PERFORMANCE PROPERTIES OF CRM ASPHALT BINDERS CONTAINING WAX ADDITIVE

by

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ABSTRACT

Rheological properties of crumb rubber modified (CRM) binder with wax additive were evaluated at high, intermediate and low temperatures. CRM binders were blended using two wax additives and then artificially short-term and long-term aged using the rolling thin film oven (RTFO) and pressure aging vessel (PAV) procedures. Superpave binder tests were carried out on the binders through the rotational viscometer (RV), the dynamic shear rheometer (DSR), and the bending beam rheometer (BBR). The viscosity properties were evaluated using the RV at two testing temperatures of 135℃ and 120℃ for three different periods of 30, 120, and 240 minutes. In general, the results of this study concluded that (1) the wax additives in asphalt binder obviously decrease the viscosity; (2) the addition of wax additives is effective to get better the rheological properties of asphalt binder in high-temperature; (3) the rubberized mixes with wax additive are expected to have better haul management; (4) the use of crumb rubber positively influence rutting and cracking properties.

CHAPTER 1

Introduction

Background

Approximately 300 million scrap tires are generated each year in the United States, and 85% of scrap tires is being utilized. Also, 5.5% of scrap tire is being consumed for the civil engineering (Rubber Manufacturers Association, 2012). 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 concluded that crumb rubber modified (CRM) binders could produce asphalt pavements which result in decreased traffic noise, reduced maintenance costs and improved resistance to rutting and cracking (Huang et al., 2002; Lee et al., 2007; Liang and Lee, 1996; Ruth and Roque, 1995; Shen et al., 2005). Due to these benefits, there is an increasing interest in using CRM binders in hot mix asphalt (HMA) pavements in some states in the United States and other countries (Bahia and Davies, 1994; Lee et al., 2006).

The "warm mix asphalt" (WMA) refers to technologies which allow a significant reduction of mixing and compaction temperatures of asphalt mixes through lowering the viscosity of asphalt binders. Reduced production and paving temperatures would decrease the energy needed to produce the HMA, reduce emissions and odors from asphalt plants, and make the working conditions better at the plant and paving site. Aside from the obvious benefit, there are other advantages of using the WMA, such as longer paving seasons, longer hauling distances, reduced wear and tear of the plants, reduced ageing of binders, reduced oxidative hardening of binders and ability of opening the site to traffic sooner, etc (Hurley and Prowell, 2005 a;, Hurley and Prowell, 2005 b; Hurley and Prowell, 2006; Gandhi and Amirkhanian, 2007).

According to the previous study (Edwards et al., 2006), there is an obvious risk when using wax warm additives in cold climatic conditions. Although wax crystallization improves rutting resistance, other asphalt properties such as susceptibility to low temperature cracking, resistance to fatigue and adhesion properties may be affected in a negative way. However, the addition of crumb rubber into the asphalt binder increases the asphalt pavement resistance to cracking in low temperature. If the wax additives and the rubber are used together, the asphalt pavement resistance to plastic deformation and cracking is expected to be improved. Also, with the wax additives, the mixing and compaction temperatures of CRM asphalt mixes can be reduced.

In general, CRM asphalt mixes are compacted at a higher temperature than conventional mixes, based on the field experience (Amirkhanian and Corley, 2004). With lower compaction temperatures, the use of CRM mixes might result in several problems such as inadequate volumetric properties (i.e., high air voids) and poor short-term and long-term performances. Also, the viscosity increase can negatively affect on workability of asphalt mixture and it requires the higher temperature to maintain the binder viscosity for the proper workability, and other environmental problems can be caused by the use of more fossil fuel.

Therefore, if the technologies of WMA are incorporated into the CRM binder, optimum mixing and compaction temperatures of the CRM mixes are expected to be decreased and be comparable to those of conventional mixes. Although the problem of increased viscosity due to the rubber can be solved with warm additives, a gradual increase in viscosity with time needs to be evaluated for the hauling time considerations to carry the asphalt mixture from the asphalt plant to the field (Lougheed and Papagiannakis, 1996).

Purpose of the Study

The objective of this study is to investigate the performance properties of CRM binders containing wax additives and to quantify the viscosity change depending on the mixing temperature and the hauling period through Superpave binder tests. Control binders are used to compare with the CRM binders. The warm CRM binders are manufactured with two commercial wax additives, LEADCAP and Sasobit, and artificially aged using rolling thin film oven (RTFO) and pressure aging vessel (PAV) procedures. The viscosity properties for the binders are evaluated in the original state, and the rutting resistance properties in the original state and after RTFO aging, the fatigue cracking properties at intermediate temperature after RTFO+PAV aging methods, and the low temperature cracking properties in the original state, after RTFO aging and after RTFO+PAV procedures are evaluated.

CHAPTER 2

Literature review

Crumb Rubber

According to the Rubber Manufactures Association, huge amount of scrap tires are being consumed every year, and these tires are generating serious problems such as fire dangers and provide breeding grounds for rodents, snakes, mosquitoes and other pests, causing health hazard and environmental problems (Snyder, R.H., 1998; Clark et al., 1992; Jang et al., 1998). A number of methods have been applied in attempt to find more effective ways to recycle the scrap tires, and one of the methods among them is to use the crumb rubber in modification of asphalt binders. It is reported that the asphalt industry can absorb up to 40% of scrap tires (Avraam I. Isayev, 2005). Rubber, steel, and fiber are main components that composed tires. The rubber among them is major material in the tire (approximately 60% by weight). In addition, the rubber is comprised of several compounds such as natural, synthetic rubbers, carbon black and other mineral fillers (Mark, J. E. et al., 2005). Though the natural and synthetic rubber percentage varies from truck tire to passenger car tires, the ground rubber is quite uniform and the ground rubber industry is not based on specific type of tire (Ruth, 1997).

In general, there are two types of process to produce crumber rubber modified (CRM) binder, the wet process and the dry process. In the wet process, fine CRM is blended with the asphalt binder. In the dry process, coarse CRM is used to replace aggregate in the asphalt mixture. The wet process is more efficient in improving properties of an asphalt mixture (Takallou et al., 1991). Crumb rubber is known to absorb liquids and swell, depending on the temperature and viscosity of the liquids it is absorbing (Irena et al., 2006). Interaction of the rubber particles with the asphalt binder can be affected by several factors such as temperature and mix type, rubber size and texture, chemical composition of the asphalt binder (Leite et al., 2003). Scrap tires used as crumb rubber modifier for asphalt binder improve paving performance and safety by being a cost effective modifier for the highway pavement industry (Amirkhanian, 2003).

CRM Asphalt Binder

Many researchers have performed to use scrap tires in asphalt industry. The first application in HMA was seen in an open-graded friction course (OGFC) in 1975 (Arizona Department of Transportation, 1989). The applications of CRM into asphalt binder have been increasing by several states. One of the reasons for this utilization of CRM was conducted with the passage of the Intermodal Surface Transportation Efficiency Act (ISTEA) in 1991. The U.S. government mandated the utilization of scrap tire rubber in asphalt.

Other studies concluded that CRM binders could produce asphalt pavements with diverse advantages relating to pavement performance, including increased resistance to rutting and cracking, decreased traffic noise, and reduced maintenance costs (Huang et al., 2002; Lee et al., 2007; Liang and Lee, 1996; Ruth and Roque, 1995; Shen et al., 2005). Due to benefits, the interest for use of CRM binders in HMA pavements is increasing in the Unites States and other countries (Bahia and Davies, 1994; Lee et al., 2006).

Warm Mix Asphalt

Asphalt mixtures are divided into two categories HMA and cold mix asphalt (CMA). HMA properties show much better performance compared to the CMA. Thus, HMA is being used for the higher volume traffic. The mix type and binder grade govern the mixing temperature. Although the CMAs are more environmentally friendly, cold mix properties are not as good as the HMA properties due to the poor coating of the aggregate and the presence of water in the mix. Due to a curing time to open up to traffic, the CMAs are not used for a higher traffic volume road (Olle et al., 2004). To overcome some of these problems, a study conducted by Kolo Veidekke suggested the asphalt mix at somewhat lower temperatures than conventional HMA which was called as warm asphalt (Koenders et al., 2000). The tests on this warm asphalt were successfully conducted in both laboratory and in the field in Norway, Britain and Netherlands. The production temperature of WMA is in the range of 100-140 °C, while as for HMA it ranges between 150-170 °C (AAPA, 2001). The main advantage with the warm asphalt is to reduce temperatures of production and placement, producing less fumes, less emissions at the plant, less energy consumption, less wear and tear on the plant and less aging of the binder (Hurley and Prowell, 2005; Gandhi and Amirkhanian, 2007). Since WMA was introduced in 2000, it attracted considerable attention of the highway engineering community because of its advantages over both HMA and CMA (NCAT, 2005).

