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# Effect of Crumb Rubber Dissolution on Low-Temperature Performance and Aging of Asphalt–Rubber Binder

Amir Ghavibazoo and Magdy Abdelrahman

Asphalt binder plays a critical role in defining the low-temperature performance of asphalt pavement, and, therefore, enhancing its mechanical behavior at low service temperatures through modification always has been of great interest. Crumb rubber modification of asphalt is one of the common practices in the industry. However, the effect of a crumb rubber modifier (CRM) on low-temperature performance of the binder is not well understood. A CRM swells by absorbing the aromatics and light molecular components of asphalt at low interaction temperatures (i.e., 160°C) and dissolves at higher interaction temperatures (i.e., 190°C, 220°C). Each of those activities affects the performance of the CRM asphalt differently. In this research, the activities of CRMs in asphalt controlled accurately through regulating the interaction conditions and the effect of each of those activities on low-service-temperature properties of asphalt were studied by using the bending beam rheometer (BBR) and modulated differential scanning calorimetry. The BBR was used to measure the mechanical behavior of CRM asphalt and its liquid phase at low temperatures as a function of CRM dissolution, and modulated differential scanning calorimetry was used to investigate possible changes in glass transition of the liquid phase of the modified binder. Results indicate that the stiffness and  $m$ -value of the modified binder are developed in two different manners, and the factors that affect these two parameters are different. Also, results show that through certain interaction conditions, optimization of the low-temperature performance of the CRM asphalt is possible.

Among several types of distresses on pavement, thermal cracking is of considerable concern and interest to highway engineers, especially in Canada and the northern region of the United States. High cooling rate and very low temperatures result in shrinkage of the pavement and consequently develop tensile stresses on pavement. When those stresses exceed the fracture stress of the surface layer of the pavement, thermal cracking develops. Stiff asphalt pavements are more prone to low-temperature cracking. Stiffness of the asphalt pavement at high service temperatures depends primarily on aggregate structure, while at low service temperatures stiffness of the pavement highly depends on stiffness of the asphalt binder. Therefore, high stiffness of asphalt binder is considered the predominant cause of thermal cracking of pavement. Thus, measuring and controlling the stiffness

of the asphalt at very low temperatures are crucial in constructing durable pavements.

A Superpave® specification has suggested the bending beam rheometer (BBR) test to determine the performance of asphalt binder at very low temperatures. This test measures the load and deflection and calculates the creep stiffness,  $S(t)$ , and  $m$ -value of asphalt samples. Creep stiffness represents how the asphalt binder resists the constant creep loading, and the  $m$ -value represents the rate of stress relaxation by asphalt binder flow and is calculated on the basis of changes in creep stiffness of asphalt binder by the loading time. These properties of asphalt change by its modification.

Crumb rubber modification of asphalt is a well-established practice in the asphalt industry. Therefore, the effect of a crumb rubber modifier (CRM) on low-temperature performance of asphalt and its resistance to thermal cracking has been widely studied. Bahia (1) and Billiter et al. (2) investigated the effect of CRM on low-temperature performance of different binders. They stated that CRM improves the stiffness of the binder at low temperatures but degrades its  $m$ -value (2). Billiter et al. also investigated the effect of high-temperature curing conditions on low-temperature properties of CRM Modified Asphalt (CRM binder) (3). They concluded that high-temperature curing conditions improve the homogeneity of the modified binder as well as its creep stiffness at low temperatures (3). However, they did not test the  $m$ -value of the modified asphalt.

The changes in low-temperature properties of CRM binder have been attributed to different effects of CRM in asphalt. Billiter et al. stated that tire rubber has very low sensitivity to temperature and keeps its elasticity at such temperatures (2). Therefore, tire rubber can function as elastic filler in asphalt at very low temperatures, close to the glass transition temperature of asphalt and improves asphalt's flexibility. However, Morrison and Hesp (4) and Hui et al. (5) speculated that improvement in low temperature of asphalt in the presence of CRMs happens as a result of crack pinning and the crack blunting effect of these particles, effects that increase the toughness of the binder. Moreover, it is stated that CRMs can improve the aging susceptibility of the asphalt binder, and that improvement results in lower stiffness of asphalt after aging and consequently better physical properties at low temperatures.

Despite of all those studies, the exact contribution of CRM particles in developing the low-temperature properties of asphalt is not well understood. Previous studies by the authors show that CRM goes through different changes during interaction with asphalt. A CRM swells in asphalt through absorbing its light molecular components at low interaction temperatures (i.e., 160°C) and dissolves in asphalt at higher interaction temperatures (i.e., 190°C, 220°C). Also, the mechanism of dissolution is different depending on interaction

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temperature. Each of these activities affects the nature of the liquid phase of the asphalt binder as well as the CRM particles and accordingly changes the physical properties of modified asphalt. The CRM activities lead to two types of changes in the CRM binder: first, changes in the three-dimensional structure and composition of CRM particles through swelling and dissolution of particles; and second, changes in the composition of the liquid phase of the asphalt through the process of exchanging components between CRM and asphalt.

The complex dynamic nature of the CRM binder and the varieties of CRM activities in asphalt make it necessary to investigate the effect of each of the CRM activities on the low-temperature properties of asphalt. Therefore, in this research, the activities of CRM in asphalt were controlled by regulating the interaction condition, and a set of samples with a wide range of CRM dissolution was developed. To distinguish and separate the effect of CRM modification on the aging mechanism of the CRM binder from its effect on the low-temperature performance of the CRM binder, the low-temperature performance of the samples was investigated before and after aging. Before aging, the low-temperature properties of the CRM binder samples and their liquid phase (CRM-removed condition) were measured as a function of CRM dissolution by using the BBR. The effect of CRM modification on glass transition temperature of the liquid phase of CRM binder samples—an effect which plays an important role in defining the low-temperature mechanical behavior of CRM—was investigated through modulated differential scanning calorimetry (MDSC). After aging, the low-temperature properties of the CRM binder samples were measured through the standard BBR test as a function of CRM dissolution.

