ISSN 1996-3343

Asian Journal of Applied Sciences

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Asian Journal of Applied Sciences 5 (8): 522-537, 2012
ISSN 1996-3343 / DOI: 10.3923/ajaps.2012.522.537

Influence of Mineral Filler Particle Size and Type on Rheological and Performance Properties of SMA Asphalt-filler Mastics

R. Muniandy, Eltaher Aburkaba, R. Yunus, H. Hamid and H. Salihudin
Department of Civil Engineering, Faculty of Engineering, University of Putra Malaysia, 43400, Serdang, Selangor, Malaysia

Corresponding Author: Eltaher Aburkaba, Department of Civil Engineering, Faculty of Engineering, University of Putra Malaysia, 43400, Serdang, Selangor, Malaysia Tel: +603-89466373/6377 Fax: +603-86567129

ABSTRACT

The performance of fillers in Stone Mastic Asphalt (SMA) pavements is unclear due to the various interaction effects of filler with asphalt binders, depending on the filler percentage, type and particle size. In this study, a laboratory investigation was conducted on the properties of asphalt binder and filler as a function of type and particle size. One asphalt binder and four filler types with different mineralogy were selected to assess the filler particle size and type effect. The selected fraction of mineral filler was blended with the asphalt binder in three different size proportions of 100/0, 50/50 and 0/100 passing the 75/20 micron sieve. To investigate the influence of filler particle size and type on mastics rheological and performance properties, Dynamic Shear Rheometer (DSR) was used over a broad range of temperatures and aging. The data obtained from this study led to the evaluation of the effects of filler type and the particle size on mastic performance. The analysis of data at the given filler/asphalt ratio showed that medium to coarse particle size filler improves the rutting and the coarse to medium particle size improves the fatigue cracking resistance of the tested mastics. Furthermore, the results from this study indicated that the fine particle size mastics seemed to lead a lower viscosity, higher penetration and lower softening point. The ceramic filler regardless the particle size was found to be more effective on producing mastics that are more elastic and less susceptible to rutting and cracking than the control mastic.

Key words: Filler type, particle size, SMA mastic, rheological property, performance properties

INTRODUCTION

The term mineral filler is typically referred to the mineral fine particle with physical size passing the 200-mesh sieve (smaller than 75 micron). The use and the application of mineral filler in asphalt mixtures are intended to improve the properties of binder by reducing the binder's inherent temperature susceptibility (Tunnicliff, 1962). Fillers play a dual role in asphalt mixtures, first; they act as a part of the mineral aggregate by filling the voids between the coarser particles in the mixtures and thereby strengthen the asphalt mixture, second; when mixed with asphalt, fillers form mastic, a high-consistency binder or matrix that cements lager binder particles together; most likely a major portion of the filler remains suspended in the binder while a smaller portion becomes part of the load bearing framework (Harris and Stuart, 1995). Being a thicker material than asphalt itself, mastic can bring more stiffness to the mixture. Additionally, it improves the adhesive qualities and provides greater thickness of asphalt binder which eventually helps to slow down the aging process. The filler material passing the number 200 standard mesh sieve, usually comprise a major amount of the total aggregate in SMA pavement. This large portion of the mineral filler with asphalt binder contributes to the interlocking of the coarse aggregate and mineral fillers which are of the same mineralogical composition as coarse aggregates but have variations in surface roughness and angularity; usually show different capacities to adsorb a given type of asphalt component; fillers particles absorb a portion of the oils in asphalt binder and the particles swell during the interaction with asphalt binder; therefore increasing the viscosity and stiffness of the asphalt-filler mastic (Bardesi *et al*., 1999).

Most research on the effect of the filler in asphalt mixtures is mainly based on engineering properties of the fillers such as gradation and filler content. Only a few research works have been dedicated to investigate the physicochemical properties of filler-asphalt systems. These properties are believed to have direct and significant influence on the performance of the asphalt mixture. Kim *et al*. (2003) tested sand particles mixed with plain asphalt binders and asphalt mastics. They concluded that the filler type affected the fatigue behavior of asphalt binders and mastics. Fillers also stiffened the binders and hydrated lime was more effective in stiffening binders than limestone fillers. Another conclusion was that even if the fillers stiffened the binders, they acted in such a way that they provided better resistance to microcracking and thus an increased fatigue life. Kavussi and Hicks (1997) in a study of four types of filler-limestone, quartz, fly ash and kaolin-attributed the higher stiffening potential of kaolin to the fineness and the surface affinity to bitumen. Also they indicated that as different filler possess different properties, they can alter the physical or chemical properties of the binder in different ways. Superior Performing Asphalt Pavements (Superpave), Superpave Mix Design (Superior Performing Asphalt Pavements, Superpave Mix Design, 1996) previous research showed that the addition of mineral fillers (such as limestone powder) to asphalt could improve the rutting resistance performance. The mineral powder improved the high-temperature thermal properties, presumably because its small particle size which resulted in a large area of the interface between mineral powder and asphalt. Mogawer and Stuart (1996) studied whether mastic and mixture properties can distinguish good mineral fillers from poor ones. Eight mineral fillers with known performance were obtained from three European countries. Mastics were tested for stiffness using the Bending Beam Rheometer (BBR), DSR and ring-and-ball softening point. They found that none of the tests distinguished among mastics with good and poor fillers. However, there was good correlation between the free binder content and the stiffness of the mastics measured by the BBR and the stiffening power measured using the Ring-and-Ball apparatus. Anderson (1987) illustrated that the size of the fine affected rheological behavior but the source of the asphalt and the mineralogy of the fine also had a significant effect on rheological behavior. Anderson *et al*. (1983) studied the effect of physicochemical properties of the filler on performance. They concluded that the mineral filler stiffens asphalt and that stiffening varies significantly between different fillers. In another study, Anderson and Tarris (1982) reported that fineness alone is not sufficient for defining how a fine will behave in an asphalt mixture. They concluded that different fillers and fines reacted differently with different asphalts. Ward and McDougal (1979) studied baghouse fillers from 16 different sources with a wide variety of particle size distribution, mineralogy and other physical properties, he indicated that fine dust, primarily 20 μm and finer, tended to combine with the bituminous binder and act as an asphalt extender. Anderson and Goetz (1973) examined the stiffening effect of a series of one-sized fillers ranging from 0.6 to 75 mm (passing No. 200 sieves). They concluded that both the size of the filler and bitumen binder composition had a significant influence on stiffening effect and that a proportion of the bitumen could be replaced by fine filler (<10 µm) but the mixtures produced were very sensitive to changes in the filler type.