CHAPTER 3

Materials and methods

Chapter 3 provides descriptions of the materials included in this study as well as the procedures employed to accomplish the research objectives. Figure 1 illustrates the experimental design followed during this research. This chart provides whole research process containing artificial aging process and specific test equipment to evaluate each property of asphalt binder. This experimental plan was selected to examine the effects of several variables on control binders and CRM binders with warm additives. The below shows full name of the abbreviation used in this study.

PG: Performance Grade
CRM: Crumb Rubber Modifier
RTFO: Rolling Thin Film Oven
PAV: Pressure Aging Vessel
RV: Rotation Viscometer
DSR: Dynamic Shear Rheometer
BBR: Bending Beam Rheometer

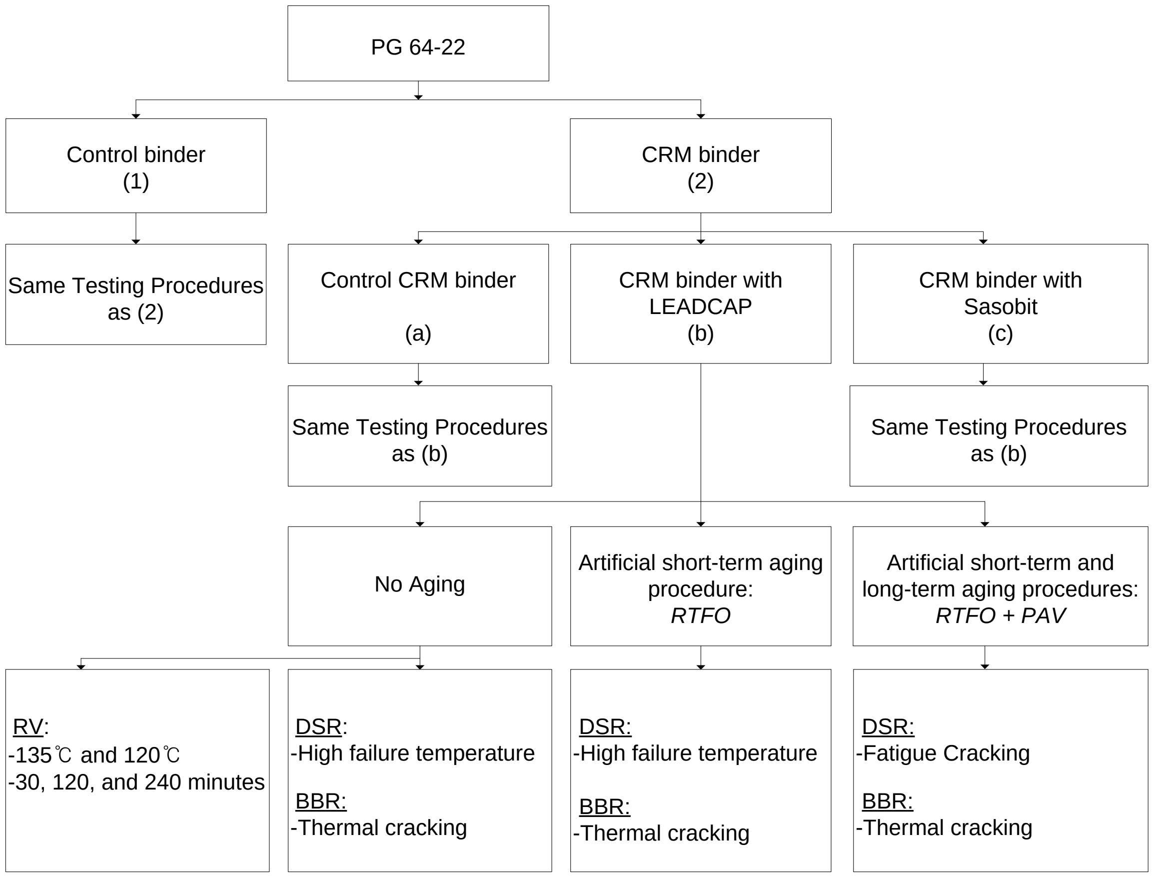


Figure 1. Flow chart of experimental design

Materials

Asphalt binder

Performance grade (PG) 64-22 asphalt binder was used in this study. Characteristics of the asphalt binder are presented in Table 1.

Table 1. Properties of base asphalt binder (PG 64-22)

Aging states	Test properties	Test result
Unaged binder	Viscosity @ 135℃	0.531 Pa-s
	G*/sin δ @ 64℃	1.415 kPa
RTFO aged residual	G*/sin δ @ 64℃	2.531 kPa
RTFO + PAV aged residual	G*sin δ @ 25℃	2558 kPa
	Stiffness @ -12℃	287 MPa
	m-value @ -12℃	0.307

Crumb Rubber Modifier (CRM)

The crumb rubber included in this study was obtained from one source. This source used the mechanical shredding method to process scrap passenger tires into crumb rubber. Figures 2 and 3 show gradation of crumb rubber and CRM, respectively. According to previous studies, smaller particle size of crumb rubber is more effective for CRM binder properties such as permanent deformation and cracking resistance (Glover and Bullin, 1997). CRM binder was produced with the rubber passed -40 mesh of 425 μm for economical efficiency and homogenized modification.

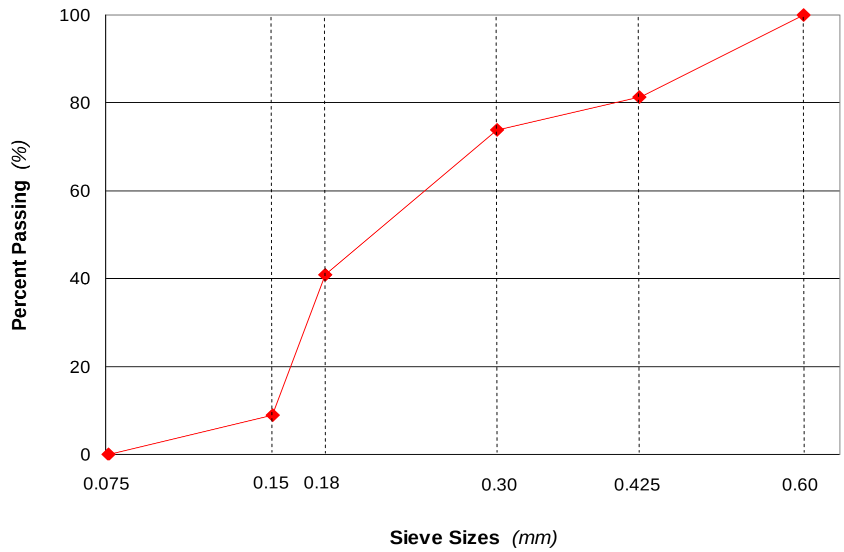


Figure 2. Gradation of CRM used in this study

Figure 3. CRM used in this study

CRM binder

There are two processes to produce the CRM binder, wet process and dry process. The CRM is added into the binder before the mixing with the aggregate in wet process. On the other hand, the CRM is added during the mixing process of the binder and the aggregate in dry process. In general, the wet process is used for laboratory experiment. The reason is that the wet process is easier to manage the binder quality than the dry process. Therefore, the binder mixing used in this study was the wet process. In the wet process, the CRM is added to the base asphalt binder before introducing the binder in the asphalt concrete matrix. The CRM binder was produced in the laboratory at 177 ℃ for 30 minutes by an open blade mixer at a blending speed of 700 rpm. The percentage of crumb rubber added for CRM binder was 10% by weight of the base binder. Figure 4 shows the setup used to manufacture the CRM binder in this study.