## MATERIALS AND METHOD

### Materials

Asphalt materials from two sources, Flint Hill Resources and Murphy Oil Corporation, with the same PG grade of 58-28, were used in this research and were denoted NF and M, respectively. Also, two CRM batches, one from truck tires (TR) and one from passenger car tires (WTG), were used in this research. Both CRM batches were produced by ambient method and were provided by Liberty Tire Recycling. The CRM particle size, in all interactions, was controlled to be smaller than the No. 30 (0.599 mm) mesh and larger than the No. 40 (0.422 mm) mesh, according to the U.S. standard system. Properties of the materials are listed in Tables 1 and 2.

### Interactions

All interactions were conducted by using  $1,200 \pm 100$  g of asphalt in 1-gal paint cans. An aluminum heating mantle (100B TM634)

TABLE 1 Properties of Asphalt Binder Under Study

Asphalt Type	PG Grade	Physical Properties at 58°C (before aging) $[G^*/\sin(\delta)]$ (Pa)	Physical Properties at -18°C (before aging)	
			$S(60)$ (MPa)	$m$ -Value
Flint Hill (NF)	PG 58-28	1,233.2	121	0.474
Murphy (M)	PG 58-28	1,643.2	103	0.455

NOTE:  $S(60)$  = creep stiffness after 60s of loading.

attached to a bench top temperature controller and a J-type thermocouple was used to control the temperature. Nitrogen gas was applied on top of all interactions to prevent any oxidation. The interaction parameters were selected on the basis of results of the previous studies by this research group to control the dissolution of CRM in asphalt (6, 7). Table 3 shows the list of interactions, their related code and parameters, and the percentage of dissolution of CRM in asphalt. The reliability of all interactions and testing was validated by running replications on a limited number of samples based on feasibility.

### CRM Extraction Method

The CRM extraction method was carried on as described in detail in other publications by this research group (6, 8). In this study, 10 g of modified asphalt were diluted in Toluene and drained through the No. 200 (75  $\mu$ m) mesh and washed with extra toluene until the filtrate became colorless. The retained particles were dried in the oven at 60°C for 12 h to ensure removal of all solvent residues.

### Extraction of Liquid Phase of Modified Asphalt

To obtain the liquid phase of the CRM binder, the required amount of CRM binder was heated to 165°C and drained through No. 200 (75  $\mu$ m) mesh in the oven at 165°C for 25 min. Immediately, the extracted liquid phase was stored at -12°C to prevent any unwanted aging or reaction.

### Asphalt Aging

To age the neat asphalt binder and modified asphalt binder, the standard method suggested by Superpave specifications was followed. The samples were short-term-aged through the rolling thin-film oven

TABLE 2 Properties of CRM Under Study

CRM Type	Source	Process Method	Percentage of Acetone Extract	Percentage of Polymer	Percentage of Carbon Black	Percentage of Other
TR	Truck tire	Ambient	3.85	57.42	30.84	7.89
WTG	Passenger car tire	Ambient	5.59	55.45	31.41	7.55

TABLE 3 Interactions and Related Parameters

Interaction Code	AC Type	CRM Type	CRM Concentration (%)	Temp. (°C)	Mixing Speed (Hz)	Time (min)	CRM Dissolution (%)	Rutting Parameter [ $G^*/\sin(\delta)$ ] (Pa)
NF-WTG-10%-10Hz160°C-240 min	NF	WTG	10	160	10	240	13.9	2,479
NF-WTG-10%-10Hz190°C-240 min	NF	WTG	10	190	10	240	23.1	2,214
NF-WTG-10%-30Hz190°C-120 min	NF	WTG	10	190	30	120	31.0	2,193
NF-WTG-10%-30Hz190°C-240 min	NF	WTG	10	190	30	240	41.2	1,787
NF-WTG-10%-30Hz190°C-480 min	NF	WTG	10	190	30	480	55.0	1,798
NF-WTG-10%-50Hz190°C-120 min	NF	WTG	10	190	50	120	49.8	2,119
NF-WTG-10%-50Hz190°C-240 min	NF	WTG	10	190	50	240	69.5	2,121
NF-WTG-10%-10Hz220°C-120 min	NF	WTG	10	220	10	120	41.1	1,589
NF-WTG-10%-10Hz220°C-240 min	NF	WTG	10	220	10	240	71.7	1,488
NF-WTG-10%-50Hz220°C-240 min	NF	WTG	10	220	50	240	83.6	1,443
NF-WTG-20%-10Hz160°C-240 min	NF	WTG	20	160	10	240	13.5	8,189
NF-WTG-20%-10Hz190°C-240 min	NF	WTG	20	190	10	240	35.9	7,434
NF-WTG-20%-30Hz190°C-120 min	NF	WTG	20	190	30	120	33.6	6,984
NF-WTG-20%-30Hz190°C-240 min	NF	WTG	20	190	30	240	35.1	6,084
NF-WTG-20%-50Hz190°C-180 min	NF	WTG	20	190	50	180	57.4	4,264
NF-WTG-20%-50Hz190°C-240 min	NF	WTG	20	190	50	240	60.1	4,203
NF-WTG-20%-10Hz220°C-60 min	NF	WTG	20	220	10	60	44.8	3,893
NF-WTG-20%-10Hz220°C-120 min	NF	WTG	20	220	10	120	51.8	3,127
NF-WTG-20%-10Hz220°C-240 min	NF	WTG	20	220	10	240	68.1	2,028
NF-WTG-20%-50Hz220°C-240 min	NF	WTG	20	220	50	240	82.6	1,182
NF-TR-20%-10Hz190°C-240 min	NF	TR	20	190	10	240	30.7	6,025
NF-TR-20%-50Hz190°C-240 min	NF	TR	20	190	50	240	52.8	4,125
NF-TR-20%-10Hz220°C-240 min	NF	TR	20	220	10	240	72.6	1,857
M-TR-20%-10Hz190°C-240 min	M	TR	20	190	10	240	24.7	11,015
M-TR-20%-50Hz190°C-240 min	M	TR	20	190	50	240	55.0	7,098
M-TR-20%-10Hz220°C-240 min	M	TR	20	220	10	240	64.1	3,644

