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Optimizing the Mixing Procedure of Warm Asphalt Rubber with Wax-Based Additives through Mechanism Investigation and Performance Characterization

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Abstract

Wax-based additives can be used as flow improvers to enhance the workability of asphalt rubber (AR). Conventionally, warm asphalt rubber (WAR) is produced by preparing AR first and then blending it with warm mix asphalt (WMA) additive. However, directly mixing WMA additive, base asphalt and crumb rubber together may save more energy since the early incorporation of WMA additive also helps decrease the production temperature of AR. To assess the feasibility of incorporating wax-based additives at an earlier stage, this study investigates the influence of the mixing procedure on WAR prepared by two wax-based additives, i.e., commercial Sasobit and conventional paraffin wax. Rheological tests on WAR revealed no significant difference between WARs prepared by different procedures. However, the direct mixing method led to worse WAR workability compared to the traditional

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mixing procedure. Chemical analysis on the liquid phase of WARs (crumb rubber removed) indicated that independent of the type of wax-based additive, there is less wax in the liquid phase of WARs when the additive is added earlier, which may be caused by the absorption of wax by crumb rubber during the interacting process. Thus, it is not recommended to replace the traditional mixing procedure with the direct mixing method.

Keywords: Asphalt rubber; warm mix asphalt; wax; rheological property; workability; interaction

1 Introduction

Asphalt rubber (AR), which is defined as raw bitumen modified by no less than 15% of crumb rubber modifier (CRM) by total binder weight [1], has gained increasing interest due to its excellent mechanical performance and tyre-road noise reduction function [2] and [3]. During its preparation process at elevated temperature, CRM absorbs the light fractions of base binder and releases polymer chains, such as natural rubber and styrene-butadiene rubber, resulting in higher percentage of heavy molecules in asphalt, thus higher viscosity [4], [5], [6] and [7]. Although the high viscous behavior enhances the rutting resistance of asphalt, it brings the concerns of worse pumpability, mixability and workability. In general, the production temperature of AR is 20-30 ^{o}C higher than that of base binder, leading to more energy consumption and higher construction emission [8]. During the past decade, warm-mix asphalt (WMA) technology has been successfully applied to alleviate the workability

concern of AR [9] and [10]. Warm asphalt rubber (WAR) binders with lower viscosities at mixing and compacting temperatures can be prepared by incorporating WMA additives into AR binder before mixing it with aggregates. A 15-30 ^{o}C reduction can be achieved by using different WMA additives [8], [10], [11], [12], [13], [14] and [15]. Among various types of WMA additives, organic additives, in most cases wax-based additives, have been reported to be effective in improving AR's workability without compromising its mechanical properties [11], [12], and [13].

Attributed to its low melting point and good flowability at elevated temperature, wax is usually recognized as flow improver of asphalt binder. Various studies have shown that commercial wax product prepared by Fischer-Tropsch (FT) synthesis process positively affects not only workability, but also rutting and fatigue resistance of asphalt [2], [7], [8], [10], [11], [15], and [16]. Meanwhile, despite its potential negative effect on low-temperature cracking resistance, traditional paraffin wax was found to be a potential WMA additive for AR binders, since its adverse effect on low-temperature performance can be compensated by CRM [13]. To prepare WARs with wax additives, the following two procedures can be adopted: 1) conventional method: mixing CRM and base binder first and then adding wax additive; 2) direct mixing method: directly mixing CRM, base binder and wax additives together. Between these two methods, the direct mixing method may save more energy as the preparing temperature of AR can also be reduced due to the earlier incorporation of WMA additive. Once the wax is incorporated, the viscosity of binder decreases,

which brings positive effect on homogenous distribution of crumb rubber in base binder and makes the mixing work easier. However, it is still unclear that whether these two mixing procedures may lead to different interactions among CRM, raw binder and WMA additive, thus different final workability and rheological properties of WAR.

The performance of WAR with wax additives prepared by the conventional method has been well studied, while the research on the direct mixing method is relatively limited [12] and [17]. Thus, this study aims to evaluate the feasibility and effectiveness of incorporating wax-based WMA additives at an earlier stage of WAR production. To achieve this objective, the rheological properties, including penetration, softening point, viscosity, Superpave rutting parameter, and Superpave fatigue parameter of WAR binders were characterized and compared. In addition, to reveal the interaction mechanism, chemical analyses including Differential Scanning Calorimeter (DSC) test, Gel Permeation Chromatography (GPC) test and wax content test were also conducted.

2 Experimental program

2.1 Preparation of AR and WARs

Asphalt with a penetration grade of 60/70 (Pen 60/70), a common type of asphalt in Hong Kong, was used as the base binder. Crumb rubber with 40-mesh size was used and the content was 18% by weight of base binder. Two different types of wax

79 additives were selected and used, namely Sasobit (commercial WMA additive
80 produced by the Fisher-Tropsch process) and 56# paraffin wax (conventional wax),
81 and their dosages were determined as 3wt% and 1.5wt%, respectively, based on the
82 manufacture's recommendation and preliminary test results [13]. Both the
83 conventional and direct mixing methods were applied to produce WARs, leading to in
84 total four WARs. These WARs are labeled as ARS, ARW, ARSD and ARWD,
85 representing AR with Sasobit prepared by conventional method, AR with Wax
86 prepared by conventional method, AR with Sasobit prepared by direct mixing method,
87 and AR with Wax prepared by direct mixing method, respectively. Table 1 provides
88 detailed description on the sample IDs and the corresponding mixing conditions of
89 each test binder.