Figure 4. CRM binder blending setup

LEADCAP

The LEADCAP is classified as an organic WMA additive, which is a wax-based composition including crystal controller to adjust crystalline degree of wax material at the low temperature and adhesion promoter to enhance adhesion between asphalt and aggregate. Figure 5 shows LEADCAP used in this study.

Sasobit

Sasobit is a product of Sasol Wax. It is a long chain aliphatic hydrocarbon obtained from coal gasification using the Fischer-Tropsch. After crystallization, it forms a lattice structure in the binder that is the basis of the structural stability of the binder containing Sasobit (Figure 6).

Figure 5. LEADCAP

Figure 6. Sasobit

Experimental Procedure

Rotational Viscometer (RV) Test

A rotational viscometer was utilized to measure the viscosity of each binder at 135℃ per AASHTO T 316. A 10.5g binder sample was tested with a number 27 cylindrical spindle (10.5 mL) rotated with constant speed (20 rpm) for CRM binder. The control binders without modifiers were tested in accordance with the same procedure except an 8.5g sample was tested with a number 21 spindle (8mL). A different weight and spindle were used for the CRM binder to allow additional space for rubber particles between the wall of the sample tube and the smaller diameter spindle.

According to the Superpave, the maximum viscosity of unaged asphalt binder is 3.0 Pa-s (3000 cP). Figure 7 shows a set of Rotational viscometer.

Figure 7. Rotational viscometer

Dynamic Shear Rheometer (DSR) Test

The high temperature rheological properties of each binder were measured using a dynamic shear rheometer (DSR) per AASHTO T 315. In the DSR test, the original binders and RTFO residual binders were tested with 25 mm spindle and parallel plate and the binders (RTFO+PAV residual) were tested using an 8 mm parallel plate at 25 ℃. The complex shear modulus (G*) and phase angle (δ) of binder was measured from 64℃ to 88℃, respectively. Binders were tested in all aging condition such as original, short term aging, and long term aging. The CRM binder was tested using a 2mm gap between the plates, while a 1mm gap was used for the control binders.

Figure 8. Dynamic Shear Rheometer (DSR)

Bending Beam Rheometer (BBR) Test

BBR test was utilized to evaluate crack property at low temperature per AASHTO T 313. The stiffness and m-value was measured from -12℃. Figure 9 shows BBR tester used in this study.

Usually, two aging process (RTFO+PAV residual) have to be performed to conduct the BBR test. However, samples in original condition were tested to evaluate cracking resistance without aging at low temperature.

Figure 9. Bending Beam Rheometer (BBR)

CHAPTER 4

Results

Two of the available commercial wax additives (LEADCAP and Sasobit) were selected in producing the warm binders. The process was performed with wax additives at specified concentration (1.5% by weight of the binder) followed by hand mixing for 1 minute to achieve consistent mixing.

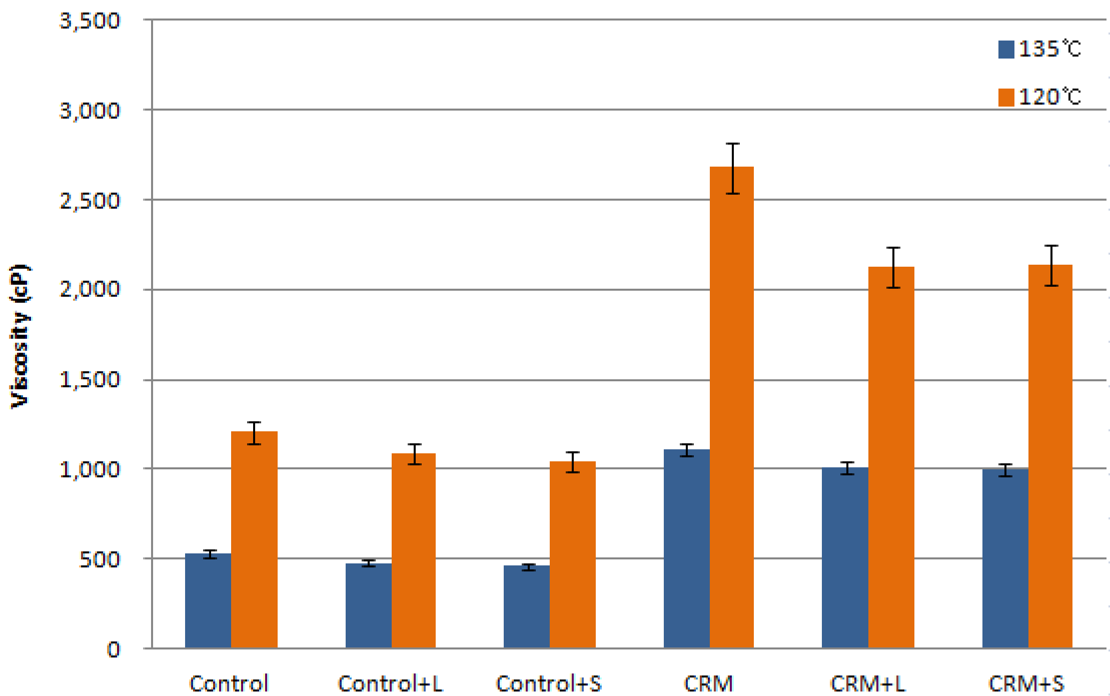
The warm asphalt binder were artificially aged using the RTFO process for 85 min at 163℃ and the PAV for 20 hours at 100℃. Table 2 explains the arrangement of binders with wax additives used in this study.

Table 2. Designation of binder and description

Designation	Description	Method
Control	Base binder	-
Control + L	Binder with 1.5% LEADCAP	Hand mix
Control + S	Binder with 1.5% Sasobit	Hand mix
CRM	Binder with 10% CRM by total binder weight	Blender mix
CRM + L	Binder with 10% CRM and 1.5% LEADCAP	Blender mix + Hand mix
CRM + S	Binder with 10% CRM and 1.5% Sasobit	Blender mix + Hand mix

Rotational viscosity

The viscosity of asphalt binder at high temperature is considered to be one of important properties since it represents the binder's ability to be pumped through an asphalt plant. Viscosity is an indication of pumpability of asphalt binder to thoroughly coat the aggregate in asphalt concrete mixture and was measured using rotational viscometer (Asphalt Institute, 2003). Figure 10 shows the values of the viscosities measured by Brookfield viscometer at 135℃ and 120℃. The viscosity of Control + L and Control + S measured at 135℃ was 0.480 Pa-s and 0.459 Pa-s, respectively. These values are 90% and 86% of control binder viscosity respectively. The addition of both wax additives was observed to reduce the viscosity at both testing temperatures compared to the control binders. This result indicates that the addition of wax additive is effective to reduce the mixing and compaction temperatures. In addition, the effect of wax additive in terms of reducing the binder viscosity was evidently showed in the CRM binder. Also, two wax additives exhibited slightly different viscosity results. The result at 120℃ shows similar trends with the finding at 135℃. However, the decrease of viscosity of CRM binders at 120℃ is observed to be relatively higher than the control binders, compared to the result at 135℃, indicating that two wax additives into the CRM binder are more efficient to reduce the viscosity at 120℃ compared to the result at 135℃.



*1 cP = 10^{-2} P = 10^{-3} Pa·s = 1 mPa·s

Figure 10. Viscosity of the binders with wax warm additives

It was clear that the addition of wax additives resulted in a conspicuous decrease of viscosity. Previous study mentioned the gradual increase of CRM binder viscosity over time (Lougheed and Papagiannakis, 1996). The viscosity for CRM binder was measured for 120 and 240 minutes. Figures 11 and 12 depict the time versus viscosity values for 120 minutes at 135℃ and 120℃, respectively. From the result, it is obvious that the application of wax additives into the CRM binders reduces binder viscosity. The CRM binders also show much higher viscosity than the control binders. The viscosity changes of control binder show stabilization between 20 and 40 minutes as seen in the Figure 11. This trend is exhibited in all tests done with the control binder without rubber. The viscosity results of CRM binders show a different viscosity change. All asphalt binders containing CRM exhibited a gradual increase in viscosity after approximately 30 minutes.

The RV test was also performed to evaluate the viscosity change at 120℃ that is used for WMA. The result shows similar trends with the finding at 135℃. However, the viscosity increase of CRM binders at 135℃ is observed to be relatively higher than the viscosity increase of CRM binders at 120℃, indicating that two wax additives into CRM binder are more effective to maintain the viscosity at 120℃ than the standard temperature of 135℃.

