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ABSTRACT

Rubberized asphaltic materials have been frequently combined with warm mix asphalt technologies to tackle the issues of high energy consumptions and emissions during construction. Effective and accurate characterization of binder properties is conducive to the improvement of long-term pavement performance. The current study aims to quantify the effects of rubber content and warm-mix additives on rutting and thermal cracking performance of crumb rubber modified bitumen (CRMB), and explore the rubber and additives modification mechanisms and their impacts on the binder performance. CRMBs containing different rubber contents and warm-mix additives after long-term aging were subject to multiple stress creep and recovery (MSCR) tests and low-temperature frequency sweep tests using a dynamic shear rheometer (DSR) with the 4-mm loading plate, to investigate the high- and low-temperature performance, respectively. Rheological tests were also conducted on the bitumen and rubber phases of CRMB to understand the rubber modification mechanism. Results show that CRMB binders have superior rutting and thermal cracking resistance due to rubber modification. The improvement of high- or low-temperature performance is more prominent at higher rubber concentrations. The effects of warm-mix additives on the rutting and thermal cracking performance are different. Generally, the wax-based additive improves the rutting resistance but negatively affects the low-temperature performance. By contrast, the chemical-based additive has an opposite effect except for the high-temperature performance of neat bitumen. The stiffening of the bitumen phase and the contribution of swollen rubber particles in the bitumen matrix together contribute to the peculiar viscoelastic response of CRMB, i.e., stiffer/softer and more elastic at high/low temperatures. This modification mechanism explains the superior rutting and thermal cracking performance of CRMB.

Keywords: Bitumen, Crumb rubber, Warm-mix additives, Rutting, Thermal cracking, Rheology

70 **INTRODUCTION**

71 **Crumb Rubber Modified Bitumen**

72 Bitumen modification using crumb rubber from scrap tires has been increasingly popular in the context of

73 circular economy (Leng et al. 2018; Nanjegowda and Biligiri 2020). Although crumb rubber modified

74 bitumen (CRMB) has been reported to improve the engineering properties of binders (Singh et al. 2017;

75 Wang et al. 2018), its high viscosity has caused some concerns during construction, such as poor

76 pumpability, mixability, and workability (Wang et al. 2018; Yu et al. 2018). Besides, the requirement of

77 higher production temperatures of rubberized asphalt mixtures increases the heat energy consumption and

78 greenhouse gas emissions and generates more asphalt fumes, which compromises the working conditions

79 of paving crews at the construction site (Farshidi et al. 2013). The emergence of warm mix asphalt

80 (WMA) technologies provides an effective solution to the above issues by decreasing the construction

81 temperatures of rubberized asphalt (Wang et al. 2018; Yu et al. 2017). Since the combination of CRMB

82 with WMA is a relatively new implementation in the sustainable asphalt paving industry, it is important to

83 elucidate its long-term performance characteristics either in the laboratory or in the field.

84 Permanent deformation, fatigue, and thermal cracking are the primary distress modes of asphalt

85 pavements. Past research has demonstrated that the performance-related properties of the bituminous

86 phase has predominant effects on the durability of asphalt mixture (Bahia et al. 2001). The effective and

87 accurate characterization of binder performance is of great importance from the point of view of its

88 potential applications (Hajj and Bhasin 2017): (a) as a binder grading tool for design specification; (b) as a

89 screening/ranking tool to examine the influence of modifiers and additives; (c) to obtain fundamental

90 material properties of binders to be used as model inputs to predict the mechanical performance of

91 bituminous mixtures. Past studies have looked into the effects of rubber modification and various WMA

92 additives on the rutting and thermal cracking performance of CRMB binders through traditional test

93 methods and parameters (Daly and Negulescu 1997; Kim et al. 2010; Sebaaly et al. 2003; Singh et al.

94 2017). It was generally reported that rubber modification can improve the binders' resistance to permanent

95   deformation after long-term aging. Although rubber modification has been seen to improve the low-

96   temperature performance of binders, cautions need to be taken to properly design the CRMB, e.g., size

97   and content of crumb rubber (Sebaaly et al. 2003). In terms of WMA additives, their effects on the

98   properties of CRMB vary with the type of used WMA additives. Organic additives and chemical additives

99   usually affect the rutting or thermal cracking performance of CRMB binders in a different manner

100   (Akisetty et al. 2009; Kim et al. 2014; Yu et al. 2016). Therefore, it is necessary to characterize the high-

101   and low-temperature performance of binders for specific material combinations.

102   The fatigue performance of warm CRMB has been systematically investigated in a previous study (Wang

103   et al. 2020). Usually, contradictory measures were taken to increase the resistance of binders to permanent

104   deformation and thermal cracking. Balancing the high- and low-temperature performance is a major

105   challenge to mitigate these distresses. The current study emphasizes characterizing high- and low-

106   temperature performance and exploring the mechanism of the rubber modification to optimize the binder

107   design and to extend the durability of rubberized asphalt pavements.

108   **Binder Characterization for Rutting**

109   Under repeated traffic loadings, the accumulated strain in the bituminous binder is regarded as the main

110   reason for the rutting of asphalt pavements. Different methods and criteria have been developed to

111   characterize the propensity of a binder to permanent deformation under periodic loading. The Superpave

112   performance grading (PG) system uses the viscoelastic parameter ($G^*/\sin \delta$) measured from DSR as a

113   rutting parameter at high temperatures. The rutting parameter obtained in the linear viscoelastic range can

114   estimate the total dissipated energy during a loading cycle, which is believed to be related to rutting. To

115   minimize rutting, the energy dissipated per loading cycle should be minimized. Hence in a stress-

116   controlled test, the rutting parameter $G^*/\sin \delta$ should be maximized for binders at both fresh and short-

117   term aged states (Anderson and Kennedy 1993). However, many studies have demonstrated the

118   inadequacy of $G^*/\sin \delta$ in correlating with mixture rutting performance, especially for polymer modified

119   binders (Bahia et al. 2001). Attempts have been made to replace this inaccurate rutting parameter.

120   Sybilski (1994) proposed the concept of the zero-shear viscosity (ZSV) at 60 °C to characterize the

121   binder's rutting resistance. Good correlations between ZSV of binders and rutting performance of

122   mixtures were observed. However, other researchers found that highly polymer-modified binders, which

123   behave as viscoelastic solids, exhibit extremely high viscosity gradients at low shear rates, leading to

124   unrealistically high ZSV values using model predictions (De Visscher and Vanelstraete 2004).

125   Alternatively, the concept of low shear viscosity (LSV) was introduced to overcome this issue (Morea et

126   al. 2010).

127   Since the rutting parameter was obtained using small cyclic reversible loadings, the contribution of binder

128   damage accumulation was not considered. To address this, Bahia et al. (2001) developed the repeated

129   creep recovery (RCR) test using DSR to simulate the intermittent nature of traffic loading during the

130   NCHRP 9-10 project. The RCR test can separate the dissipated energy between permanent deformation

131   and delay elasticity. A novel parameter G_v derived from the Burger's model was introduced to

132   characterize the binder's resistance to permanent deformation. Considering the significant stress

133   dependency of polymer modified binders and different loading stress conditions, D'Angelo et al. (2007)

134   improved the RCR by introducing multiple stress creep and recovery (MSCR) tests. The MSCR is a

135   simple and performance-related test for both ummodified and modified binders. The non-recoverable

136   creep compliance (J_{nr}) and percent recovery were used to characterize the stress dependence and elastic

137   response of bituminous binders. Parameters from MSCR tests have been demonstrated to have a much

138   better correlation to mixture rutting performance than the existing Superpave binder criteria (D'Angelo

139   2009).

140   **Binder Characterization for Thermal Cracking**

141   Thermal cracking, including low-temperature shrinkage cracking and thermal fatigue cracking, is the

142   primary distress of asphalt pavements operating in cold regions such as northern American and northern

143   Europe. In Europe, most of the thermal cracking is low-temperature shrinkage cracking. With the decrease

144   of temperature, significant tensile stresses will develop in the asphalt surface layer and ultimately lead to

145   the initiation and propagation of cracks. As cracks mainly occur in the binder or mastic phase, it is vital to

146   select appropriate binders in mix design that satisfy the requirements of low-temperature performance

147   (Hajj et al. 2019). Many methods were proposed to evaluate the low-temperature properties of binders,

148   such as the Fraass breaking point test and low-temperature ductility test. However, these traditional tests

149   cannot accurately predict the critical temperature at which thermal cracking occurs (Wang et al. 2017).

150   The inadequacy is more significant when using these tests for the assessment of polymer modified binders

151   (Isacsson and Lu 1995).

152   The current Superpave PG system utilizes the bending beam rheometer (BBR) test to determine the low-

153   temperature PG of binders. Two parameters (i.e., creep stiffness and m-value (relaxation rate)) obtained

154   from the BBR test were used to determine the critical cracking temperature by applying two threshold

155   limits on them. The low-temperature PG of binders is ruled as the higher of below two values based on

156   two critera: the temperature above which the maximum creep stiffness should not exceed 300 MPa and the

157   temperature above which the minimum m-value should not be less than 0.3. The creep stiffness is directly

158   related to the thermal stress built up in the bituminous material when temperature declines. Meanwhile,

159   the m-value shows the ability to retain the viscoelasticity and relaxing the accumulated thermal stress.

160   Standard BBR testing requires a relatively large amount of materials (15 g for each beam sample) which

161   may be inconvenient and difficult when assessing recovered binders or emulsion residues. Besides, BBR

162   tests often underestimate the low-temperature performance of polymer modified bitumen (PMB) (Lu et al.

