Investigation into the Effects of Filler on the Mechanical Behavior of Bituminous Mortar

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ABSTRACT: The work presented in this article investigates the effect of filler type and filler amount on the mechanical properties of bituminous mortar. The mortar comprises of filler, binder and fine fractions of sand. As a base binder three kinds of polymer modified binders were considered. The variables for the fillers included hydrated lime, backhouse fines and filler amount in mortar. For each binder type seven different filler combinations were selected resulting in a total of 21 mortar types. The mortars were then subjected to a 1000 hour long term aging in a weatherometer. Then, the mechanical behavior of the aged mortars was investigated using Dynamic Shear Rheometer (DSR). For DSR testing, a special test geometry developed for mortar testing was utilized. For the various mortars, master curves were constructed at a selected reference temperature using time-temperature superposition principle. Based on the master curve results, the effects of varying the type and amount of filler were analyzed. Analysis of the results showed that the use of hydrated lime resulted in stiffening effect for two of the three binders. Increase of the filler amount resulted in increase of complex modulus. The use of backhouse fines resulted in a decrease of complex modules at high temperatures. The observed effects were generally binder dependent.

KEY WORDS: DSR, mortar, filler, master curve, aging.

1 INTRODUCTION

Porous Asphalt (PA) is widely used as a surfacing layer on Dutch motorways. This is because of its excellent noise reducing characteristics. However, as compared to other mixtures, such as dense asphalt concrete, its life span is very limited. The life span of PA is determined by raveling performance. Raveling, which is the loss of stone from the pavement surface, is the dominant failure type observed in PA layers. Raveling failure mainly occurs in two modes, i.e., cohesive and adhesive. Cohesive mode refers to failure in the bituminous mortar bridge in stone-stone contact areas within the mixture. Adhesive mode refers to the detachment of stones due to adhesive failure in the bituminous mortar and stone contact area. Even though the governing failure modes of raveling are well known, understanding the mechanisms that lead to the adhesive and cohesive failures is yet considered complex for a number of reasons. One among these is the difficulty of unraveling the intricately complex interaction of the various component materials at meso and micro scale which ultimately influence the adhesive and cohesive performance of the mixture.

The type of binder and mineral filler used in PA mixtures influence the adhesive and cohesive performance of mixtures. Mineral filler is usually added to asphalt concrete mixtures to stiffen the binder and ultimately to improve mixture performance. For PA mixtures in the Netherlands only certified fillers are used. For PA mixtures use of hydrated lime filler, Wigro 60K, is mandatory. Literature shows that the use of hydrated lime in asphalt mixtures in general is beneficial (Lesueur and Little, 1999, Little and Petersen, 2005). Other studies showed that its use in asphalt concrete mixtures improve fatigue performance (Lesueur and Little, 2001). Hydrated lime was also shown to improve mixture resistance to aging by adsorbing reactive components from the binder (Johansson, 1998, Petersen et al. 1987). Observations from laboratory and field tests also supported hydrated lime can substantially reduce moisture susceptibility of the mixture, and serve as anti-striping agent. Because of the aforementioned advantages its use is widely recommended for asphalt concrete mixtures in general.

Depending on the nature of the binder and the physical properties of the mineral filler, the effect of various fillers is different for different binders (Hopman, 1998, Little and Petersen, 2005). Existing knowledge on understanding the general effect of filler on mastic and mixture performance implies the mineral composition and physical properties of filler, such as particle size distribution, density and shape, could affect the mixture performance as a result of chemical and physical interaction (Faheem et al. 2012, Verhasselt, 2004). To evaluate and quantify the effects of filler on mastics, laboratory testing on a mastic level is generally suggested.

