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The effect of crumb rubber modifier (CRM) on the performance properties of rubberized binders in HMA pavements

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

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

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Abstract

The application of crumb rubber modifier (CRM) in asphalt mixtures is intended to improve the properties of binder by reducing the binder's inherent temperature susceptibility. During the interaction with asphalt binder, the CRM particles absorb a portion of the oils in asphalt binder and the particles swell; therefore increasing the viscosity and stiffness of the CRM binder. Still, the performance properties of CRM binders in hot mix asphalt (HMA) pavement are considered to be unclear due to the various interaction effects of CRM with asphalt binders, depending on the CRM percentage, source and size. In this study, a laboratory investigation was conducted on the properties of CRM binders as a function of CRM processing method and percentages. A total of twenty-four CRM binders (3 binder sources * 2 CRM processing methods * 4 CRM percentages) were produced and artificially aged through an accelerated aging process. Evaluation of the CRM binders included the following testing procedures: Viscosity at high temperature, performance properties at high and intermediate temperatures, and cracking properties at low temperature. The results from this study indicated that the higher CRM percentages for CRM binders seemed to lead to a higher viscosity, a better rutting resistance and a less chance for low temperature cracking. In general, the ambient CRM was found to be more effective on producing the CRM binders that are more viscous and less susceptible to rutting and cracking.

Keywords: HMA pavements; Crumb rubber modifier; Rutting resistance; Low temperature cracking

1. Introduction

1.1. Background

Crumb rubber has been manufactured by two major methods: ambient and cryogenic grinding. Each method can produce crumb rubber of similar particle size, but the primary difference between them is the particle surface texture. Crumb rubber particles resulting from ambient processing have an irregular shape with a rough texture due to the tearing and shredding action of the rubber particles in the cracker mills. The crumb rubber particles produced by the cryogenic method, on the other hand, have smooth surfaces, which resemble shattered glass. This difference in particle surface texture results in the ambient particles having higher surface area than the cryogenic crumb rubber [1].

The increasing usage of CRM in asphalt pavements requires a better understanding of its effects on the physical, chemical, and performance properties of CRM binders. Generally, the addition of CRM to asphalt binders is intended to improve some of binder's properties such as reducing the inherent temperature susceptibility of the binder. The improvement of the properties of CRM binders largely depends on the interaction between CRM and asphalt binders where the CRM particles swell in the binders to form a viscous gel; resulting in an increase in the viscosity of the CRM binders [2–7]. However, the properties of CRM binders at a wide range of temperatures are considered to be somewhat unclear due to the various interaction effects of CRM with asphalt binders, largely depending on the

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

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chemistry of the asphalt binder (i.e., source of the binder) and the CRM as well as the percentage, particle size and texture of the CRM and the interaction temperature and time.

1.2. Research objective and scope

The main objective of this research project was to investigate the performance properties of CRM binders due to CRM processing method and percentage through selected Superpave binder tests. The CRM binders were produced in the laboratory incorporating two CRM sources (ambient and cryogenic) and four CRM percentages (5%, 10%, 15%, and 20%) into three base binders. The CRM binders were artificially aged using PAV (pressure aging vessel) procedure. The viscosity and rutting properties for unaged CRM binders, and the cracking properties at intermediate