163   2017). To overcome this limitation, researchers have explored the possibility of using a DSR with parallel

164   plates of 4 mm in diameter (4-mm DSR) as an alternative to the BBR (Farrar et al. 2015; Lu et al. 2017;

165   Oshone 2018; Sui et al. 2011; Wang et al. 2019). Besides the primary advantage of requiring a small

166   amount of binder, 4-mm DSR is a simple and more accurate method than BBR when measuring the low-

167   temperature rheological properties to determine the accumulated thermal stress (Farrar et al. 2013). It was

168   also reported that 4-mm DSR has good repeatability and good consistency among data collected from

169   different DSR plate sizes (Hajj et al. 2019; Sui et al. 2010).

RESEARCH OBJECTIVES AND SCOPE

The objectives of this study include: (1) to quantify the effects of rubber content and warm-mix additives on rutting and thermal cracking performance of CRMB binders through new-generation rheological tests; and (2) to explore the modification mechanism of rubber and additives for the binder performance. MSCR tests were performed on the short-term aged binder samples to characterize the rutting performance. 4-mm DSR frequency sweep (FS) tests were performed on the long-term aged binder samples to characterize the thermal cracking performance. Furthermore, FS tests were also done on the bitumen and rubber phases of CRMB to gain insights into the rubber modification mechanism and its impact on the overall binder performance.

Together with a previous study on fatigue performance (Wang et al. 2020), this study is also part of the attempt to characterize the binder properties in the whole temperature range (high-, intermediate- and low-temperature) with only one DSR instrument using different plate sizes (25 mm, 8 mm, and 4 mm) as shown in Figure 1. This unified DSR method is deemed to be a technical breakthrough enabling improvements in the capacity of providing performance-related specifications for bituminous binders.

MATERIALS AND METHODS

Raw Materials and Binder Sample Preparation

Penetration grade 70/100 bitumen (Nynas) and fine CRMs from scrap truck tires (ambient grounding, size ranging from 0 to 0.5 mm) were used to prepare CRMB binders. High shear mixer was applied to mix the blend of neat bitumen and rubber of different percentages (5%, 10%, 15%, and 22% by weight of neat bitumen) for 30 minutes at 180°C with a mixing speed of 6000 rpm. This mixing procedure was optimized to allow sufficient rubber swelling to achieve optimized rheological properties (Wang et al. 2020). The produced CRMBs were designated as CRMB-5, CRMB-10, CRMB-15, and CRMB-22. Two types of non-foaming warm-mix additives, i.e., wax-based solid additive (W) and chemical-based liquid additive (C), were added to neat bitumen and CRMB-22 at 160°C and mixed for 10 minutes. The resultant binders were designated as 70/100-W, 70/100-C, CRMB-22-W, and CRMB-22-C. The reason why additives were only added to CRMB-22 is that CRMB-22 exhibited extremely high viscosities, which will significantly

196   influence its pumpability, mixability, and workability if not reduced (Leng et al. 2017). The detailed

197   material properties and binder preparation process can be found in (Wang et al. 2020).

198   **Rotational Viscosity**

199   To examine the effect of rubber modification and warm-mix additives on the binder viscosity, the

200   Brookfield viscometer was used to measure the rotational viscosities of different binders at a constant

201   rotational speed of 20 rpm using the #27 cylindrical spindle (spindle diameter=11.76 mm, side

202   length=33.02 mm, effective length=39.29 mm). Viscosity tests were conducted at various temperatures,

203   110, 135, 160, 177, and 190°C, which cover the temperature range of production, transport, and

204   construction (Zhang et al. 2015).

205   Figure 2a shows the rotational viscosities of CRMB binders at various temperatures. It is obvious that

206   binder viscosity decreases with the increase of testing temperature. With the increase of rubber content,

207   the binder viscosity increases dramatically. Even at 190°C, the rotational viscosity of CRMB-22 has

208   exceeded 4000 mPa·s. Excessively high viscosities of CRMB will impede its application in asphalt

209   production and construction. Based on the recommended specification for rubberized bitumen in

210   California (State of California Department of Transportation 2003), the apparent viscosity of CRMB at

211   190°C should be in the range of 1500-4000 mPa·s to ensure the proper plant production. CRMB binders

212   with rubber contents lower than 15% have acceptable viscosities. Therefore, warm-mix additives need to

213   be incorporated into CRMB-22 to reduce the viscosity. Figure 2b shows the effect of warm-mix additives

214   on the viscosity of CRMB binders. For comparison, additives were also added to neat bitumen. As

215   expected, both additives effectively reduce the viscosity of both neat bitumen and CRMB. Particularly, the

216   viscosity of CRMB-22 has reduced to lower than 4000 mPa·s at 190 °C, which satisfies the specifications

217   for rubberized bitumen as proposed by Caltrans (California Department of Transportation). Therefore, for

218   the rest of the study, warm-mix additives were only added to CRMB-22 and neat bitumen for comparison

219   reason.

Laboratory Ageing Procedure

All fresh binder samples were short-term aged using oven aging as an alternative to the standard rolling thin film oven (RTFO) test. This is because the RTFO ageing procedure encounters flowing and collecting issues for highly viscous binders (e.g., CRMB) (Bahia et al. 1998). A modified oven aging procedure, in which bitumen samples with a thickness of 1.25 mm were aged at 163°C for 2 h, was used to replace the standard RTFO aging procedure in this study (Wang et al. 2020). A part of the short-term aged samples were subject to MSCR tests. The remaining short-term aged samples were further aged by pressure aging vessel (PAV) tests. The long-term aged samples were subject to 4-mm DSR tests.

Preparation of Bitumen and Rubber Phases of CRMB

In terms of bitumen and rubber phases of CRMB, considering the CRMB-22 binder as an example, the bitumen phase of CRMB-22, which is designated as CRMB-22-BP, was extracted by filtering the insoluble rubber particles from CRMB-22 with a mesh sieve (0.063-mm) at 163°C. The swollen rubber samples were prepared to represent the rubber particle phase in CRMB. Cylindrical rubber samples (2-mm in thickness and 8-mm in diameter) cut from waste truck tire tread were soaked in hot bitumen at 180°C to prepare the swollen rubber samples. The detailed sample preparation process illustrated in Figure 3 can be found in (Wang et al. 2020). Both CRMB-22-BP and swollen rubber samples were subject to FS tests by DSR.

MSCR Test Method

The MSCR test was conducted using a DSR with 25-mm parallel plates AASHTO T 350-19. Considering the weather conditions in the Netherlands, the maximum pavement temperature is less than 60°C (Bijsterveld et al. 2001). Therefore, the testing temperature for binder high PG characterization in this study was selected as 64°C, which is regarded as sufficient. The predetermined temperature was stabilized within +/- 0.1°C tolerance for 10 minutes. The chosen two stress levels (0.1 kPa and 3.2 kPa) can characterize both linear and non-linear responses of binders. The test protocol includes ten creep (1 s) - recovery (9 s) cycles at each stress level. Before the twenty creep-recover cycles for the two stress levels, a first ten cycles at 0.1 kPa were applied for conditioning the sample to reach the steady state to minimize

246   the effects of delayed elasticity (Golalipour 2011). The non-recoverable creep compliance (J_{nr}) and

247   percent recovery (R) were calculated. Since rutting is primarily critical during the earlier in-service period

248   of pavements at high temperatures, MSCR tests were performed on short-term aged binder samples to

249   simulate the aging after the road construction.

250   **4-mm DSR Test Method**

251   Using 4-mm parallel plates, FS tests from 1 to 100 rad/s were conducted at low temperatures from -30 to

252   10°C with an incremental step of 10°C. It was reported that DSR measurements at low temperatures may

253   generate errors in the values of dynamic data due to instrument compliance. Using small-diameter plates

254   with a high gap between the plates at low temperatures is recommended to reduce the instrument

255   compliance error (Schroter et al. 2006). In the current study, a gap of 3-mm between the plates was used

256   with the 4-mm parallel plate geometry, which was validated and recommended by other institutions

257   (Wang et al. 2019). Besides, automatic real-time compliance corrections were done using the pre-input

258   machine compliance for the 4-mm parallel plates on the measuring system. To accommodate the specimen

259   on such a small plate, a specifically designed butterfly silicone mold was manufactured to prepare and

260   install the samples on the DSR plates as shown in Figure 4. The detailed sample preparation steps can be

261   found in (Wang et al. 2019). When chamber temperature drops to -30°C, the resulting binder shrinkage

262   could potentially cause its de-bonding from the top plate. To ensure sufficient adhesion between the

263   sample and plates, the normal force was set automatically to zero during the cooling phase. For each type

264   of binder, a minimum of three replicates were tested and average results were reported.

265   **Frequency Sweep Test Method**

266   FS tests of CRMB and bitumen phase binder samples were conducted using the parallel-plate

267   configuration (25-mm diameter and 1-mm gap) from 0.1 to 100 rad/s at temperatures from 10 to 70°C. To

268   ensure measurements within the linear viscoelastic (LVE) range, a strain level of 0.1% under strain-

269   controlled mode was chosen.

270   Compared to binders, the viscoelastic response of swollen rubber is less sensitive to temperature.

271   Therefore, the rheological properties of swollen rubber were measured using the 8-mm parallel plates over

272   a temperature range of -10~130°C. The measurements were performed at a strain level of 1% under strain-

273   controlled mode from 0.1 to 100 rad/s. The detailed testing setup can be found in (Wang et al. 2020).

274   **RESULTS AND DISCUSSION**

275   **Repeatability of DSR Test Results**

276   For modified binders containing particulate matter such as crumb rubber, the variability of binder test

277   results is always a concern for accurate characterization. It was recommended that the gap between the

278   DSR parallel plates should be higher than four times the maximum particulate size (FHWA 2014). This is

279   to eliminate the influence of the particle-to-particle interaction between the parallel plates. Therefore,

280   considering the crumb rubber particle size in this study, the gap height might be accommodated to 2 mm.