With the framework of PA application, meso mechanics study being conducted at Delft University of Technology relies on tests carried out on bituminous mortar. The bituminous mortar, which comprises of bitumen, filler and fine fractions of sand with maximum grain size of 0.5 mm, is what is believed to play an important role in cohesive performance of the PA mixture (Muraya, 2007). This implies the effect of filler need also to be investigated at mortar scale for PA mixtures. The work presented in this article discussed the laboratory investigation carried out on various types of filler-binder combinations for bituminous mortars. First the composition of the mortar was selected based on a specific PA mixture recipe. Then the amount and type of filler, and the binder type were varied to obtain different matrix of mortars. As a base binder, three different polymer modified binders (PMB) were selected. For each PMB, seven different types of mortars were produced, resulting in a total of twenty-one mortar types for the three binders. The mortars were then subjected to specific aging protocol. After aging was completed response characterization was made using Dynamic Shear Rheometer (DSR) test. In the DSR testing, specially designed test geometry that was previously developed for mortars was utilized (Huurman et al.2009 and 2010, Woldekidan et al, 2010&2012). Based on the obtained results, the effect of varying the filler type and amount on the mechanical behavior of mortar for the different PMB was assessed.

2 MATERIALS

The compositions of the mortars consisted of polymer modified bitumen, filler and fine fractions of sand (fractions less than 0.5mm). The mortar composition is given in Table 1. In Table 1, filler type notation “a” is for hydrated lime filler referred as Wigro 60K. It consists of 25~35% calcium hydroxide. Filler type “b” denotes Wigro filler with 0% calcium hydroxide and filler type “c” denotes Wigro filler with 14% calcium hydroxide (Nevul, 2010).

Table-1 Mortar composition

Composition	Mix 1 [gm]	Mix 2 [gm]	Mix 3 [gm]	Mix 4 [gm]	Mix 5 [gm]	Mix 6 [gm]	Mix 7 [gm]
Filler	77.40	92.68	62.11	77.40	77.40	68.14	85.42
Backhouse fines	15.29	0.00	30.57	15.29	15.29	16.31	14.40
Sand	4.65	4.65	4.65	4.65	4.65	5.01	4.34
PMB	92.68	92.68	92.68	92.68	92.68	99.8	86.52
Filler type	a	a	a	b	c	a	a

The mortars were divided in three categories based on the three types of polymer modified bitumen (PMB) used. In each category seven different mortars were made according to the composition in Table 1, resulting in a total of twenty-one mortars. These mortars were then used to obtain insight on the effect of filler type and amount on the mechanical properties of mortars. Thus, the following three effects were investigated for mortars made from the different PMB:

- Effect of backhouse fines (Mix 1,2 and 3)
- Effect of filler type (Mix 1, 4 and 5)
- Effect of filler amount (Mix 6 and 7)

The selected polymer modified binders were all suitable for applications in porous asphalt layer. The three types of PMB used for the mortars are coded as A, B and C.

3 EXPERIMENTAL

3.1 Aging

To simulate the effect of aging on the mortar, the mortar was first subjected to long term aging protocol. The protocol developed during the previous meso mechanics project was followed (Huurman et al, 2009). This protocol requires production of thin mortar slabs to be placed in a weatherometer Suntest XXL machine (Figure 1). The recommended thickness of the slab is 2 mm.

In preparing the mortar slabs the component materials were first heated in an oven to a temperature of 190°C. After heating, the components were mixed according to the mortar composition given in Table 1. The mortar was then poured inside a rectangular steel frame that was designed with a 2 mm height to guarantee the required mortar thickness. By placing a silicon paper on the top, the mortar was leveled using a steel roller. In this process, the excess mortar was pushed to the side leaving a 2 mm thick mortar slab inside the steel frame. After cooling, the excess mortar around the steel frame was trimmed. This procedure was repeated for all mortar types. The resulting 21 rectangular mortar slabs with 2 mm thick were finally placed in the aging machine as shown in Figure 1 (b).