Since Stone Mastic Asphalt (SMA) contains large amount of filler (8-12%) by total weight of aggregate, Still; the performance properties of asphalt-filler mastics in SMA pavement are considered to be unclear due to the various interaction effects of filler with asphalt binders, depending on the filler percentage, type and particle size, therefore, the objectives of this study was to determine the influences and effects of filler particle size and type on the filler mastic rheological, viscoelastic and performance properties through selected traditional and Superpave binder tests.

MATERIALS AND METHODS

Substances: Since, the performance of the fillers were of concern in this study, the commonly used 80/100 penetration grade soft binder was selected. This is to make sure there are no additional properties derived from additives if modified binders such as 60/70 and PG 76 were used.

Four types of mineral filler namely; Limestone (LS), Ceramic Waste (CW), Coal Fly Ash (CFA) and Steel Slag (SS) with three different particle size with proportions of filler 100/0, 50/50 and 0/100 (passing 75 µm, passing 20 µm) were used and evaluated for direct comparison.

Preparation of mineral fillers: Fillers were crushed and ground to pass the standard sieve size 75 and 20 micron. The L0, C0, F0 and S0 represent the finest particle size (passing 20 micron sieve and retained on the pan). L10, C10, F10 and S10 represent the coarsest (passing 75 micron and retained on 20 micron sieve). The L5, C5, F5 and S5 is an intermediate (medium) between the fine and the coarse. An important property of these filler combinations is that they possess different surface areas (the smaller the particle size the larger the surface area). This is important since the larger the surface area of particles the larger the amount of asphalt needed to coat such particles.

Preparation of mastics: During the development of the Superpave mix design system, researchers in the Strategic Highway Research Program (SHRP) simplified the criteria that govern the interaction between mineral filler and asphalt binder into a single parameter; the Dust/Asphalt (D/A) ratio.

First, asphalt binder and batches of fillers passing the 75 and 20 µm sieves were prepared and heated 20°C higher than the mixing temperature in order to facilitate mixing. The coarse, medium and fine filler fractions were combined with the desired proportions. The appropriate amount of asphalt was then added to produce a fine to asphalt ratios by percentage by weight that was used in the mixtures (Table 1). The mastics were prepared by blending the filler with the original asphalt on a hot plate to provide uniform heating. A mechanical mixer module IKA Labortechnik, RW 20 DZM.n was used to blend the filler and asphalt binder at established mixing temperatures of 160°C. The appropriate mixing temperatures were determined in accordance with AASHTO (1995b) T316-04 using the rotational viscometer. The mixing process was carefully performed to break down chunks of filler to ensure homogenous dispersion. An "X" shaped propeller was used to stir the asphalt-filler mastic, at speed of approximately 500 rpm. The mixing temperature was kept constant to produce homogeneous mixtures during the mixing process. The mastic was continuously stirred as it cooled to prevent settling. At the end of the mixing operation, the mastic was used to prepare specimens for the penetration, softening point, viscosity, RTFO, PAV and DSR tests.

Table 1: Filler/asphalt ratio for the twelve mastics

Filler type	Mastic type	Filler/asphalt ratio
Limestone	L10	1.62
	L5	1.59
	L0	1.58
Ceramic waste	C10	1.63
	C5	1.62
	C0	1.60
Coal fly ash	F10	1.67
	F5	1.66
	F0	1.62
Steel slag	S10	1.64
	S5	1.61
	S0	1.54

Preparation of specimens: A total of twelve asphalt-filler mastic specimens were produced and aged through an accelerated aging process. The mastics were first aged by using the Rolling Thin Film Oven Test (RTFO) in accordance with AASHTO (1995a-c) T 240-03 to simulate the short-term aging conditions. The Pressure Aging Vessel (PAV) was then used in accordance with AASHTO (1995a) to simulate the changes in physical and chemical properties that occur in asphalt binder and mastics as a result of long term, in-service oxidative aging in the field. This method involved oxidation of asphalt binder and mastics in the RTFO followed by the oxidation of the residue in the PAV. The measured rheological properties consisted of complex shear modulus (G^*) and phase angle (δ).

The data obtained from this study led to the evaluation of the influences and the effects of filler type and the particle size on rutting and fatigue cracking resistance at high and intermediate temperature, respectively using the Dynamic Shear Rheometer (DSR) in accordance with AASHTO (1993a-c) T 315.

Asphalt-filler mastic testing: The rheological characterization of asphalt binder has traditionally been based on measurements of viscosity, penetration, ductility and softening point temperature. These measurements are generally not sufficient to thoroughly describe the rheological and failure properties of asphalt binder needed to relate binder properties to mixture properties and to pavement performance. In order to accurately relate binder properties to pavement performance it is necessary to undertake more fundamental testing of binder/or mastic.

At present the most commonly used method of detailed rheological testing of binders is by means of dynamic mechanical methods using oscillatory-type testing, generally conducted within the region of Linear Viscoelastic (LVE) response. These oscillatory tests are undertaken using DSR which apply oscillating shear stresses and strains to samples of bitumen sandwiched between parallel plates at different loading frequencies and temperatures (Airey and Brown, 1998; Goodrich, 1988). The Superpave binder specifications require the asphalt binder to be tested in three critical stages: (a) the first stage is represented by an original asphalt binder which has to be transported, stored and handled prior to mixing with the aggregate, (b) the second stage is represented by the aged asphalt binder after hot mix asphalt production and construction (short-term aging) and (c) the third stage is represented by an asphalt binder which undergoes further aging during a long period of service.