281   However, to make comparable results with the conventional DSR setup of 25-mm diameter and 1-mm gap

282   for neat bitumen, the 1-mm gap setting was also applied to the tests of CRMB binders. Test results from

283   three replicates were compared as shown in Figure 5a to verify the validity of the 1-mm gap for CRMB

284   binders. It can be seen that the strain responses of three replicates at different creep-recovery cycles are

285   overlapped with each other. The calculated values of non-recoverable compliance and recovery at 3.2 kPa

286   are also shown in Figure 5a. The coefficients of variation for both $J_{nr,3.2,}$ and $R_{3.2}$ are less than 10%, which

287   are generally acceptable for engineering purposes. In terms of the 4-mm DSR test, the variability of FS

288   test results is shown in Figure 5b. Both vertical and horizontal axes are plotted in the arithmetic scale to

289   more clearly see the variance of values. For both complex modulus and phase angle, the three replicates

290   yield quite close results.

291   To further check the result variability between different replicates, a one-way analysis of variance

292   (ANOVA) was performed on the measured values of complex modulus and phase angle. A confidence

293   level of 95% was used. The ANOVA results are summarized in Table 1. For either shear strain from

294   MSCR test or complex modulus and phase angle from 4-mm DSR FS test, the *F* value is smaller than the

295   *F-critical*, which means there is no significant difference between the results from the three replicates. In

296   addition, the *P-value* is much higher than the significance level, indicating the testing results are quite

297   repeatable and not affected by the rubber particle interactions or sample preparation process. Therefore,

298   the binder tests carried out in this study using the adopted DSR configurations have good repeatability.

299   **High-temperature Rutting Performance**

300   *Creep and Recovery Strain Response*

301   Figure 6 shows the strain responses of the first creep and recovery cycle at 3.2 kPa for different binders. A

302   semi-logarithmic plot was used to compare the strain difference more clearly. It can be found from Figure

303   6a that the accumulated strain of neat bitumen 70/100 increases dramatically under the creep stress. With

304   the increase of rubber content, less accumulated strains of CRMB binders were observed. For instance, the

305   accumulated strain of CRMB-22 after the creep stage was only around 12% of that of CRMB-5. The main

306   creep deformation of neat bitumen is viscous flow at high temperatures while for CRMB binders, it

307   changes to viscoelastic flow due to rubber modification. During the recovery stage, neat bitumen 70/100

308   almost shows no strain recovery, further indicating that viscous flow is the main type of creep deformation

309   for neat bitumen. It also implies that viscosity can be regarded as a primary parameter to characterize the

310   high-temperature performance of neat bitumen. By contrast, CRMB binders show obvious strain

311   recoveries due to the delayed elasticity. The higher the rubber content, the less non-recoverable strain

312   (permanent deformation). Viscosity is insufficient as a parameter to characterize the high-temperature

313   performance of CRMB binders. Therefore, parameters, which are capable of capturing the delayed

314   elasticity, should be developed to evaluate the rutting resistance of highly modified binders.

315   Figure 6b shows the effects of two warm-mix additives on the creeping and recovering properties of

316   binders. For the wax-based additive, it decreased the accumulated strain of neat bitumen during the creep

317   stage but did not significantly change the strain recovery ability. By contrast, the addition of wax-based

318   additives maintained the creep strain response but slightly increased the recoverable strain. In either way,

319   wax-additives can facilitate the deformation resistance of binders. For the chemical-based additive, it has

320   an insignificant effect on the creep-recovery response. However, it seemed to soften CRMB-22 by

321   increasing the accumulated creep strain and decreased the recoverable strain, hence reducing the

322   resistance to permanent deformation. Besides the above findings, the modification of warm-mix additives

323   did not change the main creep deformation mechanism of binders.

324   *Non-recoverable Compliance and Percentage Recovery*

325   Two parameters from MSCR test results, namely non-recoverable compliance and percentage recovery,

326   were used to capture the delayed elasticity and characterized the high-temperature properties of binders.

327   Table 2 summarizes MSCR test results of both neat bitumen and CRMB with warm-mix additives. It is

328   apparent that the J_{nr} values of bitumen at both stress levels significantly decreased as the rubber content

329   increased, indicating an improved rutting resistance of CRMB. In addition, CRMB binders had a

330   considerably higher ability to recover (R) than the unmodified bitumen 70/100 at both stress levels. The

331   lower J_{nr} and higher percent recovery of CRMB compared to neat bitumen resulted from the superior

332   polymer network established by the bitumen-rubber interaction (Wang et al. 2020).

333   With regard to warm-mix additives, the addition of wax-based additive to both 70/100 and CRMB-22

334   decreased the J_{nr} value but had an insignificant effect on the percent recovery. The increased resistance to

335   permanent deformation is attributed to the microcrystalline structure of the wax-based additive when

336   temperature drops below its melting temperature (around 110 °C). Uniformly distributed wax particles

337   will form lattice structures at service temperature (64 °C in this case) to stiffen the binder (Yu et al. 2016).

338   The chemical-based additive generally had insignificant effects on the MSCR results of neat bitumen. By

339   contrast, the chemical-based additive seemed to soften CRMB-22 and slightly decreased the percent

340   recovery.

341   The stress sensitivity parameter J_{nrdiff} seems to lack ubiquity to characterize the stress sensitivity of

342   CRMB binders. From Table 2, all CRMB binders except CRMB-5 and 70/100-W exceeded the maximum

343   allowable J_{nrdiff} value (75%) as stated in the specification AASHTO M 332-19. However, the low J_{nr}

344   values of these binders demonstrate that they have adequate resistance to permanent deformation. The

345   parameter J_{nrdiff} unfairly penalizes binders with low J_{nr} values. Alternatively, the most recent

346   specification AASHTO M 332-19 addresses the concern by removing the J_{nrdiff} requirement for binders

347   having a $J_{nr3.2}$ value of 0.5 kPa⁻¹ or lower at the selected test temperature. To remedy the unsuitability of

348   the J_{nrdiff} parameter for accreditation purposes, an alternate parameter $J_{nrslope}$ was proposed in Equation

349   1. It is defined as the change in J_{nr} for an incremental change in applied stress τ (Stempihar et al. 2018).

$$J_{nrslope} = \frac{dJ_{nr}}{d\tau} = \frac{J_{nr3.2} - J_{nr0.1}}{\tau_{3.2} - \tau_{0.1}} \times 100 \qquad (1)$$

350   Where $\tau_{3.2}$ and $\tau_{0.1}$ are the stress levels of 3.2 kPa and 0.1 kPa. $J_{nr3.2}$ and $J_{nr0.1}$ are the coressponding J_{nr}

351   values at the two stress levels. From Table 2, it can be seen that all binders meet the requirement of stress

352   sensitivity (lower than 75%) using the $J_{nrslope}$ parameter, which can be considered as a more appropriate

353   representation of stress sensitivity. $J_{nrslope}$ was also reported to have a much better correlation with an

354   incremental increase in rut depth (Stempihar et al. 2018). CRMB binders exhibited less stress sensitivity

355   as expected using the new parameter. The acceptable $J_{nr3.2}$ and percent differences for varying levels of

356   traffic are specified in AASHTO MP 19-10. Using the alternate parameter $J_{nrslope}$, the traffic level each

357   binder can reach at the temperature of 64°C was also shown in Table 2. Neat bitumen with and without

358   warm-mix additives are suitable for pavements with standard traffic conditions. With the increase of

359   rubber content, CRMB can be used for heavier traffic conditions.

360   **Low-temperature Rheology and Performance Grading**

361   *Correlation between 4-mm DSR Measured Data and BBR Parameters*

362   While BBR is a flexural test in the time domain, DSR measures the shear rheological properties of binders

363   in the time/frequency domain. Therefore, FS measurements from DSR must be mathematically

364   transformed to be comparable to those from BBR. Previous studies have developed methods to convert

365   DSR data into the parameters related to BBR tests (i.e., interconversion from dynamic frequency sweep to

366   shear stress relaxation) as shown in Table 3. The corresponding low-temperature PG criteria for binders

367   were also proposed using 4-mm DSR, and they are summarized in Table 3.

368   Regarding the methods of interconversion from dynamic FS to shear stress relaxation, both exact

369   conversion methods based on linear viscoelastic theory and approximate conversion methods were used as

370   mentioned in Table 3. The exact interconversion using the generalized Maxwell model relates the shear

371   relaxation modulus $G(t)$ in time domain to the storage modulus $G'(\omega)$ and loss modulus $G''(\omega)$ in the

372   frequency domain by the following equations.

$$G(t) = \sum_{i=1}^{n} g_i e^{-t/\lambda_i} \tag{2}$$

$$G'(\omega) = \sum_{i=1}^{n} g_i \frac{\omega^2 \lambda_i^2}{1 + \omega^2 \lambda_i^2} \tag{3}$$

$$G''(\omega) = \sum_{i=1}^{n} g_i \frac{\omega \lambda_i}{1 + \omega^2 \lambda_i^2} \tag{4}$$

373   where g_i and λ_i define the discrete relaxation spectrum and represent the stiffness and relaxation time of

374   the ith Maxwell component. ω is the angular loading frequency from DSR tests. By fitting the dynamic

375   frequency sweep data to Equations 3 and 4, the shear relaxation modulus in time domain can be obtained

376   by Equation 2.

