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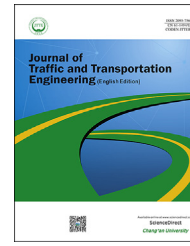

Original Research Paper

Effect of production process on performance properties of warm rubberized binders

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HIGHLIGHTS

- Interaction of rubberized binder and wax additives as a function of different production processes was investigated.
- The wet process has better performance in terms of rutting and fatigue resistance compared to dry process.
- The production process does not have significant effect on the stiffness and viscosity properties of warm rubberized binder.

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ABSTRACT

The study presents an experimental evaluation of performance properties of two different production processes of warm rubberized binder. Two types of rubberized binder were produced through dry process and wet process and two of the available wax additives were added into the rubberized binders (i.e., LEADCAP and Sasobit). Rubberized binders with wax additives were 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). In general, the results of this study indicated that (1) the viscosity properties have been found to be similar between dry and wet processes, (2) the rubberized binders manufactured by wet process were observed to have the higher rutting resistance than those by dry process, (3) the wet process resulted in better performance in the fatigue cracking test than the dry process, and (4) the blending method was found to have little influence of stiffness properties.

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1. Introduction

Crumb rubber modifier (CRM) is an important material in terms of improving neat asphalt performance and disposal of scrap tires. Service life of pavement is getting short due to the increase in loading and new axle configuration. In addition, a large number of scrap tires are produced and wasted every year with the development of auto industry. Wasted scrap tires are considered as a cause which lead to serious

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environmental issues. The addition of crumb rubber into asphalt binder can be a potential solution for recycling of wasted tires and produce asphalt pavements that exhibit increased pavement life, decreased traffic noise, reduced maintenance costs and resistance to rutting and cracking (Azizian et al., 2003; Huang et al., 2002; Kim and Lee, 2015; Lee, 2007; Palit et al., 2004; Ruth and Roque, 1995; Shen and Amirkhanian, 2005; Shen et al., 2017; Xiao, 2006; Xiao et al., 2009; Xie and Shen, 2013, 2016a; 2016b; Way, 1998). As a result, the use of crumb rubber in hot mix asphalt (HMA) pavements is getting popular in some states in the United States and other countries (Kim et al., 2014; Lee et al., 2006).

During the reaction time in rubberized binder production, the rubber particles absorb the light fractions of asphalt binder and swell. The absorption and swelling increase the binder viscosity. Increased viscosity of rubberized binder requires an appropriate increase in production temperature. Therefore, incorporation of warm mix asphalt (WMA) with rubberized binder is recommended based on decreasing production temperature of asphalt mixture.

Environmental benefits of warm mix asphalt (WMA) has been proved by reducing mixing and compaction temperature of asphalt mixtures, better working conditions, reduced paving time, improved air quality and workability (Jamshidi et al., 2013; Kim and Lee, 2016; Kanitpong et al., 2007; Mazumder et al., 2016; Mogawer et al., 2011; Prowell et al., 2007; Xiao and Amirkhanian, 2010; Wasiuddin et al., 2007). Also, the use of warm additives can improve engineering properties of the asphalt binder (Kim et al., 2014; Kim and Lee, 2015, 2016; Yang et al., 2012).

Even though the rubberized binder shows several advantages, the production process is remained as a considerable task which affects the whole construction procedure. There are three general processes used for creating rubberized asphalt pavements which are: dry process on-site, wet process on-site, and wet process at terminal. In this research, two types of mixing methods, dry process on-site and wet process on-site, are studied. Rubber particles in the dry process is considered to be an aggregate replacement in the mix. In the wet process, rubber particle is considered as the asphalt binder additive. This additive is field blended with asphalt binder in a mixing tank at high temperature (175 °C–200 °C) for 45–60 min (FHWA, 2014). Different performance properties of the rubberized binder are expected by the application of different processes. Rubberized binders produced by the wet process exhibited the better performance properties compared to the control asphalt binder (Lee et al., 2008). The reason is that the binder can be blended properly and in a controlled manner through mixing equipment. However, the dry process is also an attractive method on manufacturers' view. The dry process is easier and more economic to produce the rubberized mix since it needs neither the mixing tanks nor additional processes. Also, incorporating more rubber particles through dry process can provide environmental benefits. Previous research projects demonstrated that the interaction of bitumen and CRM neglected due to the larger CRM particle size, high CRM content and additives (Shen et al., 2017). The dry process has the inconsistent field performance varying from two to twenty years, depending on its CRM type, content and construction method. In Georgia, a modified dry process exhibited good performance using smaller size and low content of CRM with a cross link agent (transpolyoctenamer (TOR) polymer) (Shen et al., 2017).