NOTE: Temp. = temperature.

(RTFO), following ASTM standard D2872-12e1. Then the RTFO residue was long-term-aged by using the pressure aging vessel (PAV), following the ASTM standard D6521-08. The PAV residue was stored in separate small containers at room temperature for further testing.

To ensure a complete flow of the samples in the RTFO bottles (especially in the case of CRM binder samples), the suggested method by Bahia et al. was applied (9). In this method, a stainless steel rod 127 mm by 6.4 mm in size was placed in each bottle to ease the flow of the samples and prevent them from rolling out; these actions were observed during the preliminary studies by this research group and reported in other literature (9, 10).

### Use of BBR

The BBR from Applied Test Systems was used to determine the flexural creep stiffness and  $m$ -value of the CRM binder samples and their liquid phase at low service temperatures. All tests were performed following the ASTM standard D 6648-08. Samples were prepared with aluminum molds. Aged and unaged samples were preheated up to 165°C and then poured into the mold, which was covered with clear plastic sheets. The filled mold was kept on the bench until its temperature decreased below 60°C. Then the exposed face of the mold was trimmed with a hot spatula, and the sample was cooled to -5°C for fewer than 5 min. Then the sample was demolded and kept in a methanol bath at -18°C for 60 ± 5 min for temperature equilibration. All BBR tests were conducted at -18°C, and test results were recorded for loading after 60 s. All tests were replicated three times for reliability reasons.

### Modulated Differential Scanning Calorimetry Analysis

Glass transition is a reversible change from a brittle or glassy state to a rubbery or viscous state (or vice versa). Glass transition is one of the most important thermal phenomenon that governs the physical behavior of amorphous materials at very low temperatures (11, 12). The glass transition temperature (i.e.,  $T_g$ ) represents the range of temperatures at which the transition to glassy state takes place. During this transition, several changes happen to the mechanical, optical, and thermodynamic properties of the materials. Therefore, there are different instruments to measure the glass transition temperature of a material. One of the most common and accurate methods is differential scanning calorimetry (DSC), which measures the changes in the heat flow of the sample as a function of temperature and demonstrates the glass transition as a stepwise drop in its heat flow (13).

In this research, the DSC was used in a modulated setup, MDSC, in which in addition to heating the sample in a linear mode, the temperature oscillates in a sinusoidal fashion to separate the glass transition, as a reversible thermal phenomenon, from crystallization and melting, as a nonreversible thermal phenomenon (14). The MDSC test was performed by using a Q1000 differential scanning calorimeter from TA Instruments (USA). Samples with a mass of 10 ± 2 mg were sealed in the hermetic aluminum pans. The thermal history of all samples was deleted by heating them to their melting point and then quenching them to -90°C with the same cooling rate of 20°C/min. The MDSC setup was selected on the basis of extensive research by Kriz et al. on application of MDSC on neat and modified asphalt binder (11). The

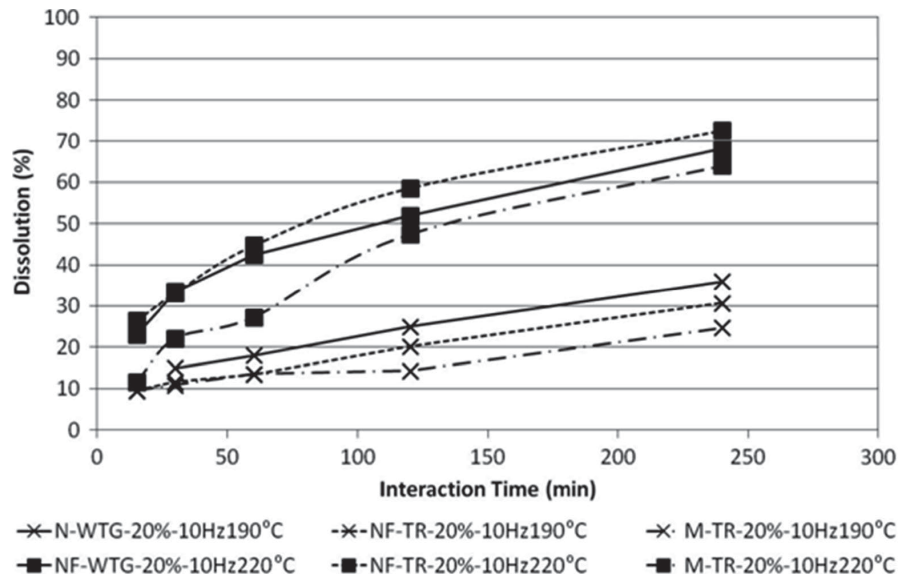


FIGURE 1 Trend of CRM dissolution by interaction condition.

modulation amplitude was 2°C, the modulation period was 60 s, and the linear heating rate was 2°C/min.