377   The shear stress relaxation modulus can also be converted from FS data by using the empirical conversion

378   methods. The approximation method proposed by Ninomiya and Ferry (Ninomiya and Ferry 1959) is

379   given in Equation 5.

$$G(t) = G'(\omega) - 0.4G''(0.4\omega) + 0.014G''(10\omega)|_{\omega=2/\pi t} \tag{5}$$

380   Alternatively, Christensen further simplified the approximate expression as

$$G(t) \approx G'(\omega)|_{\omega=2/\pi t} \tag{6}$$

381   After obtaining the relaxation modulus curve in the time domain, the *m*-value is determined as the

382   relaxation rate at the time of interest. Lu *et al.* (Lu et al. 2017) utilized an approximate model originally

383   proposed by Anderson *et al.* (Anderson et al. 1994) to correlate BBR creep stiffness with modulus from

384   DSR. This model requires only the complex modulus and phase angle for the interconversion as shown in

385   Equation 7. The *m*-value was also empirically approximated as Equation 8 at the temperature and

386   frequency of interest.

$$S(t) = \frac{3G^*(\omega)}{1 + 0.2 \sin(2\delta)} \tag{7}$$

$$m = \delta/90 \tag{8}$$

387   Where $S(t)$ is creep stiffness at time t. δ is phase angle.

388   Similarly, Oshone (Oshone 2018) proposed empirical equations to determine creep stiffness and m-value

389   as shown in Equations 9 and 10.

$$S(t) = 1.28G^*(\omega) + 19.2 \tag{9}$$

$$m = 0.008\delta + 1 \tag{10}$$

390   Equations 7 and 9 are linear functions derived by empirically correlating DSR with BBR testing results.

391   Besides the interconversion process from the frequency domain to time domain, Hajj *et al.* (Hajj et al.

392   2019) also converted the shear response of binders to the uniaxial response using the following equation.

$$S(t) = G(t)\,(1 + 2v) \tag{11}$$

393   where v is the Poisson's ratio of binder. It was assumed as 0.35 in this study, which was believed to be

394   more reasonable at low temperatures based on the laboratory test results (Benedetto et al. 2007). By doing

395   so, original grading criteria for BBR can be directly applied to the DSR derived parameters. It was

396   reported that the exact interconversion method (Equations 2-4) and approximate conversion method

397   (Equation 5) give an almost identical stress relaxation curve (Sui et al. 2011). For simplicity, the empirical

398   conversion method as shown in Equation 5 was used in this study.

399   *Black diagram*

400   The raw dynamic data of different binders from 4-mm DSR frequency sweep tests were compared in the

401   black diagrams (Figure 7). A black diagram is a useful tool to analyze the rheological data. It can identify

402   possible data discrepancies, verify time-temperature equivalence and thermo-rheological simplicity, and

403   compare different types of bitumen.

404   It can be seen from Figure 7 that there are no obvious discontinuities or sudden changes in the slope of the

405   curves. The smooth curves indicate that 4-mm DSR with the current test configurations can generate

406 reliable rheological data. The test samples are also confirmed as thermo-rheologically simple. Unlike the

407 black diagrams in the high-temperature range (Wang et al. 2018), the curves of binders in the black space

408 in the low-temperature range do not show any symbolic patterns. Although bitumen with the addition of

409 CRM becomes more elastic as reflected by the shift of rheological data towards lower phase angle (left in

410 the figure), the change in the elastic behavior is not as significant as in the high-temperature range. This is

411 because, at low temperatures, the bitumen matrix is stiffer than rubber pariticles. From the

412 micromechanical point of view, it has a more dominant impact than rubber particles on determining the

413 rheological properties of CRMB. With the same phase angle value, CRMB binders exhibit lower complex

414 moduli compared to unmodified bitumen. This implies that CRMB may possess improved low-

415 temperature performance than unmodified bitumen, which will be discussed in the following subsections.

416 *Analysis methods for interpreting 4-mm DSR data*

417 There are two main transformations required to obtain BBR parameters from the DSR test results: (a)

418 converting dynamic data from the frequency domain to the time domain, and (b) converting shear

419 response to flexural response. Then, the critical cracking temperatures for low-temperature PG can be

420 determined by the BBR criteria, i.e., $S(t)$=300 MPa and m=0.30 at t=60 s at PG temperature + 10°C. To

421 demonstrate the calculation process, the neat bitumen 70/100 was taken as an example in this section.

422 • **Step 1**. The Christensen-Anderson-Marasteanu (CAM) model was used to build the viscoelastic

423   master curves at a reference temperature using the FS data (Figure 8);

424 • **Step 2**. The shear stress relaxation modulus curve in time domain was converted using the

425   approximation method as given in Equation 5. The master curves of storage modulus and loss

426   modulus were derived by the following relationships.

$$G'(\omega) = |G^*| \sin \delta, \text{ and } G''(\omega) = |G^*| \cos \delta \qquad (12)$$

427 • **Step 3**. Convert the shear relaxation modulus to flexural creep stiffness using Equation 11 as

428   shown in Figure 9.

429 • **Step 4**. Determine the value of $S(t)$ and m-value at $t= 60$ s through the creep stiffness master

430 curve. The m-value was determined by taking the first derivative after obtaining the trendline

431 equation. The calculated values of S and m are shown in Table 4.

432 • **Step 5**. Calculate the critical cracking temperatures by interpolation. Steps 1-4 at a different

433 reference temperature were repeated. The selected reference temperatures should bracket specified

434 values of S and m. The critical cracking temperatures were thus determined by interpolating

435 between passing and failing temperatures based on the limiting values of S and m (see Equations

436 13 and 14).

$$T_{c,S} = T_1 + \frac{(T_1 - T_2)(\log 300 - \log S_1)}{\log S_1 - \log S_2} - 10 \tag{13}$$

$$T_{c,m} = T_1 + \frac{(T_1 - T_2)(0.3 - m_1)}{m_1 - m_2} - 10 \tag{14}$$

437 where $T_{c,S}$ and $T_{c,m}$ are the critical temperatures or true grade controlled by the creep stiffness and m-

438 value respectively. T_1 is the temperature at which S or m passes the criterion while T_2 is the temperature at

439 which S or m fails the criterion. S_1 and S_2 are the creep stiffness (MPa) at T_1 and T_2. m_1 and m_2 are the

440 creep rate at T_1 and T_2.

441 *Critical cracking temperature and Delta T_c parameter*

442 Using the above calculation process, the derived values of S and m from 4-mm DSR test results at

443 different temperatures are summarized in Table 4. In general, binders with a lower creep stiffness and a

444 higher creep rate have improved resistance to thermal cracking. The values of S and m highlighted in bold

445 and italic in Table 4 are the data that bracket the specifications and are used to calculate the critical

446 cracking temperatures (Equations 13 and 14). It can be seen from Table 4 that there are no consistent

447 trends for the change in creep stiffness and creep rate of different binders at different temperatures. At the

448 temperatures that bracket the specifications (shaded data), the addition of wax-based additives to neat

449 bitumen increased the creep stiffness and decreased the creep rate. This is because the wax may crystallize

450 in binders at low temperatures, resulting in a stiffening effect. By contrast, the chemical-based additive

451   decreased the stiffness and increased the creep rate of the neat bitumen. The polymers and oils in the

452   chemical additive may be conducive to improve the cracking resistance. Similar effects of warm-mix

453   additive were found on CRMB. Briefly, wax-based additives negetively affect the thermal cracking

454   performance of binders while chemical-based additives can improve the low-temperature performance.

455   Comparing the neat bitumen with CRMB binders, rubber modification decreases the stiffness and

456   increases the creep rate at low temperatures. Futher increasing the rubber content, the improvement of

457   low-temperature performance is more prominent. The above findings are consistent with previous BBR

458   test results for characterizing the low-temperature performance of CRMB binders (Akisetty et al. 2010).

459   The low PGs of different binders based on the current PG specifications are also shown in Table 4. The

460   addition of warm-mix additives does not change the low-temperature PG of neat bitumen as -28°C. The

461   modification by CRM further decreases the low-temperature PG. When increasing the CRM content to

462   22%, the low PG of CRMB is improved to -40°C compared to other CRMBs with lower CRM contents

463   which have a low PG of -34°C. The wax-based additive increases the continuous low PG of CRMB by

464   1.1°C while CRMB-22 with the chemical-based additive decreases the continuous low PG by 1.8°C.

465   Since the current PG grading system adopts an increment of 6°C, binders having the same PG may have a

466   slightly different performance at a certain temperature. Therefore, the critical temperatures (true

467   continuous grade) of different binders for low-temperature PG calculated using Equations 13 and 14 are

468   summarized in Table 5. To account for the different governing mechanisms for the performance grade of a

469   binder, a new parameter called ΔT_c was defined below

$$\Delta T_c = T_{c,S} - T_{c,m} \qquad (15)$$

470   The sign of ΔT_c indicates whether the performance grade of the binder is governed by its creep stiffness

471    $(+\Delta T_c)$ or creep rate $(-\Delta T_c)$. The absolute magnitude of ΔT_c indicates the degree to which the binder is

472   governed by either creep stiffness or creep rate. ΔT_c values for different binders were shown in Table 5.

473   It can be seen from Table 5 that both $T_{c,S}$ and $T_{c,m}$ of CRMB gradually decrease as the increase of rubber

474   content, indicating a lower low-temperature PG. With regard to the effect of warm-mix additives, the

475   addition of wax-based additive increases the critical temperatures of both neat and rubber modified

476   binders while chemical-based additive slightly decreases the critical temperature. In addition, it is

477   noteworthy that the $T_{c,S}$ of 70/100 based binder (with/without warm additives) is higher than the

478   corresponding $T_{c,m}$, resulting in a positive value of ΔT_c. By contrast, CRMB based binder has the opposite

479   situation in which its $T_{c,S}$ is lower than $T_{c,m}$. However, there is not a clear trend of the effects of rubber

480   content and warm additives on the value of ΔT_c. The different signs of ΔT_c of neat bitumen and CRMB

481   implies that the low-temperature PG of 70/100 based binders are creep stiffness controlled while CRMB

482   binders are *m*-value controlled. Creep stiffness does not present a complete picture of binder cracking

483   tendency at low temperatures. This is because bitumen is a viscoelastic material, which is able to relax

484   applied stresses. In other words, if given sufficient time, bitumen will shed the built-up stresses when

485   applying a load or changing the temperature condition. This ability to relax the stresses of binders is

486   defined as creep rate or *m*-value in the BBR test.