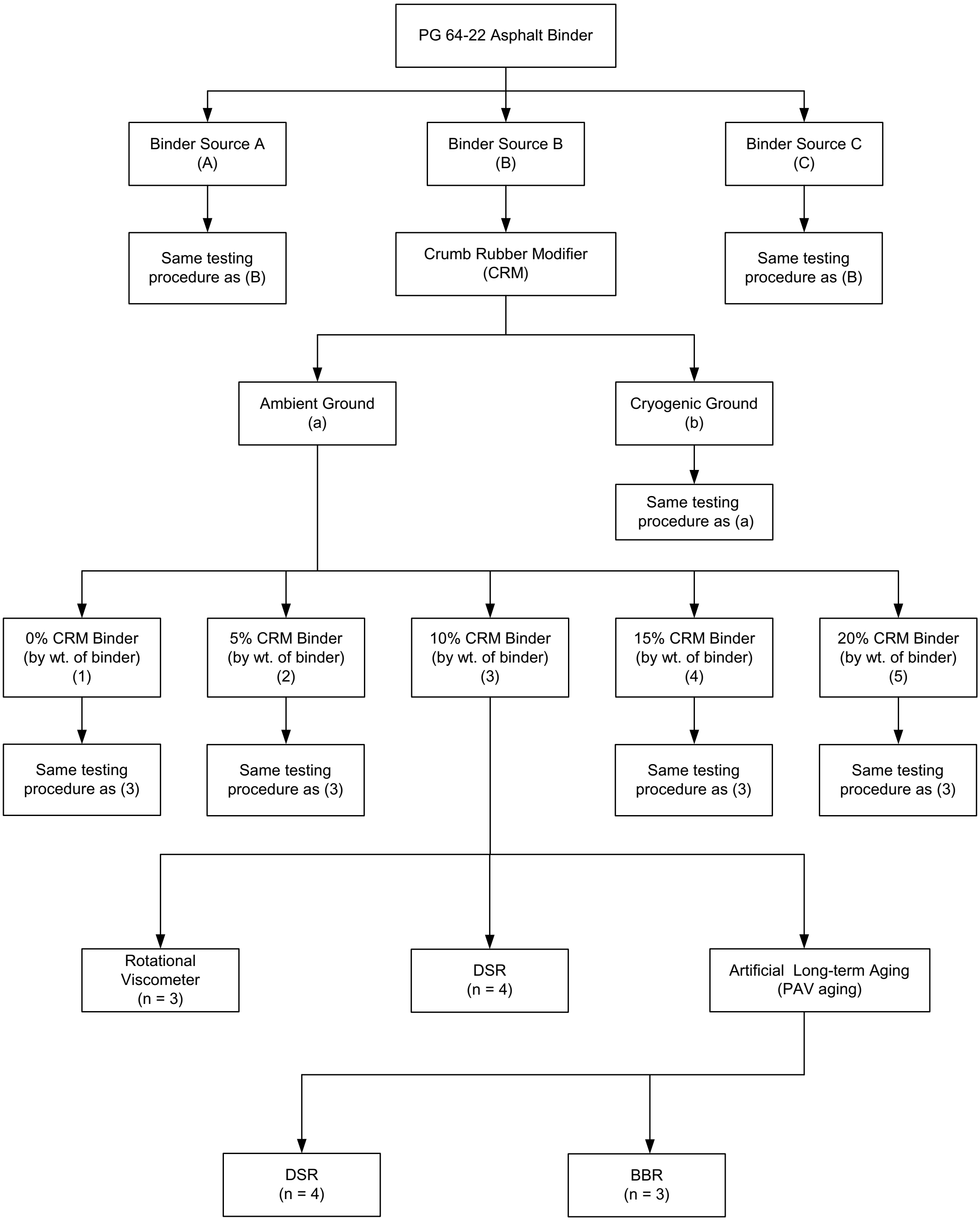

Fig. 1. Flow chart of experimental design procedures.

and low temperatures for aged CRM binders were evaluated. Fig. 1 shows a flow chart of the experimental design used in this study.

2. Materials and test program

2.1. Materials

2.1.1. Asphalt binders

Three asphalt binders all graded as PG 64-22, 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 used in this study was obtained from two sources. One source used the ambient grinding method to process scrap passenger tires into crumb rubber and the other used the cryogenic grinding process. One size of crumb rubber was obtained from each source:−40 mesh (0.425 mm), which is widely used to produce the CRM mixtures in South Carolina. The gradation of each crumb rubber is shown in Fig. 2. The surface texture of each CRM was determined using a scanning electron microscope (SEM) at a magnification level of 120× (Fig. 3).