This study was conducted to evaluate the performances of rubberized binders with wax additives depending on different production processes. Two 10% rubberized binders were produced through different mixing conditions (dry process and wet process). Rubberized binders were experienced artificial aging process through the rolling thin film oven (RTFO) and pressure aging vessel (PAV). Superpave binder tests were performed in three aging state (original, short-term aging, and long-term aging). Fig. 1 shows a flow chart of the experimental design used in this study.

2. Experimental design

2.1. Materials

Performance grade (PG) 64-22 asphalt binder was used to produce the rubberized asphalt binder. Table 1 shows the binder properties. Same crumb rubber produced by mechanical shredding at ambient temperature was used for both production processes. Table 2 shows a gradation of crumb rubber. The percentages of crumb rubber added for rubberized binder was 10% by weight of the base binder (600 g of base binder + 60 g of crumb rubber). The consistency of the CRM was maintained throughout the study, only one batch of crumb rubber was used in this study.

This study included an evaluation of two commercial wax additives, LEADCAP and Sasobit. 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 (Kim et al., 2013). Sasobit is a fine crystalline, long chain aliphatic hydrocarbon produced from coal gasification using the Fischer–Tropsch process at temperatures below its melting point Sasobit forms a lattice structure in asphalt binders that is a basis for the stability of asphalts modified with sasobit (Kumar et al., 2017).

2.2. Production of rubberized binders with wax additives

The wet rubberized binder was produced with a virgin binder of PG 64-22 in the laboratory at 177 °C for 30 min by an open blade mixer at a blending speed of 700 rpm (Lee et al., 2006, 2007; Putman, 2005). The dry process binder used the same CRM and virgin binder. CRM was added into virgin binder preserved at 177 °C and then mixed by hand. Blending period and method of dry process were selected considering the mixing condition in mixture production plant.

The process of warm rubberized binder included the addition of wax additive at a specified content (1.5% by the weight of the rubberized binder) followed by hand mixing for a minute to achieve a consistent mixing. The content of 1.5% was suggested by the manufacturer. The rubberized binders containing wax additives were then artificially aged using the RTFO aging process for 85 min at 163 °C and the PAV for 20 h at

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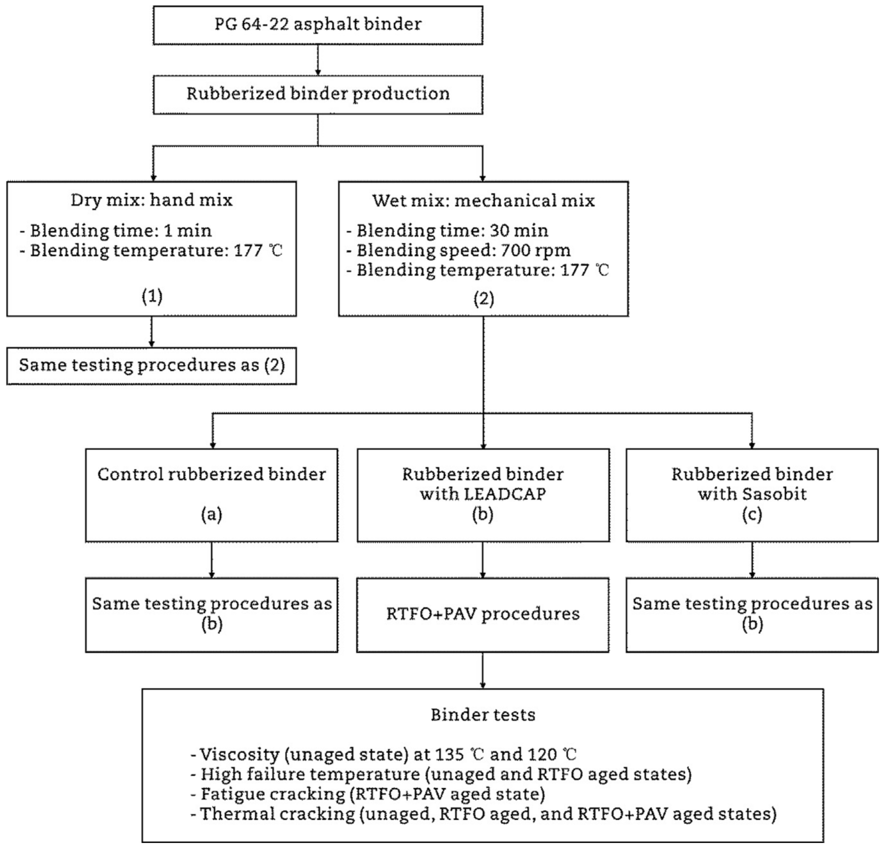