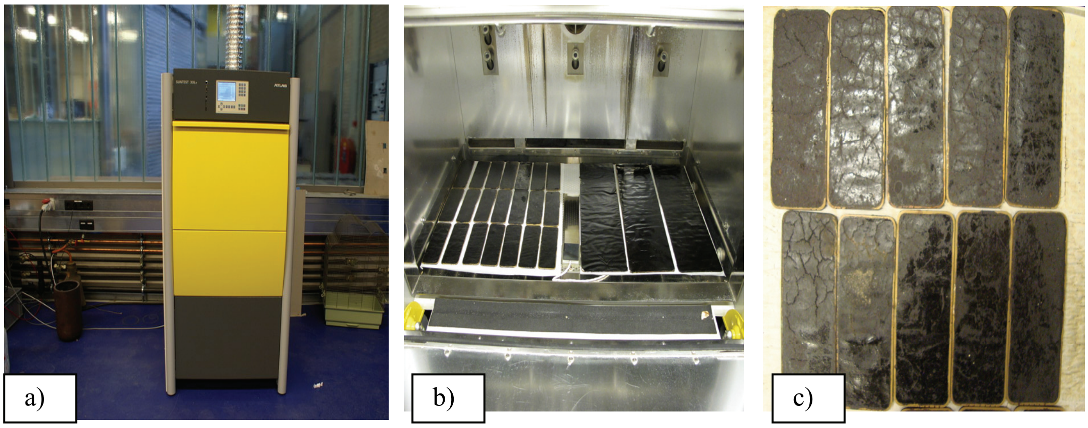

Figure1: Aging machine (a), 2mm thick mortar samples (b), aged mortar samples (c)

Aging was then performed for 1000 hours. During this time period, the mortar slabs were subjected to Ultraviolet (UV) radiation with intensity of 60 W/m2. In addition a 70% relative humidity was kept at a temperature of 40°C which in combination results in a surface temperature of about 70°C. Subjecting the mortar to these environmental conditions for 1000 hours was found to simulate 1 to 3 years of practical aging (Hagos et al. 2009). Fig.1(c) illustrates mortar samples after1000 hours of aging.

3.2 DSR testing

The aged mortars were then used to make DSR test samples. For sample preparation, the aged materials were first heated to a temperature of 190°C for half an hour. The mortar moulds and spatulas were also heated to a similar temperature. Then the heated mortar was pressed into a mould to obtain a cylindrical DSR test specimen. For each mortar type five test specimens were produced. Out of these, the best two samples were selected for DSR testing. Figure 2 illustrates the steps involved from sample preparation to mounting the specimens on the DSR machine.

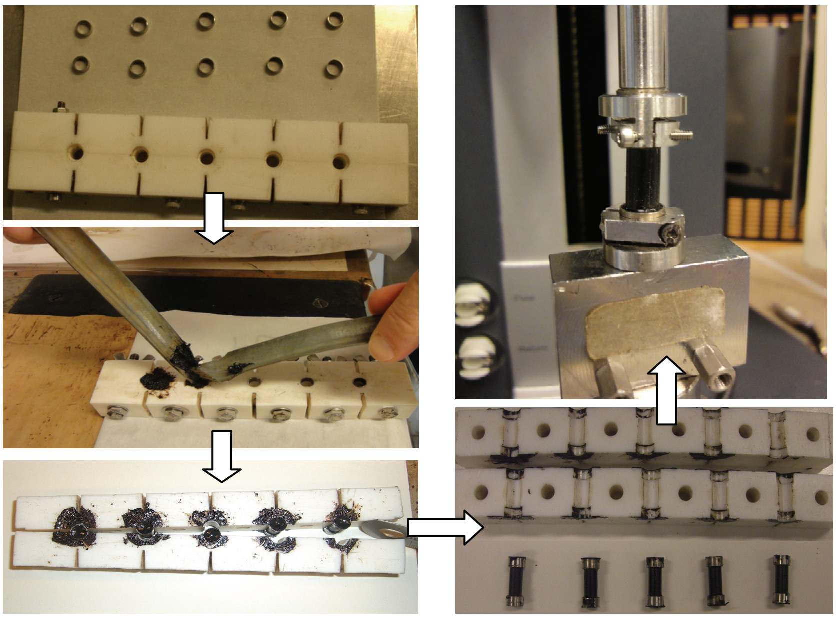

Figure 2: Illustration on sample preparation, extraction and test setup in the DSR

To obtain the mechanical behavior of the mortars frequency sweep tests were conducted at nine different temperatures, ranging from -10°C to 70°C at 10°C increment. For each mortar type two frequency sweep tests were carried out using two different mortar samples. The obtained results at various temperatures and frequencies were then used to form a master curve by using the Time-Temperature Superposition (TTS) principle (Christensen,1982).