## RESULTS AND DISCUSSION

### Dissolution of CRM in Asphalt

Dissolution of CRM in asphalt was extensively studied in previous publications by this research group (6, 8). It was shown that dissolution of CRM in asphalt mainly depends on interaction temperature, and the effect of time and mixing speed is temperature dependent. Also, the mechanism of dissolution varies by changing the temperature, even though the extent of dissolution may be the same. In this research, the dissolution of CRM in asphalt is controlled by regulating the interaction conditions to obtain a set of samples with a wide range of CRM dissolutions. Figure 1 presents

the dissolution trend of CRM in asphalt under different interaction conditions for the selected CRM and asphalt types.

As can be seen in Figure 1, the trend of dissolution is the same for all CRM and asphalt types. However, there is a slight difference in the extent of dissolution that needs further investigation. These results are in accordance with the results of previous studies by this research group (6, 8). In subsequent sections, the effect of the dissolution of CRM on developing the low-temperature performance of modified asphalt is investigated

### Low-Temperature Properties of CRM Binder Before Aging

To determine the low-temperature performance of the CRM binder, a BBR test was conducted on each sample. Figure 2 presents the

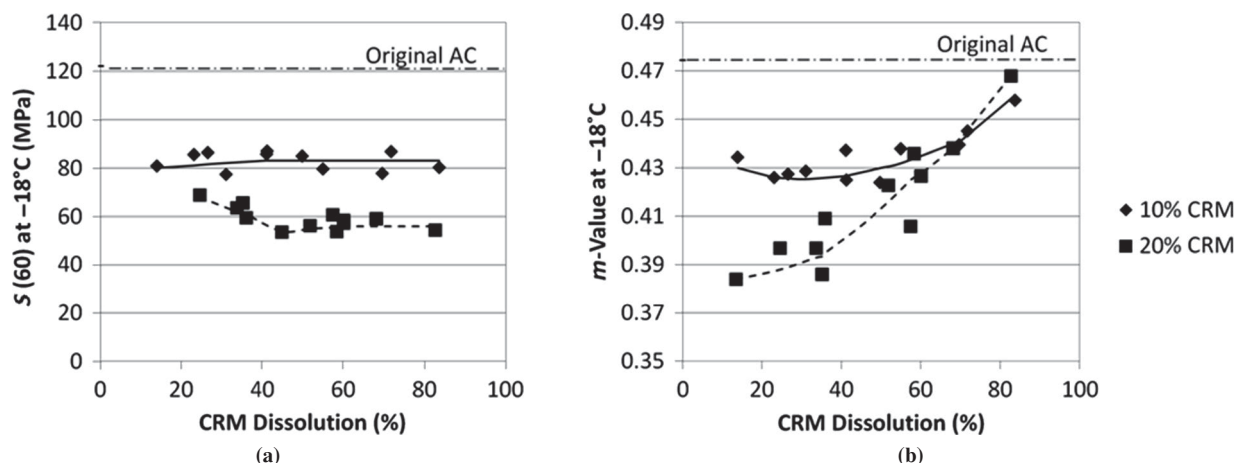


FIGURE 2 Effect of CRM dissolution on (a) stiffness and (b) *m*-value of CRM asphalt before aging (AC = asphalt cement).



creep stiffness,  $S(60)$ , and  $m$ -value of the CRM binder samples as a function of CRM dissolution.

From results in Figure 2, it can be seen that the addition of CRM and increasing its concentration decrease both the stiffness and  $m$ -value of the modified binder at very low CRM dissolutions, in accordance with the results in other studies (1, 3, 15). The decrease in stiffness is advantageous, while the decrease in  $m$ -value is disadvantageous to the low-temperature performance of the CRM binder. These changes in stiffness and  $m$ -value, at a low level of CRM dissolution, indicate that the presence of flexible CRM particles in the asphalt matrix lowers its resistance to deflection but deteriorates the asphalt's flow capacity and consequently its stress relaxation. These effects intensify by increasing the CRM concentration.

Also, at higher CRM concentration (20%), increasing the CRM dissolution improves the low-temperature properties of the CRM binder in regard to stiffness. But no such trend is observable in the case of the lower CRM concentration (10%). This fact can be attributed to the trade-offs between the reduction in flexibility of the remaining CRM particles in the matrix owing to their dissolution and the decrease in the stiffness of the liquid phase (explained in the next section) owing to the release of CRM components into the asphalt matrix. The former happens as the CRM particles lose their polymeric components (their flexible portion) into the asphalt matrix and become nonelastic fillers. The latter happens because of the changes in composition of the liquid phase that alter its low-temperature properties. In the case of the samples with 10% CRM concentration, these two phenomena completely offset each other; therefore, increasing the dissolution of CRM does not change the stiffness of the total matrix. But in the case of samples with 20% CRM concentration, the lower stiffness of the liquid phase, owing to the release of CRM components, dominates the stiffening that was gained as a result of the loss of the flexible CRM particles, and, consequently, the stiffness of the whole matrix of CRM binder decreases.

Figure 2b illustrates that increasing the CRM concentration significantly decreases the  $m$ -value of the CRM binder at low dissolution levels. Also, increasing the CRM dissolution improves the  $m$ -value of the CRM binder, and finally at extensive CRM dissolution, the modified asphalt regains its original  $m$ -value. This result reveals that the  $m$ -value is highly governed by the properties of the liquid phase of the matrix, which is in accordance with its definition; it represents the rate of stress relaxation by asphalt binder flow.

To investigate further the causes behind these trends, the BBR and DSC tests were conducted on the liquid phase of the CRM binder (CRM-removed condition), and the results are presented in subsequent sections.

