (150)	7.6	81.4
200 (75)	18.6	100.0

2.3. Recycling of aged CRM binders

Virgin CRM binders produced using the base binders of PG 64-22 were used for the recycling of 0% and 15% long-term aged (LTA) binders. The virgin binder grade was selected based on the previous research which concluded that in case of 15% RAP, the PG grade of the asphalt binder added for the recycling can be the same as that used in 0% RAP [17,18]. With respect to 25% and 35% long-term aged (LTA) binders, the base binders of PG 58-22 were utilized to produce virgin CRM binders for the recycling (Fig. 1). The recycled aged CRM binders were then artificially aged through RTFO and PAV processes. In total, 36 CRM binders (3 binder sources * 4 LTA binder percentages * 3 aging levels) were produced and evaluated during this study.

2.4. Superpave binder tests

The Superpave binder tests are used to quantify the asphalt's performance at three stages of its life: in its original state, after mixing and construction, and after in-service aging [16]. In this study, the properties of these CRM binders were evaluated using selected Superpave binder test procedures including the viscosity test (AASHTO T 316), the bending beam rheometer (BBR) test (AASHTO T 313), and the dynamic shear rheometer (DSR) test (AASHTO T 315: with the plate gap adjusted to 2 mm). The plate gap adjustment was used to eliminate the influence of rubber particle size [19–21]. Three duplicate samples were tested by the rotational viscometer, the BBR, and the DSR. The results were reported as the average of these tests.

2.5. Analysis method

Statistical analysis was performed using the statistical analysis system (SAS) program to conduct analysis of variance (ANOVA) and Fisher's LSD comparison with an $\alpha = 0.05$. The primary variables included the binder sources (A, B, and C) and the LTA binder percentages (0%, 15%, 25%, and 35%).

3. Results and discussion

3.1. Original state binder (no aging)

3.1.1. Viscosity of recycled aged CRM binders

The viscosity of asphalt binders at high temperature is an important property since it reflects the binder's ability to be pumped through an asphalt plant, thoroughly coat the aggregate in a hot mix asphalt (HMA) mixture, and be placed and compacted to form a new pavement surface [16]. Fig. 2 shows the viscosity at 135 °C for the recycled aged CRM binders. A general trend was found that the viscosity of the CRM binders with 15% long-term aged (LTA) binder was the highest and that of the CRM binders with 25% LTA binder was lowest for all binder sources. The different virgin binder grades (PG 64-22 for 15% LTA binder and PG 58-22 for 25% RAP binder) are thought to be the main reason for the difference of the viscosities of the binders. All the recycled aged CRM binders satisfied the maximum limit for viscosity of asphalt binders at 135 °C set forth by Superpave (i.e., 3.0 Pa s). In addition, the recycled CRM binders made with binder source A had higher viscosities than those produced with binder sources B and C. This is considered to be attributed to the initial higher viscosity of the base binder A (Table 1).

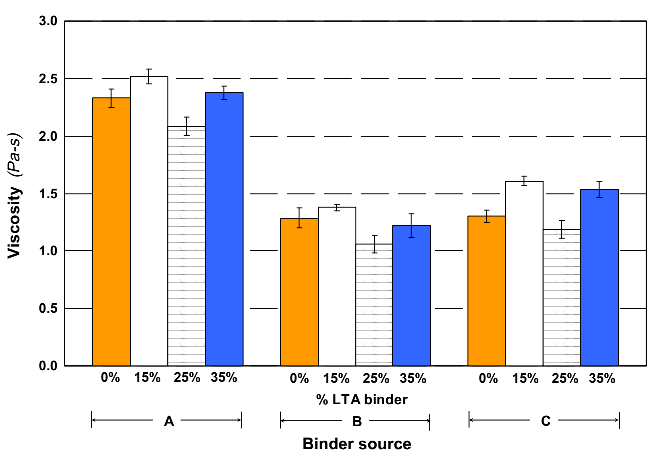

Fig. 2. Viscosity of recycled aged CRM binders (no aging) at 135 °C.