90 Both Sasobit and 56# paraffin wax can be completely dissolved in asphalt, while
91 CRM remains in small particulate form in asphalt after interaction. To investigate the
92 interaction among different components of AR and WARs, the liquid phase of AR and
93 WARs were extracted by passing the hot binders through a mesh #200 sieve [5]. Right
94 after they were prepared, the AR and WARs were dropped onto the sieve which was
95 placed on top of a custom-designed container. Then the whole extraction system was
96 placed into an oven at 150 ^{o}C for 30 minutes to drain the liquid phase through the
97 sieve. The extracted liquid phase was stored at 0 °C to prevent further ageing or
98 reaction. Each extraction process could produce approximately 50g extracted liquid

phase from 400g AR or WAR binders. The liquid phases of WARs were labeled as L-WAR in this paper.

2.2 Testing Program

Conventional binder property tests conducted in this study included penetration, softening point and ductility tests [18], [19], and [20].

Viscoelastic properties of the AR and WAR binders as well as their liquid phases were characterized by the dynamic shear rheometer (DSR) test. The high- and intermediate-temperature performances were characterized by the Superpave rutting parameter and fatigue parameter, respectively [21]. 2mm gap was used for all DSR tests to reduce the influence of CRM particles [5], [22], and [23]. Unaged binders were used for Superpave rutting parameter measurement (with 25mm-diameter plates) and Pressure Aging Vessel (PAV) aged binders were used for Superpave fatigue parameter measurement (with 8mm-diameter plates). Besides, the complex modulus and phase angle were recorded for rheological analysis. For each test, two replicates were prepared.

The workabilities of AR and WARs were evaluated by three parameters, including rotational viscosity [24], air void content of Marshall Specimen (SMA10, 4.0% design air void) corresponding to each binder [25, 26], and number of gyrations of Superpave Gyratory Compactor (SGC) samples (SMA 10, 7.0% air void) to achieve the same specimen height [26]. The mixing and compaction temperatures of the

119 samples with AR were 176 ^{o}C and 160 ^{o}C, respectively, while the samples with
120 WARs were mixed at 160 ^{o}C and compacted at 144 ^{o}C. Three replicates were
121 prepared and tested.

122 The interaction among asphalt, CRM and WMA additives was investigated through
123 chemical analyses, including Differential Scanning Calorimeter (DSC) test, Gel
124 Permeation Chromatography (GPC) test, and wax content test [27]. All these tests
125 were performed on the extracted liquid phases of the test binders.

126 The thermal properties of L-WARs were measured using the Mettler Toledo
127 instruments DSC3. The melting temperatures (T_m) of the binder components were
128 determined by heating the samples from -20 ^{o}C to 150 ^{o}C at a rate of 5 °C/min.

129 The molecular weight distribution of L-WARs was evaluated by GPC test. A P230
130 Elite GPC with three columns (M, NT and NN) was used to separate the constituents
131 of asphalt binder based on molecular size. Each sample was dissolved into
132 Tetrahydrofuran (THF) and then filtered through a 0.2μm Polytetrafluoroethylene
133 (PTFE) syringe filter prior to being placed into the injection module. During the GPC
134 test, the asphalt-THF solution was drained through columns and allowed to flow at a
135 rate of 0.5 ml/min, and the temperature of the columns were maintained at 40 °C. The
136 components' concentration in the eluent was recorded using a differential
137 refractometer, and the resulting chromatogram was analyzed to obtain the molecular
138 size distribution.

139 To measure the wax content, a distillation process was applied to extract the wax from

asphalt components at 550 °C. The distilled components were dissolved in ether/ethanol (50/50, V/V) solvent and crystallized at -20 °C. The crystallized waxes were collected by filtration and their weights were measured.

3 Test results

3.1 Rheological Properties of AR and WARs

Figure 1 describes the rheological properties of the test binders. According to Figure 1a and 1b, the incorporation of CRM decreased the penetration and ductility and increased the softening point of base asphalt. Regardless of the mixing procedure, the effects of Sasobit on penetration and softening point were similar to those of CRM, while paraffin wax provided the opposite modification effects. WMA additives had insignificant effect on ductility, since the homogeneous structure of asphalt was destroyed by CRM. Figure 1c shows the Superpave rutting parameters of all test binders at various temperatures. The failure temperatures of ARS and ARSW were above 88 ^{o}C, while those of AR, ARW and ARWD were between 82 ^{o}C and 88 ^{o}C [21]. The Superpave rutting parameters of ARW and ARWD were lower than AR, but still much higher than that of the base binder. These results indicate that Sasobit is beneficial to the rutting resistance of AR while paraffin wax has negative effect, which is consistent with the results of penetration and softening point tests. No obvious difference can be observed between WARs prepared by different mixing procedures. Figure 1d shows that all binders with CRM have superior fatigue resistance than base asphalt. Both Sasobit and paraffin wax negatively affected the

161 fatigue properties of AR. Among the four WARs, ARS and ARSD showed the best
162 fatigue resistance, with the threshold temperature lower than 16 ^{o}C ($G^{*}\sin\delta$ <5MPa).
163 Besides, the intermediate-temperature fatigue performance of WAR is independent on
164 the mixing procedure.