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

Aging states	Test properties	Binder sources		
		A	B	C
Unaged binder	Rotational viscosity @ 135 °C (Pa-s)	0.703	0.472	0.430
	$G^*/\sin\delta$ @ 64 °C (kPa)	2.413	1.468	1.279
RTFO aged residue	$G^*/\sin\delta$ @ 64 °C (kPa)	6.075	2.579	2.810
RTFO + PAV aged residue	$G^*\sin\delta$ @ 25 °C (kPa)	3352.1	3573.5	4074.3
	Stiffness @−12 °C (MPa)	141.3	232.3	217.0
	m-value @−12 °C	0.359	0.321	0.307

2.2. Preparation and aging of CRM binders

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. The CRM binders were manufactured using two CRMs and three base binders in the laboratory at 177 °C for 30 min by an open blade mixer at a blending speed of 700 rpm [8]. This mixing condition matches the field practices used in South Carolina to produce field mixtures. In total, twenty-four CRM binders (3 binder sources * 2 CRM processing methods * 4 CRM percentages) and three control binders were produced and evaluated during this study. The CRM and control binders were then artificially aged through an accelerated aging process (PAV aging for 20 h at 100 °C) [9].

2.3. Superpave binder tests

The properties of these CRM binders were evaluated using selected Superpave binder test procedures including the viscosity test (AASHTO T 316), BBR (bending beam rheometer) (AASHTO T 313), and DSR (dynamic shear rheometer) (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 [10–12]. Four duplicated samples were tested by the DSR, and three duplicate samples were tested by the rotational viscometer and the

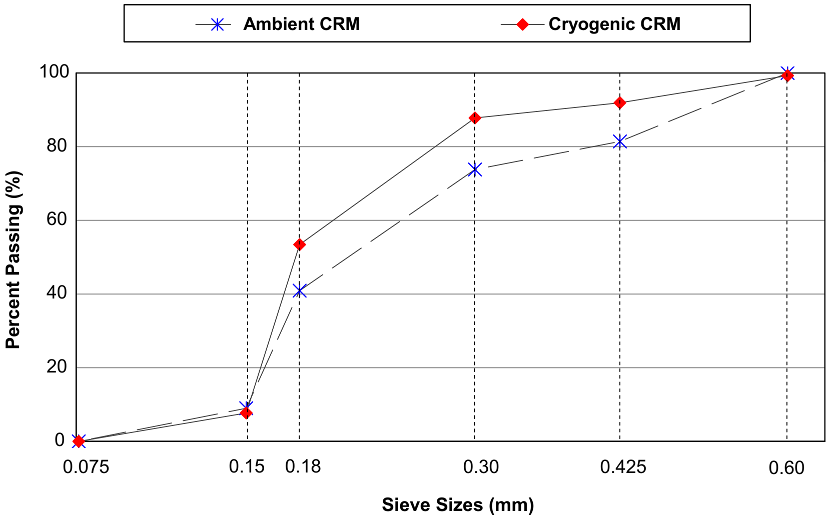

Fig. 2. Gradations of two CRMs.

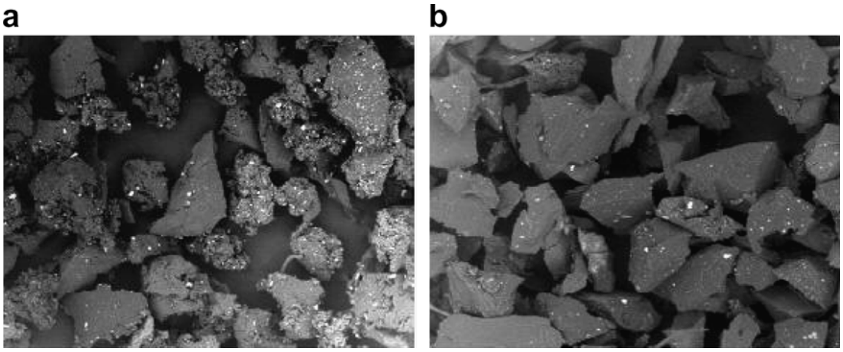

Fig. 3. SEM micrographs at 120× magnification of (a) ambient CRM (−40 mesh) and (b) cryogenic CRM (−40 mesh).