487   Understanding the different controlling mechanisms can have two benefits in optimizing the binder design.

488   Firstly, neat bitumen is more suitable in the climates where rapid changes to cold temperatures are often

489   observed. This is because high *m*-value CRMB binders may encounter a rapid increase in thermal stress

490   that can lead to cracking before relaxation can occur (Marasteanu and Cannone Falchetto 2018). CRMB is

491   more suitable for climates where cold temperatures stay for an extended period because more relaxation of

492   CRMB takes place due to its higher *m*-value. Secondly, to further improve the low-temperature

493   performance grades of binders, different strategies should be used for neat bitumen and CRMB. For neat

494   bitumen, emphasis should be put on decreasing the creep stiffness while for CRMB, efforts should be

495   done in increasing the creep rate.

496 **Modification Mechanism for the High- and Low-temperature Performance**

497 CRMB can be regarded as a binary composite in which rubber particles are embedded in the bitumen

498 matrix. To figure out how the rubber modification and warm-mix additives influence the binder

499 performance, the bitumen and rubber phases of CRMB-22, CRMB-22-W and CRMB-22-C were separated,

500 and their rheological properties were investigated through frequency sweep tests. In general, bitumen-

501 rubber interaction controls the binder properties through the following ways: (1) changing the mechanical

502 properties of bitumen matrix due to the loss of light fractions absorbed by rubber and the potential

503 released components from rubber; (2) changing the mechanical properties of rubber due to rubber

504 swelling; (3) changing the volume fraction of rubber due to swelling (Wang et al. 2020). With the

505 obtained viscoelastic data at various frequencies and temperatures, master curves were established based

506 on the time-temperature superposition principle (TTSP).

507 *Effect of Rubber Modification*

508 Figure 10 presents the viscoelastic master curves of bitumen and rubber phases at a reference temperature

509 of 30°C. Firstly, comparing neat bitumen 70/100 and CRMB-22, CRMB-22 has higher complex moduli

510 than 70/100 at low frequencies (high temperatures) and lower complex modulus at high frequencies (low

511 temperatures). In the whole frequency range, the phase angle of CRMB-22 is lower than that of 70/100,

512 indicating more elastic behaviors. Considering low/high frequencies correspond to high/low temperatures

513 in the frame of master curves, CRMB-22 is stiffer than 70/100 at high temperatures while softer at low

514 temperatures. This coincides with the finding that CRMB-22 has improved both high-temperature rutting

515 and low-temperature cracking performance. Secondly, it can be found that the bitumen phase CRMB-22-

516 BP is stiffer and more elastic than neat bitumen 70/100 because of the loss of light components absorbed

517 by rubber particles, which increases the proportions of asphaltenes in bitumen. Asphaltenes are primarily

518 responsible for the increase of complex modulus and decrease of phase angles (Apostolidis et al. 2017).

519 Thirdly, comparing the bitumen phase (CRMB-22-BP) with the swollen rubber phase, the swollen rubber

520 sample has lower moduli at high frequencies and higher moduli at low frequencies. This means CRMB-22

521 will have a smaller creep stiffness and a higher creep rate than the neat bitumen at low temperatures,

522   which is exactly the same as measured in the 4-mm DSR tests. Standing from a micromechanics point of

523   view, the property changes of the bitumen phase and the inclusion of swollen rubber particles in the

524   bitumen matrix together contribute to the peculiar viscoelastic response of CRMB-22, i.e., stiffer and

525   more elastic at high temperatures, softer and more elastic at low temperatures. This finding was also

526   verified by the authors using micromechanical modelling (Wang et al. 2020). These peculiar viscoelastic

527   responses of CRMB-22 explain why CRMB in general has improved resistance to both rutting and

528   thermal cracking.

529   *Effect of Warm-mix Additives*

530   The warm additives were added to CRMB binders at a relatively low temperature after the bitumen-rubber

531   mixing process. Therefore, the additives mainly influence the properties of the bitumen matrix instead of

532   the rubber phase (Yu et al. 2017). Figure 11 presents the viscoelastic master curves of bitumen phases

533   containing warm-mix additives at a 30°C. For neat bitumen 70/100, the addition of wax-based additives

534   resulted in a significant increase in complex modulus and reduction in phase angle. The reason has been

535   explained before, which is due to the stiffening effect of wax. By contrast, the addition of chemical-based

536   additives seemed to slightly soften the binder. Chemical-based additives had insignificant effects on the

537   viscoelastic properties of binders. Comparing the bitumen phases of CRMB binders with and without

538   additives, similar effects of warm additives on the properties of bitumen phases were observed. The

539   findings from the viscoelastic master curves further verify the conclusions in the previous sections and

540   reveal how additives influence the high- and low-temperature performance of binders. Based on the above

541   analysis, it should be noted that although warm-mix additives can be used to effectively reduce the

542   viscosity of CRMB and hence reduce the construction temperatures, the type of additives should be

543   cautiously selected to ensure the high- and low-temperature performance are not compromised.

544   **CONCLUSIONS AND RECOMMENDATIONS**

545   The present study investigated the high- and low-temperature performance of warm crumb rubber

546   modified bitumen (CRMB) binders using MSCR and low-temperature FS tests. The obtained relaxation

547   parameters from 4-mm DSR tests were used to determine the low-temperature PG by directly applying the

548 BBR criterion. Two transformations were done in this process, namely converting viscoelastic master

549 curves from the frequency domain to the shear relaxation modulus in the time domain, and converting

550 shear response to flexural response by assuming a constant Poisson's ratio. The rheology of the bitumen

551 and rubber phases of CRMB was investigated to gain insights into the rubber and additives modification

552 mechanism and its impact on the binder performance. The following conclusions can be drawn:

553 • CRMB binders have superior rutting and thermal cracking resistance due to rubber modification.

554   The improvement of high- or low-temperature performance is more prominent at higher rubber

555   concentrations.

556 • Warm-mix additives have different effects on high- or low-temperature performance. Generally,

557   the wax-based additive improves the rutting resistance while having adverse effects on the low-

558   temperature performance. By contrast, chemical-based additive slightly impairs the high-

559   temperature rutting resistance while improving the low-temperature performance.

560 • In terms of the critical cracking temperature, the low-temperature PG of 70/100 based binders is

561   creep stiffness controlled while CRMB binders are m-value controlled. Rubber modification

562   changes the controlling mechanism of low-temperature performance.

563 • The stiffening of the bitumen phase and the inclusion of swollen rubber particles in the bitumen

564   matrix together contribute to the peculiar viscoelastic response of CRMB, i.e., stiffer and more

565   elastic at high temperatures, softer and more elastic at low temperatures. This modification

566   mechanism explains the superior rutting and thermal cracking resistance of CRMB.

567 • Although warm-mix additives can effectively reduce the viscosity of CRMB and hence reduce the

568   construction temperatures, the type of additives should be cautiously chosen to ensure high- and

569   low-temperature performance are not compromised.

570 In future studies, BBR tests on binders can be performed to further verify the conclusions from 4-mm

571 DSR tests. High- and low-temperature performance of asphalt mastic and mixture are recommended to be

572 investigated to verify the findings at the binder level.

DATA AVAILABILITY STATEMENT

All data, models, and code generated or used during the study appear in the submitted article.

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727

728 **Table 1.** One-way ANOVA results between different replicates of CRMB-22.

Source of variation		*SS*	*DF*	*MS*	*F*	*P-value*	*F-critical*
MSCR	Shear strain	40993.33	2	20496.67	0.3387	0.7127	2.9972
4-mm DSR FS	Complex modulus	6.82E+09	2	3.41E+09	0.2667	0.7669	3.1588
	Phase angle	0.0197	2	0.0098	0.0021	0.9979	3.1682

729 *Note: SS=Sum of Squares, DF=degree of freedom, MS= Mean Square.

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731 **Table 2.** Summary of MSCR results of different binders at the short-term aged state.

Binder type	J_{nr} (1/kPa)		J_{nrdiff}	$J_{nrslope}$	R (%)		Traffic level*
	0.1 kPa	3.2 kPa	(%)	(%)	0.1 kPa	3.2 kPa	
70/100	3.489	3.938	12.87	14.48	1.55	0.00	S
70/100-W	0.602	2.478	311.63	60.52	45.78	0.18	S
70/100-C	3.323	3.778	13.69	14.68	1.52	0.00	S
CRMB-5	1.336	1.780	33.23	14.33	22.35	3.73	H
CRMB-10	0.466	0.914	96.14	14.45	48.12	15.47	V
CRMB-15	0.142	0.413	192.86	8.71	76.32	32.45	E
CRMB-22	0.022	0.182	727.27	5.16	91.44	41.66	E
CRMB-22-W	0.019	0.176	826.32	5.06	93.42	45.69	E
CRMB-22-C	0.046	0.292	534.78	7.94	86.57	35.26	E

732 *Note: S=Standard, H=Heavy, V=Very Heavy, E=Extremely Heavy.

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734 **Table 3.** Methods and criteria for low-temperature grading binders using 4-mm DSR.

Reference	Conversion methods	Creep stiffness grading criterion	m-value grading criterion
Sui et al. 2011	Generalized Maxwell model or Ninomiya and Ferry approximation method	$G(t)$<180 MPa at t=7200 s at actual PG temperature	m>0.26 from $G(t)$ at t=7200 s at actual PG temperature
Farrar et al. 2015	Christensen approximation method	$G(t)$<143 MPa at t=60 s at PG temperature + 10°C	m>0.28 from $G(t)$ at t=60 s at PG temperature + 10°C
Lu et al. 2017	Empirical Equation 7	$S(t)$<143 MPa at t=60 s at PG temperature + 10°C	m>0.28 at $\omega = 2/\pi t$ at PG temperature + 10°C
Oshone 2018	Empirical Equation 9	NA	NA
Hajj et al. 2019	Ninomiya and Ferry approximation method	$S(t)$<300 MPa at t=60 s at PG temperature + 10°C	m>0.30 from $S(t)$ at t=60 s at PG temperature + 10°C

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736 **Table 4.** Creep stiffness and *m*-value derived from 4-mm DSR test results.