4 RESULTS AND DISCUSSIONS

4.1 Master curve construction using TTS

In obtaining a master curve TTS factors were utilized. The shift factors give insight on the temperature susceptibility of a material. The shift factors obtained at various temperatures can be described by the Arrhenius or the Williams-Landel-Ferry (WLF) equations (Christensen,1982). In this paper, the WLF relation given in equation (1) has been utilized.

$$Log\ a_T = \frac{-C_1(T-T_0)}{C_2+(T-T_0)} \tag{1}$$

Where C1 and C2 are constants; T is the temperature in °C; T_0 is the reference temperature in °C and a_T is the shift factor. To allow automatic determination of shift factor parameters from regression analysis, a master curve model was employed. For this purpose, the modified HS (MHS) model given in equation (2) was used (Woldekidan et al, 2012):

$$(G^*(\omega))^{-1} = \left(G_0 + \frac{G_\infty - G_0}{1+\delta(i\omega\tau)^{-m_1}+(i\omega\tau)^{-m_2}} \right)^{-1} - \frac{i}{\eta_3\omega} \tag{2}$$

Where $G^*(\omega)$ denote the complex modulus; G_0, G_∞, δ, τ, m_1, m_2 and η_3 are model parameters, and i denotes the imaginary number in a complex number notation. For all mortars, master curves were constructed at a reference temperature of -10°C. For convenience, the master curves for the seven different mortars made from binder A were labeled with A1 to A7. The labels B1 to B7 were used to refer mortars from binder B, and similarly C1 to C7 were used for mortars made from binder C. For each master curve, experimental data obtained from two test specimens were utilized. As illustration, Figure 3 shows the master curve at a reference temperature of -10°C for A1 mortar.

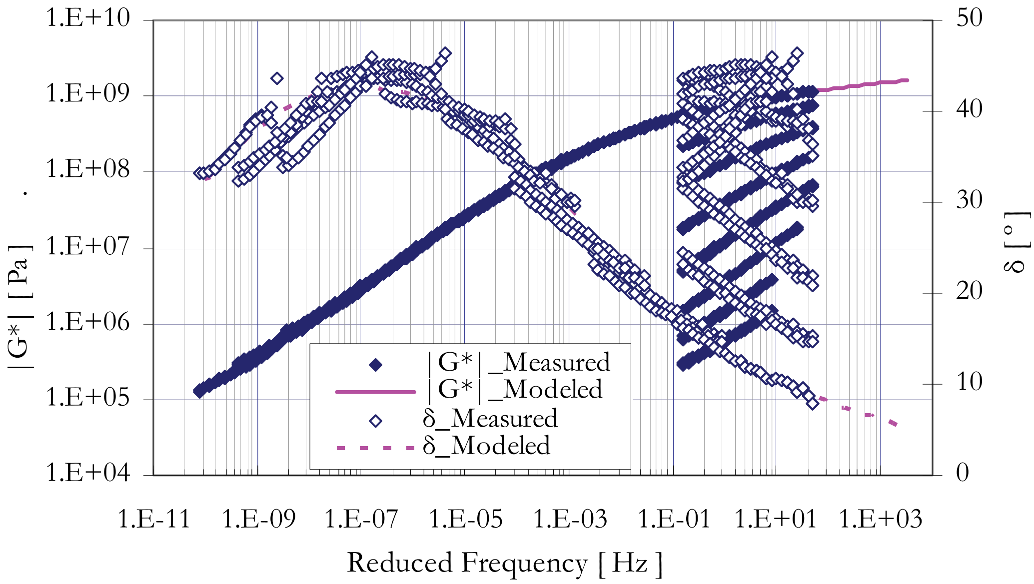

Figure 3: Master curve at a reference temperature of -10°C, A1 mortar

For brevity the individual master curve plots for the 21 mortar types are not presented. However, for all mortars the relevant model parameters for the master curves, including the shift factors parameters, are give in Table 2, 3 and 4.