BBR. The results were reported as the average of these tests.

A 10.5 g binder sample of CRM binders was tested with a number 27 spindle in the rotational viscometer at 135 °C. The control binders were tested in accordance with the same procedure except an 8.5 g sample was used with a number 21 spindle. A different test configuration was used for the CRM binders to allow additional space for rubber particles between the wall of the sample tube and the smaller diameter number 27 spindle [1]. In the DSR, the unaged binder was tested using a 25 mm parallel plate at 76 °C and the PAV-aged binder was tested using an 8 mm parallel plate at 25 °C. The BBR test was conducted using each asphalt beam (125 × 6.35 × 12.7 mm) at −12 °C.

3. Results and discussions

3.1. Original state binder (no aging)

3.1.1. Viscosity at high temperature

The viscosity of asphalt binders at high temperatures is an important property as it reflects a 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 [9]. Fig. 4 shows the viscosity results for the CRM binders tested in this research study. A general trend was found, as expected, indicating that the higher CRM percentages led to the higher viscosity of the CRM binders, and the ambient CRM produced binders having higher viscosity than the cryogenic CRM. Additionally, CRM binders produced with binder source A generally had higher viscosities than those made with binder sources B and C. This is thought to be attributed to the initial higher viscosity of the base binder A.

From an analysis of the viscosity results shown in Table 2, it is evident that the CRM percentage had a major effect on the performance of the CRM binders. In addition, the processing method used to manufacture CRM, ambient vs. cryogenic, was found to have a significant effect.

Superpave binder specifications include a maximum viscosity requirement (3 Pa s) for an unaged binder measured at 135 °C [13]. Based on this limit, all CRM binders containing 20% ambient and cryogenic CRM would be unacceptable.

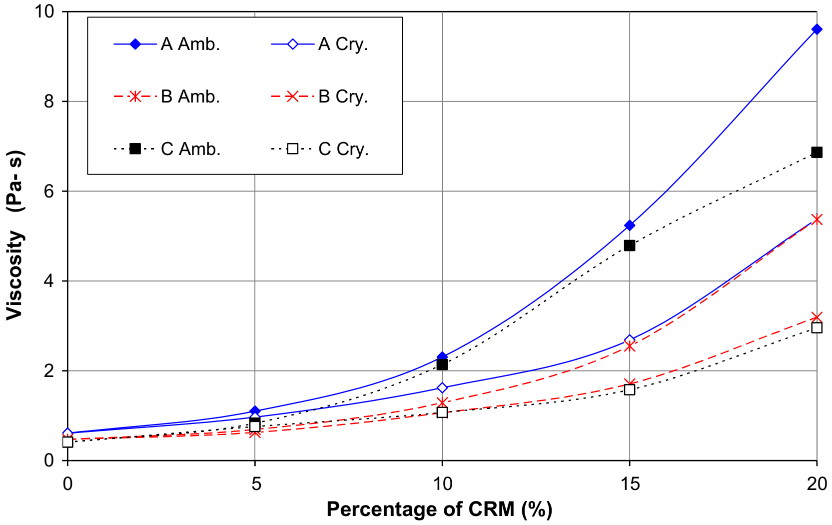

Fig. 4. Viscosity test results of unaged CRM binders (at 135 °C).

Table 2
Results of ANOVA by Duncan's multiple range test to determine differences between viscosity results of CRM binders within each binder source ($\alpha = 0.05$)

Binder source	CRM content (%)	Duncan grouping	CRM grind	Duncan grouping
A	0	a	Ambient	a
	5	b	Cryogenic	b
	10	c		
	15	d		
	20	e		
B	0	a	Ambient	a
	5	b	Cryogenic	b
	10	c		
	15	d		
	20	e		
C	0	a	Ambient	a
	5	b	Cryogenic	b
	10	c		
	15	d		
	20	e		

Viscosity results of CRM binders with the same letter, within each binder source, are not significantly different.