Binder type	-18°C		-24°C		-30°C		-36°C		Continuous low PG (°C)	Low PG (°C)
	S (MPa)	*m*	*S* (MPa)	*m*	*S* (MPa)	*m*	*S* (MPa)	*m*		
70/100	*174.7*	*0.35*	*402.4*	*0.28*	785.2	0.20	1112.4	0.16	-31.9	-28
70/100-W	*216.1*	*0.33*	*625.9*	*0.24*	1283.8	0.15	1453.9	0.13	-29.9	-28
70/100-C	*161.7*	*0.37*	*466.0*	*0.28*	1092.8	0.17	1394.4	0.13	-31.5	-28
CRMB-5	107.1	0.38	*253.2*	*0.31*	*524.7*	*0.24*	797.2	0.19	-34.7	-34
CRMB-10	92.0	0.39	*223.9*	*0.32*	*469.6*	*0.25*	723.8	0.20	-35.7	-34
CRMB-15	70.9	0.40	*163.2*	*0.33*	*333.6*	*0.27*	595.7	0.21	-37.1	-34
CRMB-22	56.0	0.42	124.9	0.36	*252.3*	*0.30*	*453.9*	*0.24*	-40.4	-40
CRMB-22-W	66.1	0.42	156.9	*0.35*	*277.4*	*0.29*	*459.2*	0.23	-39.3	-34
CRMB-22-C	61.2	0.43	134.1	0.37	*237.7*	*0.31*	*443.9*	*0.26*	-42.2	-40

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739 **Table 5.** Critical cracking temperatures and ΔT_c values for different binders.

Binder type	70/100	70/100-W	70/100-C	CRMB-5	CRMB-10	CRMB-15	CRMB-22	CRMB-22-W	CRMB-22-C
$T_{c,s}$	-31.9	-29.8	-31.5	-35.4	-36.4	-39.1	-41.8	-40.9	-42.2
$T_{c,m}$	-32.2	-30.1	-32.5	-34.7	-35.7	-37.1	-40.4	-39.3	-41.1
ΔT_c	0.3	0.3	1.0	-0.7	-0.7	-2.0	-1.4	-1.6	-1.1

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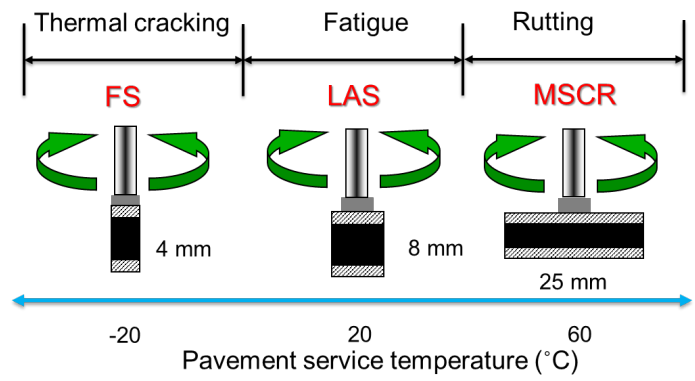
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4   **Figure 1.** Unified DSR method for binder performance characterization from low to high temperatures.

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4   (a)   (b)
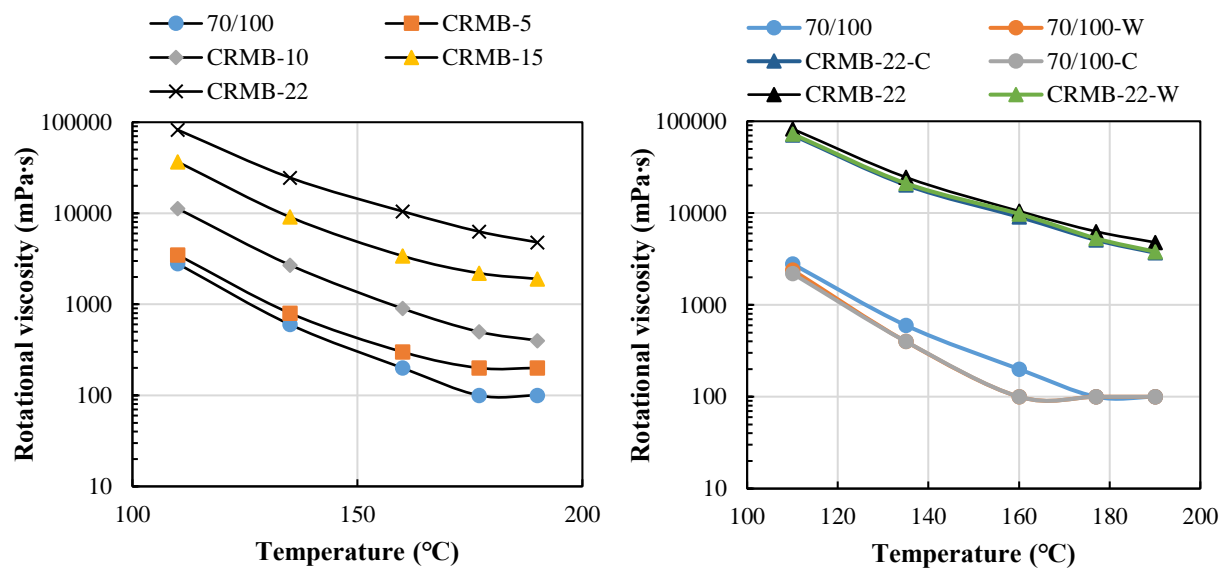
5   **Figure 2.** Rotational viscosities of CRMB binders with (a) different rubber contents; (b) warm-mix

6   additives.

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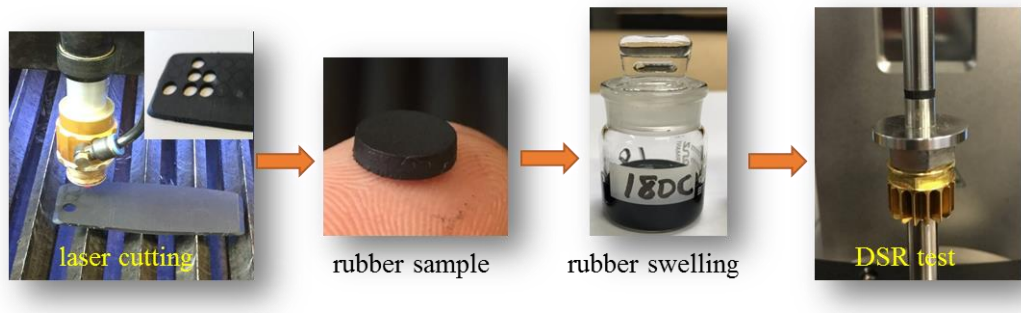
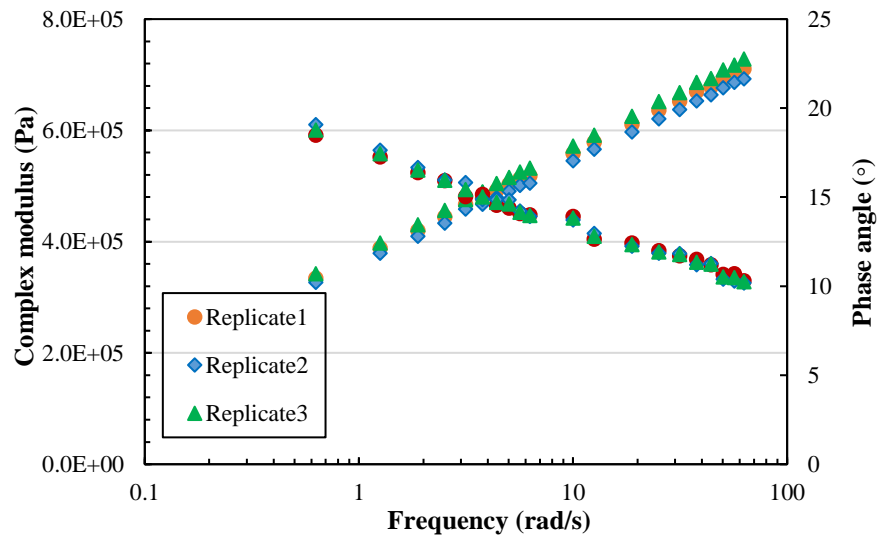2   **Figure 3.** Dry and swollen rubber samples for DSR tests.