165 *3.2 Workability Comparison of WARs*

166 As aforementioned, the workabilities of WARs were measured by their rotational
167 viscosities (Figure 2a), the air void contents of corresponding Marshall Specimen
168 (Figure 2b) and the number of gyrations of corresponding SGC samples to achieve the
169 same specimen height (Figure 2c). According to Figure 2a, both Sasobit and paraffin
170 wax were effective in reducing the viscosities of AR at all three testing temperatures.
171 For both WMA additives, the mixing procedure had insignificant influence on
172 rotational viscosity values.

173 Figure 2b shows the air void contents of the prepared Marshall Specimens, which
174 indicate that only the mixtures with ARS and ARW achieved similar air voids in
175 comparison to hot AR mixtures when the mixing and compaction temperatures were
176 16 ^{o}C lower. Besides, unlike the rotational viscosity test results, the air void content
177 results illustrated significant effect of mixing procedure. Under the same preparation
178 condition, the air void contents of the Marshall Specimens with ARSD and ARWD
179 are 1.3% and 0.7% higher than those of ARS and ARW, respectively, indicating that
180 WARs prepared by direct mixing procedure had worse workability. Similar finding
181 can also be obtained from the number of gyrations of SGC samples (Figure 2c). The

mixtures with ARSD and ARWD required more gyration numbers to achieve the same sample height as those with ARS and ARW. Since the air void contents and number of gyrations can take into the effect of aggregate-asphalt interaction during mixing on workability, while rational viscosity cannot，they are believed to be better indictors for workability of WARs.

3.3 Rheological Properties of Extracted Liquid Phase of WARs

The rheological test results have shown limited difference among the WARs prepared by different mixing procedures, regardless of the type of WMA additives. However, the effects of different mixing procedures on the performance of the extracted liquid phases are obvious (Figure 3). Figure 3a compares the failure temperatures of L-WARs and their corresponding WARs, which were determined as the temperatures when their rolling thin film oven (RTFO) aged samples have a G/sinδ value of 2.2KPa. In general, WARs have 8-10 ^{o}C higher failure temperatures compared with their corresponding liquid phases. This is because the CRM particles may act as fillers in rheological asphalt system, which increase the complex shear modulus and thus enhance the rutting resistance. For ARS and ARSD, the failure temperature difference was less than 1 ^{o}C. However, the difference between L-ARS and L-ARSD was 2.2 ^{o}C. Similarly, ARW and ARWD had close failure temperatures while L-ARW has 1.9 ^{o}C lower failure temperature compared with L-ARWD. The effect of mixing procedure on L-WARs seems more significant.

Figure 3b, 3c and 3d illustrate the results of phase angle, viscous modulus and elastic

modulus. L-ARS has larger viscous modulus, similar elastic modulus and larger phase angle compared with L-ARSD, while L-ARW has lower modulus and higher phase angle than L-ARWD. According to the previous studies, Sasobit leads to higher modulus and lower phase angle, while 56# paraffin wax has the opposite effect [11] and [13]. One possible reason is that there may be more wax additives in the liquid phase of ARS and ARW, compared with their corresponding ARSD and ARWD. The existence of CRM may narrow the difference in rheological test results of WARs. But once the CRM is removed, the distinction caused by mixing procedure becomes more noticeable.

Figure 4 presents the viscosity test results of the extracted liquid phases. It can be observed that at both 135 and 160 ^{o}C, the viscosity values of L-ARS and L-ARW were less than 2/3 of L-ARSD's and L-ARWD's values, respectively. Both Sasobit and 56# paraffin wax could enhance the flowability of asphalt binder, and the enhancement effect is more significant with a higher wax content [2], [8], and [13]. Therefore, it is believed that the direct mixing method results in lower wax content in the liquid phase of WARs.

3.4 Chemical Analysis of the Extracted Liquid Phase

Chemical tests were conducted to further verify the difference of wax amount in liquid phase of WARs. The thermal behaviors of L-WARs are shown in Figure 5. In the DSC tests, the differences in heat flow between the testing materials and the reference sample (an empty aluminum pan in this study) were monitored. The peaks

224 in the DSC curves reveal either endothermic behaviors, such as melting and
225 evaporating, or exothermic behaviors, such as cross-linking and oxidation. Figure 5
226 shows that the DSC curve of L-AR is relatively smooth within the range between -20
227 and 140 ^{o}C. L-ARS and L-ARSD exhibit two characteristic peaks with maximum
228 melting temperatures around 100 °C and 110 °C, which is attributed to the mixture of
229 linear long-chain aliphatic hydrocarbons with those melting temperatures in Sasobit.
230 L-ARW and L-ARWD show only one characteristic peak at about 57 °C, which is
231 very close to the melting point of 56$^{\#}$ paraffin wax. The thermal test results
232 demonstrate that there are certain amounts of wax additives in all WARs. Besides, it is
233 noticed that the normalized heat flow of L-WARs prepared by the traditional
234 procedure is higher, which verifies that there are more wax in L-ARS and L-ARW
235 than in L-ARSD and L-ARWD. The findings of the thermal analysis support that the
236 direct mixing procedure results in lower wax content in the liquid phases of WARs,
237 which is consistent with the findings of the rheological tests results.
238 The wax content results of L-AR and L-WARs, tested according to the European
239 standard method EN 12606-1, is shown in Figure 6. It is noted that L-AR has lower
240 paraffin compared with base binder, indicating the wax absorption effect of crumb
241 rubber. All L-WARs have higher wax content than L-AR and Pen 60/70, which is due
242 to the incorporation of wax additives. Consistent with the DSC results, L-ARS and
243 L-ARW contain more wax than their corresponding L-ARSD and L-ARWD.
244 In GPC studies of asphalt, the asphalt binder constituents are generally classified into