One of advantages of WMA binder is that it allows the longer hauling distance, because the hauling distance management of asphalt mixture depends on the binder viscosity. To evaluate longer hauling distance possibility, the RV test is performed for the longer period (240 minutes). The test results are illustrated in Figures 13 and 14, which show the viscosity versus time curves for 240 minutes at 135℃ and 120℃, respectively. The viscosity change result shows similar trend with the tests performed for 120 minutes. The results of the control binder showed slight viscosity change for the whole test period. As can be seen from the figures with CRM binder, however, the viscosity seemed to start to increase after approximately 30 to 40 minutes with stabilization of viscosity. These viscosity changes illustrate gradual increase in proportion to time. Table 3 shows the rate of viscosity increase due to the amount of aromatic oil absorption and rubber particle swelling (Lougheed and Papagiannakis, 1996) for the CRM binders. The results indicated the following trends:

- At the standard temperature of 135℃, the CRM binders showed a gradual increase in viscosity for 240 minutes.

- At the lower temperature of 120℃, there was little change in the viscosity of CRM binders over time, suggesting that the CRM mixes with the warm additive can be used for better haul management, especially for long-haul projects.
- The addition of wax additive into the CRM binders resulted in insignificant effect on the increase rate of viscosity at both testing temperature of 135℃ and 120℃.

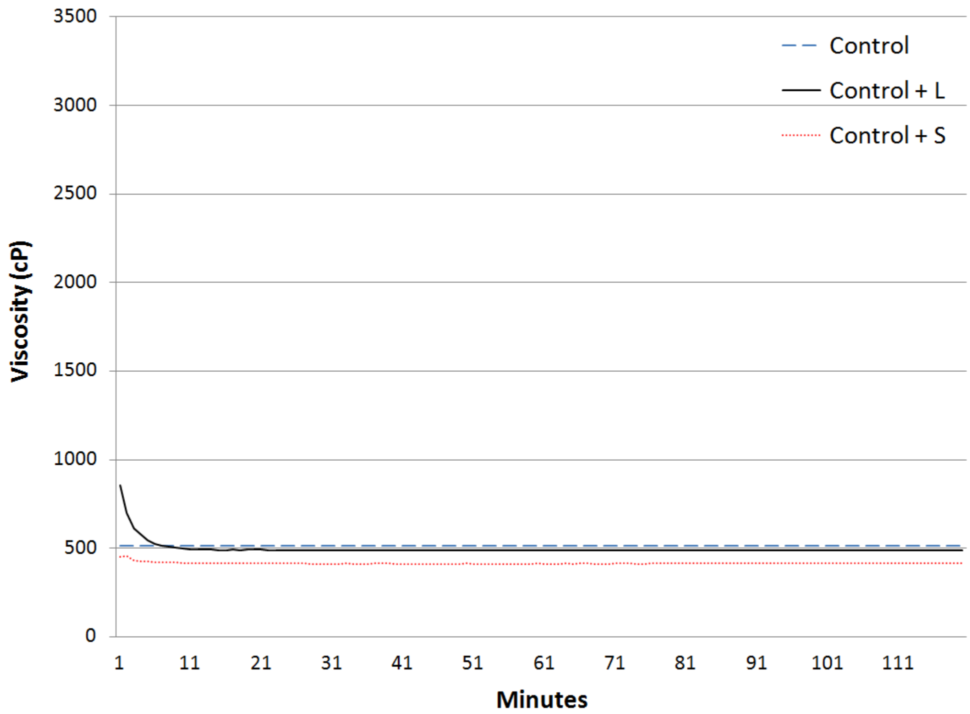
Table 3. Increase rate of viscosity

Temperature	Minutes	Increase Rate (%)		
		CRM	CRM + L	CRM + S
135℃	30	0.0*	0.0	0.0
	60	4.4**	2.6	2.6
	90	8.3	6.3	8.5
	120	12.0	9.6	12.8
	150	14.6	13.8	15.7
	180	17.0	15.7	17.6
	210	18.5	17.6	17.6
	240	19.3***	19.4	19.4
120℃	30	0.0	0.0	0.0
	60	-1.8	-1.8	-0.6
	90	-2.3	-2.4	-0.6
	120	-1.4	-1.7	1.2
	150	-1.8	-1.2	1.7
	180	-0.9	-0.6	2.9
	210	-0.5	0.6	3.4
	240	-0.5	1.2	4.0

* $\left\{1 - \frac{\text{Viscosity at 30 minutes}}{\text{Viscosity at 30 minutes}}\right\} \times 100\%$

** $\left\{1 - \frac{\text{Viscosity at 30 minutes}}{\text{Viscosity at 60 minutes}}\right\} \times 100\%$

*** $\left\{1 - \frac{\text{Viscosity at 30 minutes}}{\text{Viscosity at 240 minutes}}\right\} \times 100\%$



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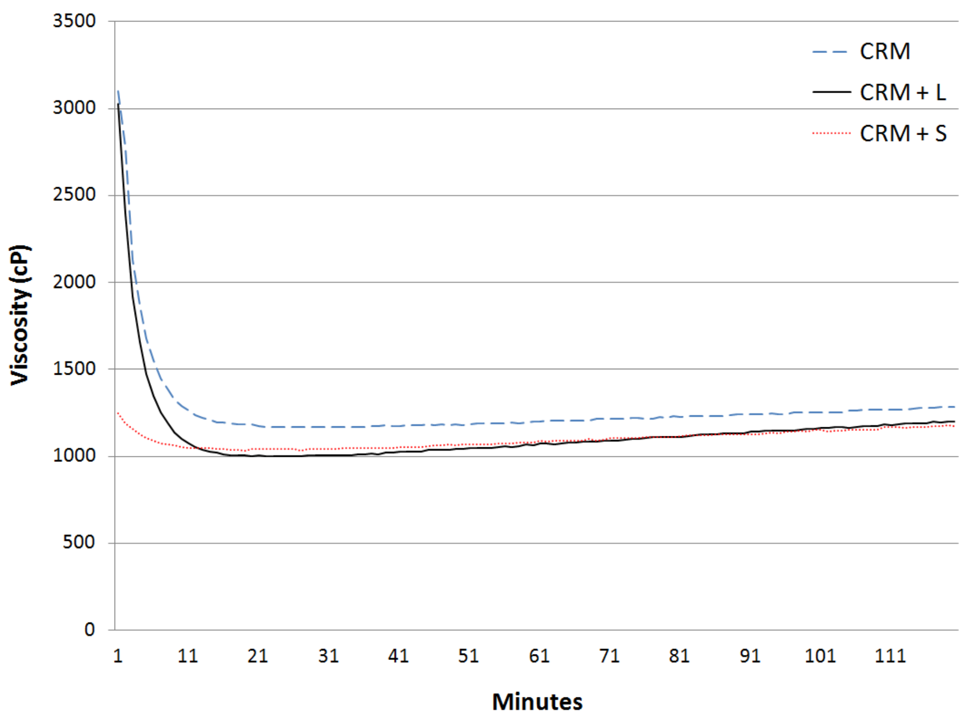
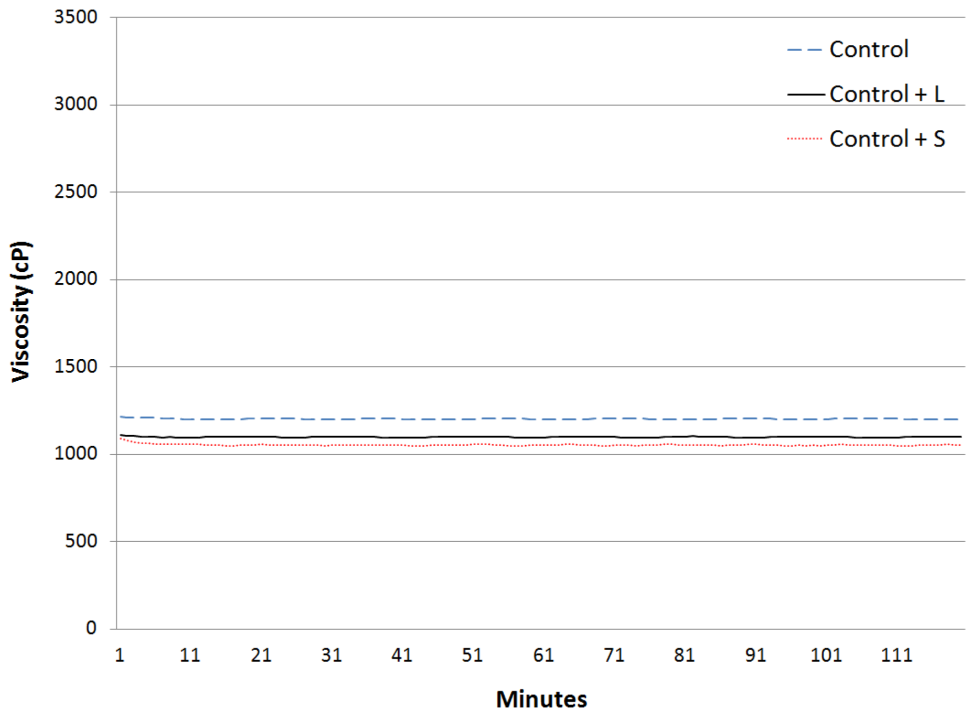