Fig. 1 – Flow chart of experimental design procedures.

100 °C, respectively. Table 3 explains the arrangement of binders with wax additives used in this study.

2.3. *Superpave binder tests*

The Superpave asphalt binder tests are used to measure the asphalt's performance at three stages of its life: in its original state, after mixing and construction, and after in-service aging. In this study the selected binder test procedures included the viscosity test (AASHTO T 316), the DSR test (AASHTO T 315), and the BBR test (AASHTO T 313). Three replicate samples were tested and the results were reported as the average of these tests. A 8.5 g sample of the control binders and a 10.5 g sample of rubberized binders were tested with a number 21 spindle and with a number 27 spindle in the Brookfield rotational viscometer at 135 °C (the standard test temperature) and at 120 °C (the mixing temperature generally used for warm mix asphalt), respectively. In the dynamic shear rheometer (DSR) test, the binders (original, RTFO residual, and RTFO + PAV residual) were tested at a frequency of 10 radians per second which is equal to approximately 1.59 Hz. Each asphalt binder both in the original state (unaged) and short-time aged state was used to determine the failure temperature. The behavior of bitumen binder at high temperatures and liquid phase can be represented by the complex shear modulus (G^*) and phase angle (δ). Thus, it is possible to evaluate both viscous and elastic behaviors of asphalt binder based on the measured complex shear modulus and the phase angle. The rutting susceptibility of the bitumen mixture in pavement engineering has been shown as $G^*/\sin(\delta)$. Obtained $G^*/\sin(\delta)$ values are used to determine the failure temperature which has less than 1.0 kPa and 2.2 kPa in original and RTFO state, respectively (Jahromi, 2017). The $G^*/\sin(\delta)$ at intermediate temperature was measured to evaluate the

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

Aging states	Test properties	Test result
Unaged binder	Viscosity, 135 °C (cP)	531
	$G^*/\sin(\delta)$, 64 °C (kPa)	1.415
RTFO aged residual	$G^*/\sin(\delta)$, 64 °C (kPa)	2.531
RTFO + PAV aged residual	$G^*/\sin(\delta)$, 25 °C (kPa)	2558
	Stiffness, −12 °C (MPa)	287
	m-value, −12 °C	0.307

Table 2 – Gradation of crumb rubber used in this study.

Sieve no. (μm)	Ambient CRM	
	Retained (%)	Cumulative retained (%)
30 (600)	0.0	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

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Table 3 – Designation and description of the binders.

Designation	Description	Blending method
CRM (W)	Binder with 10% CRM	Wet mix
CRM + L (W)	Binder with 10% CRM and 1.5% LEADCAP	Wet mix + hand mix
CRM + S (W)	Binder with 10% CRM and 1.5% Sasobit	Wet mix + hand mix
CRM (D)	Binder with 10% CRM	Dry mix
CRM + L (D)	Binder with 10% CRM and 1.5% LEADCAP	Dry mix + hand mix
CRM + S (D)	Binder with 10% CRM and 1.5% Sasobit	Dry mix + hand mix

fatigue cracking property for RTFO + PAV residual binders. The BBR test was conducted on asphalt beams (125 mm × 6.35 mm × 12.7 mm) at 12 °C, and the creep stiffness (S) of the binder was measured at a loading time of 60 s. A constant load of 100 g was then applied to the beam of the binder, which was supported at both ends, and the deflection of center point was measured continuously. Testing was performed on all three aging states (Original, RTFO residual, and RTFO + PAV residual samples).