Table 3
Results of ANOVA by Duncan's multiple range test to determine differences between $G^*/\sin\delta$ results of CRM binders within each binder source ($\alpha = 0.05$)

Binder source	CRM content (%)	Duncan grouping	CRM grind	Duncan grouping
A	0	a	Ambient	a
	5	b	Cryogenic	b
	10	c		
	15	d		
	20	e		
B	0	a	Ambient	a
	5	b	Cryogenic	a
	10	c		
	15	d		
	20	e		
C	0	a	Ambient	a
	5	b	Cryogenic	b
	10	c		
	15	d		
	20	e		

$G^*/\sin\delta$ results of CRM binders with the same letter, within each binder source, are not significantly different.

3.1.2. Performance properties at high temperature

In general, the higher $G^*/\sin\delta$ values indicate that the binders will be less susceptible to permanent deformation at high pavement temperatures [9]. The rutting resistance parameter, the $G^*/\sin\delta$, of the control and CRM binders was measured at 76 °C and the results are shown in Fig. 5. Generally, the $G^*/\sin\delta$ did follow the same trend for all of the combinations tested. For all three binder sources, there is an increase in $G^*/\sin\delta$ with an increase in CRM percentages. The statistical results indicate that there were statistically significant differences in the $G^*/\sin\delta$ of CRM binders as a function of CRM percentages (Table 3). The differences between the CRM binders produced with ambient and cryogenic CRM were also statistically significant at the 5% level, with an exception of binder source B. This finding is consistent with the surface texture of two CRMs (Fig. 3). Ambient CRM interacts with asphalt binder more easily and quickly than cryogenic CRM, as the former has a much higher surface area due to its porous surface texture [14]. Therefore, the CRM binders with ambient CRM will result in more absorption of the light parts of the asphalt binder, leading to a better rutting properties (higher $G^*/\sin\delta$ values).

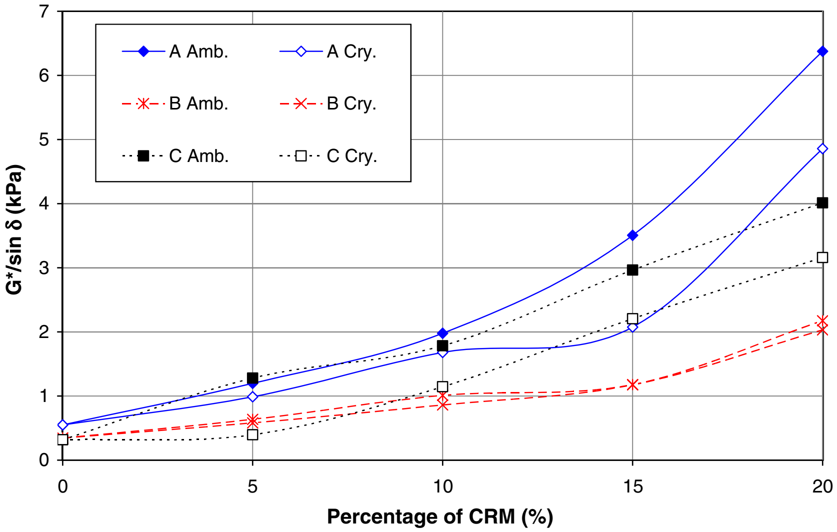

Fig. 5. DSR test results of unaged CRM binders (at 76 °C).

Similar to viscosity results, the CRM binders produced from binder source A showed significantly greater $G^*/\sin\delta$ values than those produced from binder sources B and C. It should be mentioned that the base binders had different $G^*/\sin\delta$ values. The $G^*/\sin\delta$ of base binder A at 76 °C was 38% and 42% higher than those of base binders B and C, respectively (Fig. 5).