245 several groups according to the molecular weight [28], [29], [30] and [31]. In this
246 study, the GPC chromatogram was divided into three parts according to the
247 occurrence of peaks. The large molecular size (LMS), medium molecular size (MMS)
248 and small molecular size (SMS) were defined corresponding to the earliest part, the
249 middle part and the latest part, respectively. Table 2 presents the molecular weight
250 distributions of L-AR and L-WARs.
251 Sasobit is a crystalline, long-chain aliphatic polymethylene hydrocarbon with carbon
252 chain length ranging from C45 to C100 plus, while conventional macrocrystalline
253 paraffin waxes have carbon chain lengths ranging from C25 to C70. According to
254 literature, the average molecular weight of Sasobit and 56$^{\#}$ paraffin wax are
255 1000-1200 g/mol and 400-500 g/mol, respectively [32] and [33]. Therefore, based on
256 the molecular weight data in Table 2, Sasobit and 56$^{\#}$ paraffin wax molecules should
257 belong to MMS and SMS, respectively. Figure 7 compares the molecular weight
258 distributions of different WARs. L-ARS was found to have higher percentage of
259 MMS than L-ARSD, while L-ARW had higher percentage of SMS compared with
260 L-ARSD, which are consistent with the findings of the DSC tests, i.e., there are more
261 wax additives in the liquid phases of WARs prepared by the traditional procedure.
262 Besides, it can be noticed that the LMS percentages of ARSD and ARWD are higher
263 than those of their corresponding ARS and ARW, possibly due to the more complete
264 dissolution of CRM polymers.

4. Discussion

4.1 Feasibility of Adding WMA Additives at an Earlier Stage

Table 3 provides a summary on the similarity and difference of the two mixing procedures, based on the test results of this study. It was found that the mixing procedure did affect the interaction among various components of WAR and thus its final performance. Compared with the traditional mixing method, the direct mixing method allows for longer interaction time for wax additive and other components. Despite the lower interaction temperature, the longer interaction time promoted the penetration of wax additives into CRM, as evidenced by the wax content test results. Rheological analysis on WARs showed almost no difference between different mixing procedures, because the effect of CRM is more dominant. Finally, since the direct mixing method was found to compromise the workability of AR, it is not recommended to replace the conventional mixing procedure.

4.2 Appropriate Method to Measure Workability of Asphalt Rubber

In this study, the rotational viscosity test results were found to contradict to the results of the air void content and number of gyrations measurement. To measure the rotational viscosity of asphalt binder, the commonly used spindle is the number 27$^{\#}$ and the volume of asphalt sample is 10.5 ml. After interaction with base binder, CRM particles swell to three to five times of their original volumes by absorbing the light fractions of asphalt [4] and [34]. As a result, the test AR sample cannot be treated as a simple Newton fluid anymore, because of the solid rubber particles inside. Besides,

286 the space for liquid asphalt among the chamber wall, spindle wall and CRM particles
287 is very limited (Figure 8). During the testing, the CRM particles may produce
288 resistance to the rotation of the spindle, demanding additional torque to maintain the
289 constant rotational speed. As a result, the viscosity difference of liquid phases might
290 be masked by the particle effect.
291 In addition, the size effect of insoluble CRM particles may lead to different speeds
292 between liquid asphalt phase and the CRM particles when pumping and mixing the
293 binders with aggregates. The size of CRM is larger than part of the fine aggregates
294 and fillers even before swelling, and the density difference makes CRM unable to
295 maintain the same moving speed with asphalt and aggregate. Therefore, the relative
296 movement among CRM, liquid asphalt and aggregate is very complicated. Therefore,
297 the rotational viscosity test is not recommended to be conducted directly on AR to
298 evaluate its workability. Instead, it is worth to further investigate whether the
299 viscosity value of the liquid phase of AR can better describe its workability.

300 5. Findings and Recommendations

301 In this study, a series of rheological tests and chemical analyses were conducted on
302 AR and wax-additive-based WAR binders to characterize the effects of different
303 mixing procedures. Based on the outcome of this study, the following findings and
304 recommendations have been obtained:

1. Sasobit enhances the high-temperature performance of AR binder while 56# paraffin wax has the opposite effect. Both additives negatively affect the intermediate-temperature fatigue performance.
2. For WAR binders with either Sasobit or 56# paraffin wax, the effect of the mixing procedure on their mechanical performance is insignificant.
3. The direct mixing method leads to poorer workability of WAR compared with the traditional method. But the rotational viscosity test cannot effectively detect such difference.
4. The mixing procedure affects the interaction among the components of WARs. The wax content of the liquid phase of the WARs prepared by the direct mixing method is lower than that prepared by the conventional method.
5. It is not recommended to replace the traditional mixing method with the direct mixing method because of the compromised workability of WAR.
6. Further study on a more appropriate workability index for AR binders is recommended.