2.4. *Statistical analysis method*

A statistical analysis was performed using the statistical analysis system (SAS) program to conduct an analysis of variance (ANOVA) and fisher's least significant difference (LSD) comparison with an $\alpha = 0.05$. The primary variables included the wax types (Control, LEADCAP, and Sasobit) and the production processes (dry and wet). The ANOVA was performed first to determine whether significant differences among sample means existed. In the analyses of this study, the significance level was 0.95 ($\alpha = 0.05$), indicating that each finding had a 95% chance of being true. Upon determining that there were differences among sample means using the ANOVA, the LSD was then calculated. The LSD is defined as the observed differences between two sample means necessary to declare the corresponding population means difference. Once the LSD was calculated, all pairs of sample means were compared. If the difference between two sample means was greater than or equal to the LSD, the population means were declared to be statistically different (Prybutok, 1989).

3. Results and discussions

3.1. *Rotational viscosity*

The binder viscosity is considered to be one of the important properties which decides the production temperature of asphalt mixture since it reflects the ability to be pumped through an asphalt plant, thoroughly coat aggregate in a HMA mixture, and be placed and compacted to form a new pavement surface. Figs. 2 and 3 show the experimental values of the viscosities measured at 135 °C and 120 °C, respectively. In general, there was little difference by production process of rubberized binder, except for control binder measured at 135 °C. However, it is clear that the addition of wax additives into the rubberized binder decreases the binder viscosity regardless of production process. The results indicate that the addition of wax additives results in decreasing the mixing and compaction temperatures for rubberized binders manufactured by both dry and wet processes. In addition, the viscosity reduction rate of viscosity at 120 °C was higher than at 135 °C irrespective of the blending method, suggesting that the addition of wax additive is more efficient to reduce the viscosity of the binder at 120 °C. Also, the use of wax additives for rubberized binder is advantageous to reduce the mixing and compaction temperature considering the 120 °C for the manufacturing temperature of warm mix asphalt. Although at 120 °C the rubberized binder shows the increased viscosity values than the 135 °C, the viscosity values of rubberized binders at 120 °C meet the current maximum requirements set forth by Superpave (i.e., 3000 cP).

The statistical significance of the change in the viscosity as a function of WMA additive and production process was examined and results are shown in Tables 4 and 5. The data

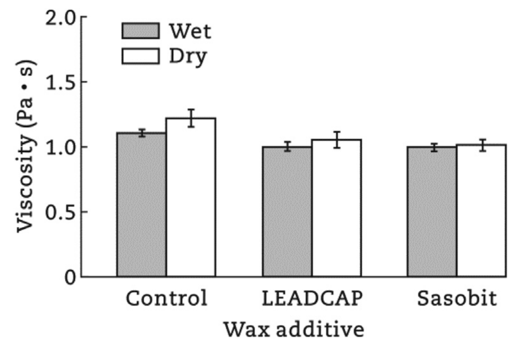

Fig. 2 – Viscosity of the rubberized binders with wax additives at 135 °C.

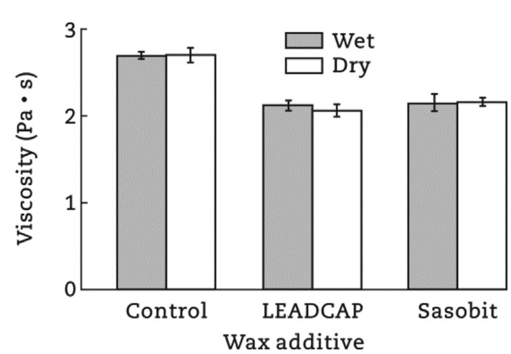

Fig. 3 – Viscosity of the rubberized binders with wax additives at 120 °C.

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Table 4 – Statistical analysis results of the viscosity as a function of blending method and wax additive ($\alpha = 0.05$) (viscosity at 135 °C).

Wax additive	Blending method	Control		LEADCAP		Sasobit	
		1	2	1	2	1	2
Control	1	–	S	S	N	S	S
	2		–	S	S	S	S
LEADCAP	1			–	N	N	N
	2				–	N	N
Sasobit	1					–	N
	2						–

Note: 1: wet mix; 2: dry mix; N: non-significant; S: significant.

Table 5 – Statistical analysis results of the viscosity as a function of blending method and wax additive ($\alpha = 0.05$) (viscosity at 120 °C).