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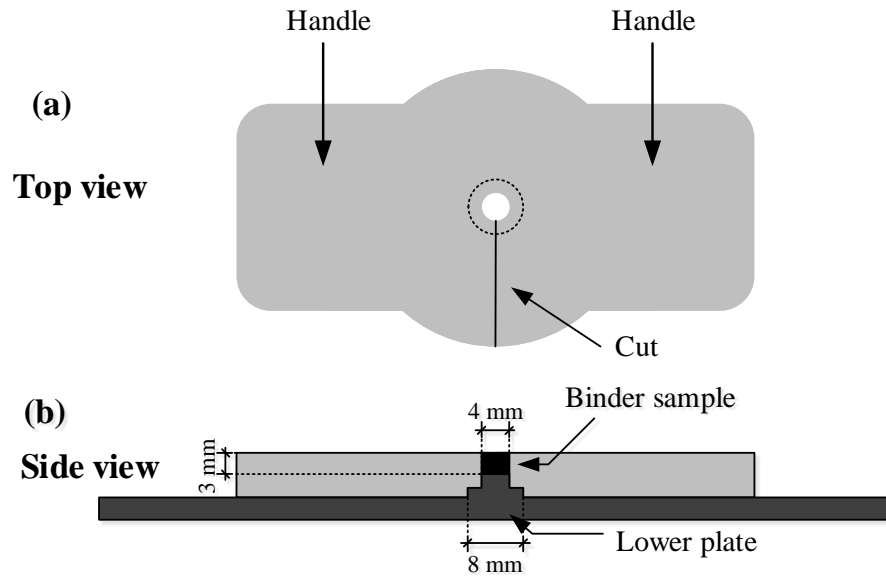
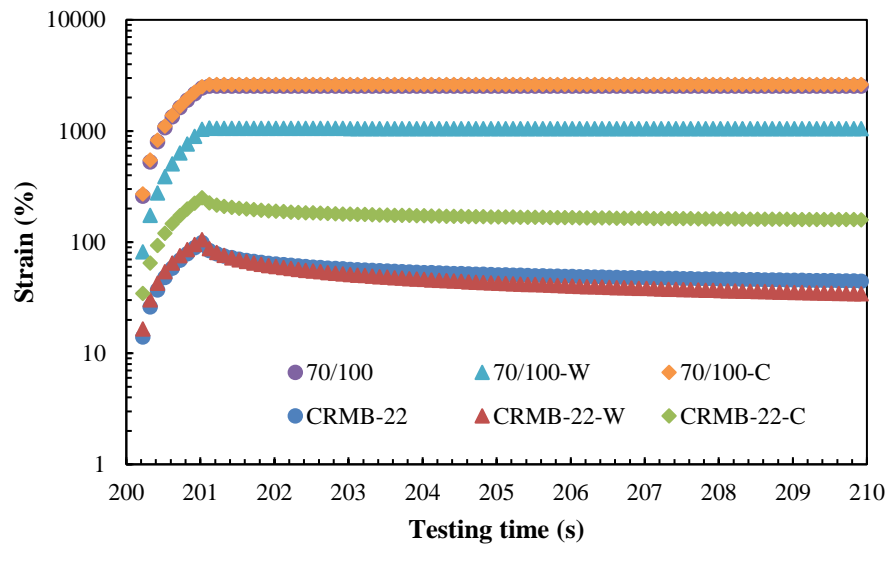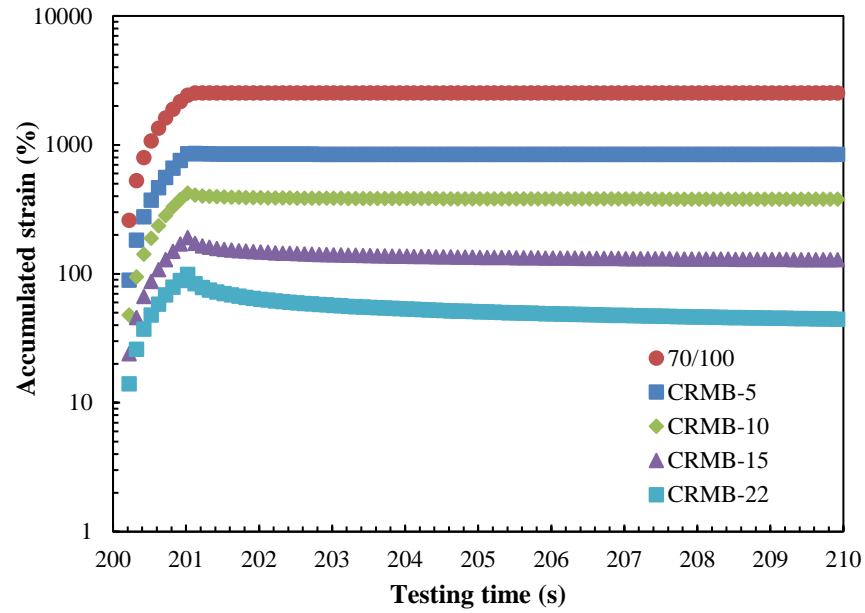**Figure 4.** The butterfly silicone mold for 4-mm DSR sample installation: (a) top view; (b) side view.

(a)

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(b)

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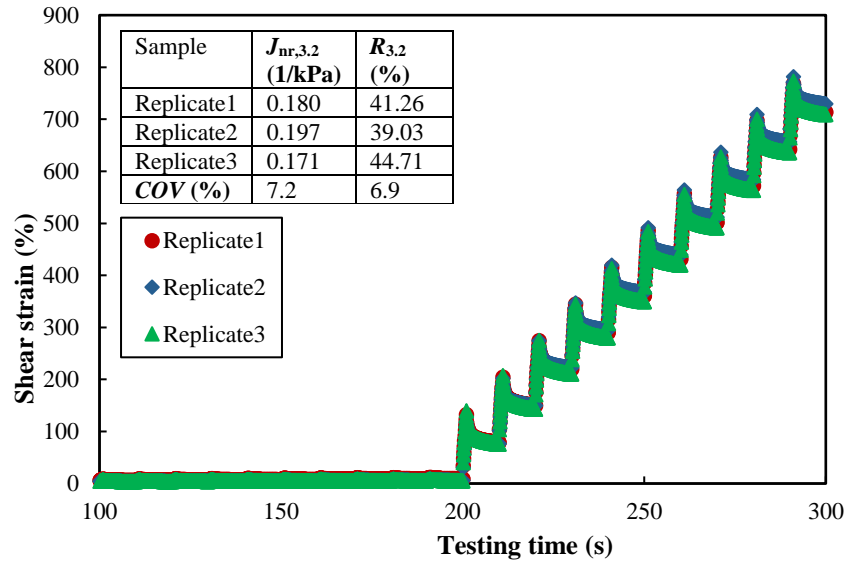
3   **Figure 5.** Variability of binder test results from CRMB-22 samples: (a) MSCR test using 25-mm plates at

4   64 °C; (b) Frequency sweep test using 4-mm plates at -30 °C. (COV=coefficient of variation)

5

(a)

(b)

Figure 6. Creep and recovery strain responses of different binders at 3.2 kPa: (a) CRMB with different rubber contents; (b) Binders with warm-mix additives.

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(a)

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(b)

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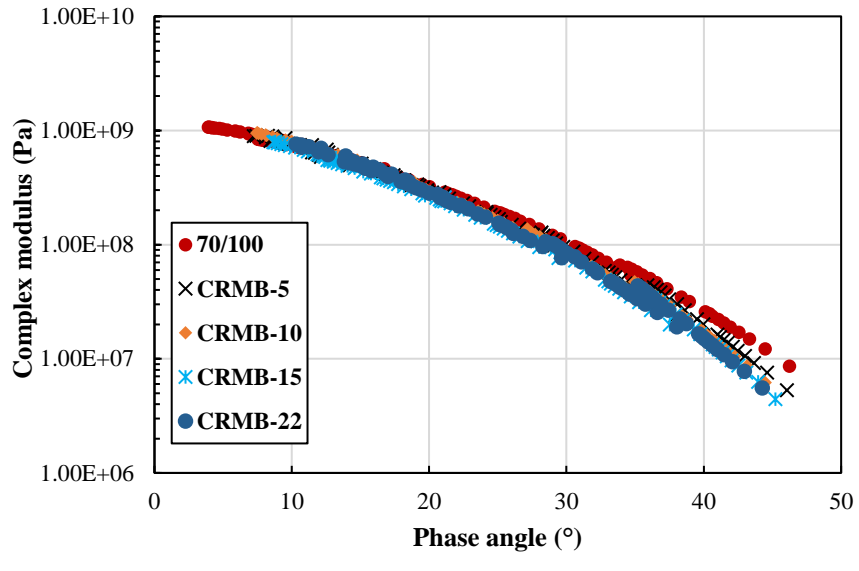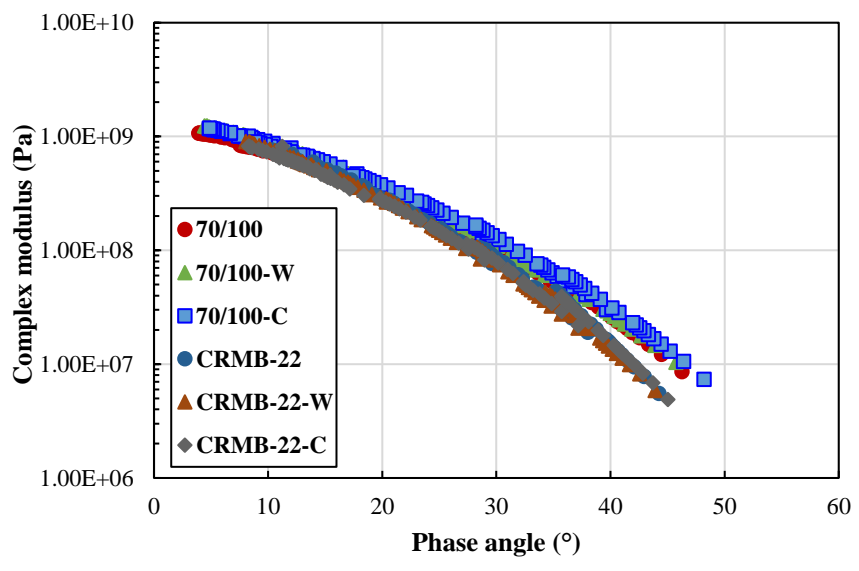
3 **Figure 7.** Black diagram of (a) CRMB binders and (b) binders with warm-mix additives.