(b)

Figure 11. Viscosity change during 120 minutes at 135℃;

(a) Control binder and (b) CRM binder



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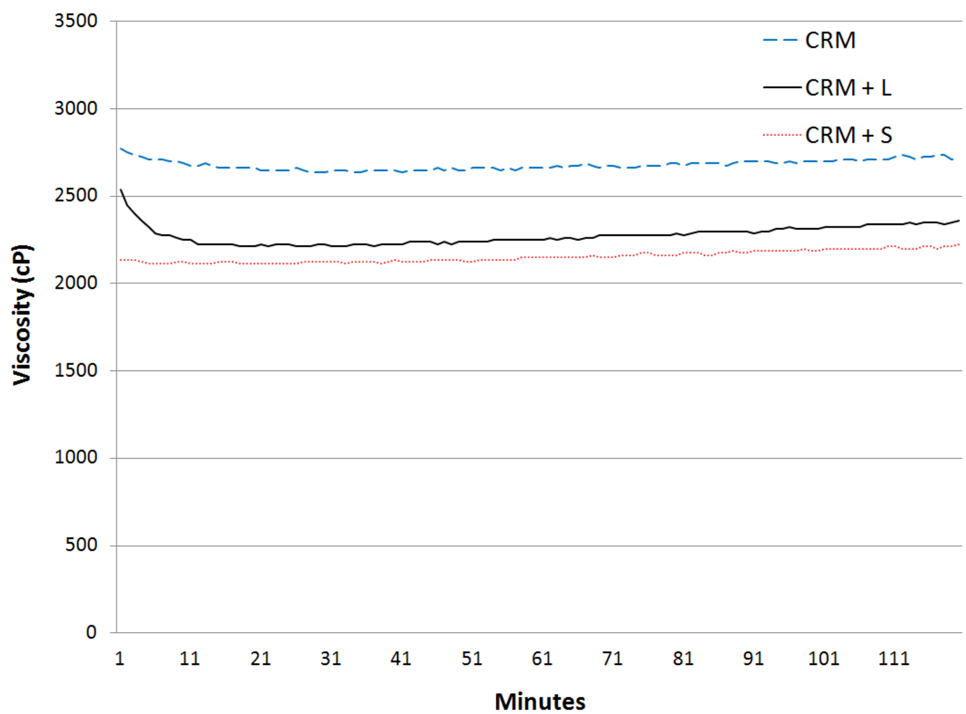
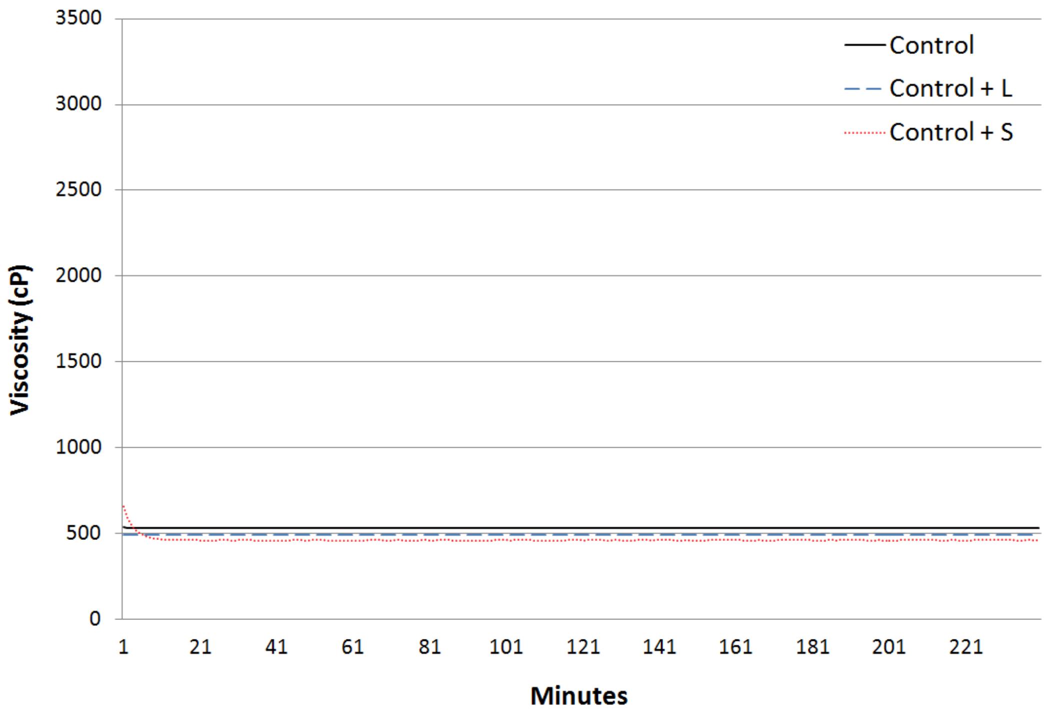


(b)

Figure 12. Viscosity change during 120 minutes at 120℃;