Rheological and superpave asphalt binder and mastics tests: The DSR tests reported in this study were performed under the following test conditions:

- Superpave SHRP asphalt binder and mastics parameters (AASHTO, 1993a-c) T 315
- **Mode of loading: Controlled-stress:** Temperatures: 64, 58 and 52°C for un-aged and RTFO-aged binder and 25, 22 and 19°C for PAV-aged asphalt binder only (PG-Grading) to determine: Complex Modulus (G*), Phase angle (δ), Rutting parameter (G*/sinδ) and Fatigue parameters (G*. sinδ)
- **Frequency used:** 1.59 Hz (10 rad sec^{-1}) for un-aged, RTFO-aged and PAV-aged
- **Parallel plate geometries:** 8 mm diameter with 2 mm gap for PAV-aged at intermediate temperatures, 25 mm diameter with 1 mm gap for un-aged and RTFO-aged at high temperatures
- **Stress amplitude:** Within LVE response of τ = 0.12, 0.22 and 50 kPa for un-aged, RTFO-aged and PAV-aged, respectively
- Dynamic rheological analysis for the asphalt binder and mastics
- **Mode of loading:** Controlled-stress and control strain
- **Temperatures:** At high temperatures 46-82°C (Seven values) Rutting parameters (G*/sinδ) and failure temperature (temperature step test, on un-aged binder and mastics) and at intermediate temperature 20°C number of cycles to failure (time sweep test on RTFO-aged)
- **Frequency used:** 1.59 Hz (10 rad sec^{-1}) for un-aged and 10 Hz for RTFO-aged
- **Parallel plate geometries:** 8 mm diameter with 2 mm gap for RTFO-aged at intermediate temperatures, 25 mm diameter with 1 mm gap for un-aged at high temperatures
- **Stress and strain amplitude:** Within LVE response; shear stress, τ = 0.12 kPa for un-aged and strain level, γ = 1% for RTFO-aged.

The rheological properties of the binders and mastics were measured in terms of their complex shear modulus (stiffness), G* and phase angle δ (viscoelastic balance of rheological behavior). The DSR rheological data for the 80/100 penetration grade asphalt binder and the twelve mastics were then presented in the form of isochronal plots of complex modulus, G* and phase angle, δ, rutting parameter (G*/sinδ) at various temperatures as well as in the form of graphs of complex modulus versus number of cycles to failure.

RESULTS AND DISCUSSION

Asphalt binder physical, rheological and performance parameters: The asphalt binder was graded in accordance with AASHTO (1993a) MP1 to verify the performance grade. The rutting resistance parameter (G*/sinδ) of the un-aged and RTFO-aged asphalt binder was measured at 64, 58, 52°C and the fatigue parameter (G*.sinδ) of the PAV-aged asphalt binder was measured at 25, 22 and 19°C in control stress mode. Table 2 summarizes the results and properties of the base asphalt binder used in this study. The creep stiffness and direct tension is not considered for this region.

From Table 2 it can be observed that the percentage of the mass loss of RTFO residue, Rut-parameter (G*/sinδ) for un-aged, RTFO-aged and Fatigue parameter (G*.sinδ) requirements of the AASHTO (1993a) MP1 of 1% maximum, 1 kPa minimum, 2.20 kPa and 5000 kPa maximum respectively was fulfilled and the binder graded as PG52-22.

Table 2: Asphalt binder physical and rheological properties

Test	Measured value	Standard used	Requirements
Un-aged binder			
Penetration (0.1 mm), 100 g, 5 sec, 25°C	84	ASTM D 5	80-100
Softening Point (°C)	48	ASTM D 36	>45
Specific Gravity at 25°C	1.03	ASTM D 70	-
Rotational viscosity (Pa.s) @			
135°C	0.413	ASTMD 4402	3 max
165° C	0.1	ASTMD 4402	-
Flash point	230°C	AASHTO T48	219 min
Dynamic Shear, G*/sind , 52°C @ 10 red sec^{-1}, 1.59 Hz (kPa)	1.15	AASHTO TP5	1 kPa min
Aged binder @ 10 red sec^{-1}, 1.59 Hz			
Mass loss, RTFO (%)	0.10%	AASHTO TP5	1 max
RTFO aged residue G*/sind @ 52°C (kPa)	2.424	AASHTO TP5	2.20 kPa min
PAV aged residue G*sind @ 22°C (kPa)	114.9	AASHTO TP5	5000 kPa max
Creep Stiffness, S, m-value	Not tested	AASHTO TP1	300 MPa, 0.30 min
Direct tension, failure strain (%)	Not tested	AASHTO TP3	1 min

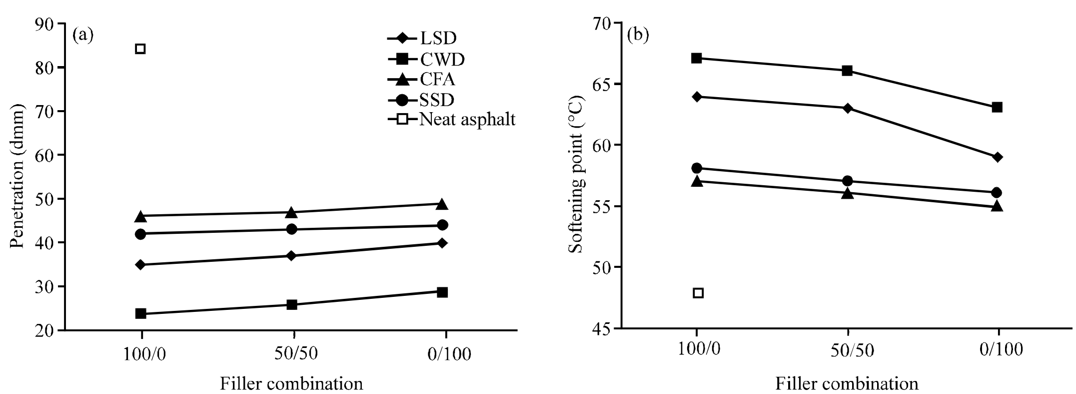

Fig. 1(a-b): (a) Penetration and (b) Softening point of neat asphalt and mastics

Mastic rheological properties

Penetration and softening point tests: The penetration tests of un-aged neat asphalt and the twelve mastics were conducted in accordance with ASTM D5: Standard Test Method for Penetration of Asphalt binders. Figure 1a shows at given F/A ratio, the Penetration decreases with the increase of filler particle size regardless of filler type. The smaller the particle size the higher the penetration was. Test results also indicate that the ceramic waste filler produced mastic having the lowest Penetration than the other fillers. The main reason of the decrease of penetration is that as F/A ratio increases much free asphalt (effective asphalt) transforms to fixed asphalt (absorbed asphalt) which in turn stiffen the mastic.