The statistical significance of the change in the viscosity as a function of LTA binder percentage and binder source was examined and the results are shown in Table 3. The data indicated that the binder source has a significant effect on the viscosity of the recycled aged CRM binders. When compared within each binder source, the CRM binders with 15% and 25% LTA binders were found to have a significant difference in the viscosity for all binder sources.

3.1.2. High failure temperature of recycled aged CRM binders

In general, the higher failure temperature values indicate that the binders are less susceptible to permanent deformation at high pavement temperature [16]. The failure temperature of the recycled CRM binders in original state (i.e. without aging) was measured and the results are shown in Fig. 3. For all three binder sources, CRM binder with 15% LTA binder resulted in the highest failure temperature, followed by CRM binder with 35% LTA binder. With respect to 25% LTA binder, using softer grade of PG 58-22 as a virgin binder, the CRM binder from binder sources A and B showed the lowest failure temperature within the same source. Similar to the viscosity results, the recycled CRM binders made from binder source A showed significantly higher failure temperature values than those produced with binder sources B and C. It should be mentioned that the base binders had different failure temperature values. The failure temperature of base binder A

Table 3
Statistical analysis results of the viscosity of recycled aged CRM binders (no aging) as a function of LTA binder percentage and binder source ($\alpha = 0.05$)

Viscosity (135 °C)		Binder source A				Binder source B				Binder source C			
		1	2	3	4	1	2	3	4	1	2	3	4
Binder source A	1	–	S	S	N	S	S	S	S	S	S	S	S
	2		–	S	S	S	S	S	S	S	S	S	S
	3			–	S	S	S	S	S	S	S	S	S
	4				–	S	S	S	S	S	S	S	S
Binder source B	1					–	N	S	S	N	S	N	S
	2						–	S	S	N	S	S	S
	3							–	S	S	S	S	S
	4								–	N	S	S	S
Binder source C	1									–	S	N	S
	2										–	S	N
	3											–	S
	4												–

LTA binder percentage 1: 0% (control); 2: 15%; 3: 25%; 4: 35%.
N: non-significant, S: significant.

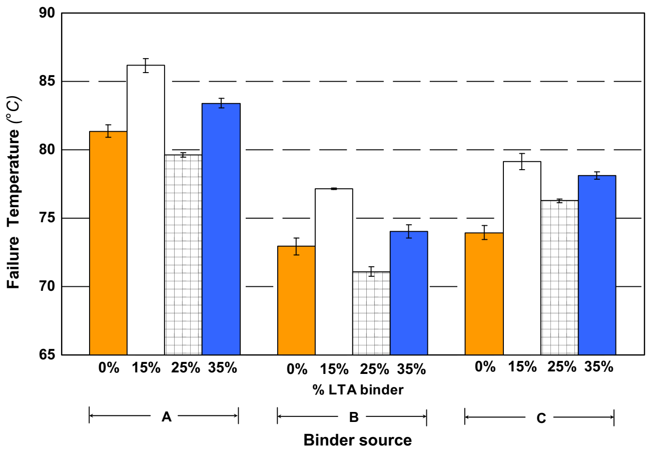

Fig. 3. High failure temperature of recycled aged CRM binders (no aging).

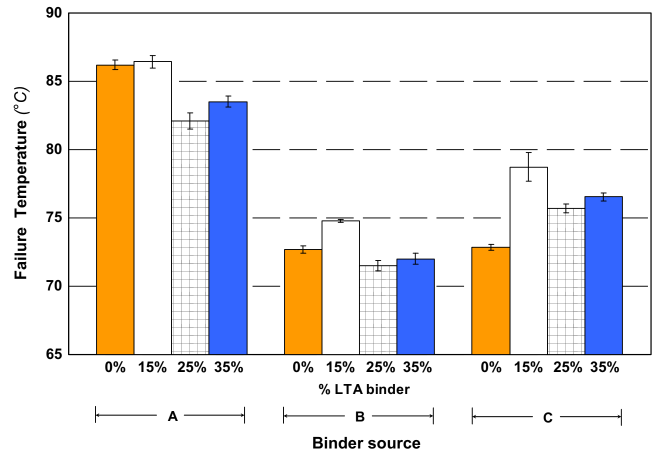

Fig. 4. High failure temperature of recycled aged CRM binders (RTFO residual).

was 2.8 °C and 4.0 °C higher than those of base binders B and C, respectively (Table 1).