(a) Control binder and (b) CRM binder



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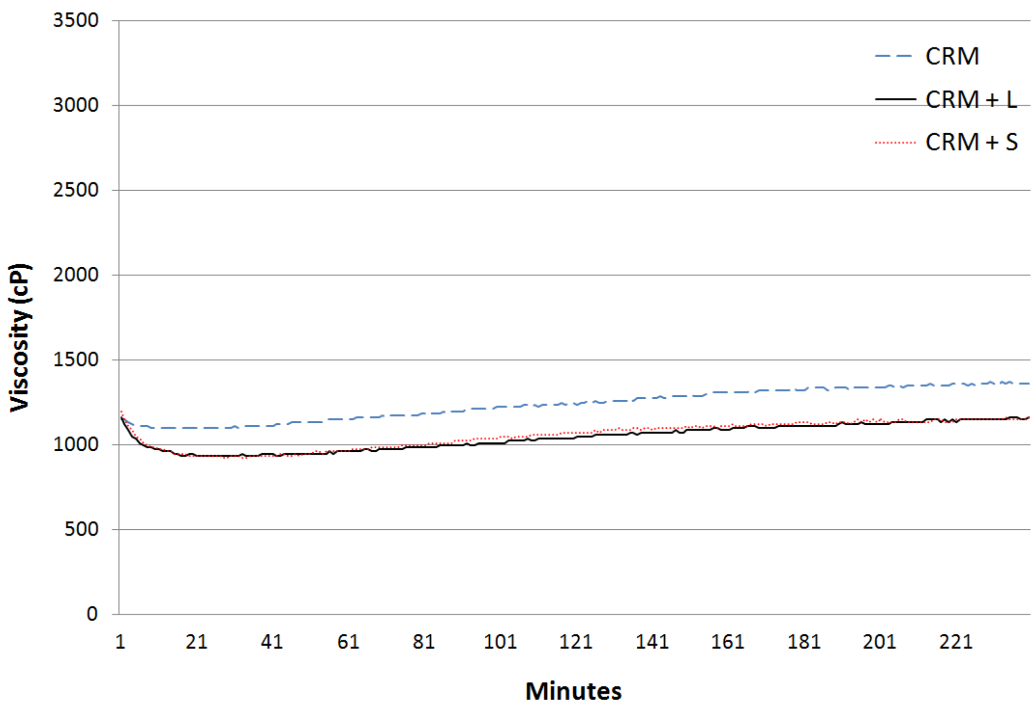
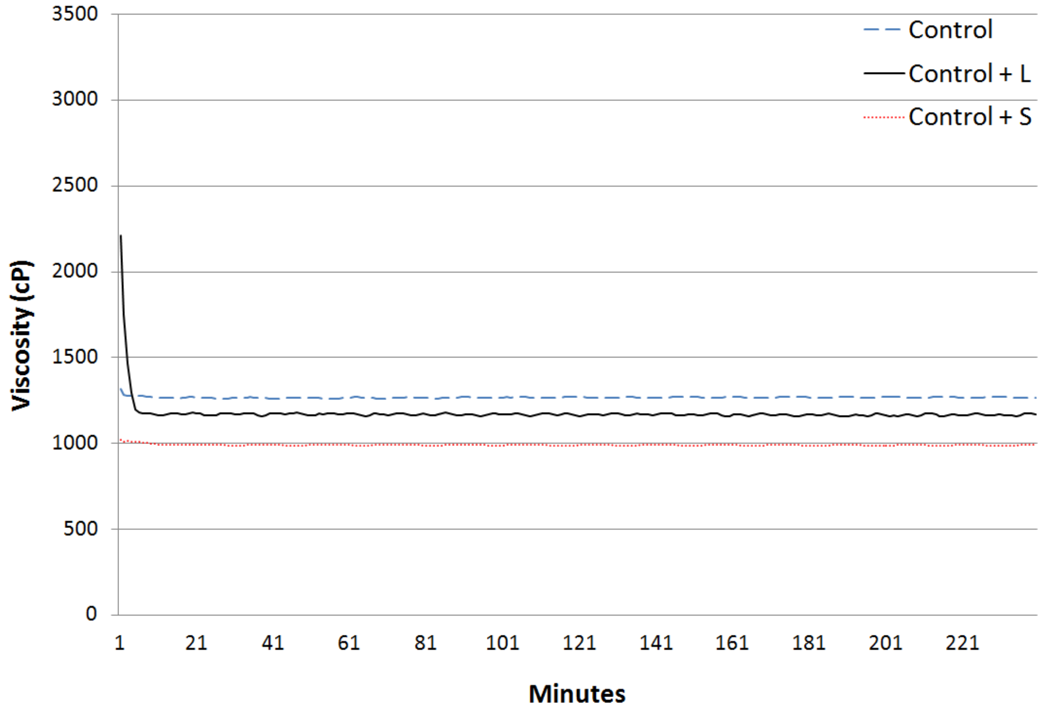


(b)

Figure 13. Viscosity change during 240 minutes at 135℃;

(a) Control binder and (b) CRM binder



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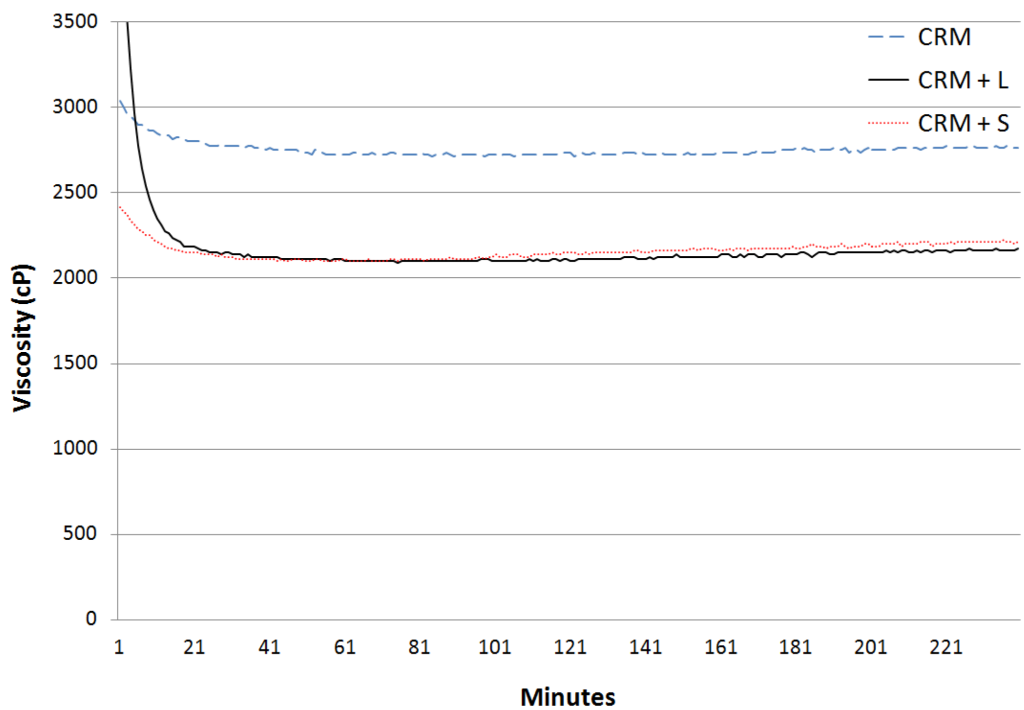


(b)

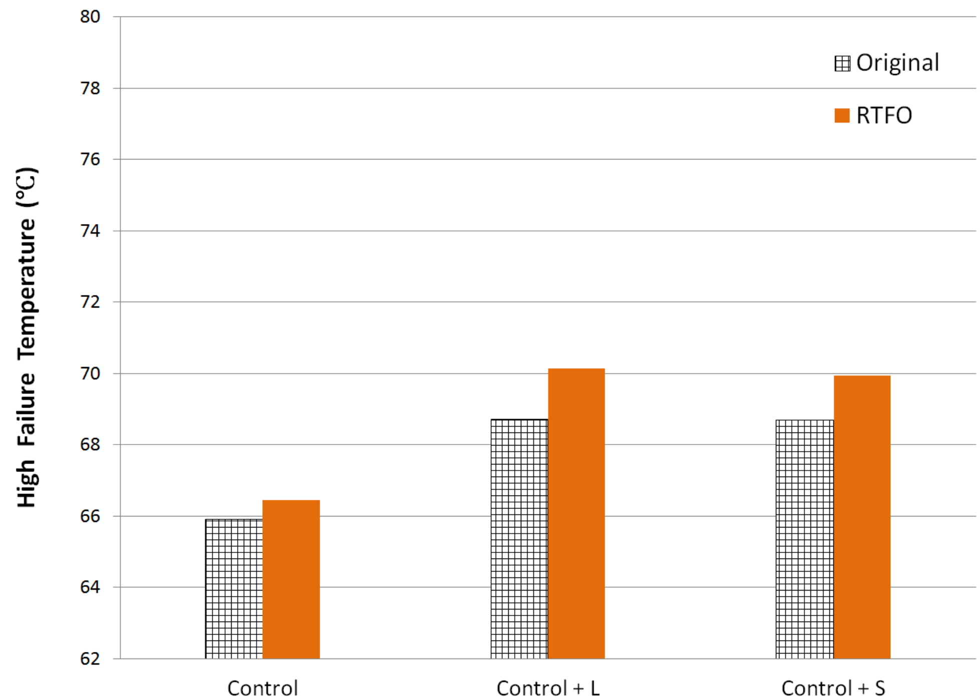
Figure 14. Viscosity change during 240 minutes at 120℃;

(a) Control binder and (b) CRM binder

DSR Test

Rutting property

The high failure temperature of binders in original state and after short term aging was measured and illustrated in Figure 15. The performance grade of binder can be decided based on the high failure temperature considered permanent deformation at high pavement temperature. In general, the CRM asphalt binders resulted in the higher failure temperature than the control binders regardless of aging state. In addition, the application of wax additive into binders was observed to increase the high failure temperature in both aging states, indicating that the addition of wax additives positively influence permanent deformation in high temperature. As a result, both the wax additives and the crumb rubber particles play a significant role in improving rutting resistance.