### Low-Temperature Properties of Liquid Phase of CRM Binder Before Aging

Figure 3 presents the BBR test results on liquid phase of the CRM binder before aging. To investigate the effect of CRM particles and their dissolved portion, the changes in stiffness and  $m$ -value are presented in different illustrations. Results in Figure 3, *a* and *b*, show the changes in stiffness and  $m$ -value of the liquid phase, respectively, as a function of CRM dissolution percentage (calculated on the basis of weight of the original CRM). Results in Figure 3, *c* and *d*, show, respectively, the changes in stiffness and  $m$ -value of the liquid phase as a function of percentage of released rubber in the asphalt (percentage of dissolved CRM based on the weight of the asphalt).

Results in Figure 3a show that at low levels of CRM dissolution (lower than 40%), the stiffness of the liquid phase of CRM binder with 20% CRM concentration is higher than that for the CRM binder with 10% CRM concentration, and both are higher than those for original asphalt. This outcome indicates that at this level of CRM dissolution, absorption of light molecular components of asphalt is the cause of the increased stiffness of the liquid phase of the binder. Therefore, the liquid phase of the CRM binder with 20% CRM shows higher stiffness than does the one with 10% CRM.

By increasing the CRM dissolution, the stiffness of the liquid phase of CRM binder decreases remarkably. Results in Figure 3a show that the stiffness of the liquid phase of the CRM binder with 20% CRM concentration decreases faster as a function of CRM dissolution than that of the CRM binder with 10% CRM concentration. The stiffness of the liquid phase of the CRM binder with 20% CRM concentration is higher than that of the one with 10% CRM concentration at low CRM dissolutions (below 40%), and it is lower at high CRM dissolutions (above 40%). Improvement in stiffness is inversely correlated with the amount of released CRM in the asphalt. The combination of results in Figure 3, *a* and *c*, indicates that two different phenomena are involved in modifying the stiffness of asphalt at low temperatures: first, absorption and desorption of the light molecular weight components of asphalt by CRM particles; and second, the release of polymeric and filler components of the CRM into the asphalt matrix. Absorption of light molecular components at low dissolution levels increases the stiffness of the liquid phase significantly higher than for the original binder, as explained before. Increasing the dissolution of CRM leads to desorption of these components back into the asphalt matrix and consequently decreases the stiffness of the liquid phase. The release of polymeric and filler components of the CRM into the asphalt matrix changes the composition of the liquid phase of the CRM binder and consequently changes its behavior at low temperatures.

Figure 3b shows the effect of CRM dissolution on the  $m$ -value of the liquid phase of CRM binder samples with two CRM concentrations. In the cases of both CRM concentrations, the  $m$ -value of the liquid phase decreases first and then increases by increasing the CRM dissolution. The  $m$ -value of the liquid phase of the CRM binder with 20% CRM concentration is significantly lower than that of the CRM binder with 10% CRM concentration, and both are significantly lower than that of the original binder. Increasing the CRM dissolution in asphalt to above 40% increases the  $m$ -value of the liquid phase of CRM binder with both CRM concentrations. Figure 3d shows that at high CRM dissolutions (above 70%), the liquid phase of the CRM binder with 20% CRM concentration has the same  $m$ -value as that of the CRM binder with 10% CRM concentration, even though the amount of the released CRM components in asphalt is much higher in the case of samples with 20% CRM concentration.

Also, comparing results in Figure 3b with results in Figure 2b reveals that the  $m$ -values of all CRM binder samples are very close to the  $m$ -values of their related liquid phases, especially at very low and very high CRM dissolution levels.

All these results prove the statement in the previous section that the  $m$ -value of the binder is mainly governed by the liquid phase of the asphalt, and the effect of CRM particles and released CRM components is marginal. In addition, these results reveal that the  $m$ -value of the liquid phase of the asphalt depends on the aromatics and oily phase of the asphalt that can be absorbed and desorbed by the CRM particles rather than on the high molecular weight components.