Wax additive	Blending method	Control		LEADCAP		Sasobit	
		1	2	1	2	1	2
Control	1	–	N	S	S	S	S
	2		–	S	S	S	S
LEADCAP	1			–	N	N	N
	2				–	N	N
Sasobit	1						N
	2						–

Note: 1: wet mix; 2: dry mix; N: non-significant; S: significant.

indicated that the both wax additives have a significant effect on the viscosity value at both testing temperatures (135 °C and 120 °C). However, in most cases (except for the control rubberized binder at 135 °C), the results showed that, within each binder type, the binders have no significant difference in the viscosity depending on the blending method.

3.2. *Rutting property*

The higher failure temperature from the DSR test indicates that the binders are less susceptible to rutting or permanent deformation at high pavement temperatures. The failure temperature of binders in original state and after short term aging were measured from 64 °C until it failed. The results are shown in Fig. 4. In general, the control rubberized binders manufactured by wet process were observed to have the higher failure temperature in both aging states. In summary, the production process plays a significant role in rutting resistance of the control rubberized binder (without wax additives). In addition, the warm rubberized binder with wax additives resulted in the higher failure temperature than the control binders regardless of aging state, indicating that the addition of wax additives positively affect rutting resistance for plastic deformation. This finding is consistent with the previous observations (Kim et al., 2014, 2017). The asphalt pavement resistance to plastic deformation is improved by increased viscosity due to wax crystallization under the laying and compaction temperatures.

The statistical results of the change in the high failure temperature values for no aging and RTFO aging are shown in Tables 6 and 7. In general, the production process was found to have little effect between LEADCAP and Sasobit, except for the dry mix of LEADCAP and Sasobit in RTFO aging. The data indicated that the wax additives have a significant effect on the high failure temperature values regardless of aging. For no aging, the differences between control binder and the warm rubberized binder containing LEADCAP or Sasobit are statistically significant.

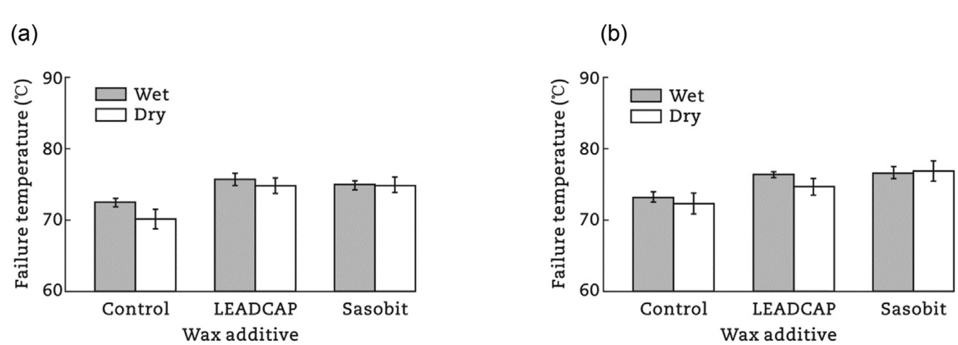

Fig. 4 – High failure temperature of the rubberized binders with wax additives. (a) Unaged binders. (b) RTFO aged binders.

Table 6 – Statistical analysis results of the high failure temperature as a function of blending method and wax additive ($\alpha = 0.05$) (unaged).

Wax additive	Blending method	Control 1	Control 2	LEADCAP 1	LEADCAP 2	Sasobit 1	Sasobit 2
Control	1	–	S	S	S	S	S
	2		–	S	S	S	S
LEADCAP	1			–	N	N	N
	2				–	N	N
Sasobit	1					–	N
	2						–

Note: 1: wet mix; 2: dry mix; N: non-significant; S: significant.

Table 7 – Statistical analysis results of the high failure temperature as a function of blending method and wax additive ($\alpha = 0.05$) (RTFO).

Wax additive	Blending method	Control 1	Control 2	LEADCAP 1	LEADCAP 2	Sasobit 1	Sasobit 2
Control	1	–	N	S	N	S	S
	2		–	S	S	S	S
LEADCAP	1			–	N	N	N
	2				–	N	S
Sasobit	1					–	N
	2						–

Note: 1: wet mix; 2: dry mix; N: non-significant; S: significant.