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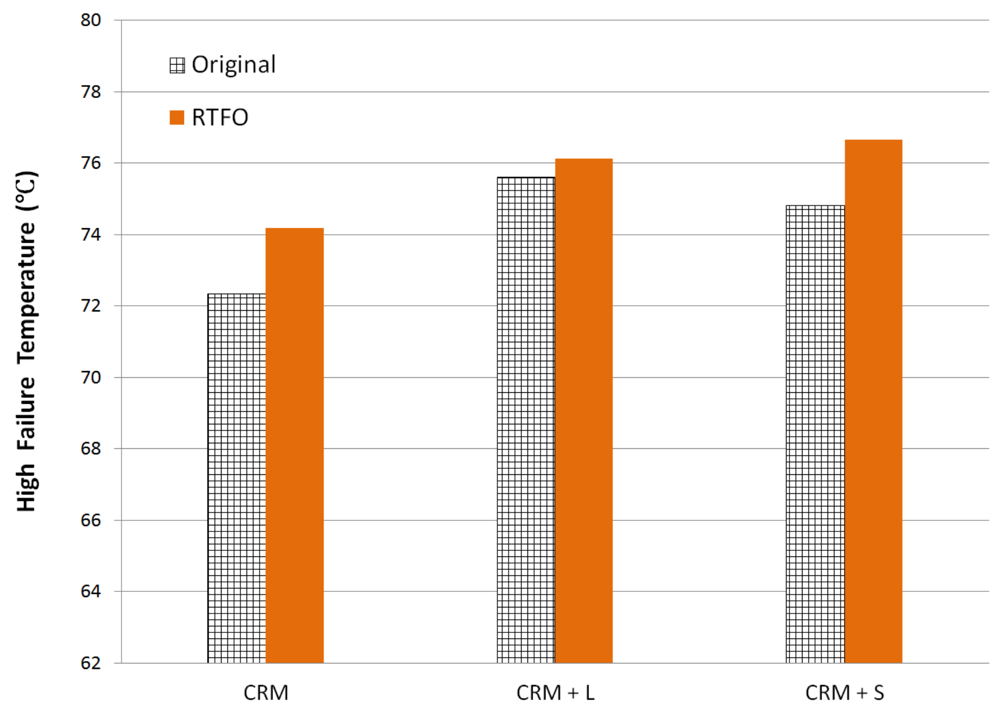

(b)

Figure 15. High failure temperatures; (a) Control binder and (b) CRM binder

Fatigue cracking property

The low G*sin δ values are generally considered to be desirable attributes from the standpoint of fatigue cracking resistance (Asphalt Institute, 2003). The G*sin δ values of the binders (RTFO + PAV residual) were measured using the DSR at 25℃ and the results are illustrated in Figure 16. The G*sin δ values were found to be 2563, 2270, 2987, 1585, 1072, and 2075 kPa for the binders of Control, Control+L, Control+S, CRM, CRM+L, and CRM+S, respectively. This trend, the binder containing Sasobit show highest value and the binder containing LEADCAP has lowest value, was consistent in both binders (Control binder and CRM binder) and the CRM binder exhibited the lower G*sin δ values than the control binder. From the result, it is predicted that the CRM binder have possible higher resistance on fatigue cracking at intermediate temperature compared to the control binder. It is obvious that the wax additive of LEADCAP is effective on increasing resistance to fatigue cracking of the WMA binders. Also, all the values satisfied the maximum requirement of 5,000 kPa suggested by Superpave.

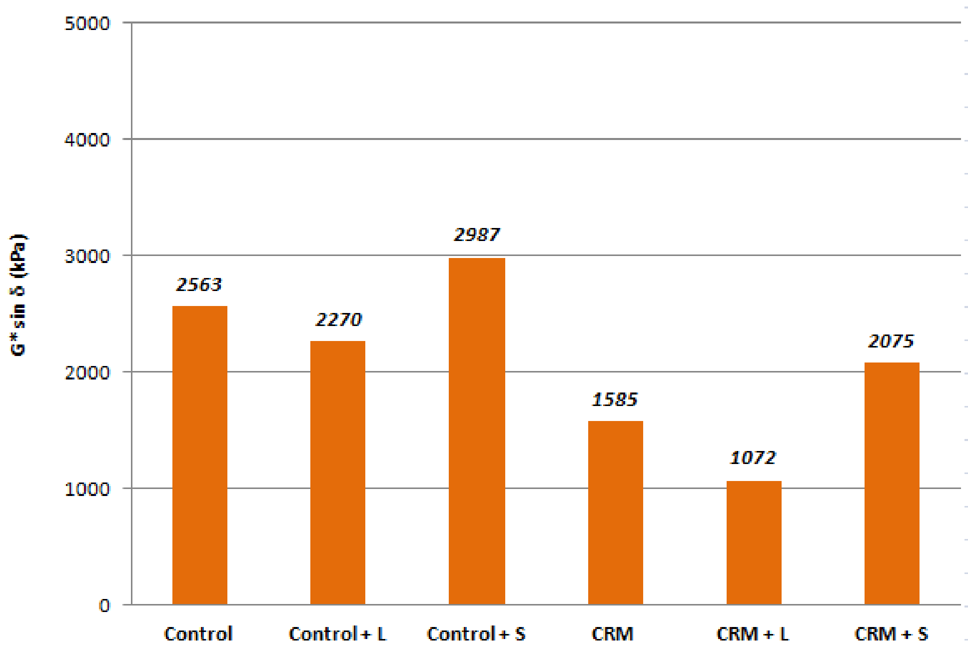

Figure 16. G*sin δ of the binders with wax additives

BBR Test

Superpave asphalt binder specification includes a maximum value of 300 MPa for creep stiffness, and the decrease in stiffness is expected to lead to smaller tensile stresses in the asphalt binder and less chance for low temperature cracking (Asphalt Institute, 2003). BBR test was carried out for three aging states (original, RTFO aged, and RTFO+PAV aged) using the BBR at -12℃ to observe the influence of aging level on low temperature cracking. Figures 17 to 4-10 illustrate the BBR test results of control and CRM binders with wax additives at three aging states. As expected, the binder stiffness values at the original state are found to be lower than those after aging, meaning that the binders are getting brittle over the aging process.

At the original state, the control and CRM binder stiffness values at -12℃ are measured to be 191 MPa and 167 MPa, respectively. The higher cracking resistance for the CRM binder is possibly attributed to the thicker film as a result of the presence of the rubber particles. The binders with wax additives showed similar trend. The CRM binder with LEADCAP is found to have the lowest stiffness values of 143 MPa, which is approximately 25% lower than the control binder stiffness.

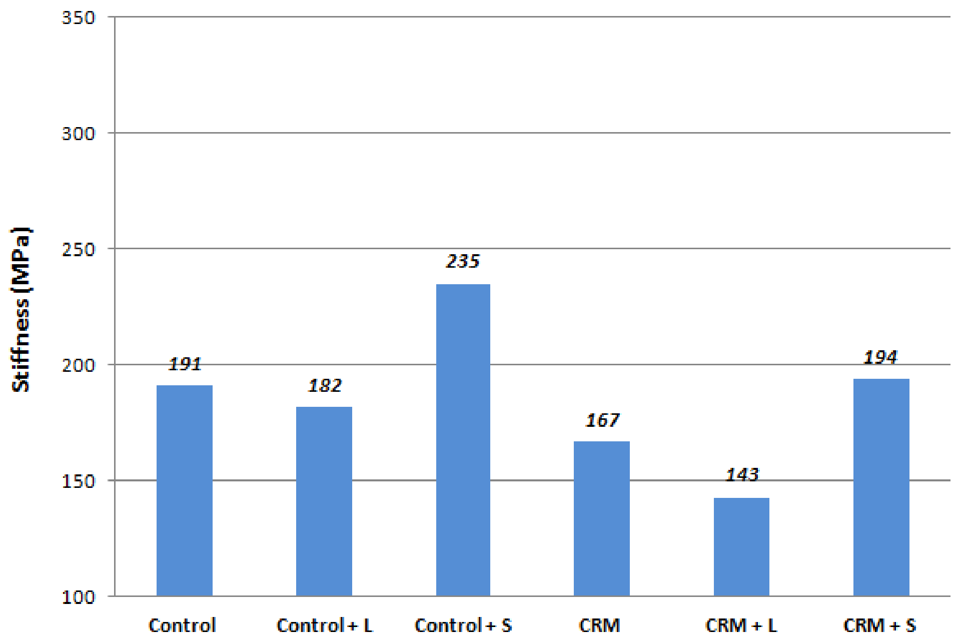

Figure 17. Stiffness at -12℃ (Original)

After the RTFO aging process, the binders exhibited similar properties at -12℃ (Figure 18). When compared with the control binder, the CRM binder is observed to have 32% lower stiffness value (166 MPa at -12℃). Overall, the CRM binders with wax additives resulted in approximately 40MPa lower stiffness than the control warm binders, indicating that the low temperature cracking resistance can be improved by the use of rubber particles. The binder stiffness values are found to be increased with the addition of Sasobit.