Table 2 WLF factors and MHS model parameters for category A mortars at T_{ref}=-10^{0}C

	WLF Factors				MHS model parameters				
Mortar	C_1 (-)	C2 (-)	m_1 (-)	m_2 (-)	δ_1 (-)	τ (s)	G_∞ (MPa)	G_0 (MPa)	η_3 (MPa.s)
A-1	24.81	132.46	0.18	0.50	3.37	2.64	2328.86	0.08	1.73E+09
A-2	30.16	170.51	0.18	0.46	3.07	2.21	2328.86	0.05	1.73E+10
A-3	23.83	122.44	0.18	0.50	3.93	3.31	2328.86	0.05	1.73E+10
A-4	36.83	223.60	0.16	0.42	2.45	0.43	2328.86	0.05	5.67E+12
A-5	22.53	114.86	0.18	0.51	3.86	3.18	2328.86	0.07	5.67E+12
A-6	24.97	133.64	0.17	0.50	3.85	1.77	2328.86	0.04	5.67E+12
A-7	21.75	102.53	0.19	0.51	3.35	11.70	2328.86	0.14	5.67E+12

Table 3 WLF factors and MHS model parameters for category B mortars at T_{ref}=-10^{0}C

	WLF Factors				MHS model parameters				
Mortar	C_1 (-)	C2 (-)	m_1 (-)	m_2 (-)	δ_1 (-)	τ (s)	G_∞ (MPa)	G_0 (MPa)	η_3 (MPa.s)
B-1	25.10	135.43	0.18	0.50	3.37	2.64	2328.86	0.08	1.73E+09
B-2	21.23	120.42	0.20	0.52	3.33	0.88	2328.86	0.14	1.73E+08
B-3	20.99	120.17	0.20	0.51	3.23	0.59	2328.86	0.09	1.73E+08
B-4	19.34	98.97	0.20	0.56	4.05	0.84	2328.86	0.03	1.73E+08
B-5	20.21	113.81	0.21	0.54	3.70	0.61	2328.86	0.05	1.73E+08
B-6	20.07	112.83	0.20	0.54	3.84	0.53	2328.86	0.06	1.73E+08
B-7	20.26	113.83	0.21	0.53	3.10	0.68	2328.86	0.06	1.73E+08

Table 4 WLF factors and MHS model parameters for category C mortars at T_{ref}=-10^{0}C

	WLF Factors				MHS model parameters				
Mortar	C_1 (-)	C2 (-)	m_1 (-)	m_2 (-)	δ_1 (-)	τ (s)	G_∞ (MPa)	G_0 (MPa)	η_3 (MPa.s)
C-1	23.59	121.90	0.20	0.56	3.81	45.01	2328.86	0.10	1.73E+09
C-2	24.22	126.37	0.20	0.56	3.88	54.13	2328.86	0.08	1.73E+09
C-3	22.86	116.97	0.19	0.56	3.78	34.58	2328.86	0.08	1.73E+09
C-4	22.17	113.05	0.18	0.58	4.74	21.99	2328.86	0.08	1.73E+09
C-5	21.69	110.06	0.19	0.58	4.23	25.25	2328.86	0.13	1.73E+09
C-6	20.53	103.06	0.17	0.55	3.97	15.13	2328.86	0.17	1.73E+09
C-7	22.29	112.55	0.20	0.57	3.66	40.27	2328.86	0.17	1.73E+09

In the master curve fits high R-squared values, i.e. of 0.96 and above, were obtained for both the phase angle and the complex modulus curves. This indicates the good result repatability of the utilized mortar test setup.

4.2 Effects of filler composition on test results

To evaluate the effect of the different filler content and type on the mortar mechanical behavior, comparison of master curves were performed. Figure 4 shows the master curve comparisons for mortars made from binder A. Figure 5 and Figure 6 similarly present the comparisons for mortars for binder B and C, respectively. From the results presented in Figure 4 to Figure 6, it was observed that filler type and content in general have a varying effect on the mechanical properties. The effects observed on the mechanical property seem to depend on the type of binder used in the mortar. For each mortar category, the effects are analyzed in detail in the following section.