The statistical results of the change in the failure temperature are shown in Table 4. It is evident that the differences between the long-term aged (LTA) binder percentages are statistically significant in all cases within each binder source. Also, the binder source is found to have a significant effect on the failure temperature of the recycled CRM binders regardless of the LTA binder percentage.

3.2. Short-term aging (RTFO aging)

After the RTFO aging procedure at 163 °C for 85 min, the failure temperature of the recycled aged CRM binders (RTFO residual) was measured and the results are illustrated in Fig. 4. The general trend is similar to the findings for high failure temperature as shown in Fig. 3. Similar to the original state, the CRM binder with 15% LTA binder shows the highest failure temperature within each binder source. The CRM binder with 25% LTA binder and 75% virgin binder of PG 58-22 is found to have the lowest failure temperature, except for binder source C.

Fig. 5 shows the relationship of failure temperature between unaged and RTFO-aged binders, including 6 base binders (3 PG 58-22 binders and 3 PG 64-22 binders) and 12 recycled aged CRM binders (3 binder sources * 4 LTA binder percentages). It is observed that the failure temperatures of unaged and short-term aged binders have a linear relationship. Relatively, the CRM binders resulted in somewhat lower R^2 value (0.8483) than the base binders (0.9325), and the finding is consistent to the previous studies. Huang et al. [22] observed that the coarse-ground tire rubber-modified binders spilled from the bottles during the RTFOT process. McGennis [23] and Lee et al. [24] reported that the fine rubber-modified binders exhibited unusual RTFO aging characteristics during the DSR testing. However, these unusual aging characteristics of CRM binders are only limited to the short-term aging (RTFO aging method). After the short-term and long-term aging processes (RTFO + PAV aging methods), the aging

Table 4
Statistical analysis results of the failure temperature of recycled aged CRM binders (no aging) as a function of LTA binder percentage and binder source ($\alpha = 0.05$)

Failure temperature (°C)		Binder source A				Binder source B				Binder source C			
		1	2	3	4	1	2	3	4	1	2	3	4
Binder source A	1	–	S	S	S	S	S	S	S	S	S	S	S
	2		–	S	S	S	S	S	S	S	S	S	S
	3			–	S	S	S	S	S	S	N	S	S
	4				–	S	S	S	S	S	S	S	S
Binder source B	1					–	S	S	S	S	S	S	S
	2						–	S	S	S	S	S	S
	3							–	S	S	S	S	S
	4								–	N	S	S	S
Binder source C	1									–	S	S	S
	2										–	S	S
	3											–	S
	4												–

LTA binder percentage 1: 0% (control); 2: 15%; 3: 25%; 4: 35%.
N: non-significant, S: significant.

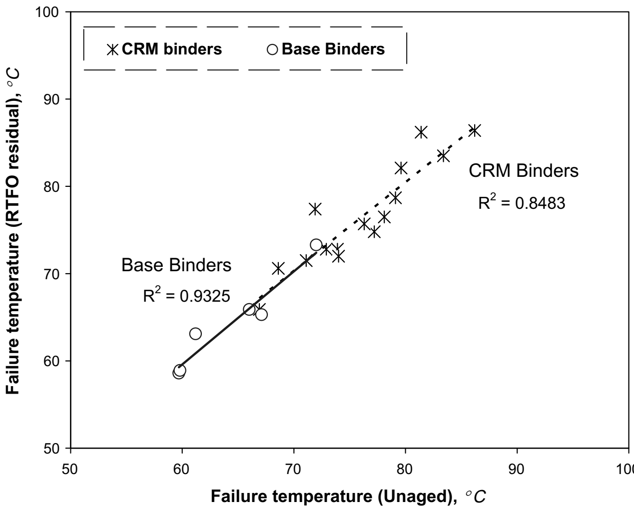

Fig. 5. Relationship of high failure temperature between unaged and RTFO-aged recycled aged CRM binders.