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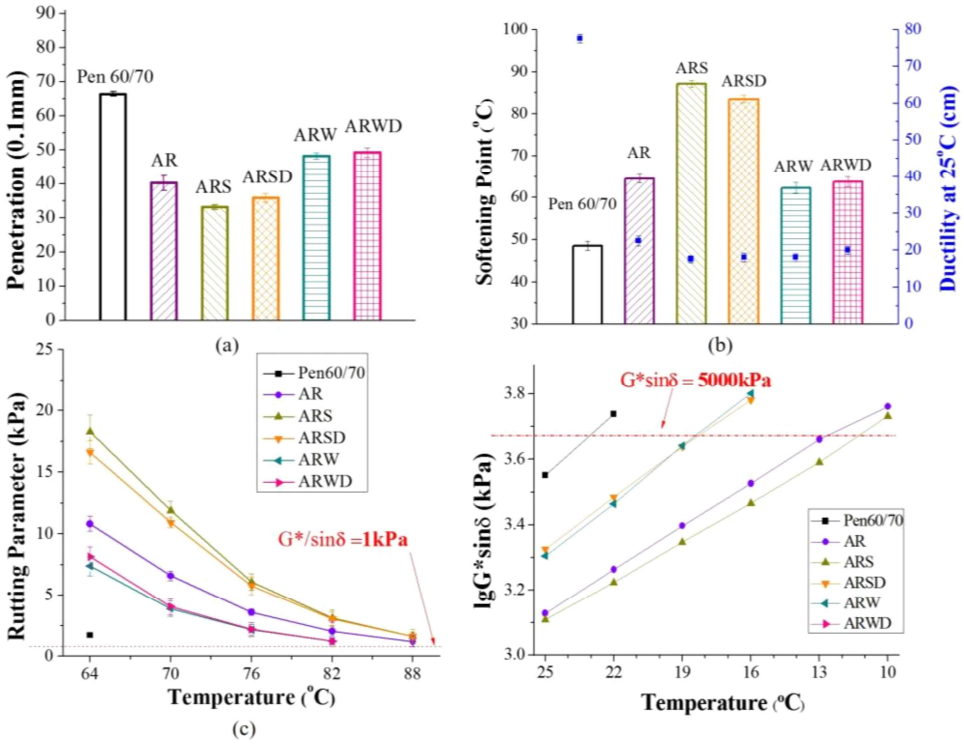

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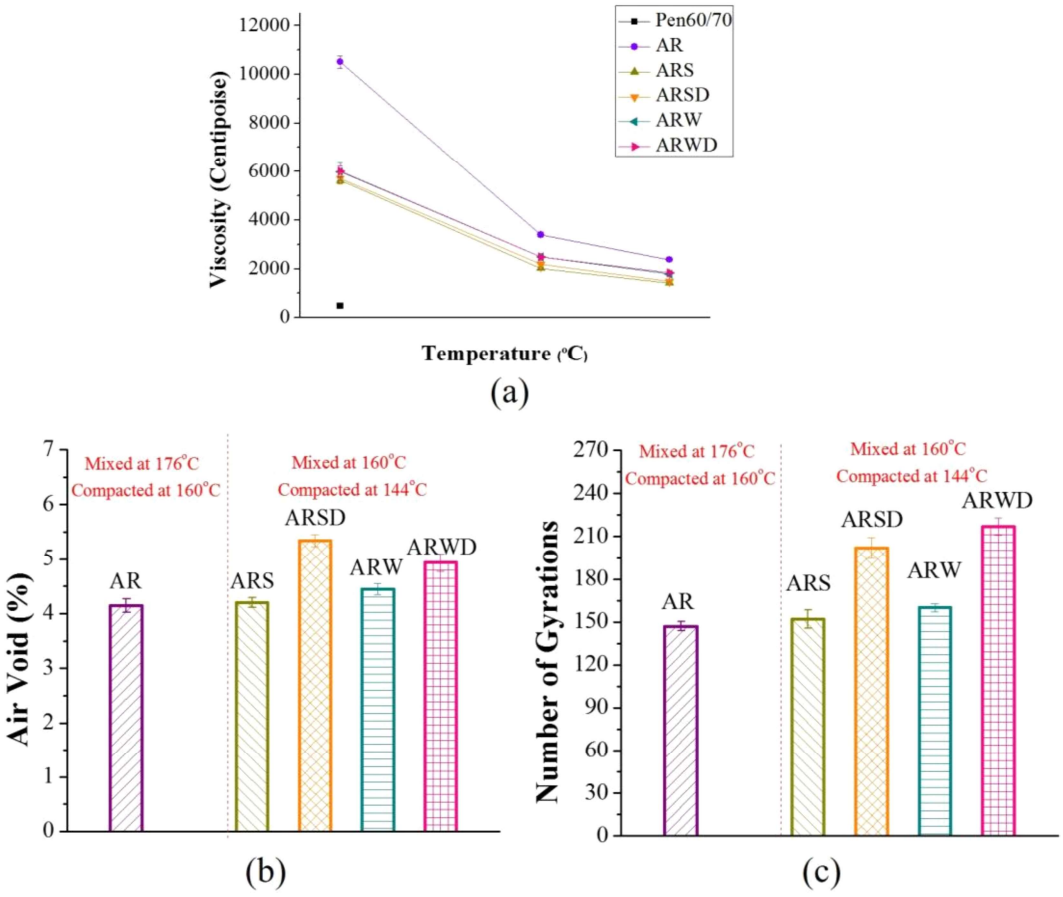
455 **Figure 1.** Rheological Properties of WARs: (a) Penetration; (b) Softening point and Ductility;
456 (c) Superpave rutting parameter; and (d) Superpave fatigue parameter



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458 **Figure 2.** Workability Evaluation of WARs: (a) Rotational Viscosity; (b) Air voids of
459 Marshall Specimens; (c) Number of Gyrations of SGC Specimens