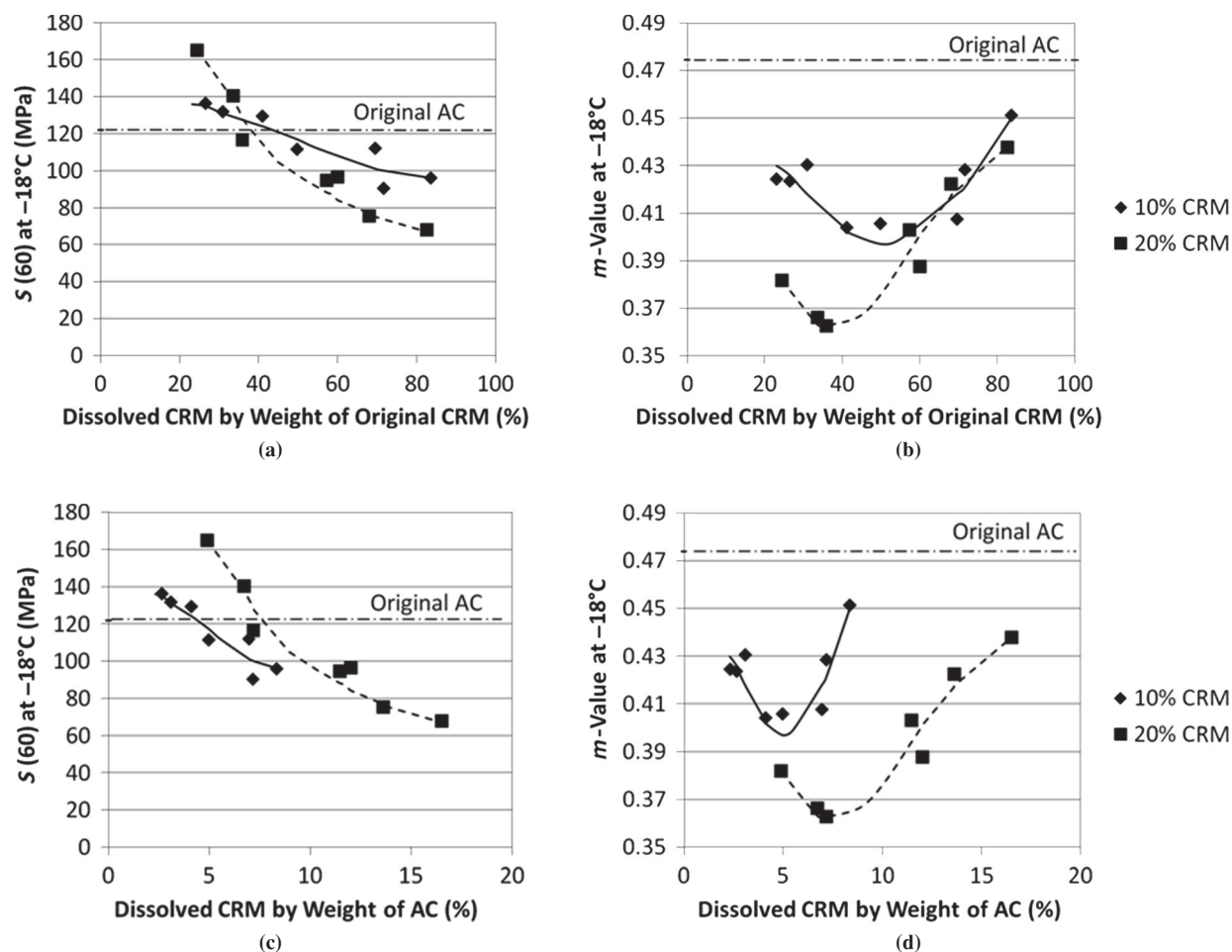


FIGURE 3 Calculations of (a) stiffness, (b)  $m$ -value of liquid phase of CRM asphalt as a function of dissolved CRM by weight of original CRM, (c) stiffness, and (d)  $m$ -value of liquid phase of CRM asphalt as a function of dissolved CRM by weight of asphalt.

### Low-Temperature Properties of CRM Binder After Aging

The PAV residue samples were tested by the BBR, and the results are presented in Figure 4 as a function of CRM dissolution. The CRM dissolution in this figure was calculated after the samples were aged through PAV; therefore, the dissolution values are different from the ones presented in Figures 2 and 3. The dissolution test results on PAV-aged samples show that standard PAV procedure leads to extensive dissolution of CRM in asphalt and consequently changes the nature of the CRM binder samples significantly. This result needs further investigation that is not in the scope of this work.

As can be seen in Figure 4a, stiffness of the aged samples is lower than that for the aged unmodified asphalt. The samples with the higher CRM concentration (20%) have lower stiffness than the samples with the lower CRM concentration (10%). Moreover, stiffness of the CRM binder increases by increasing the dissolution percentage of CRM. This trend is different from what was observed in the case of CRM binder samples before aging in Figure 2a. The difference can be attributed to the effect of CRM particles on the aging mechanism of asphalt.

The changes in  $m$ -value of the aged CRM binder as a function of CRM dissolution are presented in Figure 4. Results indicate that the

$m$ -value of the CRM binder with 20% CRM concentration is higher than that for the CRM binder with 10% CRM concentration and the aged unmodified asphalt. Also, increasing the CRM dissolution increases the  $m$ -value of the CRM binder at both CRM concentrations (10% and 20%). This result can be again attributed to the abundance of the aromatics and light molecular weight components in the asphalt matrix at this level of CRM dissolution.

A comparison of results in Figures 4 and 2 indicates that the aging has remarkably less effect on low-temperature properties of the CRM binder samples compared with the original asphalt, and increasing the CRM concentration decreases this effect. This observation indicates that CRM can enhance the low-temperature properties of asphalt in two manners: first, improving its mechanical behavior at low temperatures; and second, changing its aging process and making it less susceptible to aging.

### Glass Transition Temperature of Liquid Phase of CRM Binder

To understand the effect of CRM dissolution on glass transition of the liquid phase of the CRM binder samples, the MDSC test was conducted on the liquid phase of a selected number of them. Figure 5

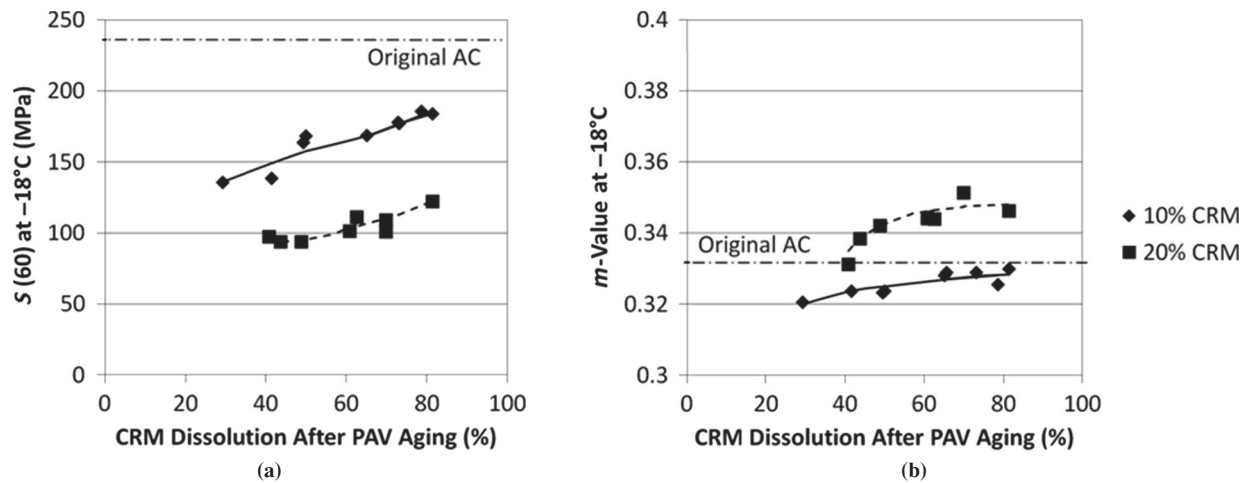


FIGURE 4 Effect of CRM dissolution on (a) stiffness and (b)  $m$ -value of CRM asphalt in long-term aged condition.