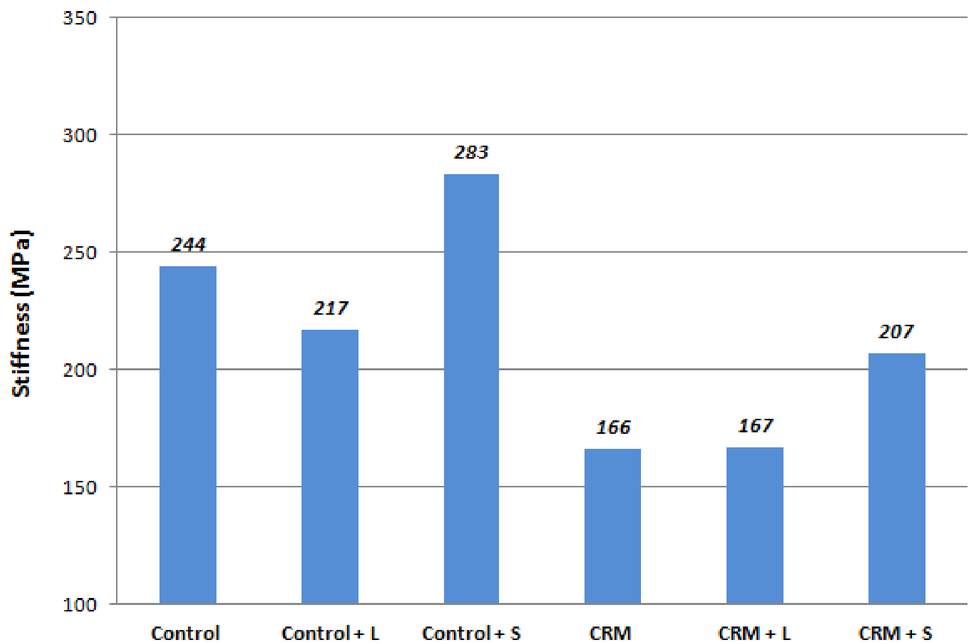

Figure 18. Stiffness at -12℃ (after RTFO)

The BBR test results of RTFO+PAV residual binders are depicted in Figure 19. All the binders satisfied the requirement set forth by Superpave (maximum 300 MPa) except for Control+S. The CRM binder showed approximately 48% lower stiffness value than the control binder. The binders with wax additives resulted in similar trend. Especially, addition of LEADCAP into the CRM binder exhibited the lowest stiffness value (189 MPa), which is 52% lower than the control binder stiffness (287 MPa). The use of CRM to modify the asphalt binder is concluded to be very effective to enhance the thermal cracking properties (measured from the BBR test at -12℃), and it is expected that the CRM binder with LEADCAP will have the best performance in terms of low temperature cracking resistance, among six binder types used in the study.

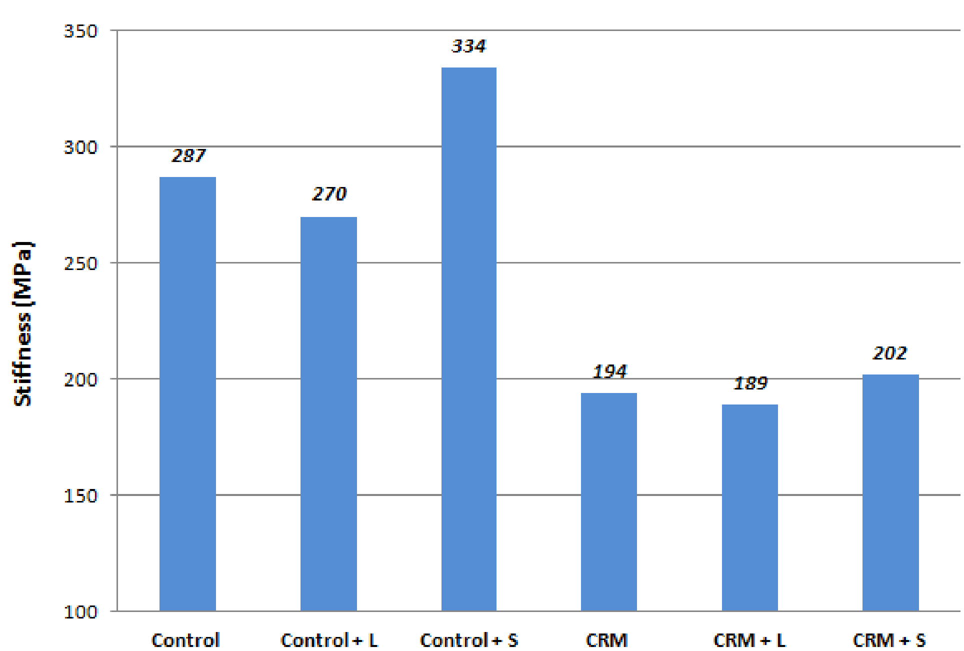

Figure 19. Stiffness at -12℃ (after RTFO+PAV)

CHAPTER 5

SUMMARY AND CONCLUSIONS

To characterize the properties of control and CRM binders with wax additives, the CRM binder was produced using 10% by the weight of binder in the laboratory. The warm binders were made with the wax additives of LEADCAP and Sasobit, and artificially short-term and long-term aged. A series of Superpave binder tests were carried out using the rotational viscometer, the DSR, and the BBR to determine the performance properties of the binders. Table 5-1 shows the comprehensive data for this study. From the test results, the following findings were drawn for the materials used in this study.

Table 4. Comprehensive data

Binders	Viscosity (cP)		High Failure Temp. (℃)		G*sin δ at 25℃ (kPa)	Stiffness at -12℃ (MPa)		
	135℃	120℃	Orig.	RTFO		Orig.	RTFO	PAV
Control	531.2	1207.7	65.92	67.46	2563	191	244	287
Control+L	479.7	1088.8	68.72	71.14	2270	182	217	270
Control+S	459.0	1045.0	68.69	70.93	2987	235	283	334
CRM	1111.7	2680.0	72.35	74.18	1585	167	166	194
CRM+L	1007.5	2126.7	75.61	76.13	1072	143	167	189
CRM+S	1000.0	2136.7	74.81	76.66	2075	194	207	202

(1) The addition of two wax additives resulted in significantly decreasing the viscosity at 135℃ and 120℃, indicating the production and paving temperature of the CRM mixes can be reduced using the wax additive.

(2) The rubberized binders showed a gradual increase of viscosity value as a function of test periods, which is different with the control binder. Although the rubberized binders showed gradual viscosity increase over time, the highest value meets the current requirement of maximum 3,000 cP.

(3) The rubberized mixes with wax additive are expected to have better haul management, based on the viscosity increase over time at 120℃.

(4) Both the additives and crumb rubber particles were observed to be effective on increasing rutting resistance (measured from the DSR test at high temperature). It was found that the additive incorporated with the CRM binder plays a significant role in the resistance for permanent deformation of asphalt pavement.

(5) From the DSR test at intermediate temperature (25℃), it appeared that the rubber particles are considered to improve fatigue cracking resistance, and the use of LEADCAP was useful to improve this effect.

(6) According to the BBR test results for three aging states, stiffness values were increased by aging level. This result indicates that the aging negatively influences the low temperature cracking, as expected. The addition of Sasobit into the asphalt binder resulted in stiffness increase at low temperature, but adding the LEADCAP into the binder was found to produce the binder with lower stiffness values. Especially, the CRM binders with the LEADCAP additive showed the lowest stiffness values regardless of the aging level.

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