3.2. Long-term aged binder (PAV aging)

3.2.1. Fatigue cracking properties at intermediate temperature

The Superpave binder specification has a maximum value of 5000 kPa for $G^*\sin\delta$, and low values of $G^*\sin\delta$ are considered desirable attributes from the standpoint of resistance to fatigue cracking [9]. After PAV aging, the fatigue resistance parameters, $G^*\sin\,\delta$ values, of the control and CRM binders were measured using the DSR at 25 °C and the results are illustrated in Fig. 6. In general, the higher CRM percentages seemed to lead to the lower $G^*\sin\delta$ of the CRM binders, but this trend was not consistent. From Duncan's multiple range test (Table 4), the statistical differences of $G^*\sin\delta$ as a function of CRM percentages varied depending on the binder source and the CRM percentage used. Additionally, the difference between ambient and cryogenic CRM was found to have an insignificant effect, at the 5% level, on $G^*\sin\delta$ of the CRM binders produced from binder sources A and B.

With respect to the effect of binder source on $G^*\sin\delta$ of CRM binders, the CRM binders produced with binder source A were considered to be the most resistant to fatigue cracking. This is also thought to be attributed to the lower $G^*\sin\delta$ of the base binder A.

Table 4
Results of ANOVA by Duncan's multiple range test to determine differences between $G^*\sin\delta$ results of aged CRM binders within each binder source ($\alpha = 0.05$)

Binder source	CRM content (%)	Duncan grouping	CRM grind	Duncan grouping
A	0	a	Ambient	a
	5	b	Cryogenic	a
	10	b, c		
	15	c		
	20	c		
B	0	a	Ambient	a
	5	b	Cryogenic	a
	10	b, c		
	15	b, c		
	20	c		
C	0	a	Ambient	a
	5	b	Cryogenic	b
	10	b		
	15	c		
	20	d		

$G^*\sin\delta$ results of CRM binders with the same letter, within each binder source, are not significantly different.

It should be noted that the variance of $G^*\sin\delta$ values (at 25 °C) obtained from four duplicated samples was much greater than that of $G^*/\sin\delta$ values (at 76 °C), and this may be related to the difference of the sample amount used at two DSR tests (for unaged and PAV aged CRM binders), especially in the CRM binders with high CRM percentages. Also, the CRM particles remaining in the binder might be another reason of the greater variance of G^* sin δ at 25 °C.

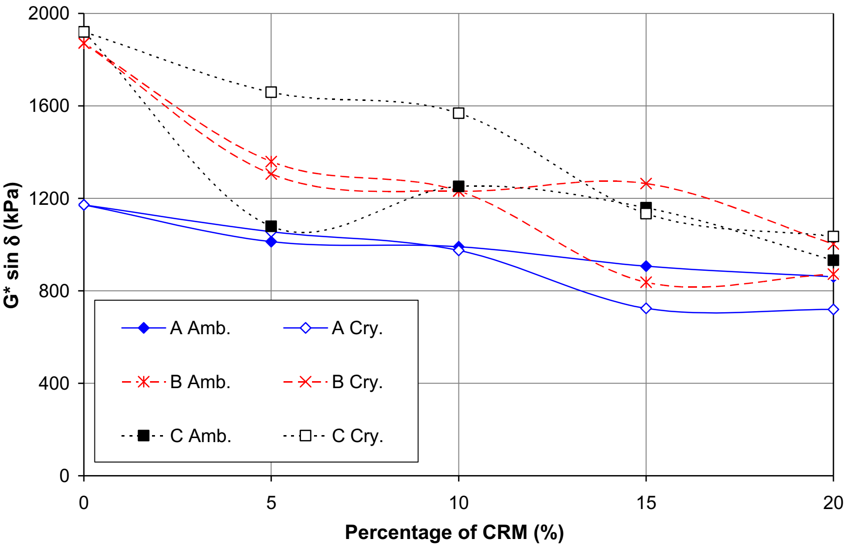

Fig. 6. DSR test results of aged CRM binders (at 25 °C).