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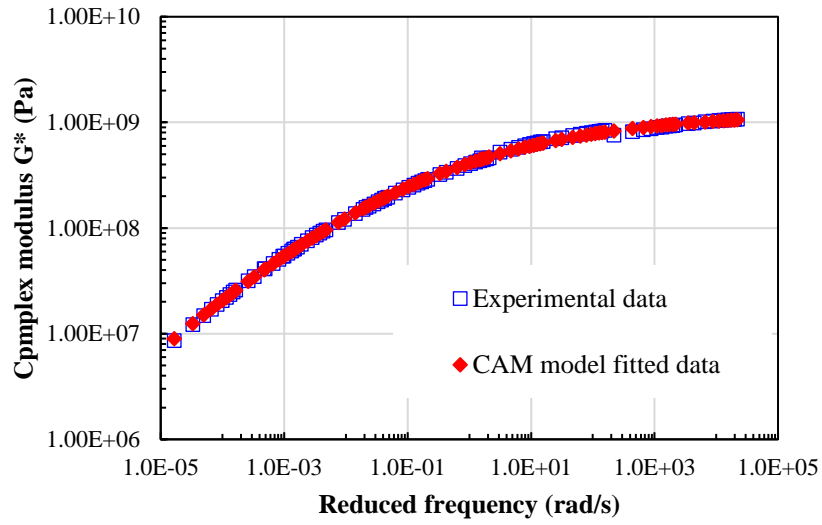
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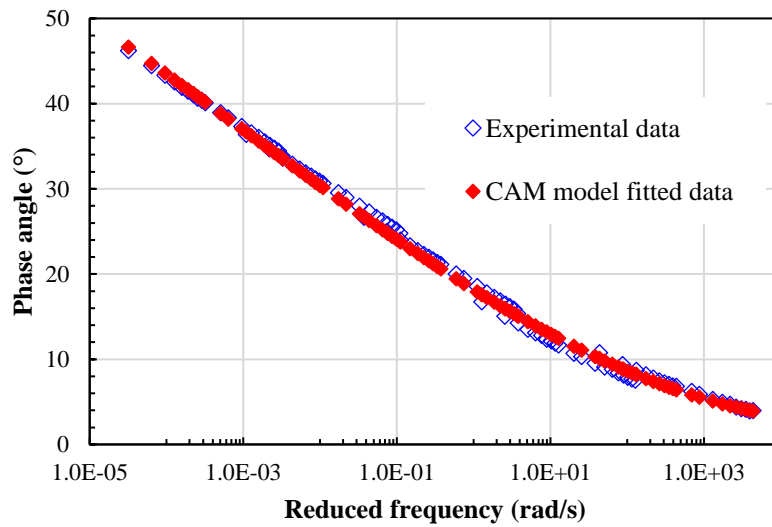
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(b)

3   **Figure 8.** (a) Complex modulus and (b) phase angle master curves of neat bitumen 70/100 at a reference

4   temperature of -18 °C.

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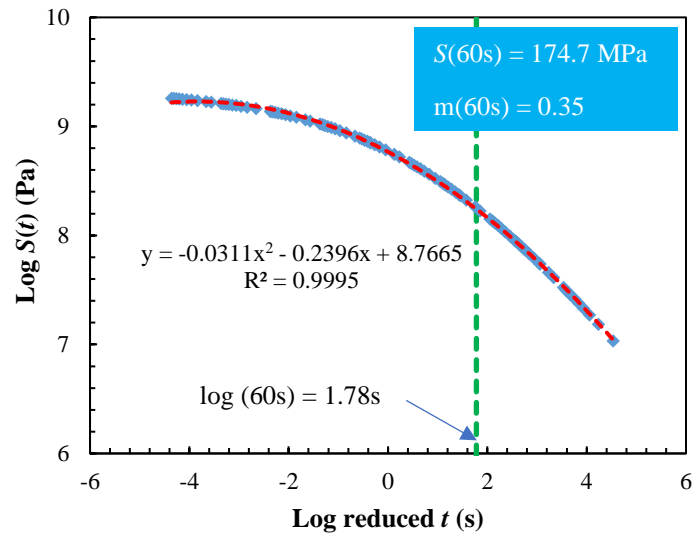
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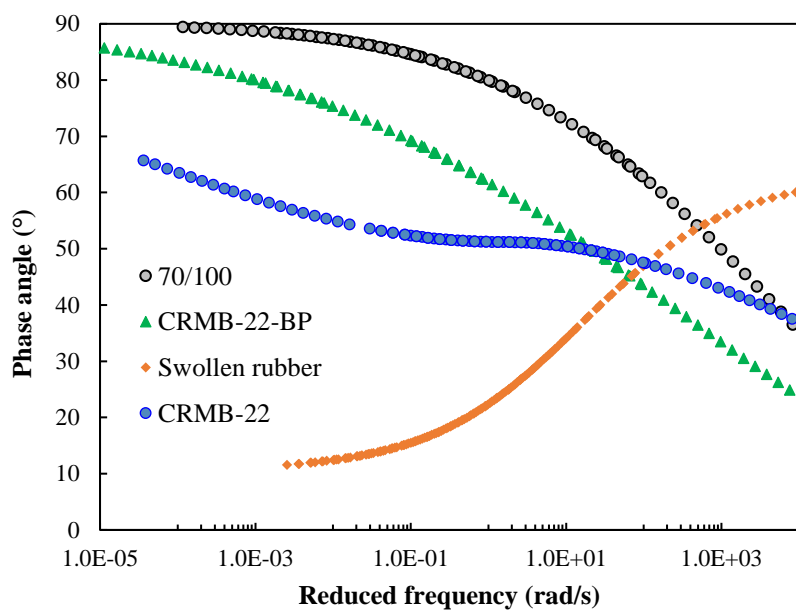2   **Figure 9.** Master curve of creep stiffness at a reference temperature of -18 °C.
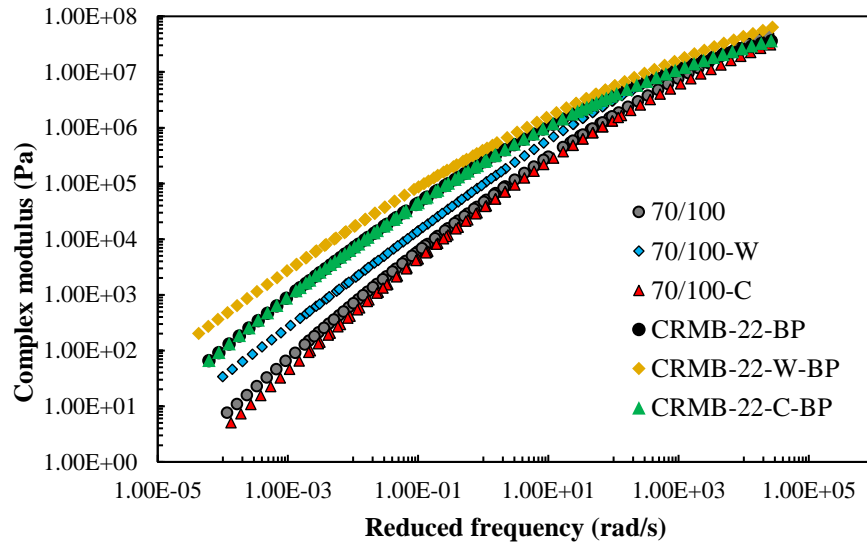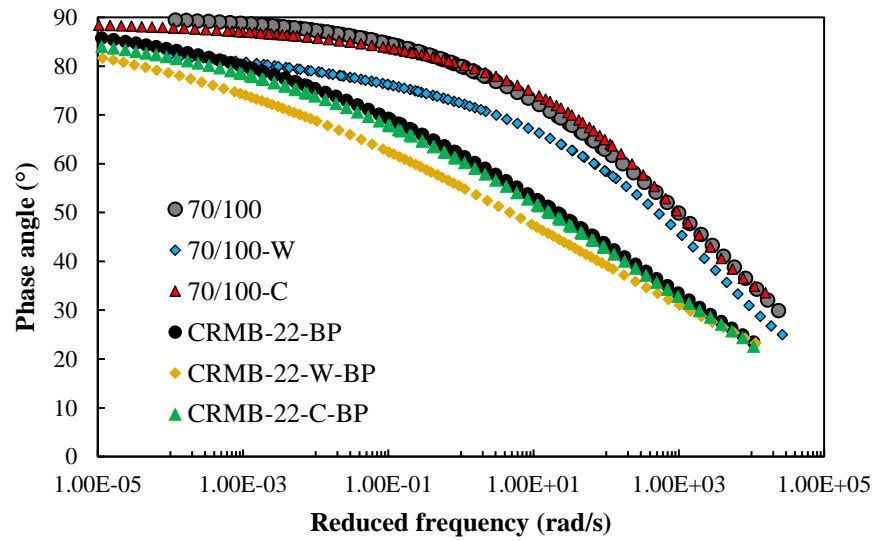
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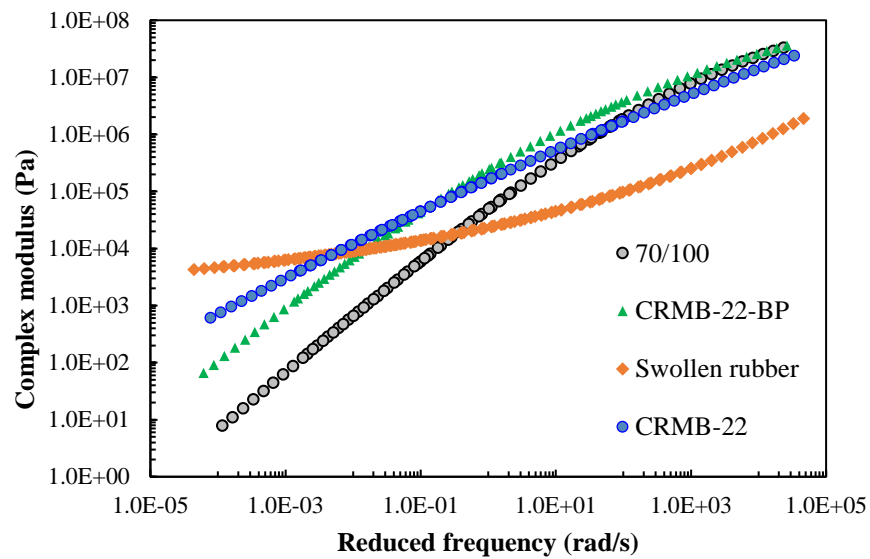
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(a)

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(b)

3 **Figure 10.** Viscoelastic master curves of bitumen and rubber phases: (a) complex modulus and (b) phase

4 angle.

5

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(a)

1

2

(b)

3   **Figure 11.** Viscoelastic master curves of bitumen phases containing warm-mix additives: (a) complex

4   modulus and (b) phase angle.

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