The softening point was used to evaluate high temperature properties of neat asphalt binders and mastics using the Ring-and Ball Apparatus in accordance with ASTM D36. Softening point increases with the increase of particle size; the coarser the particle size the higher the softening point was as showing in Fig. 1b. Among the four fillers ceramic waste scores the highest softening point regardless the filler particle size.

Viscosity properties test: The viscosity of asphalt binders at high temperatures is an important property as it reflects a binder's ability to be pumped through an asphalt plant, thoroughly coat the aggregate in Hot Mix Asphalt (HMA) mixture and be placed and compacted to form a new pavement surface.

The viscosity tests of un-aged neat asphalt binder and mastics were conducted by a Brookfield viscometer in accordance with ASTM D 4402. The viscosity test temperatures covered were 135 and 165°C. The rotational viscosity was determined by measuring the torque required to maintain a constant rotational speed (20 rpm) of a cylindrical spindle (Z3DIN 27 mm) while submerged in bitumen maintained at a constant temperature. Figure 2a and b show the viscosity result at both temperatures. A general trend was observed as expected. At given F/A ratio, the viscosity increases (stiffen) with the increase of filler particle size (The coarser the particle size the higher the viscosity was) regardless the filler type, this is due to increased filler/asphalt ratio. Also the ceramic filler mastic showed higher viscosity at both temperatures than the other fillers mastics.

At given F/A ratio a general trend was observed that, penetration decreased, softening point increased and viscosity (at both temperatures) of the twelve mastics increased as the filler particle size increases regardless the filler type. In terms of filler type, the penetration, softening point and viscosity of mastics containing ceramic waste were found to be superior to those containing other types of fillers. The summary of penetration grade asphalt and the twelve laboratory blended mastics properties results are presented in Table 3.

Dynamic rheological analysis of un-aged and aged binder and mastics: One of the major outcomes of the Strategic Highway Research Program (SHRP) was a performance-based asphalt binder specification which was designed to be applicable to both modified and unmodified asphalt binders, including binders with modifiers dispersed, dissolved or reacted with the base asphalt. A major objective of the asphalt research program was to identify and validate engineering properties that could be directly linked to the performance (the response to traffic loading and environment) of asphalt binders. The pavement distress modes that are considered in this study are rutting, caused by inadequate shearing resistance in the asphalt mixture and load associated fatigue cracking.

Rheological properties of un-aged asphalt-filler mastics

Rutting parameter: The rheological properties of the un-aged asphalt-filler mastics were measured in terms of complex modulus (G^*) and phase angle (δ). The permanent deformation

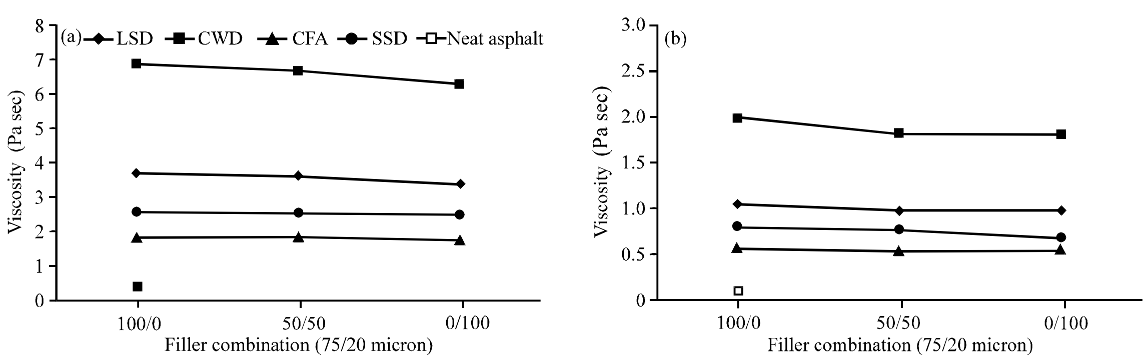

Fig. 2(a-b): Viscosity of neat asphalt and mastics at (a) 135°C and (b) 165°C

Table 3: Summary of asphalt binder and mastics traditional properties results

Material	Softening point (°C)	Penetration (mm)	Viscosity (Pa sec)	
			135°C	165°C
Neat asphalt	48	84	0.413	0.100
L10	64	35	3.713	1.034
L5	63	37	3.612	0.970
L0	59	40	3.375	0.967
C10	67	24	6.863	1.978
C5	66	26	6.652	1.812
C0	63	29	6.279	1.796
F10	57	46	1.862	0.563
F5	56	48	1.837	0.542
F0	55	49	1.775	0.542
S10	58	42	2.563	0.789
S5	57	43	2.550	0.763
S0	56	44	2.475	0.675

Table 4: Ranking of un-aged mastics at reference temperature of 52°C

Mastic type	G* (kPa)	δ (°C)	Rutting parameter, G*/sinδ (kPa)	Ranking
L10	3.86	59.7	4.47	8
L5	3.83	57.7	4.53	7
L0	3.80	68.3	4.09	12
C10	4.17	49.9	5.45	4
C5	4.15	43.9	5.99	1
C0	3.91	61.7	4.44	9
F10	3.32	46.9	4.55	6
F5	3.28	43.8	4.74	5
F0	3.26	52.3	4.12	11
S10	4.34	51.8	5.52	3
S5	4.28	47.4	5.81	2
S0	4.24	73.6	4.42	10

rutting parameters (G*/sinδ) were then determined at a loading frequency of 1.59 Hz in control stress mode at a reference high temperature of 52°C at which rutting is believed to be important, the performance (ranking) of the twelve mastics are presented in Table 4.