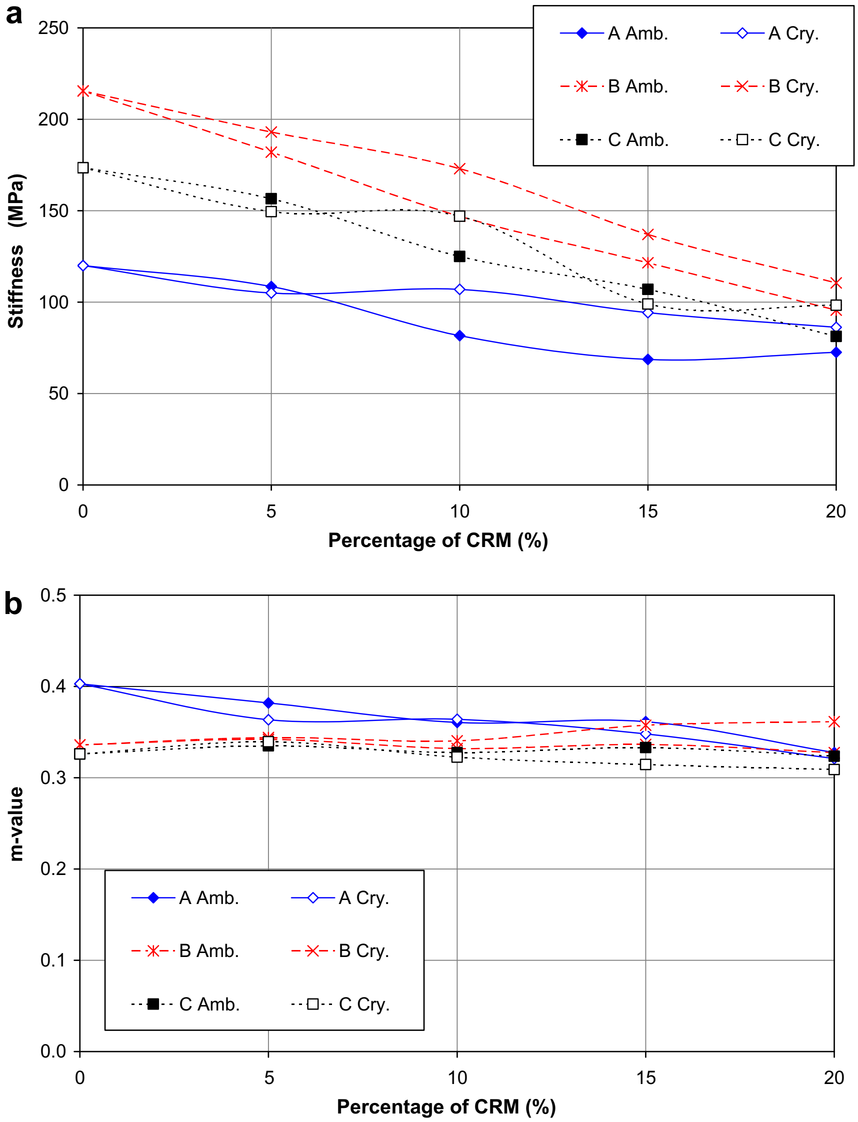

Fig. 7. BBR test results of aged CRM binders: (a) stiffness; (b) *m*-value.

3.2.2. Cracking properties at low temperature

To prevent thermal cracking, creep stiffness has a maximum limit of 300 MPa, and the decrease in stiffness leads to smaller tensile stresses in the asphalt binder and less chance for low temperature cracking [9]. From the BBR tests at −12 °C, the shrinkage resistance parameters, stiffness and *m*-value, of the control and CRM binders were calculated, and the results are shown in Fig. 7. The stiffness of CRM binders did tend to decrease as the CRM percentages increased from 5% to 20%, regardless of the binder source and CRM processing methods. In addition, the CRM binders produced with ambient CRM generally showed the lower stiffness values than those with cryogenic CRM, and the difference was statistically significant at the 5% level (Table 5). It is important to note that the CRM binders with ambient CRM had a better resistance on low temperature cracking, as well as permanent deformation at high temperature.