represents the changes in glass transition of the liquid phase of CRM binder samples with different CRM dissolution percentages. The glass transition temperature range was determined through specifying the starting and ending points of the stepwise drop in reversible heat flow of the sample by using the TA Universal Analysis software, as presented in Figure 5.

Results in Figure 5 show that the glass transition temperature of the asphalt narrows significantly at low levels of dissolution of CRM, where the activities of CRM are limited to absorption of the aromatics and other light molecular components of asphalt and swelling. But by increasing the dissolution of CRM, the glass transition temperature range of the liquid phase widens again, close to the same range of the neat asphalt, and that result can be attributed to the desorption of the aromatics and light molecular weight components by CRM. These results agree with the fact, explained in

other studies, that the glass transition temperature of the asphalt is governed by the aromatics and light molecular weight components of asphalt (12, 16).

A comparison of the trend of the changes in glass transition temperature range of the liquid phase with its stiffness and  $m$ -value, explained previously in Figure 3, indicates that the pattern of changes in glass transition temperature is more similar to the pattern of changes in  $m$ -value than to the stiffness. This finding can be attributed to the fact that both parameters ( $m$ -value and glass transition) are governed by the aromatics and light molecular weight components in asphalt while the stiffness is governed by the amount of released components of CRM in the liquid phase. However, because of the different nature of the two measurement methods (BBR and MDSC) and limitation in results, developing a direct correlation between the results is not possible in this research.

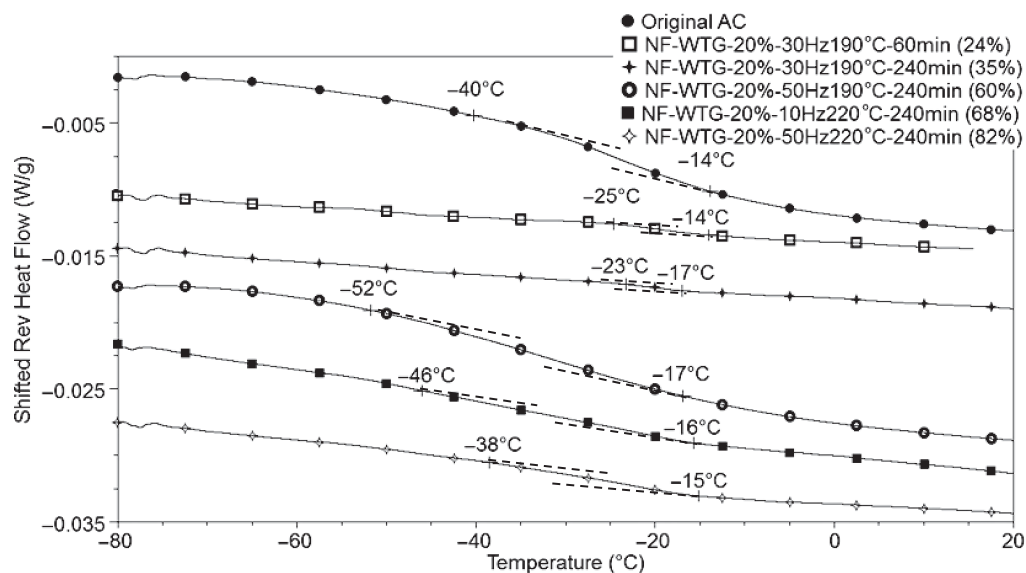


FIGURE 5 Glass transition of liquid phase of CRM asphalt samples by CRM dissolution percentage.