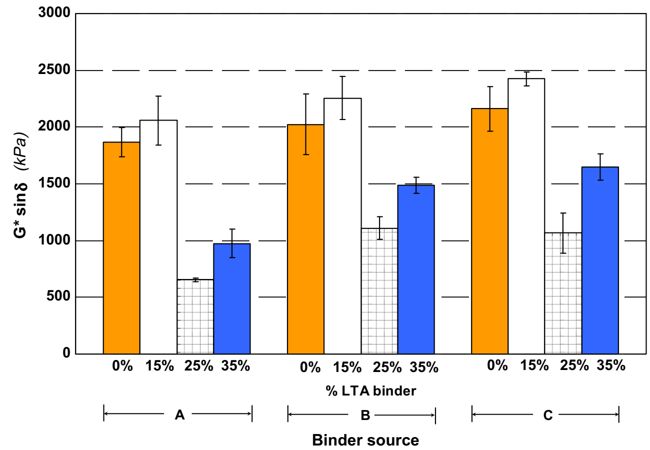

Fig. 6. $G^{*}\sin\delta$ of recycled aged CRM binders (RTFO + PAV residual) at 25 °C.

characteristics of CRM binders are quite similar to those of control binders without CRM [13,17,25].

3.3. Long-term aging (RTFO + PAV aging)

3.3.1. Properties at intermediate temperature of recycled aged CRM binders

The product of the complex shear modulus, G^{*}, and the sine of the phase angel, δ, is used in the Superpave binder specification to help control the fatigue of asphalt pavements. The low values of $G^{*}\sin\delta$ are generally considered desirable attributes from the standpoint of resistance to fatigue cracking [16]. After RTFO and PAV procedures, the $G^{*}\sin\delta$ values of the recycled CRM binders (RTFO + PAV residual) were measured using DSR at 25 °C and the results are shown in Fig. 6. The $G^{*}\sin\delta$ values were found to be 1868, 2057, 654, and 975 kPa for CRM binders with 0%, 15%, 25%, and 35% long-term aged (LTA) binders (from binder source A), respectively. This trend, the highest at 15% LTA binder and the lowest at 25% LTA binder, was consistent to the binders from binder sources B and C. In terms of the effect of binder source, the recycled CRM binders produced with binder source A were thought to be the most resistant to fatigue cracking. Again, this is considered to be attributed to the lower $G^{*}\sin\delta$ value of the base binder A.

Using one-way analysis of variance, the statistical significance of the change in the $G^{*}\sin\delta$ values was examined (Table 5). There was no significant difference at the $\alpha = 0.05$ level between the $G^{*}\sin\delta$ values of recycled CRM binders with 0% and 15% LTA binders within each binder source. On the other hand, the differences between the CRM binders with 25% and 35% LTA binders were statistically significant for all binder sources. There was no significant difference between the CRM binders produced with binder sources B and C and made with the same long-term aged (LTA) binder percentage.

Table 5
Statistical analysis results of the $G^{*}\sin\delta$ of recycled aged CRM binders (RTFO + PAV residual) as a function of LTA binder percentage and binder source ($\alpha = 0.05$)

$G^{*}\sin\delta$ at 25 °C (kPa)		Binder source A				Binder source B				Binder source C			
		1	2	3	4	1	2	3	4	1	2	3	4
Binder source A	1	–	N	S	S	N	S	S	S	S	S	S	N
	2		–	S	S	N	N	S	S	N	S	S	S
	3			–	S	S	S	S	S	S	S	S	S
	4				–	S	S	N	S	S	S	N	S
Binder source B	1					–	N	S	S	N	S	S	S
	2						–	S	S	N	N	S	S
	3							–	S	S	S	N	S
	4								–	S	S	S	N
Binder source C	1									–	N	S	S
	2										–	S	S
	3											–	S
	4												–

LTA binder percentage 1: 0% (control); 2: 15%; 3: 25%; 4: 35%.
N: non-significant, S: significant.