The CRM binders produced from binder source A showed lower stiffness values than those produced from binder sources B and C. However, the stiffness difference within binder sources was found to be smaller as the CRM percentages increased (Fig. 7a). The finding indicates that the effect of binder source on the CRM binder at low temperature may lessen as the CRM percentages increases.

Fig. 7b depicts the change in the *m*-value as a function of the CRM percentage. As shown in this figure and Table 6, the effect of CRM percentage on the *m*-value was not significant at the 5% level. Similarly, the processing method employed to manufacture CRM had an insignificant effect, with the exception of binder source B.

Table 5
Results of ANOVA by Duncan's multiple range test to determine differences between stiffness results of aged CRM binders within each binder source ($\alpha = 0.05$)

Binder source	CRM content (%)	Duncan grouping	CRM grind	Duncan grouping
A	0	a	Ambient	a
	5	b	Cryogenic	b
	10	c		
	15	d		
	20	d		
B	0	a	Ambient	a
	5	b	Cryogenic	b
	10	c		
	15	d		
	20	e		
C	0	a	Ambient	a
	5	b	Cryogenic	b
	10	c		
	15	d		
	20	e		

Stiffness results of CRM binders with the same letter, within each binder source, are not significantly different.

Table 6
Results of ANOVA by Duncan's multiple range test to determine differences between m-value results of aged CRM binders within each binder source ($\alpha = 0.05$)

Binder source	CRM content (%)	Duncan grouping	CRM grind	Duncan grouping
A	0	a	Ambient	a
	5	b	Cryogenic	a
	10	b		
	15	b		
	20	c		
B	0	a	Ambient	a
	5	a	Cryogenic	b
	10	a		
	15	b		
	20	b		
C	0	a	Ambient	a
	5	b	Cryogenic	a
	10	a		
	15	a		
	20	a		

m-value results of CRM binders with the same letter, within each binder source, are not significantly different.

These findings were consistent with the previous research [3].

4. Summary and conclusions

To investigate the performance properties of CRM binders as a function of CRM processing method and percentage, twenty four CRM binders were produced in the laboratory, using two CRM sources, four CRM percentages and three base binders (PG 64-22). The CRM binders were artificially aged through an accelerated aging process. A series of selected Superpave binder tests were conducted using rotational viscometer, DSR, and BBR to evaluate the viscosity and rutting properties at high temperature and the cracking properties at intermediate and low temperatures. From these test results, the following conclusions were drawn for the materials used in this study:

1. The higher CRM percentages used to produce CRM binders, as expected, led to an increase in the viscosity at 135 °C, which is related to the increase in the CRM mass through binder absorption. The ambient CRM resulted in higher viscosity values than the cryogenic CRM at the same percentage usage, and this is attributed to the increased surface area and irregular shape of the ambient CRM.
2. The rutting properties of CRM binders improved as the CRM percentage increased. The ambient CRM was found to be more effective on producing the CRM binders that are less susceptible to rutting at high pavement temperatures.
3. In general, the higher CRM percentages seemed to lead to better fatigue cracking properties of the CRM binders, but the difference between ambient and cryogenic CRM was not found to have a significant effect on the $G^*\sin\delta$ of the CRM binders at the 5% level.
4. The higher CRM percentage resulted in the lower stiffness of CRM binders, and the CRM binders produced with ambient CRM showed a better resistance on low temperature cracking than those with cryogenic CRM. The binder source influence on the CRM binder properties at low temperature was not as significant as the CRM percentage increased.
5. The CRM percentages and the processing methods (ambient vs. cryogenic) used to manufacture CRM were not found to have statistically significant effects on change in the m-value.
6. It is recommended to conduct another study to evaluate the effect of CRM particle size using the same test combinations. Also, further study with many other binder and CRM sources is needed to generalize these findings.

Acknowledgements

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