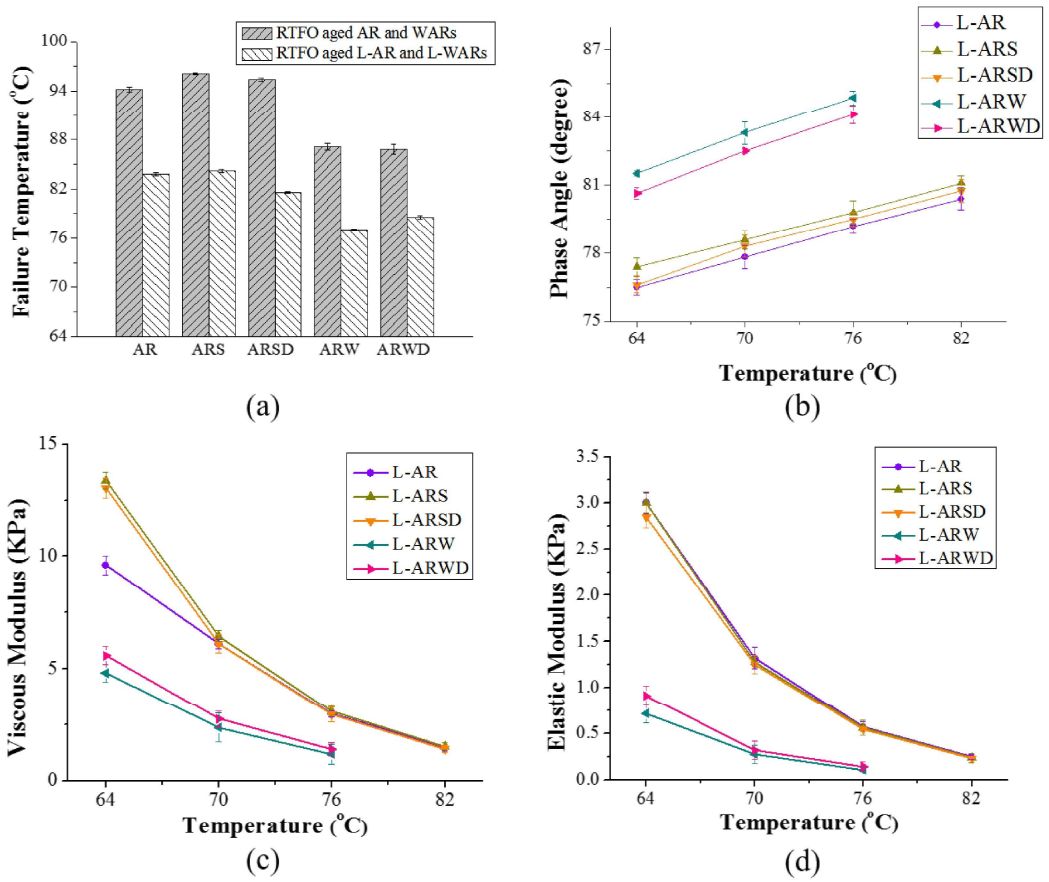


Figure 3. Rheological Properties of L-WARs: (a) Failure temperature; (b) Phase Angle; (c) Viscous Modulus; and (d) Elastic Modulus

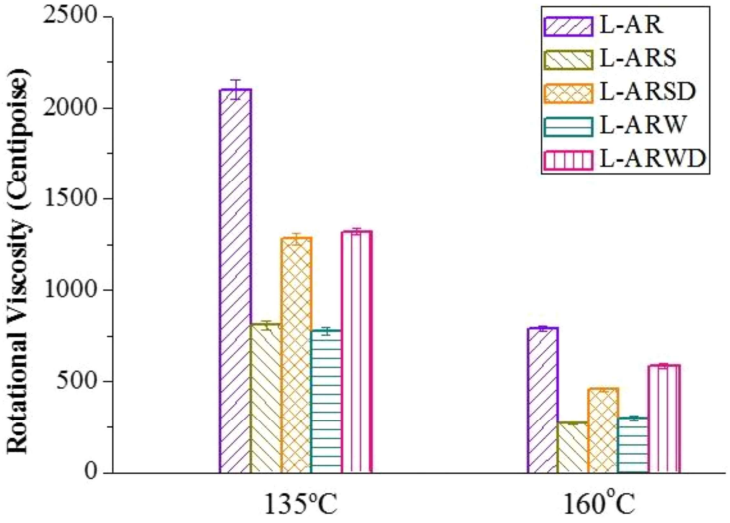


Figure 4. Rotational Viscosity of L-WARs

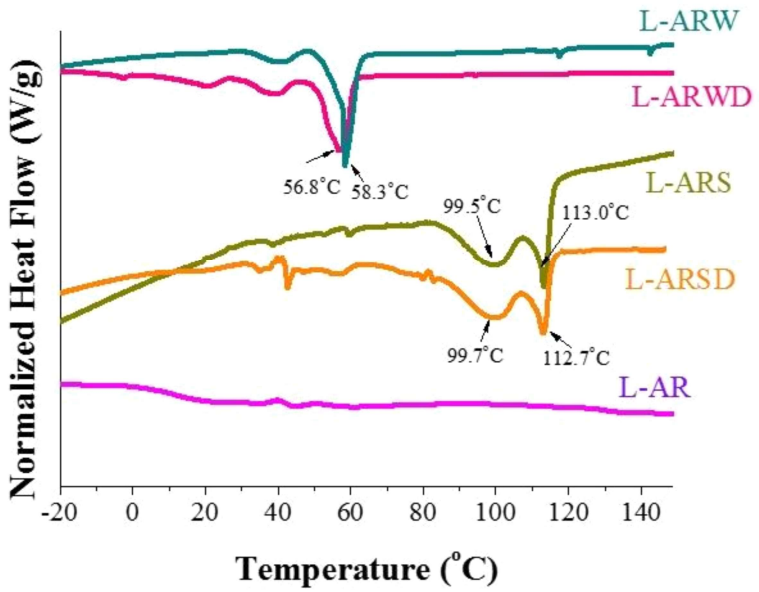


Figure 5. DSC results of L-WARs (heat flow was normalized by the sample weight)