3.3. *Fatigue cracking property*

The product of the complex shear modulus (G*) and the sine of the phase angle (δ) is used in Superpave binder specification to help control the fatigue of asphalt pavements. The lower values of G*sin(δ) are considered desirable attributes from the standpoint of resistance of fatigue cracking. The G*sin(δ) values of the binders (RTFO + PAV residual) were measured using the DSR at 25 °C and the results are illustrated in Fig. 5. The rubberized binders produced with dry process is found to have higher G*sin(δ) values compared to wet process. It indicates that the rubberized binders with wet process showed better fatigue resistance compared to the binders with dry process. The rubberized binder containing Sasobit exhibited the higher G*sin(δ) values than the other binders, indicating that the Sasobit has negative effect on the resistance of fatigue cracking due to wax crystallization which is consistent with the previous finding (Kim and Lee, 2016). However, the addition of LEADCAP into rubberized binders produced by wet and dry method reduced the G*sin(δ) values by 14.4% and 18.4%, respectively. It means that the addition of LEADCAP is effective to improve the cracking resistance at intermediate temperature. Unlike the result of viscosity and high failure temperature, significant difference was found in the result as all rubberized binders manufactured by dry method showed higher G*sin(δ) values compared to wet process in each binder type. This result indicated that the wet method is beneficial to increase cracking resistance at intermediate temperature. Also, all the values satisfied the maximum requirements of 5000 kPa by Superpave.

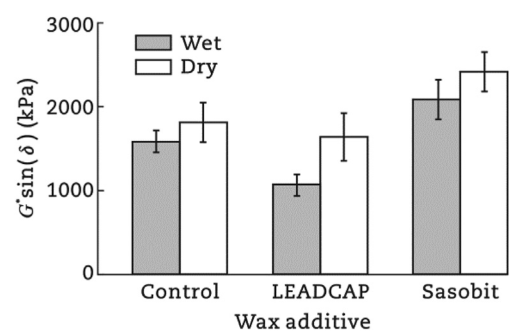

Fig. 5 – G*sin(δ) of recycled CRM binders (RTFO + PAV) at 25 °C.

The statistical significance of the change in the G*sin(δ) value as a function of WMA additive and production process was examined and results are shown in Table 8. The results indicated that wax additives have a significant effect in the G*sin(δ) value compared with each blending method. The difference of fatigue cracking property between two wax additives is observed to have significant difference based on the production process. LEADCAP modified binder seemed to have significant difference whereas insignificant difference is noted for Sasobit modified binder due to the production process.

3.4. *Thermal cracking property*

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 stress in the asphalt

Table 8 – Statistical analysis results of the G*sin(δ) as a function of blending method and wax additive (α = 0.05).

Wax additive	Blending method	Control		LEADCAP		Sasobit	
		1	2	1	2	1	2
Control	1	–	N	S	N	S	S
	2		–	S	N	N	S
LEADCAP	1			–	S	S	S
	2				–	S	S
Sasobit	1					–	N
	2						–

Note: 1: wet mix; 2: dry mix; N: non-significant; S: significant.

binder and less chance for low temperature. BBR test was carried out for three aging states (original, short-term and long-term aging states) at −12 °C to observe the effect of aging level on low temperature cracking. The stiffness of rubberized binders with wax additives using two different production processes was measured. Fig. 6 illustrates the thermal cracking property of the warm rubberized at three aging state as a function of blending methods. In comparison of production methods, the rubberized binders produced with dry process showed higher stiffness results, although the difference is not noticeable. CRM binders showed better cracking property compared to control binder in previous researches (Lee et al., 2008; Kim and Lee, 2016). It is considered that 1 min of mixing time for rubberized binder is not enough to reveal the effect to improve cracking property. Therefore, Sasobit rubberized binder produced with dry method showed less cracking resistance due to short term mixing period and wax crystallization.

In general, the rubberized binder including LEADCAP resulted in the lowest stiffness value at −12 °C and the addition of Sasobit into rubberized binder caused the higher value of stiffness. These results are shown in all aging states. The warm rubberized binders with LEADCAP showed maximum 18% decreased stiffness value compared to control binder within each binder type. According to previous research (Kim et al., 2013), LEADCAP includes crystal controller to adjust crystalline degree of wax material at the low temperature. The adjusted crystalline degree is considered to improve cracking resistance of rubberized binders containing LEADCAP. However, the rubberized binder containing Sasobit exhibited approximately 26% increased value than control binder after RTFO + PAV aging process. This finding is consistent with previous studies (Edwards and Redelius, 2003; Edwards et al., 2006; Hesp, 2004). Even though the wax crystallization of Saobit was effective to improve rutting property in DSR test, it is considered to have less flexibility at low temperature by the crystallization. Also, it is found that the thermal cracking resistance were decreasing over the aging process based on the reducing trend of stiffness value with increase of aging level, as expected.