It can be seen from Table 4 that the filler particle size and type influenced the rheological properties of asphalt binders differently. In fact, Table 4 shows that the type of filler and the particle size have different effects on the same asphalt binder due to the filler properties and physical chemical reactions between the two materials. The particle size (fine to coarse) of the filler show a relatively consistent increase in G* and decrease in sinδ regardless the filler type. The test results showed that the complex modulus (G*) increases with the increase of particle size.

This is consistent with the results of viscosity, softening point and penetration testing of asphalt-filler mastics which showed that the coarse to medium particle size of the filler regardless the filler type has caused the highest stiffening effect compared to the fine particle size mastics. This kind of behavior is expected since the higher the F/A ratio the stiffer the mix (less free asphalt). However, the ceramic waste filler (C5) and steel slag (S5) show a more pronounced increase in G* and decrease in sinδ which improved temperature susceptibility and fatigue resistance with medium particle size regardless the type followed by (F5 and L5) which indicated a general trend, that for given filler proportions and binder content the medium particle size caused the most stiffening and superior performance of all the three filler fractions. This results demonstrates that complex modulus (G*) alone is not sufficient to characterize asphalt binder/or mastic, phase angle (δ) is also need.

Fatigue parameter (G*. sinδ): The rheological properties of the PAV-aged asphalt binder and asphalt-filler mastics were measured in terms of complex modulus G* and phase angle δ (viscoelastic balance of rheological behavior) using parallel plate geometries of 8 mm diameter with 2 mm gap. The fatigue parameter (G*.sinδ) were then determined at a loading frequency of 1.59 Hz (10 rad sec^{-1}) in control strain mode (γ = 1%), since fatigue cracking was considered a strain controlled phenomenon, at a reference intermediate temperature of 20°C at which fatigue cracking is believed to be important.

The SHRP specification prescribed a relationship whereby a reduction in G*•sin δ at 10 rads sec^{-1} corresponds to improved fatigue resistance. Using the hypothesis that a reduction in G*•sinδ will correspond to improved fatigue resistance, the fatigue parameters and the ranking of the twelve asphalt-filler mastics were calculated and presented in Table 5.

The G*•sin δ values in Table 5 indicated that, the finer particle size asphalt-filler mastics exhibited more brittleness at low temperature and after been aged in PAV vessel (long term aging) compared to the other two asphalt-filler mastic fractions, this could be due to the complexity of the asphalt binder and the interaction between the constituent. Also, Table 5 indicated that, the proprietary (C10) should have far superior fatigue performance compared to the control mastics of limestone and laboratory blended fly ash and steel slag mastics which indicated a general trend that, for the given filler proportions and binder content (F/A ratio) the coarse and medium particle size (C10 and C5), (F10 and L5) and (F5, S5) perform better than the fine particle size asphalt-filler mastics regardless filler types. In terms of filler type, the rankings indicate that the ceramic waste filler tended to perform better and produced mastic having the highest fatigue resistance than the other fillers regardless the particle size.

Table 5: Ranking of PAV-aged mastics at reference temperature of 20°C

Mastic type	G* (kPa)	δ (°C)	Fatigue parameter, G*.sinδ (kPa)	Ranking
L10	62.1	67.6	57.41	5
L5	55.9	60.9	48.84	4
L0	145.0	81.5	143.40	12
C10	25.9	55.9	21.45	1
C5	36.0	60.7	31.39	2
C0	91.4	70.3	86.05	8
F10	38.7	74.6	37.31	3
F5	84.4	71.4	79.99	6
F0	97.6	78.9	95.77	10
S10	117.0	49.9	89.49	9
S5	96.3	63.2	85.96	7
S0	119.0	63.4	106.00	11

Binder and mastics rutting performance

Temperature step test: The SHRP rutting parameters (G*/sinδ) for the un-aged penetration grade asphalt (80/100) and the twelve laboratory blended mastics are presented in Table 6. The parameters have been determined at high and intermediate temperature of 46 to 82°C with increment of 6°C. The loading frequency used in the specification was selected as 1.59 Hz (10 rad sec^{-1}). The permanent deformation ranking of the asphalt binder and twelve mastics has also been included in the Table 6 as a function of the asphalt binder and mastics rutting parameters at failure temperature with higher values of G*/sinδ (behaves more like elastic solid) and higher failure temperature indicating superior rutting resistance.

The DSR rheological data for the un-aged penetration grade neat asphalt (80/100) and the twelve mastics were then presented in the form of isochronal plots (Fig. 3) of complex modulus, G* and phase angle, δ, at various temperature (42-82°C) and at a loading frequency of 1.59 Hz under control stress mode.

The isochronal plots in Fig. 3a-c show that, the medium particle size filler mastics (C5 and S5) has the highest stiffness modulus (G* value) at the lower end of the temperature domain and a high stiffness modulus at higher temperatures compared to the neat asphalt and L5 and F5 mastics. This indicates the improved (reduced) temperature susceptibility of the ceramic and steel slag mastics resulting in both increased flexibility at lower temperatures and increased hardness at high temperatures. Similar results were seen for the coarse particle size filler mastics (C10, S10, L10 and F10). On the other hand, the fine particle size filler mastics score the lowest G* value at both temperatures (high and low temperature domain). The rutting parameter results in Table 6 confirm that, the medium to coarse particle size filler mastic show superior performance than the fine particle size regardless filler type.