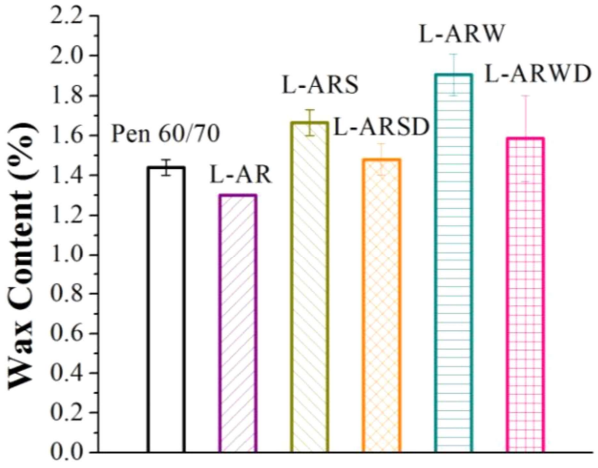


Figure 6. Wax content test results

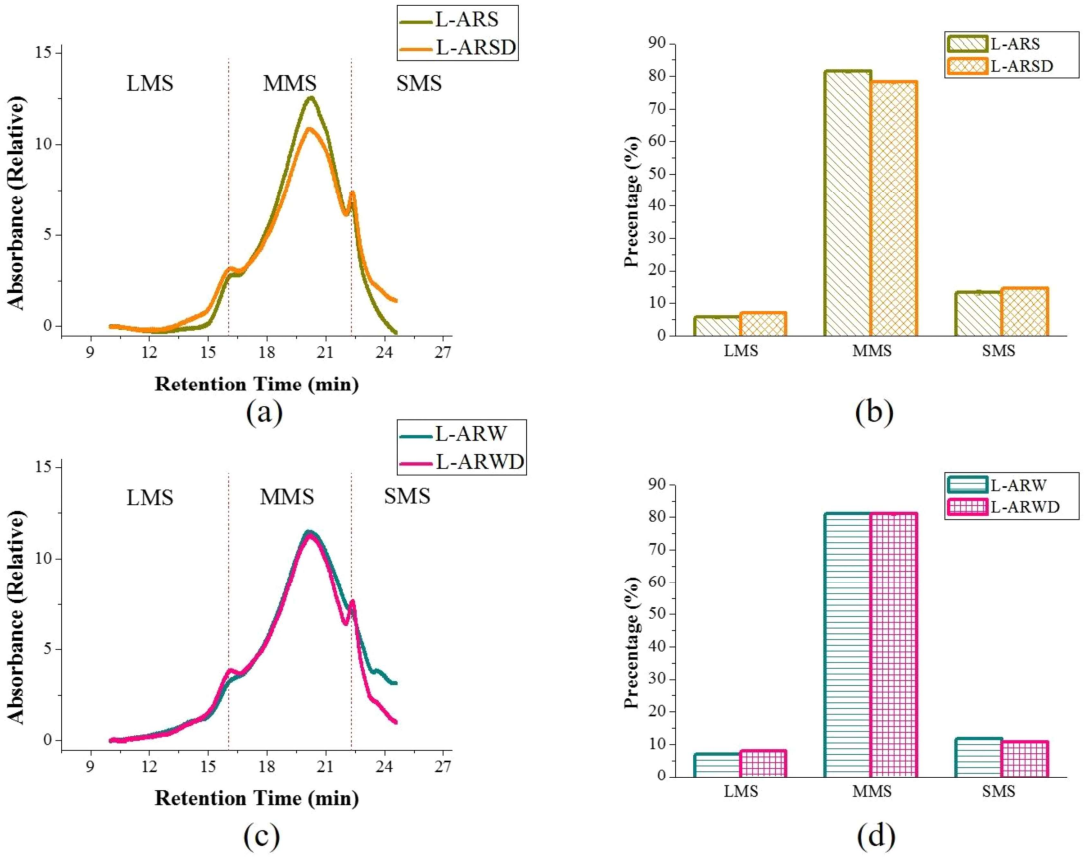
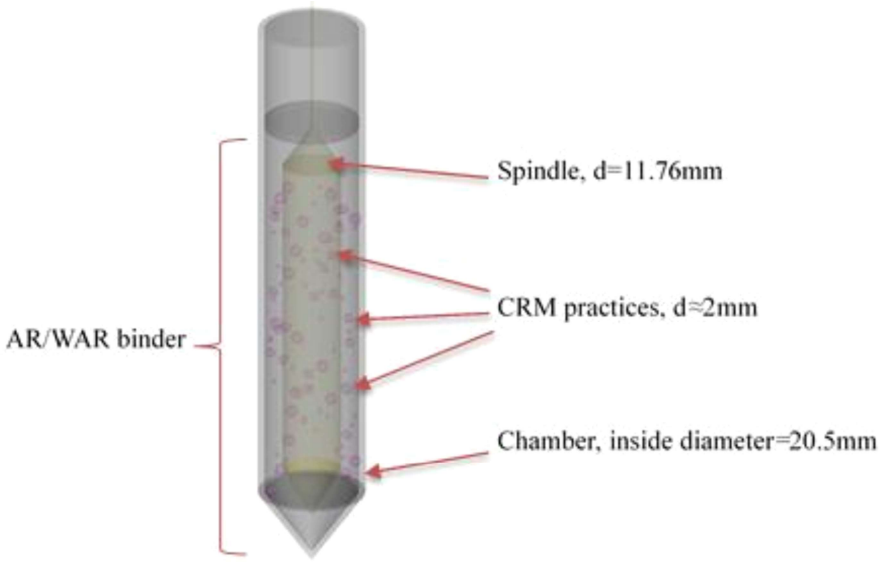