The statistical results of the change in the stiffness value measured at long-term aging state are shown in Table 9. In general, the data indicated that within each binder type, the differences by wax additives and blending methods are statistically insignificant, except for Sasobit in dry method. Control and LEADCAP binder is observed to have significant difference with Sasobit modified binder produced with dry process regardless of their blending method.

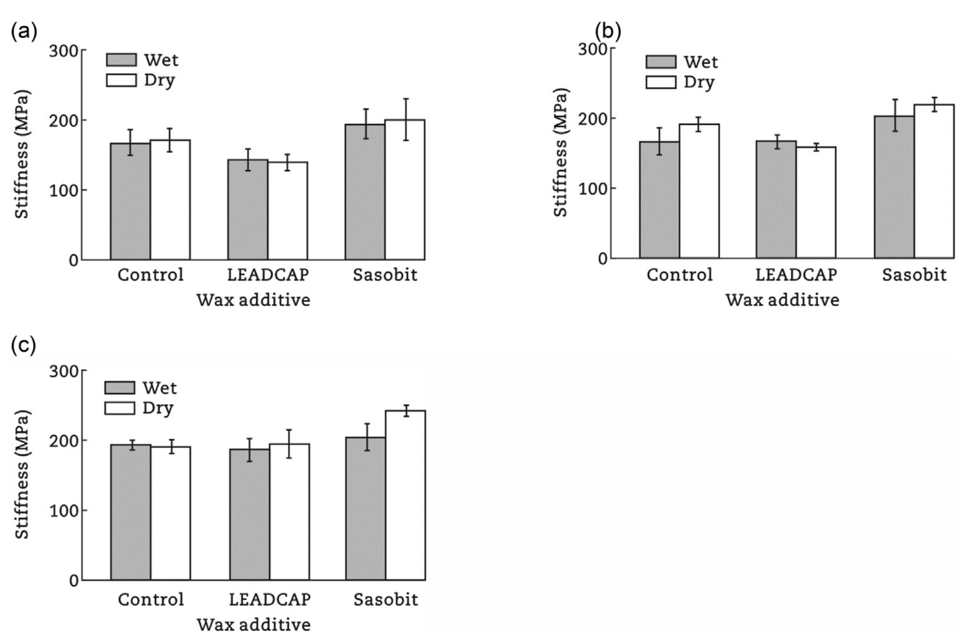

Fig. 6 – Stiffness at −12 °C of the rubberized binders with wax additives. (a) Unaged binders. (b) RTFO aged binders. (c) RTFO + PAV aged binders.

Table 9 – Statistical analysis results of the stiffness values as a function of recycling percentage and wax additive ($\alpha = 0.05$), RTFO + PAV aged binders at −12 °C.

Wax additive	Blending method	Control		LEADCAP		Sasobit	
		1	2	1	2	1	2
Control	1	–	N	N	N	N	S
	2		–	N	N	N	S
LEADCAP	1			–	N	N	S
	2				–	N	S
Sasobit	1					–	S
	2						–

Note: 1: wet mix; 2: dry mix; N: non-significant; S: significant.

4. Summary and conclusions

To investigate the effect of production process on the performance properties of warm rubberized binders, rubberized binders were produced using dry and wet methods. Warm rubberized binders were made with the wax additives of LEADCAP and Sasobit, and artificially short-term and long-term aged in the laboratory. A series of Superpave binder tests were carried out using the rotational viscometer, the DSR, and the BBR to evaluate various performance properties (viscosity, rutting, fatigue cracking, and low temperature cracking) of the binders. Based on the result of these tests, the following conclusions were drawn for the materials used in this study.

1) It is found that the blending method has little influence on the viscosity of rubberized binders with wax additives.
2) The control rubberized binders manufactured by wet process showed the higher failure temperature, suggesting superior rutting resistance.
3) The wet process showed better performance (lower $G^{*}\sin(\delta)$ values at 25 °C) in the fatigue cracking test.
4) According to the BBR test results for three aging states, the warm rubberized binders with wax additives were found to have similar trend between the wet and dry methods.
5) It is recommended to conduct further study with rubberized mixture manufactured by two processes to predict the field behavior.

Conflict of interest

The authors do not have any conflict of interest with other entities or researchers.

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