3.3.2. Properties at low temperature of recycled aged CRM binders

Superpave binder specification includes a maximum value of 300 MPa for creep stiffness, and the decrease in stiffness leads to smaller tensile stresses in the asphalt binder and less chance for low temperature cracking [16]. From the BBR tests at −12 °C, the stiffness and *m*-value of the recycled CRM binders (RTFO + PAV residual) were calculated, and the results are illustrated in Figs. 7 and 8. The stiffness values for recycled CRM binders with 0%, 15%, 25%, and 35% LTA binders (from binder source A) were found to be 129, 141, 76, and 84 MPa, respectively. The stiffness of all recycled CRM binders was much less than 300 MPa, the maximum value for Superpave binder (Fig. 7). Similar to the DSR test results at 25 °C, the stiffness values from the BBR tests showed a similar trend regardless of the binder source. In addition, the recycled CRM binder produced with binder source A was expected to have a better resistance on low temperature cracking, as well as permanent deformation at high temperature. In terms of the *m*-value, all recycled CRM binders satisfied the minimum limit set forth by Superpave (i.e., 0.300), except for the CRM binder made with binder source C and 15% LTA binder (Fig. 8).

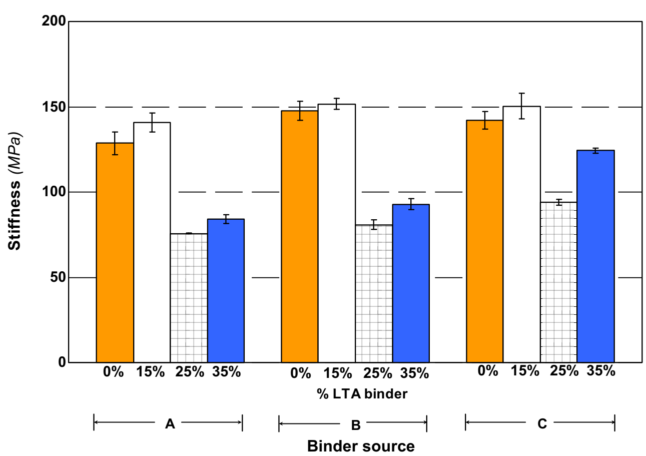

Fig. 7. Stiffness of recycled aged CRM binders (RTFO + PAV residual) at −12 °C.

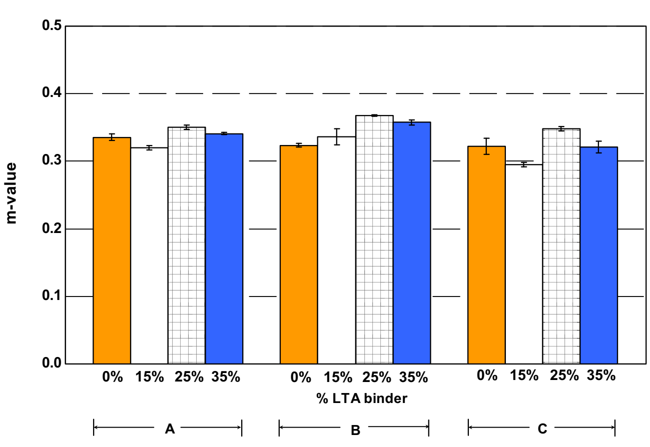

Fig. 8. *m*-Value of recycled aged CRM binders (RTFO + PAV residual) at −12 °C.

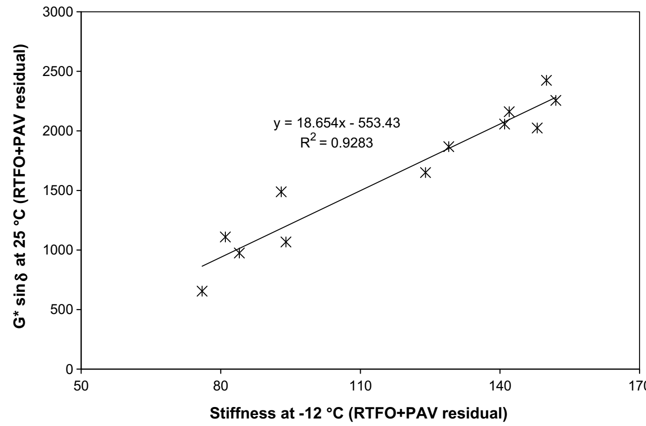

Fig. 9. Correlation of stiffness at low temperature of −12 °C with $G^{*}\sin\delta$ at intermediate temperature of 25 °C.