Figure 7. GPC test result: (a) Typical curve of L-ARS and L-ARSD; (b) Molecular size distribution of L-ARS and L-ARSD; (c) Typical curve of L-ARW and L-ARWD; and (d) Molecular size distribution of L-ARW and L-ARWD



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547 **Figure 8.** Diagram of Rotational Viscosity Measurement

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563 **Table 1** Description of Prepared Binders

Sample ID	Description
Pen 60/70	Base binder, obtained from Anderson Co., Ltd, Hong Kong
AR	Blending 18% of 40-mesh crumb rubber by the total weight of AR with base asphalt at 176 ^{o}C and 4000 rpm /min for one hour using a high shear mixer
ARS	Adding 3% of Sasobit into AR binder and high shear mixing for 10 minutes at 160 ^{o}C right after the mixing process of AR
ARW	Adding 1.5% of 56$^{\#}$ paraffin wax into AR binder and high shear mixing for 10 minutes at 160 ^{o}C right after the mixing process of AR
ARSD	Directly high shear mixing Sasobit, crumb rubber and base binder together (same mass ratio as ARS) at 160 ^{o}C for one hour
ARWD	Directly high shear mixing 56$^{\#}$paraffin wax, crumb rubber and base binder together (same mass ratio as ARW) at 160 ^{o}C for one hour

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592 **Table 2** Molecular Weight Distributions of L-AR and L-WARs

L-AR						
Peak No.	Retention Time (min)	Area%	Mn	Mw	Mz	Mw/Mn
1 (LMS)	16.19	8.10	1.11E+04	2.15E+04	9.83E+04	1.94
2 (MMS)	20.16	81.11	1.37E+03	1.81E+03	2.52E+03	1.33
3 (SMS)	22.14	10.79	4.26E+02	4.63E+02	4.92E+02	1.09
ALL		100.00	1.17E+03	3.26E+03	5.36E+04	2.78
L-ARS						
1 (LMS)	16.52	6.46	1.09E+04	1.65E+04	3.62 E+04	1.52
2 (MMS)	20.14	82.07	1.38 E+03	1.84E+03	2.60 E+03	1.34
3 (SMS)	22.10	11.48	4.32 E+02	4.73E+02	5.03 E+02	1.09
ALL		100	1.15 E+03	2.63E+03	1.62 E+03	2.28
L-ARSD						
1 (LMS)	16.20	7.05	1.17E+04	1.81E+04	4.08 E+04	1.54
2 (MMS)	20.22	78.26	1.4E+03	1.91E+03	2.67 E+03	1.35
3 (SMS)	22.37	14.69	4.13E+02	4.63E+02	5.04 E+02	1.1
ALL		100.00	1.13E+03	3.1E+03	2.2 E+03	2.7
L-ARW						
1 (LMS)	16.19	7	1.01 E+04	1.71E+04	1.15 E+04	1.70
2 (MMS)	20.16	81.21	1.38 E+03	1.84E+03	2.56 E+03	1.33
3 (SMS)	22.14	11.89	4.30 E+02	4.68E+02	4.97 E+02	1.09
ALL		100	1.15 E+03	2.77E+03	5.21 E+03	2.40
L-ARWD						
1 (LMS)	16.22	8.1	1.11 E+04	2.15E+04	9.83 E+04	1.94
2 (MMS)	20.12	81.11	1.37 E+03	1.81E+03	2.52 E+03	1.33
3 (SMS)	22.28	10.79	4.26 E+02	4.63E+02	4.92 E+02	1.09
ALL		100	1.17 E+03	3.26E+03	5.36 E+03	2.78

593 *Area%= the percentage of molecules within specific weight range

594 Mn= number-average molecular weight (g/mol, daltons)

595 Mw=weight-average molecular weight (g/mol)

596 Mz=z-average molecular weight (g/mol)

597 Mw/Mn=polydispersity index-relative spread in molecular weights

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607 **Table 3** Comparisons between Two Mixing Procedures

	Similarity	Difference
Sample preparation	Binders are prepared by same material and equipment.	The direct mixing procedure is more convenient and energy-saving.
Interaction condition	Two mixing procedures provide similar interaction time for CRM and base asphalt.	Direct mixing procedure enables more complete interaction condition for wax additive, but lower temperature for the interaction of CRM and base binder
Performance	Samples prepared by two mixing procedures have similar rutting and fatigue resistance, as well as very close rotational viscosities.	Direct mixing procedure leads to poorer workability when preparing mixture specimens.
Component interaction	In both cases, three components interact at a certain level, providing satisfactory mechanical performance and relatively good workability.	The longer interaction time results in less wax additives in liquid phase of WARs. The wax additives may be degraded or absorbed by CRM.

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