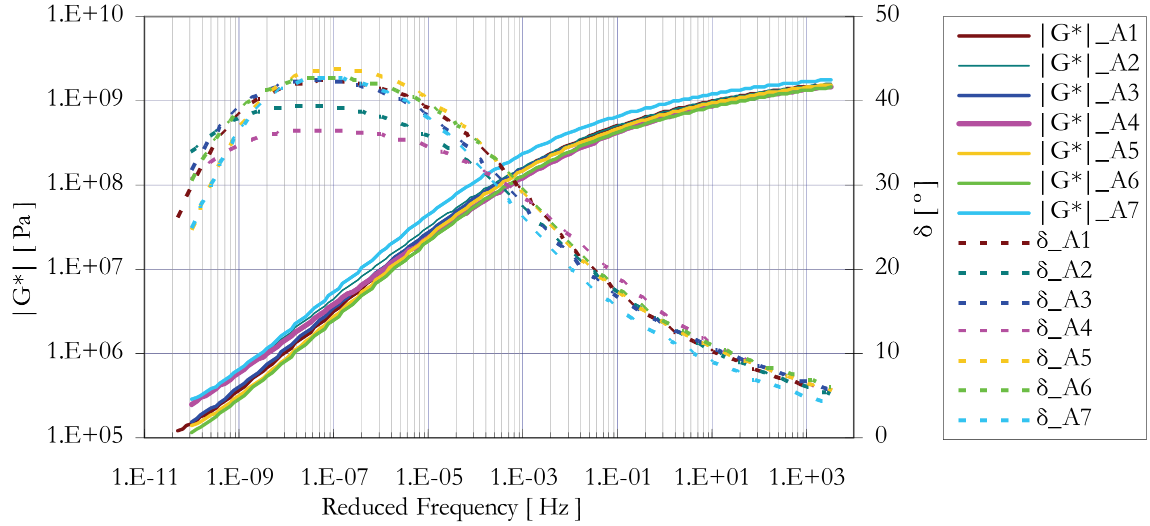

Figure 4: MC comparisons at T_{ref} = -10°C, mortars from binder A

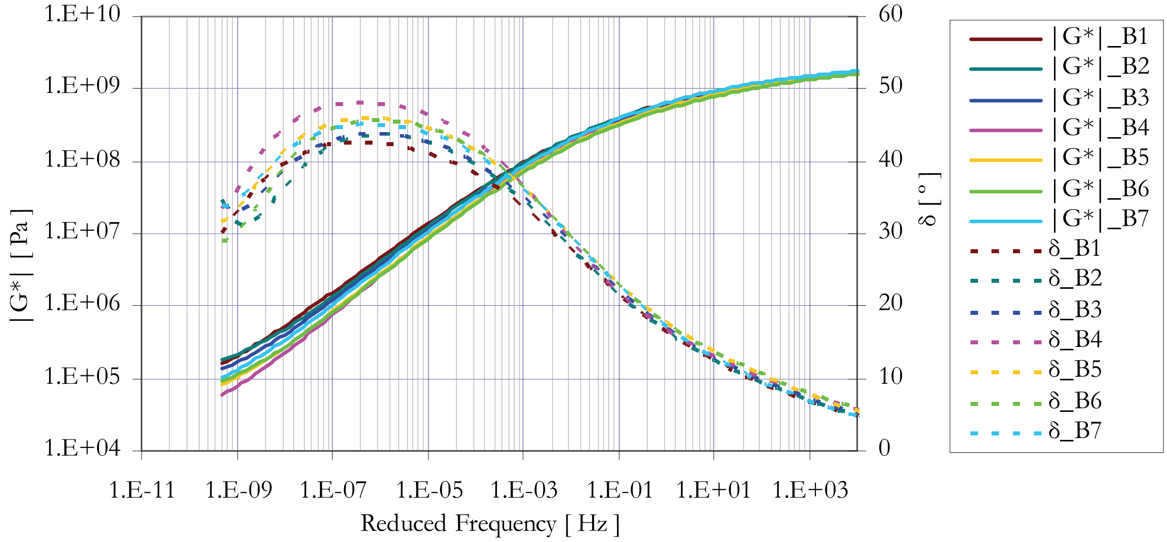

Figure 5: MC Comparisons at T_{ref} = -10°C, mortars from binder B

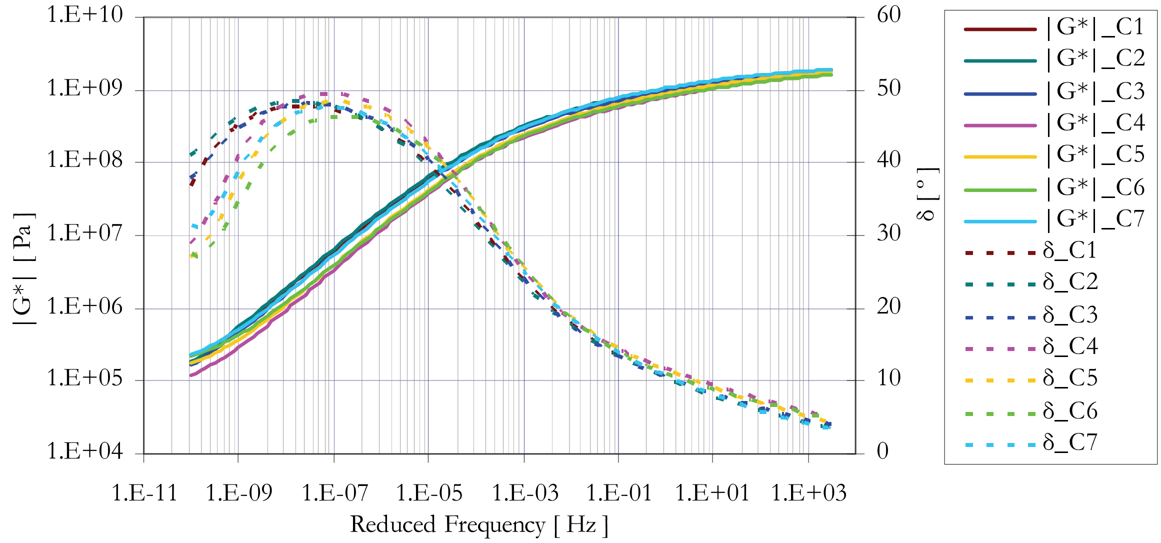

Figure 6: MC Comparisons at T_{ref} = -10°C, mortars from binder C

4.3 Effects of backhouse fines

Insight on the effects of backhouse fines was obtained from comparison of master curve results (labels 1, 2 and 3). The backhouse fines content used in these mixes were given in Table 1. From Figure 4, Figure 5 and Figure 6, the effect of backhouse fines is observed at high temperature regions.

For mortars in category A, the use of backhouse fines has resulted in a decrease of the complex modulus at high temperatures (compare master curve A2 vs. A1 and A3 in Figure 4). Increasing the content of backhouse fines from 15 gm (mortar A1) to 30 gm (mortar A3) did not result in a considerable change on the master curve results. In fact, a slight increase of complex modulus was observed.

For mortars from binder B and C, the use of 15 gm backhouse fines in mortar showed marginal effect on the master curve results (see the corresponding master curves labeled with 1 and 2 in Figure 5 and Figure 6). When the content of the backhouse fines is doubled, i.e. 30 gm, the result reveal a decrease in the complex modulus at high temperatures (see master curves with labels 3 and 2 in Figure 5 and Figure 6).

Relative to the mortars with binder A and B mortars, the effect of backhouse fines on the master curve results is very limited for mortars with binder C. Use of backhouse fines appear to have more effect on mortars with binder A than the others.