Correlation of stiffness at low temperature with $G^{*}\sin\delta$ at intermediate temperature was analyzed. Fig. 9 shows the relationship between stiffness values (from the BBR test at −12 °C) and $G^{*}\sin\delta$ values (from the DSR test at 25 °C) of the recycled CRM binders (RTFO + PAV residual). It was found that the properties of CRM binders obtained from two different test methods have high R^2 value (i.e., 0.9283). From the results, it may be possible to assume that the recycled CRM binders show similar performance at intermediate and low temperatures for the binders produced in this research project.

4. Summary and conclusions

To investigate the performance properties of laboratory-prepared recycled aged CRM binders, CRM binders were produced in the laboratory using one CRM source (ambient), one CRM percentage (10% by binder weight), and three binder sources. The CRM binders were artificially aged through accelerated aging processes. The aged CRM binders were recycled at 0%, 15%, 25%, and 35% long-term aged (LTA) binder percentages by total binder weight, and then artificially aged using the RTFO and PAV processes. A series of Superpave binder tests were carried out using the rotational viscometer, the DSR, and the BBR to evaluate the properties of the recycled aged CRM binders. From these test results, the following conclusions were drawn for the materials used in this study.

(1) CRM binders with 15% and 25% LTA binders showed the highest and lowest viscosity values, respectively, and this is considered to be attributed to different virgin binder grades (PG 64-22 or PG 58-22) used for the recycling.

(2) In general, 15% recycling (15% CRM LTA binder + 85% virgin CRM binder) seemed to lead to better rutting properties for aged CRM binders. Relatively, the recycled CRM binders made with 25% LTA binder using a softer virgin binder were found to have lower stiffness values which relate to a better resistance on low temperature cracking.
(3) Generally, the binder sources were found to have a significant effect on the properties of the recycled aged CRM binders. The binder source A was found to be more effective on producing the recycled aged CRM binders that are less susceptible to rutting at high temperature and cracking at intermediate and low temperatures. This is thought to be attributed to the higher $G^*/\sin\delta$ (at high temperature) and lower $G^*\sin\delta$ (at intermediate temperature) and stiffness (at low temperature) of the base binder A.
(4) The laboratory-prepared long-term aged (LTA) binders containing crumb rubber modifier were utilized up to 35%, and in most cases, the performance properties (i.e., rutting, fatigue cracking, and low temperature cracking properties) of recycled aged CRM binders showed the results meeting current Superpave binder requirements.
(5) It is recommended to conduct another study to evaluate the HMA mixture properties using the same CRM binders. Also, further study with many other binder and CRM sources is needed to generalize these findings.

Acknowledgements

This study was supported by the Asphalt Rubber Technology Service (ARTS) at Civil Engineering Department, Clemson University, Clemson, South Carolina, USA. The authors wish to acknowledge and thank South Carolina's Department of Health and Environmental Control (DHEC) for their financial support of this project.