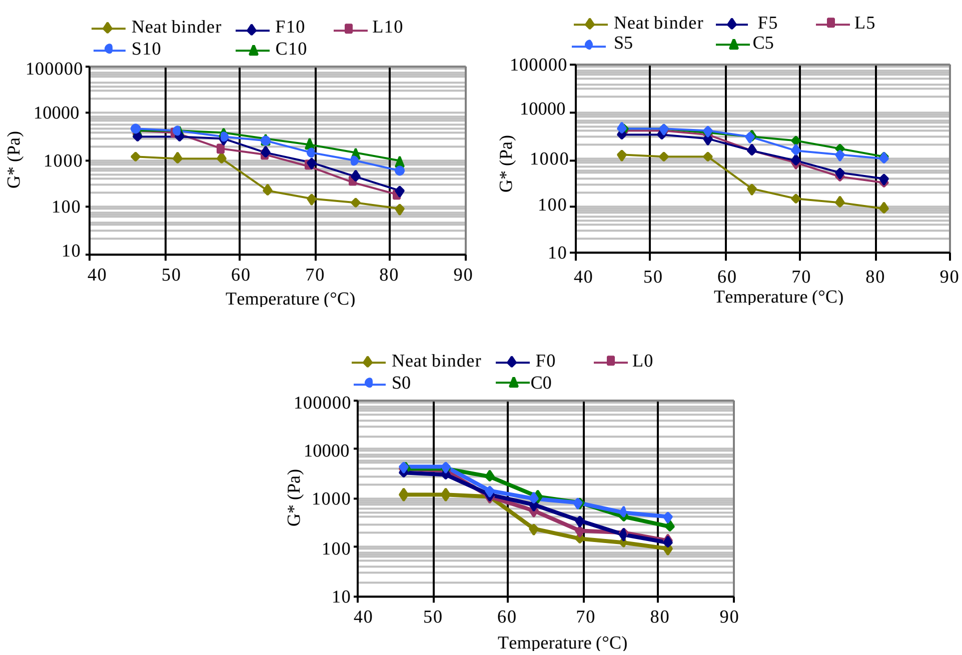

Fig. 3(a-c): Isochronal plots of neat asphalt and mastics G* for (a) Coarse, (b) Medium and (c) Fine filler particle size at 1.59 Hz

Table 6: Rutting Parameters of un-aged asphalt binder and mastics (1.592 Hz (10 rad sec^{-1})) at various temperatures

	Rutting parameter, G*/sin δ (kPa)						
Mastic type	46°C	52°C	58°C	64°C	70°C	76°C	82°C
Binder	1.18	1.15	1.10	0.232	0.152	0.126	0.101
L10	5.12	4.47	1.88	1.283	0.762	0.342	0.192
L5	5.17	4.53	3.70	1.681	0.837	0.436	0.329
L0	4.74	4.09	1.16	0.587	0.217	0.196	0.137
C10	6.30	5.45	5.19	3.584	2.514	1.432	1.011
C5	6.60	5.99	5.37	3.763	2.769	1.651	1.142
C0	4.80	4.44	2.97	1.133	0.778	0.443	0.262
F10	5.09	4.55	3.10	1.534	0.923	0.487	0.211
F5	5.31	4.74	3.14	1.732	0.975	0.511	0.378
F0	4.64	4.12	1.23	0.731	0.336	0.182	0.132
S10	6.09	5.52	3.93	2.784	1.453	0.997	0.593
S5	6.51	5.81	5.04	3.062	1.624	1.264	1.053
S0	4.57	4.42	1.39	0.993	0.783	0.534	0.412

The phase angle, δ, is generally considered to be more sensitive to the chemical structure and morphology of the asphalt binder and, therefore, more sensitive to the degree and type of modification of the asphalt binder than G* (Puzinauskas, 1979). The phase angles for the neat asphalt binder at 52°C approach 90°C and, therefore, predominantly viscous behavior, while the mastics begins to significantly improve the elasticity of the modified binders. This increase in elasticity at high temperatures can be attributed to the viscosity of the neat binder being low enough to allow the elastic network of the asphalt-filler mastic to influence the mechanical properties of the neat binder.

The phase angle isochronal plots in Fig. 4a-c show the change in rheology with the addition of filler as a reduction in δ for all the mastics and, therefore, an increased elastic behavior (response) compared to the neat asphalt and control mastic of limestone. This decrease in phase angle occurs at low and high temperature but is more significant at a temperature below 70°C for all the mastics except the fine particle size filler mastics. The steel slag and ceramic waste mastics (C10, S10, C5,) perform the best across the entire temperature domain of the plots followed by F10, F5, S5 and L10.

Stiffening effects due to filler addition can be evaluated by plotting the dynamic shear moduli (or rutting parameter) of both, the binder and mastics, as a function of type and particle size of the filler. The three plots of Fig. 5a-c below, show that the rutting parameters (G*/sinδ) and implicitly the dynamic shear moduli, of mastics obtained by adding ceramic and steel slag are much larger than those where coal fly ash or limestone were used. This may be due to the fact that ceramic and steel slag deformation resistance (G*mastic/G* Bitumen) as well as the values of G* is higher than those of the other two types of filler used in this study.

In general, greater G*/sinδ values have been obtained for the ceramic and steel slag mastics and lower values for coal fly ash and the control mastic of limestone with the relative increases in G*/sin δ being higher at the lower and intermediate temperature below 64°C. The medium to coarser size particles of steel slag mastics (S5 and S10) and ceramic waste mastics (C5 and C10) displayed the higher G*/sinδ and higher failure temperature values and were therefore ranked higher than the coal fly ash in terms of their potential rutting resistance. On the other hand, the medium to coarse size particles of fly ash mastics (F5 and F10) displayed higher G*/sinδ and failure temperature values than the control mastic of limestone (L10, L5 and L0).

In terms of filler type, the rankings indicate that the steel slag and ceramic mastics (medium to coarse size particles) tended to perform better than the control and the other mastics at low and