4.4 Effects of hydrated lime ($CaOH_2$)

To gain insight on the effect of $CaOH_2$, test results from mortars containing Wigro, Wigro 55K and Wigro 60K were compared. Mortars master curves with label 4, 5 and 1 are relevant. For mortars with binder A, no difference in master curve results was observed between mortars containing Wigro 55K and Wigro 60K (see master curves for A1 and A5 in Figure 4). The mortar with Wigro filler (0% $CaOH_2$) is found to be slightly stiffer at very low frequencies (high temperatures). In the intermediate to high frequencies, $CaOH_2$ resulted in slight stiffening effect (compare master curve A4 vs. A5 and A1 in Figure 4).

The master curves of B4 and B5 mortars in Figure 5 are comparable. Hence, the effect of Wigro 55K on mortars from binder B is found marginal. However, the use of Wigro 60K clearly resulted in an increase in complex modulus for wide range of temperatures. This can be seen from the master curve result of B1 mortar in Figure 5. Unlike mortars with binder A, the stiffening effect of $CaOH_2$ is clearer for mortars with binder B.

For mortars with binder C, Wigro 60K has resulted in an increase of the complex modulus for wide range of temperatures. The use of Wigro 55K resulted in a slight increase in complex modulus. Similar to mortars with binder B, a generally increasing trend of complex modulus is observed for an increase in $CaOH_2$ content in the mortar. This can be seen from master curve results of C1, C4 and C5 mortars in Figure 6.

4.5 Effects of filler amount

For all three categories of mortars investigated in this paper, increasing the filler content has resulted in an increase of complex modulus. This can be seen from the master curve results for mortars labeled 6 and 7 in Figure 4 to Figure 6. However, the stiffening effect cannot exclusively come from the change in filler amount. It is imperative to mention that the use of higher filler amount demands the use of relatively less binder in the mortar so as to keep similar void content in the PA mixture (see the compositions for mix 6 and mix 7 in Table 1). Hence, the observed increase in stiffness is partly a result of the relatively low amount of binder in the mortar.

5 SUMMARY AND CONCLUSIONS

This paper presented the results of the work carried out on mortars to investigate the effects of filler type and amount on the mechanical behavior. The study was based on phenomenological approach. Hence DSR frequency sweep test results were used for the analysis. The testing was carried out on laboratory aged samples. A total of 21 mortar types, made from three different PMB, denoted with A, B and C, were investigated. Effects of backhouse fines, hydrated lime and filler amount on the mechanical response were analyzed.

Results showed that the use of backhouse fines resulted in a decrease of complex modulus at high temperatures. The mortars from binder C however were relatively less sensitive. The general reduction in stiffness could be in relation to the filler-binder reaction at micro level. Further investigation is needed to understand if stiffening components of the bitumen were absorbed by the filler particles at micro level.

Test results from mortars containing Wigro, Wigro 55K and Wigro 60K fillers provided insight on the effect of $CaOH_2$. The effects were observed to be dependent on the kind of binder used in mortar. For category A mortars the effect of $CaOH_2$ resulted in a mixed trend: slight reduction of complex modulus at high temperature and a slight increase for intermediate to low temperatures. However, for category B and C mortars, the use of Wigro 60K resulted in a stiffening effect for wide range of temperatures. The effect is pronounced at high temperatures. The effect of Wigro 55K was limited for both B and C mortars and hence resulted in a slight increase of stiffness. The increase in stiffness at high temperatures is consistent with findings in literature (Hopman et al., 1999).

The effect of higher filler content in the mix was also investigated. While increasing the filler content, a slight reduction of bitumen content was necessary to keep a constant design air voids in the selected PA mixture. The observed difference in the mortar master curves, therefore, cannot exclusively be attributed to the filler effect. However, with the overall view of keeping same air void content in the PA mixture, an increase in filler content resulted in an increase in the mortar stiffness.

The filler effects on mortar behavior generally agree with findings reported for mastics in literature. The results from this study further show the effects are dependent on the binder type. Since the analysis in this paper was entirely based on mortar response characteristics, further extrapolation to durability cannot be made. Interpretation of the various effects to explain long term performance characteristics requires additional experimental work, such as strength and fatigue testing.

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