References

[1] Amirkhanian S, Corley M. Utilization of rubberized asphalt in the United States—an overview. In: Proceedings of 04 international symposium advanced technologies in asphalt pavements, South Korea; 2004. p. 3–13.
[2] Ruth BE, Roque R. Crumb rubber modifier (CRM) in asphalt pavements. In: Proceedings of the transportation congress, 1995. p. 768–85.
[3] Liang RY, Lee S. Short-term and long-term aging behavior of rubber modified asphalt paving mixtures. Trans Res Rec: J Trans Res Board 1996;1530:11–7.
[4] Huang B, Mohammad LN, Graves PS, Abadie C. Louisiana experience with crumb rubber-modified hot-mix asphalt pavement. Trans Res Rec: J Trans Res Board 2002;1789:1–13.
[5] Shen J, Amirkhanian S, Lee S-J. Effects of rejuvenating agents on recycled aged rubber modified binders. The Int J Pavement Eng 2005;6(4):273–9.
[6] Bahia HU, Davis R. Effect of crumb rubber modifiers (CRM) on performance related properties of asphalt binders. J Assoc Asphalt Paving Technologists 1994;63:414–49.
[7] Albritton GE, Barstis WF, Gatlin GR. Construction and testing of crumb rubber modified hot mix asphalt pavement. Report No: FHWA/MS-DOT-RD-99-115. Federal Highway Administration: Washington, DC; 1999.
[8] Bischoff D, Toepel A. Tire rubber in hot mix asphalt pavement. Madison, WI: Wisconsin Department of Transportation; 2004.
[9] Crockford WW, Makunike D, Davison RR, Scullion T, Billiter TC. Recycling crumb rubber modified pavements. Texas Transportation Institute Research Report 1333-1F. College Station, TX: Texas A&M University; 1995.
[10] Gunkel KO'C. Evaluation of exhaust gas emissions and worker exposure from asphalt-rubber binders in hot mix asphalt mixtures Part I: exhaust gas emissions results. Wildwood Environmental Engineering Consultants, Inc. for Michigan Department of Transportation; 1994.
[11] Caltrans. Feasibility of recycling rubber-modified paving materials. Caltrans, Sacramento, CA; Materials Engineering and Testing Services, Office of Flexible Pavement Materials; 2005.
[12] Putman BJ. Qualification of the effects of crumb rubber in CRM binder. Dissertation (Ph.D.), Clemson University; 2005.
[13] Shen J, Amirkhanian S, Lee S-J. HP-GPC charactirization of rejuvenated aged CRM binders. J Mater Civil Eng ASCE 2007;19(6):515–22.
[14] Xiao FP. Development of fatigue predictive models of rubberized asphalt concrete (RAC) containing reclaimed asphalt pavement (RAP) mixtures. Dissertation (Ph.D.), Clemson University; 2006.
[15] Lee S-J, Amirkhanian S, Shatanawi K. Effects of crumb rubber on aging of asphalt binders. In: Asphalt rubber 2006, vol. 3. California: Palm Springs; 2006. p. 779–95.
[16] The Asphalt Institute. Performance graded asphalt binder specification and testing, SP-1. Lexington, KY: The Asphalt Institute; 2003.
[17] Shen J, Amirkhanian S, Lee S-J, Putman BJ. Recycling of laboratory-prepared RAP mixtures containing crumb rubber modified binders in HMA. Trans Res Rec 2006;1962:71–8.
[18] Pavement Recycling Guidelines for State and Local Governments. FHWA-SA-98-042; 1997.
[19] Heitzman M. Design and construction of asphalt paving materials with crumb rubber modifier. Trans Res Rec: J Trans Res Board 1992;1339:1–8.
[20] Kim S, Loh SW, Zhai H, Bahia H. Advanced characterization of crumb rubber-modified asphalts, using protocols developed for complex binder. Trans Res Rec: J Trans Res Board 2001;1767:15–24.
[21] Zanzotto L, Kennepohl G. Development of rubber and asphalt binders by depolymerization and devulcanization of scrap tires in asphalt. Trans Res Rec: J Trans Res Board 1996;1530:51–9.
[22] Huang S-C, Tia M, Ruth BE. Laboratory aging methods for simulation of field aging of asphalts. J Mater Civil Eng, ASCE 1996:147–52.
[23] McGennis RB. Evaluation of physical properties of fine crumb rubber modified asphalt binders. Trans Res Rec 1995;1488:63–71.
[24] Lee S-J, Amirkhanian S, Shatanawi K. Short-term aging characterization of asphalt binder using gel permeation chromatography and selected superpave binder tests. Constr Build Mater, submitted for publication.
[25] Lee S-J, Chandra K, Amirkhanian S. The effect of crumb rubber modifier on the performance properties of rubberized binders in HMA pavements. Constr Build Mater. in press.