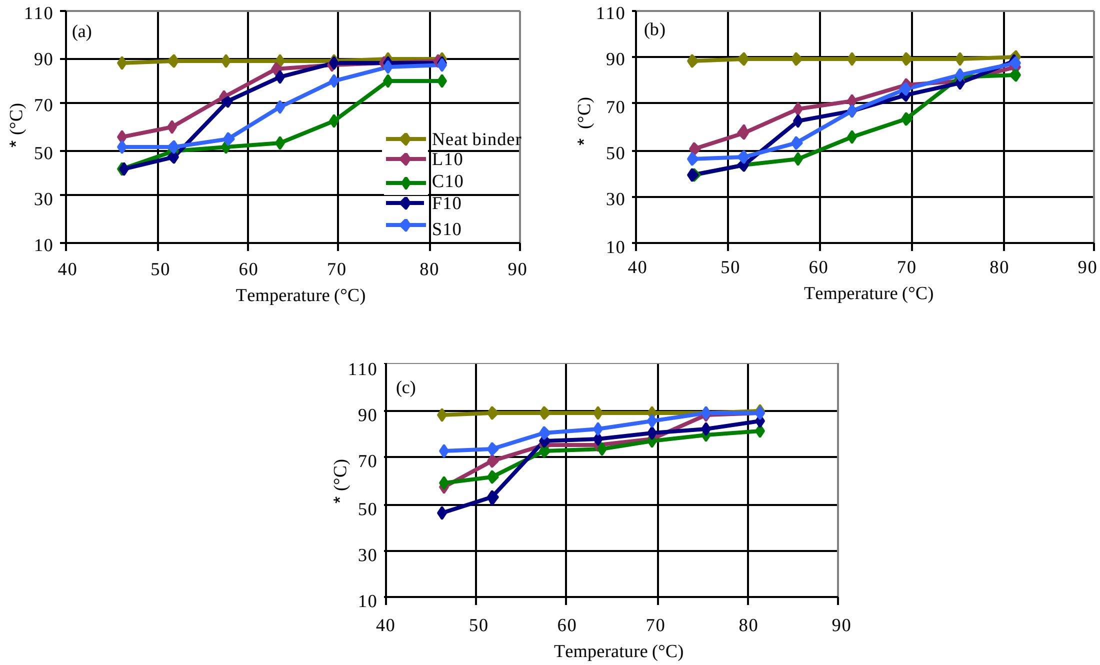

Fig. 4(a-c): Isochronal plots of neat asphalt and mastics δ for (a) Coarse, (b) Medium and (c) Fine filler particle size at 1.59 Hz

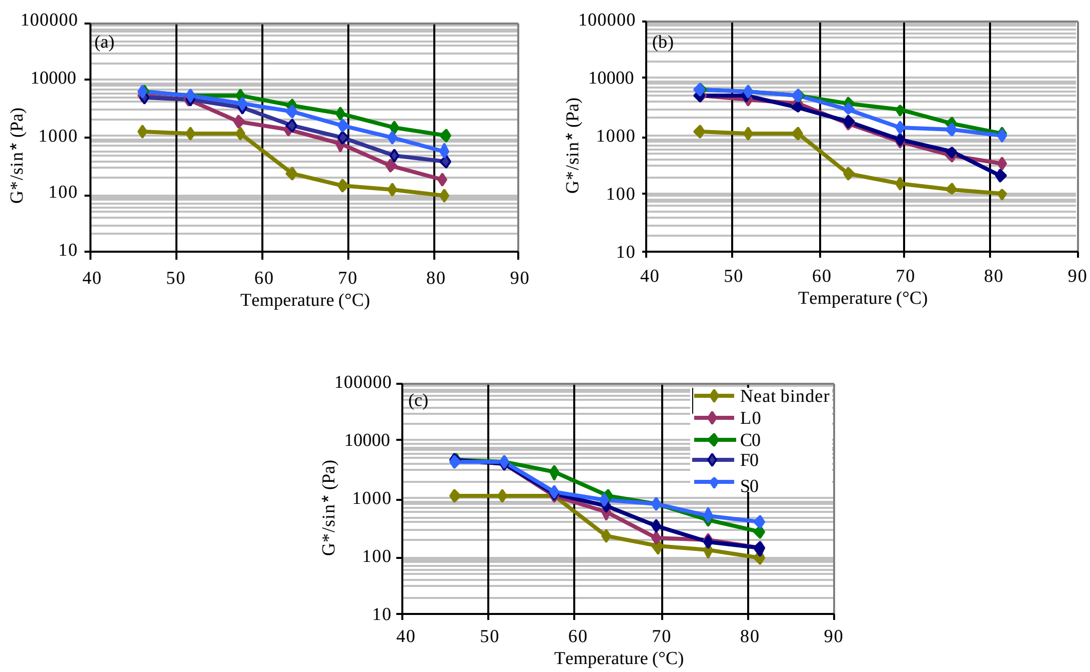

Fig. 5(a-c): Rutting parameter and failure temperature at 1 kPa of asphalt binder and mastics for (a) Coarse, (b) Medium and (c) Fine filler particle size high temperatures. The G*/sinδ did follow the same trend for all of the proportion tested. In addition, the predicted permanent deformation performance of the twelve mastics was greatly above the conventional penetration grade asphalt binder.

Effect of temperature on asphalt-filler mastics: The failure temperature of the un-aged asphalt binder and the twelve mastics was measured from the DSR temperature step test at G*/sinδ (Rutting Parameter) corresponding to 1000 Pa and the results and PG-Grading of asphalt-filler mastics are presented in Table 7. Greater failure temperature values have been obtained for the medium to coarse particle size of the steel slag and ceramic waste filler mastics (S5, C5, C10, S10) compared to the control mastics of limestone while coal fly ash mastics perform much the same as limestone mastics. Also, the coarse and medium particle size asphalt-filler mastics show a gradual change with temperature while the fine particle size asphalt-filler mastics show a rapid decline with temperature. The increment of failure temperature is very important to improving the high performance of asphalt-mastic. It will help to reduce the high temperature deformation and rutting damage of asphalt pavement. The results in Table 7 confirm once again that, the medium to coarse particle size show superior performance than the fine particle size regardless filler type.

The DSR Superpave asphalt-filler mastic properties test results in Table 7 indicated that the (L10, L5, F10, F5 and C0) increased the high temperature stiffness by two grades (S10) increased by three grades (C10) increased by four grades and (C5, S5) increased by five grades and the testing on the (L0, F0, S0) indicated that the high temperature grade was one grade higher than the base asphalt binder. A general trend was observed that, the medium to coarse filler particle size mastics regardless the filler type were performed significantly higher than that observed for the fine filler particle size mastics.

Binder and mastics fatigue performance

Time sweep test: The fatigue parameter (G*.sinδ) is measured in the linear viscoelastic range using small strains, this approach is unlikely to be useful in representing the effect of repeated cyclic loading and the changes in binder and mastic properties with accumulation of damage. The effort to develop a new test focused on simulating the fatigue phenomenon in a binder-only fatigue test such that damage behavior could be directly monitored. The DSR was used to conduct what is called a "time-sweep test." The test provides a simple method of applying repeated cycling of stress or strain loading at selected temperatures and loading frequency (Bahia *et al*., 1999).