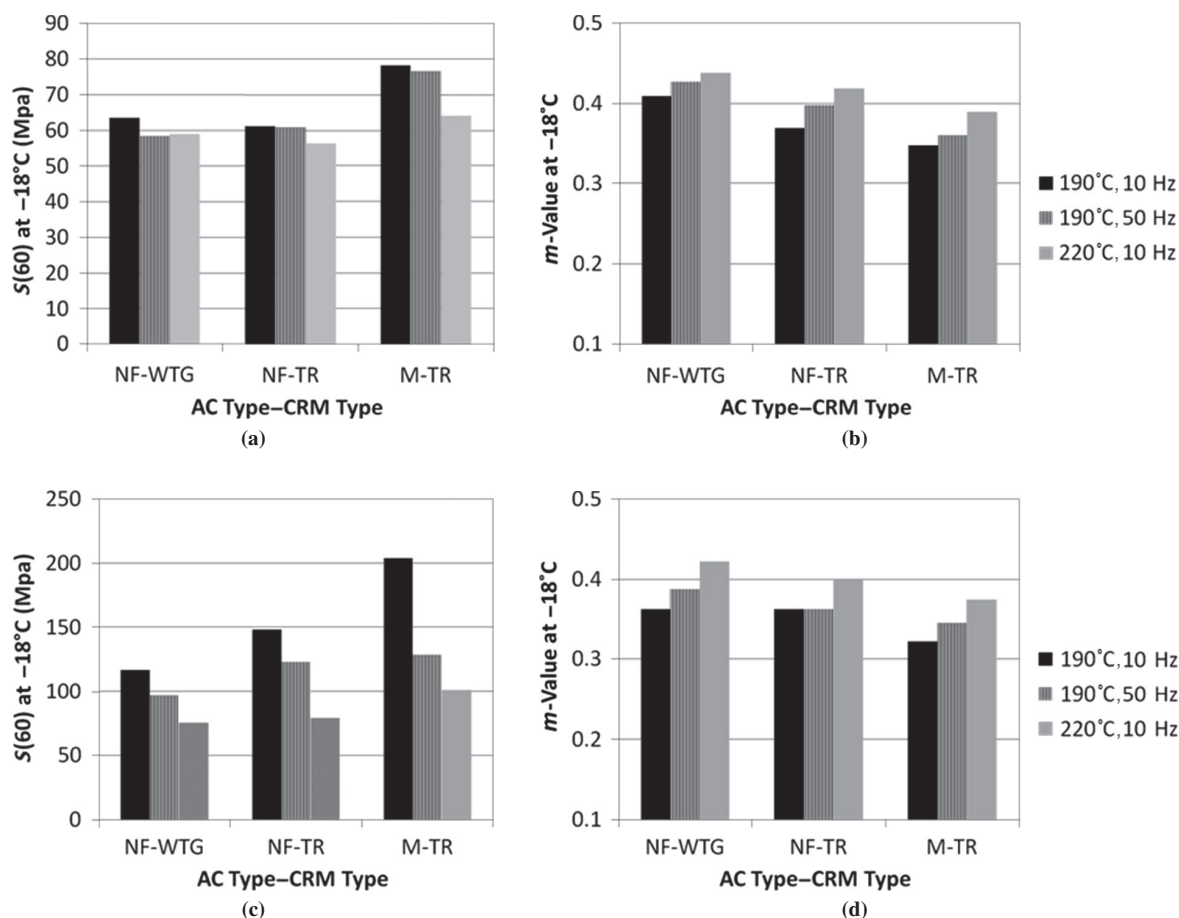


FIGURE 6 Effect of asphalt type and CRM type on (a) S(60), (b) *m*-value of CRM asphalt, (c) S(60), and (d) *m*-value of liquid phase of CRM asphalt.

### Effect of Asphalt and CRM Type

To investigate the effect of the asphalt and CRM source on the general trends that were observed in this research, a limited number of interactions were conducted with CRM and asphalt from different sources as stated in Tables 1 and 2. The effect of changing the sources of the material on the low-temperature performance development of the CRM binder is presented in Figure 6. All tests were conducted on the samples before aging.

Results in Figure 6 indicate that, however, the different types of CRM and asphalt lead to different values in two parameters related to the low-temperature performance of the CRM binder samples [*S*(60) and *m*-value], but they have no effect on the general trends that are explained in this study. The differences in the values can be attributed to differences in the extent of CRM dissolution in asphalts and to the different low-temperature performance of the original asphalt samples under study.

### CONCLUSIONS

A set of samples with a wide range of CRM dissolution was prepared at two levels of CRM concentrations (10% and 20%). The activities of CRM in asphalt and the material exchange between those two

substances were controlled by regulating the interaction conditions (temperature, mixing speed, and time). To investigate the effect of these activities on the low-temperature performance of the CRM binder, the CRM binder samples and their liquid phase were tested by the BBR. Also, to investigate the effect of CRM dissolution and exchange of materials on the glass transition temperature of the liquid phase of the binder, the MDSC test was conducted. Finally, to investigate the effect of aging on development of the low-temperature performance of CRM binder, the CRM binder samples were aged through the RTFO and PAV, on the basis of Superpave guidelines.

BBR results show that addition of CRM to asphalt can enhance (decrease) the stiffness of the asphalt at very low temperatures, and this enhancement intensifies by increasing the CRM dissolution in asphalt. At very low CRM dissolution levels (below 40%), the low stiffness of the CRM binder matrix is attributed to the flexible behavior of the elastic CRM particles in the brittle and glassy medium of asphalt. At higher levels of CRM dissolution (above 40%), at which the rubbery component of the CRM released into the asphalt matrix, the low stiffness of the CRM binder is attributed to the lower stiffness of the liquid phase of the CRM binder owing to the changes in its composition. BBR results also show that the *m*-value of the CRM binder samples is mainly governed by the aromatics and light molecular weight components in the liquid phase of the CRM binder. Therefore, at low levels of CRM dissolution,

at which the aromatics and light molecular weight components of asphalt are absorbed by the CRM particles, the CRM binder shows a deteriorated  $m$ -value. But by increasing the CRM dissolution and consequently the desorption of the aromatics and light molecular weight components from CRM particles back into the asphalt matrix, the  $m$ -value improves back to its original value and even higher. These results were proved by running the BBR test on the liquid phase of the CRM binder samples.

MDSC results proved that the glass transition temperature of the liquid phase of CRM binder is mainly governed by the aromatics and other light molecular weight components of asphalt; therefore its changes show a similar trend to the  $m$ -value of the CRM binder samples. The changes in composition of the liquid phase of CRM binder have no significant effect on its glass transition temperature.

Finally, the BBR test on PAV-aged CRM binder samples shows that samples with 20% CRM concentration show a superior low-temperature performance in comparison with the original asphalt. These results can be attributed to the effect of CRM on low-temperature performance of the asphalt as well as the aging mechanism of it, a situation that needs further investigation and is being studied by this research group. The BBR results on aged CRM binder samples show that it is possible to enhance the low-temperature performance of the CRM binder through controlling the CRM concentration and the level CRM dissolution by regulating the interaction conditions.

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