In this study time sweep test was performed on RTFO aged asphalt binder and twelve filler-asphalt mastics to simulate the effect of mixing and compaction and the testing was conducted at 20°C, a strain of 1% which is small enough to develop fatigue damage and not to cause any nonlinear damage, was selected and applied to each 8 mm diameter and 2 mm thick DSR specimen with constant loading frequency of 10 Hz in control strain mode to determine the fatigue life of the mastics. The number of cycles to failure (fatigue life) was determined from a set of complex modulus

Table 7: PG-grading of asphalt-filler mastics

	LSD			CWD			CFA			SSD		
	L10	L5	L0	C10	C5	C0	F10	F5	F0	S10	S5	S0
DSR temp. @1 kPa	66.4	67.7	62.4	81.5	82.7	65.7	68.8	69.2	61.8	75.8	83.8	63.5
SHRP PG (High temp.)	64	64	58	76	82	64	64	64	58	70	82	58

Table 8: Fatigue performance and ranking of RTFO-aged mastics

Mastic	Initial Gi* (Pa)	50% of Gi* (Pa)	No. of cycles @ 50% of Gi*	Ranking
L10	10,560.00	5,440.00	81,133.00	4
L5	9,280.00	4,664.00	88,347.00	3
L0	11,220.00	5,490.00	96,161.00	1
C10	12,060.00	6,075.00	94,959.00	2
C5	9,480.00	4,740.00	58,872.00	7
C0	8,480.00	4,200.00	73,295.00	6
F10	6,300.00	3,150.00	54,064.00	8
F5	8,960.00	4,550.00	76,907.00	5
F0	4,560.00	2,298.00	48,639.00	12
S10	7,020.00	3,480.00	52,250.00	10
S5	6,200.00	3,110.00	51,649.00	11
S0	8,280.00	4,152.00	52,856.00	9

(G*) versus time in seconds plots, the time in seconds was calculated at 50% of initial G*, the number of cycles to failure was then determined by multiplying the time at 50% of initial G* by the frequency (10 Hz). The results of time sweep test are presented in Table 8. The initial G* values are slightly different and the mastics show significantly different fatigue behavior. Six of the mastics (L0, C10, L5, L10, F5 and C0) showed high resistance to fatigue after more than 70,000 cycles, while the other mastics showed variation in fatigue life when it was defined as the number of cycles to the initial G* value by 50%.

In general, the data obtained from time sweep tests showed satisfactory performance of fine particle size asphalt-filler mastics (L0, C0 and S0), while the data from fatigue parameter (G*.sinδ) tests showed significantly poor performance of fine particle size asphalt-filler mastics. This phenomenon may be due the aging effect since the former test conducted on RTFO aged specimens (short term aging), while the later conducting on PAV aged specimens (long term aging). However, the overall predicted performance of fine asphalt-filler mastics is questionable since the finer particle size asphalt-filler mastics exhibited more brittleness and hardening with loading frequency and at low temperature and this in turn will cause significantly poor long term performance.

It can be observed from Table 8 that, the fine particle size asphalt-filler mastics of limestone and steel slag have a fatigue life approximately 15.63 and 1.15% greater than the coarse asphalt-filler mastics, respectively, while the fine particle size asphalt-filler mastics of ceramic and coal fly ash recorded a reduction in fatigue life approximately 22.81 and 10.03% compared to coarse particle size, respectively.

CONCLUSIONS

To investigate the effect of filler type and particle size on performance properties of asphalt binder and mastics, twelve mastics were produced in the laboratory, using four types of filler and three particle size proportions.

A series of selected Superpave binder tests were conducted using rotational viscometer and DSR. Mastics were artificially aged through an accelerated aging process (RTFO and PAV). The traditional (viscosity, penetration and softening point) and rheological (G* and δ) properties together with performance prediction parameters (G*/sinδ and G*.sinδ) of rutting at intermediate to high temperature (temperature steps test) and the cracking properties at intermediate temperature (time sweep test) were evaluated. From the test results, the following conclusions were drawn for the materials used in this study:

- A general trend was found, as expected regardless the type of filler, viscosity increases, penetration decreases and softening point increases with the increase of filler particle size and also shows the ceramic filler produced mastic having lower penetration, higher softening point and higher viscosity at both temperatures (135 and 165°C) than the other fillers mastics
- All twelve asphalt-filler mastics show a different increase in complex modulus with increasing temperature, particularly at high temperature. The isochronal plots show that the medium to coarse particle size of ceramic mastics have the highest stiffness modulus at the lower end of the temperature domain
- The phase angle plots for the twelve filler mastics show a reduction in phase angle this is due to the change in rheology with the addition of filler and, therefore, an increased elastic behavior. This decrease in phase angle occurs at low and high temperature but is more significant at a temperature below 70°C for all the mastics with larger decreases being experienced by the asphalt ceramic mastics regardless the particle size
- The analysis of the fundamental rheological parameters of complex modulus and phase angle, as measured with the DSR, have indicated that, the Superpave (SHRP) rutting and fatigue parameters, have predicted superior rutting performance (medium size particles) for the ceramic waste (C5) and steel slag (S5) mastic followed the coal fly ash (F5) and limestone (L5) mastic and the fatigue performance (coarse to medium size particles) of the ceramic waste (C10) and coal fly ash (F10) followed by limestone (L5) and steel slag (S5) mastics
- A general trend was observed from temperature steps test that the failure temperature of medium filler particle size mastics far superior than the other two fractions of particle size regardless filler type
- The fatigue performance from time sweep test indicated that fine limestone mastic (L0) showed far superior performance, coarse ceramic waste (C10) mastic ranked second, medium coal fly ash (F5) mastic ranked third and fine steel slag (S0) had the least
- In general, the medium to coarse particle size of the filler seems to lead to better rutting resistance and fatigue cracking properties than the fine size particle does. On the other hand, the filler type was found to have a significant effect on both $G^*/\sin\delta$, $G^*\sin\delta$ and failure temperature properties. The improvement in rutting resistance and fatigue life due to addition of filler is much greater for the ceramic mastic than for the other types. This indicates that the physicochemical interaction between asphalt binder and filler is dependent on the type of materials

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